The Case for SCEC

Thomas H. Jordan
Former Director, Southern California Earthquake Center

SCEC Annual Meeting, 11 Sept 2017
The Case for SCEC

1. The SCEC community has created an interdisciplinary, multi-institutional “virtual organization” for coordinating earthquake research in Southern California
   • Communicates useful knowledge for reducing earthquake risk and improving resilience

2. SCEC sustains deep collaborations within an open, investigator-driven program of fundamental earthquake research
   • Involves over 1000 earthquake experts at more than 70 research institutions

3. SCEC partners with many organizations to develop and disseminate authoritative earthquake information and to educate the public about the earthquake threat
   • Coordinates the Earthquake Country Alliance in California and ShakeOut drills worldwide

4. SCEC collaboratories provide a unique cyberinfrastructure for system-level modeling of earthquake phenomena
   • In 2017, SCEC was awarded 447 million CPU-hours on the nation’s most powerful supercomputers

5. Earthquake system science is revolutionizing seismic hazard analysis and earthquake forecasting
   • A continuing program of coordinated interdisciplinary research will be necessary to refine and validate the new tools of physics-based PSHA and OEF
Southern California Earthquake Center

SCEC Mission:

1. Gather data on earthquakes in Southern California and elsewhere

2. Integrate information into a comprehensive, physics-based understanding of earthquake phenomena

3. Communicate understanding as useful knowledge for reducing earthquake risk and improving community resilience

Physical representations of active fault systems and emergent earthquake behaviors
The technical issues of earthquake science can be of great interest to the public…
Dynamics of fault rupture
Nonlinear shallow crustal effects
Tsunami generation
Performance of tall buildings
"...the goal of SCEC is to integrate research findings from various disciplines in earthquake-related science to develop a prototype probabilistic seismic hazard model (master model) for Southern California..."

Through appropriate interaction and feedback, the requirements of the master model will guide data acquisition and interpretation.”

- Aki et al., SCEC proposal, 1989
SCEC1 History

- Founded in 1991 as NSF Science & Technology Center, jointly sponsored by the USGS
  - Motivation: lack of effort on Southern California earthquake problem
  - Goal: to develop a “master model” of earthquake hazards

- Organized through a series of focused studies
  - Phase I: Future Seismic Hazards in Southern California, Implications of the 1992 Landers Earthquake Sequence
  - Phase II: Seismic Hazards in Southern California: Probable Earthquakes, 1994 to 2024
  - Phase III: Accounting for Site Effects in Probabilistic Seismic Hazard Analyses of Southern California
  - Phase IV: Regional Earthquake Likelihood Models

- In 2002, “graduated” from STC Program and reconfigured as a free-standing center under a 5-year NSF/USGS collaborative agreement (SCEC2)
Proposal to the National Science Foundation and the United States Geological Survey for sponsorship of the Southern California Earthquake Center.

Submitted December 1, 2000
Southern California as a Natural Earthquake Laboratory

- Tectonical diversity of faulting
  - Well instrumented and mapped
  - Right scale for system-level earthquake research

- High-risk environment with a population of over 23 million
  - Comprises 40% of the national annualized earthquake risk

- Proving ground for new risk-reduction technologies
  - Fault-based earthquake forecasting
  - Physics-based hazard analysis
  - Performance-based design
  - Earthquake early warning

SCEC Unified Structural Representation (USR) [Shaw et al., 2015]
Schema of the SCEC Community Models, showing the main directions of information flow among the models. Box colors indicate the development status: mature (green), youthful (yellow), in utero (red).
SCEC Community Modeling Environment, April 24, 2001

1. Standard seismic hazard analysis
2. Ground motion simulation
3. Physics-based earthquake forecasting
4. Ground-motion inverse problem

Unified Structural Representation
- Faults
- Motions
- Stresses
- Seismic velocities

FSM = Fault System Model
RDM = Rupture Dynamics Model
AWP = Anelastic Wave Model
SRM = Site Response Model

Ground Forecast
Attenuation Relationship
Intensity Measures

Invert

Other Data
Geology
Geodesy

Funded for 2001-2006 by a $10M NSF/ITR grant
TeraShake Simulations of M7.7 Earthquake on the San Andreas Fault

Empirical GMPE

Physics-Based Simulation

Directivity-basin coupling

Peak ground velocity (PGV) map

Southern California Earthquake Center

Los Angeles
Santa Monica
Whittier Narrows
Narrows
Long Beach
Irvine
Palm Springs
Riverside
Riverside
San Andreas Fault


TeraShake Simulation (M7.8)
Validation Using the Virtual Earthquake Approach (VEA)

ShakeOut Scenario

M7.8 earthquake simulation on Southern San Andreas Fault
(deterministic band $f = 0-1$ Hz; stochastic band $f = 1-10$ Hz)

**The Great Southern California ShakeOut**
November 13, 2008

### Exercise Results
- Largest emergency response exercise in US history
- Golden Guardian exercise
- Public events involving 5.3 million registered participants
- Demonstrated that existing disaster plans were inadequate for an event of this scale
- Motivated reformulation of system preparedness and emergency response
- Scientific basis for the LA Seismic Safety Task Force report, *Resilience by Design*

### Scenario Results
- M7.8 mainshock
  - Broadband ground motion simulation (0-10 Hz)
- Large aftershocks
  - M7.2, M7.0, M6.0, M5.7…
- 10,000-100,000 landslides
- 1,600 fire ignitions
- $213 billion in direct economic losses
  - 300,000 buildings significantly damaged
  - Widespread infrastructure damage
  - 270,000 displaced persons
  - 50,000 injuries
  - 1,800 deaths
- Long recovery time
Resilience by Design
Report of the Los Angeles Mayoral Seismic Task Force (Lucy Jones, chair)
Released Dec 8, 2014

An ambitious plan to
– strengthen buildings
– fortify water supply and distribution system
– enhance reliable telecommunications

Team included USGS, CGS, FEMA, SCEC, and nearly 200 other partners in government, academia, emergency response, and industry.
Resilience by Design
Report of the Los Angeles Mayoral Seismic Task Force (Lucy Jones, chair)
Released Dec 8, 2014

“This Report’s approach to evaluating the severity of the risk relies on the ShakeOut Scenario… created by a multidisciplinary team convened by the Multi-Hazards Demonstration Project of the USGS…”

The Jones report demonstrated how the chain of scientific inference from hazard characterization to loss estimation can lead to implementation of effective mitigation options with well-defined costs and benefits.
2016 ShakeOut Earthquake Drills

In 2016, more than 55 million people were registered to participate in ShakeOut drills

2016 Official ShakeOut Regions
28 Regions worldwide
22 U.S. regions spanning 51 states & territories
70 additional countries with independent registrations (individuals, schools, etc.)

Participation History (worldwide)
2016: 55.9 million (+ major drills in MX, PH, etc.)
2015: 43.8 million (+ TX, IA, LA, NE, global growth)
2014: 26.5 million (+ NM, KS, FL, Quebec, Yukon, more)
2013: 25.0 million (+ Southeast, Northeast, MT, WY, CO)
2012: 19.5 million (+ Japan, New Zealand, UT, WA, AZ)
2011: 12.5 million (+ Central US, BC, OR)
2010: 8.0 million (+ Nevada and Guam)
2009: 6.9 million (+ Northern California)
2008: 5.4 million (Southern California)

Key Facts
• Participants practice “Drop, Cover, and Hold On” and other aspects of their emergency plans.
• Register at www.ShakeOut.org
Cross-Verification of ShakeOut Simulations

**M8 Simulation – 2010**

- Magnitude 8.0 “wall-to-wall” scenario on southern San Andreas Fault
  - Fault length: 545 km
  - Minimum wavelength: 200 m
- Dynamic rupture simulation on *Kraken*, 7.5 hours using 2160 cores
  - 881,475 subfaults, 250 sec of rupture
  - 2.1 TB tensor time series output
- Wave propagation simulation performed on *Jaguar*, 24 hours using 223,074 cores (220 Tflop/s sustained).
  - 436 billion grid points representing geologic model of dimension 810 x 405 x 85 km (40-m sampling)
  - 368 s of ground motions (160,000 steps of 0.0023 s)

Ground motions of outer-scale event (M8) computed deterministically up to 2 Hz

Performance of SCEC Large-Scale Simulations

4D outer/inner scale ratio

Sustained computational speed

TeraShake
ShakeOut
M8-1Hz
M8-2Hz

$1 \times 10^{13}$
$1 \times 10^{14}$
$1 \times 10^{15}$
$1 \times 10^{16}$
$1 \times 10^{17}$

TeraShake
ShakeOut
M8-1Hz
M8-2Hz

x3000 in 5 years
Uniform California Earthquake Rupture Forecast

- **Preproposal submitted to CEA**
  - Dec 3, 2003
- **UCERF2 proposal submitted**
  - Feb 14, 2005
  - Approved Mar 20, 2005
  - Started Jun 1, 2005
  - UCERF1 submitted Feb 1, 2006
  - UCERF2 submitted Sep 30, 2007
- **UCERF3 proposal submitted**
  - Dec 15, 2008
  - Approved Jun 25, 2009
  - Started Jan 1, 2010
Began the development of time-dependent, fault-based earthquake forecasts in 1988

Released first Uniform California Earthquake Rupture Forecast (UCERF2) in 2007
- Assumes fault segmentation
- Excludes multi-fault ruptures
- Over-predicts M ~6.7 events
- Inconsistent elastic rebound
- No clustering (e.g., aftershocks)

UCERF3-TI
- Time-independent, incorporated into 2014 National Seismic Hazard Maps

UCERF3-TD
- Long-term time-dependent, based on a Reid renewal statistics

UCERF3-ETAS
- Short-term time-dependent, based on Omori-Utsu statistics (ETAS model)
Working Group on California Earthquake Probabilities

Uniform California Earthquake Rupture Forecast

The UCERF projects have been major drivers of SCEC research

Field et al. (2007)
Uniform California Earthquake Rupture Forecast

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Field et al. (2014, 2015, 2017)
UCERF3 Combines Two Scales of Seismic Hazard Change

• Faults accumulate stress over centuries during quasi-static tectonic loading
  – stress cycle represented by Reid renewal models
• Faults redistribute stress in seconds during dynamic ruptures
  – earthquake sequences represented by Omori-Utsu clustering models

<table>
<thead>
<tr>
<th>Probabilistic Seismic Hazard Analysis (PSHA)</th>
<th>Operational Earthquake Forecasting (OEF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>“Seismic Climate Forecasting”</td>
<td>“Seismic Weather Forecasting”</td>
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</table>

long-term renewal models ← “medium-term gap” → short-term clustering models

| century | decade | year | month | week | day |

Anticipation time ←
California Earthquake Forecasting Models

Reid renewal

UCERF2

NSHM

long-term renewal models

“medium-term gap”

Omori-Utsu clustering

UCERF3-TD

UCERF3-ETAS

STEP, ETAS

short-term clustering models

Anticipation time

century decade year month week day
Short-term Forecasting Models

Statistical models based on the Gutenberg-Richter (magnitude-frequency) and Omori-Utsu (aftershock productivity) scaling relations

California STEP model
29 July 2008
(Gerstenberger et al., 2005)

Italy ETAS model
7 April 2009
(Marzocchi & Lombardi, 2009)

New Zealand STEP model
28 June 2011
(Gerstenberger, 2011)
Collaboratory for the Study of Earthquake Predictability (CSEP)

Cyberinfrastructure for automated, blind, prospective testing of forecasting models in a variety of tectonic environments and on a global scale

Established under a $1.2M grant by the W. M. Keck Foundation, awarded Jan 1, 2006

CSEP Testing Regions & Testing Centers
442 models under test on Sept 1, 2017
International Commission on Earthquake Forecasting for Civil Protection (ICEF)

• Charged on 11 May 2009 by Dipartimento della Protezione Civile (DPC) to:
  1. Report on the current state of knowledge of short-term prediction and forecasting of tectonic earthquakes
  2. Indicate guidelines for utilization of possible forerunners of large earthquakes to drive civil protection actions

• ICEF report: “Operational Earthquake Forecasting: State of Knowledge and Guidelines for Utilization”
  – Findings & recommendations released by DPC (Oct 2009)

Members (9 countries):
  T. H. Jordan, Chair, USA
  Y.-T. Chen, China
  P. Gasparini, Secretary, Italy
  R. Madariaga, France
  I. Main, United Kingdom
  W. Marzocchi, Italy
  G. Papadopoulos, Greece
  G. Sobolev, Russia
  K. Yamaoka, Japan
  J. Zschau, Germany

Operational Earthquake Forecasting

Timely dissemination of authoritative information about the future occurrence of potentially damaging earthquakes to reduce risk and enhance earthquake preparedness in threatened communities

Subset of ICEF Recommendations:

• Authoritative forecasts should be made available at regular intervals, during periods of normal seismicity as well as during seismic crises
  – The public expects scientists to be transparent in forecasting natural disasters using the best information and most accurate methods
  – Information vacuums spawn bogus predictions and misinformation
• Advisories should be rigorously reviewed and updated by experts in the creation, delivery, and utility of earthquake information
  – Earthquake forecasts should be consistent across spatial and temporal scales (UCERF3)
  – Operational models should be evaluated by continuous prospective testing against alternative time-dependent models (CSEP)

Bottom line: Deployment of OEF is now a requirement, not an option
Uniform California Earthquake Rupture Forecast

Week 1 aftershock probability
M7.8 (NW): 5.8 x 10^{-3}
M7.8 (SE): 0.4 x 10^{-3}

Week 1 aftershock probability (isotropic): 1.2 x 10^{-3}
Probabilistic characterization of seismic hazard at a single site requires the consideration of ~500,000 rupture variations within this fault network.

Seismogram ensembles of this size can be efficiently calculated using seismic reciprocity on the SCEC CyberShake Platform.
CyberShake Platform

Generates probabilistic seismic hazard models from large ensembles (> $10^8$) of synthetic seismograms

- UCERF2 fault-based event set
- Graves & Pitarka rupture models
- SCEC 3D seismic velocity models

(Graves et al., 2011; Wang & Jordan, 2014)
Coupling of Models in the CyberShake Workflow

- **Graves-Pitarka kinematic rupture simulator**
  - 12 TB data transfer
  - Populate DB, construct queries
    - 6 jobs per site

- **Uniform California Earthquake Rupture Forecast**
  - Mesh generation
    - 1 job per site
    - MPI, 1500-4000 cores
  - 500,000 Seismograms
  - 75M intensity measures

- **Community Velocity Model**
  - CVM-S4.26
  - \( z = 6 \text{ km} \)
  - NCSA Blue Waters
  - OLCF Titan

- **Seismogram Synthesis**
  - SGT computation
    - 2 jobs per site
    - MPI, 200-800 GPUs
    - NCSA Blue Waters
    - OLCF Titan
  - Post-processing
    - ~500,000 jobs per site
    - MPI master/worker, 3712 cores
    - NCSA Blue Waters
    - OLCF Titan

- **Data Product Generation**
  - Populate DB
  - Construct queries

A complete CyberShake model for the Los Angeles region comprises ~300 million synthetic seismograms
### CyberShake Studies

<table>
<thead>
<tr>
<th>Study ID</th>
<th>Model ID</th>
<th>Fmax (Hz)</th>
<th>Rupture Generator</th>
<th>Velocity Model</th>
<th>SGT Code</th>
<th># Sites</th>
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**SCEC Community Velocity Models**

- **CVM-S4.26**
- **CVM-H11.9**
- **CVM-S4**

**Graves & Pitarka Pseudo-Dynamic Rupture Models**

- **G&P 2014**
- **G&P 2010**
- **G&P 2007**

More accurate basin structures

\[ Z_{2500} : \text{iso-velocity surfaces at } V_S = 2.5 \text{ km/s} \]
Comparison of 1D and 3D CyberShake Models for the LA Region

IM: 3s-SA (g) at 2% in 50 yrs
Rupture generator: GP2010

3D-1D Differences
1. Lower near-fault intensities due to 3D scattering
2. Much higher intensities in near-fault basins
3. Higher intensities in the Los Angeles basins
4. Lower intensities in hard-rock areas
Southern California Earthquake Center

NGA08-mean

Los Angeles

NGA08-BA

NGA08-AS

NGA08-CB

NGA08-CY

NGA-W1 (2008) GMPEs

Boore & Atkinson (BA)
Abrahamson & Silva (AS)
Campbell & Bozorgnia (CB)
Chiou & Youngs (CY)
Comparison of 3D CyberShake Models with NGA08-mean for the LA Region

GMPEs and CyberShake models can be directly compared using averaging-based factorization based on the “seismological hierarchy”

IM: 3s-SA (g) at 2% in 50 yrs
Rupture generator: GP2010
Basin Effect Maps
(SA b-maps corrected for $V_{S30}$ using BA08)

SA-3s

T=3.0s

SA-5s

T=5.0s

SA-10s

T=10.0s

CB08  CY08  AS08  CS-LA13.4b
SCEC Committee on the Utilization of Ground Motion Simulations

- Formed in 2013, chaired by C. B. Crouse, and populated by 20 earthquake engineers and seismologists

- Using CyberShake results to develop long-period $MCE_R$ response spectra maps for the Los Angeles region
  - To be proposed as a provision for ASCE 7-22 maps for Southern California
  - Resource to consultants and local jurisdictions (e.g. LA City DBS)
  - Look-up tool ~ USGS web app tool

- Conducting verification and validation studies

- Release planned for Fall 2017
CyberShake Models for Central California

CS-CC17.3a
3D model

CS-CC17.3b
1D model

3sec SA, 2% in 50 yrs
CyberShake Research Issues

**Model improvements**
- Verify Monte Carlo sampling schemes
- Incorporate a UCERF3 rupture set
- Improve CVMs at shallow depths

**Validation**
- GMPE comparisons
- Historical and new events
- Virtual earthquakes from ambient field

**Characterization of epistemic uncertainties**
- Earthquake rupture forecast
- Pseudo-dynamic rupture model
- 3D velocity structure
- Site effects

**Push to higher frequencies**
- Fault complexity
- F-dependent attenuation
- Near-fault nonlinearity
- Near-surface nonlinearity
- Small-scale heterogeneity

High-F Project

[Map of Southern California with SA 2s and 3sec SA]
**SCEC Computational Pathways**

**Structural Representation**

1. Earthquake Rupture Forecast
   - DFR
   - AWP
   - KFR
   - AWP
   - NSR

2. Dynamic rupture model of fractal roughness on SAF
   - KFR
   - AWP
   - NSR
   - Empirical GMPE

3. CyberShake 14.2 seismic hazard model for LA region
   - AWP
   - NSR
   - Empirical GMPE

4. Full-3D tomographic model CVM-S4.26 of S. California
   - NSR
   - Empirical GMPE
   - Intensity Measures

**Other Data**
- Geology
- Geodesy

**TACC Stampede**
- Uniform California Earthquake Rupture Forecast (UCERF3)

**NCSA Blue Waters**
- CyberShake 14.2 seismic hazard model for LA region

**OLCF Titan**
- Dynamic rupture model of fractal roughness on SAF

**ALCF Mira**
- Full-3D tomographic model CVM-S4.26 of S. California
**Inference Spiral of System Science**

**Verification**: Is the model correctly computed with a specified precision?

**Formulation**: Model designed to explain observed system-level behavior

**Simulation**: Model makes predictions for comparisons with observations

**Validation**: Can the model adequately predict the specified system behavior?
**Inference Spiral of System Science**

**Verification:** Is the model correctly computed with a specified precision?

**Data Assimilation:** How should the model be adjusted to fit new empirical information?

**System Model**

**Real World**

**Simulation:** Model makes predictions for comparisons with observations

**Validation:** Can the model adequately predict the specified system behavior?
Inference Spiral of Full-3D Tomography

CVM-S4.26 (Lee et al, 2014)

- CVM-S4 starting model
- 26th iterate of a full-3D tomographic (F3DT) inversion procedure using 550,000 differential waveform measurements at $f \leq 0.2$ Hz
  - 38,000 earthquake seismograms
  - 12,000 ambient-noise Green functions

- Compute synthetic seismograms
- Compare synthetic seismograms with observed seismograms
- Invert waveform residuals for improved structural model
- Verify structural model
- Data Assimilation
Inference Spiral of Full-3D Tomography

03/28/14 La Habra Earthquake (M5.1)

Station EDW2
Observed in black
Synthetic in red

CS11: CVM-S4
CS14.2: CVM-S4.26
CS13.4: CVM-H11.9

Invert waveform residuals for improved structural model
Data Assimilation

Verify structural model
Verification

Compare synthetic seismograms with observed seismograms
Validation

Compute synthetic seismograms
Simulation
SCEC HPC Allocations

Commercial cloud value of 2017 allocations ~ $22M

- DOE ALCC
- NSF TeraGrid/XSEDE
- NSF PRAC Blue Waters
- NSF Yellowstone
- DOE INCITE
- USC HPC

Service Units Awarded (in millions)
SCEC Extreme-Scale Earthquake Simulations

Year


Sustained SCEC measured performance for a single milestone capability simulation
SCEC Computational Pathways (2001)

1. Standard seismic hazard analysis
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FSM = Fault System Model
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Other Data
Geology
Geodesy

Unified Structural Representation
Faults Motion Stresses Seismic velocities

Invert

Ground Motions

“Physics-based” simulations

“Empirical” models

Intensity Measures

Earthquake Forecast

Attenuation Relationship
Collaboratory for Interseismic Simulation and Modeling (CISM)

Cyberinfrastructure for developing system-specific, time-dependent earthquake forecasting models that are comprehensive, physics-based, data-calibrated, and prospectively testable

Established under a $2M grant from the W. M. Keck Foundation, awarded on July 1, 2015
Coupling of UCERF-ETAS to CyberShake

Because it may be a foreshock of a large San Andreas rupture, a Parkfield earthquake significantly amplifies the shaking hazard in Los Angeles.

Calculation combines UCERF2-ETAS with the CyberShake ground motion prediction model.
Hazard Map Comparison

Peak Ground Acceleration (g) at 2% PoE in 50 yrs

B. Shaw et al. (2017)
Hazard Map Comparison

Peak Ground Acceleration (g) at 2% PoE in 50 yrs

B. Shaw et al. (2017)
Hazard Histogram Comparison

Peak Ground Acceleration (g) at 2% PoE in 50 yrs

B. Shaw et al. (2017)
Hazard Curve Comparison
California Earthquake Forecasting Models

Simulator-based UCERF

- UCERF3-TD
- UCERF3-ETAS
- UCERF2
- STEP, ETAS
- NSHM

long-term renewal models

“medium-term gap”

short-term clustering models

century | decade | year | month | week | day

Anticipation time
The Case for SCEC

1. The SCEC community has created an interdisciplinary, multi-institutional “virtual organization” for coordinating earthquake research in Southern California
   • Communicates useful knowledge for reducing earthquake risk and improving resilience

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   • In 2017, SCEC was awarded 447 million CPU-hours on the nation’s most powerful supercomputers

5. Earthquake system science is revolutionizing seismic hazard analysis and earthquake forecasting
   • A continuing program of coordinated interdisciplinary research will be necessary to refine and validate the new tools of physics-based PSHA and OEF
Thank you!

“But my heart is not weary, it's light and it's free
I've got nothing but affection for all those who've sailed with me.”

- B. Dylan