HPC Use for Earthquake Research

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Southern California Earthquake Center (SCEC)

• Mission: solve problems in earthquake system science
  • Understand and model the physics of earthquake processes, from tectonic stress to fault rupture to ground motions
  • Use SoCal as our natural laboratory

• Large collaborative center
  • Multi-disciplinary Planning Committee develops yearly science plan
  • Support fundamental AND applied science
  • Over 1,000 participants
  • 18 core institutions, 44 domestic participating institutions, 13 international

• NSF & USGS funded center

• Additional support from PG&E, W.M. Keck Foundation, NSF SSI programs
SCEC Institutions
Risk = 3D (Deaths, Dollars, Downtime) =

Hazard × Exposure × Vulnerability ÷ Resilience

Earthquake system science characterizes seismic hazards – key information for reducing risk and increasing resilience
Conclusion: a paradigm shift for better resilience

Risk reduction can be achieved by

• Making risk-informed decisions (design engineers, society)

• Prioritizing risk-informed research topics: improve hazard assessment where it matters most (researchers)

Hazard assessment will improve by

• Using validated physics-based simulation models to learn about earthquake processes

• Reducing epistemic uncertainty
  • Collect more data
  • Refine and validate models
  • Quantify uncertainty and its range
Immediate motivation

• Limited recorded datasets... Most complete record databases by PEER (UC Berkeley)

NGA-West2: CA and similar tectonic regions

NGA-East: CEUS and similar tectonic regions
Essential Ingredients for Ground Motion Computations

1. Earthquake rupture forecasts (ERFs)
   - detailed representation of fault geometry
   - rupture models that capture the complexities of dynamic fault failure
   - Long-term rate of earthquakes

2. 3D models of geologic structure
   - large-scale crustal heterogeneity
   - sedimentary basin structure
   - shallow site properties

3. Calculation of wave propagation and attenuation
   - efficient anelastic wave propagation codes
   - nonlinear models of near-surface response
ShakeOut Scenario

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

M7.8 earthquake simulation on Southern San Andreas Fault
(deterministic band $f = 0$-1 Hz; stochastic band $f = 1$-10 Hz)
**TeraShake Simulations of M7.7 Earthquake on the San Andreas Fault**

Simulations indicated strong 3D focusing of ground motions from strike-slip faults in Southern California

Quantified the importance of source directivity and basin excitation effects in earthquake forecasting and PSHA
The ShakeOut Scenario

M7.8 Earthquake on Southern San Andreas Fault

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

Exercise Impacts

- Largest emergency response exercise in US history
- Demonstrated that existing disaster plans are 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*

Great Southern California ShakeOut
SCEC ground-motion simulation platforms

- SCEC ground-motion simulation platforms
  - BroadBand Platform: 1D Deterministic, Stochastic (development and production software, runs on clusters and PCs)
  - CyberShake: 3D Deterministic (complete physics-based PSHA, runs on HPC)
  - BroadBand CyberShake: 3D Deterministic CyberShake, Stochastic BroadBand Platform
  - High-F: 3D Deterministic (physics-based development for new physics, runs on HPC and clusters)

Seismic band:
- Mantle waves: 100 s, .01 Hz
- Crustal waves: 10 s, .1 Hz
- Basin waves: 1 s, 1 Hz
- Strongly scattered waves: 0.1 s, 10 Hz
- Mantle waves: 0.01 s, 100 Hz

Earthquake engineering band:
- Tanks, tall buildings: 10 s, .1 Hz
- Short buildings, houses: 1 s, 1 Hz
- Stiff structures, NPPs, equipment: 0.1 s, 10 Hz
- Tanks, tall buildings: 0.01 s, 100 Hz

SCEC simulation computations:
- Development and production software (runs on clusters and PCs)
- Complete physics-based PSHA (runs on HPC)
- Physics-based development for new physics (runs on HPC and clusters)
Broadband Platform (BBP)

BBP is an open-source distribution

Broadband 0.1-20+ Hz (deterministic up to ~ 1Hz)

Simple source and path (1D)

7 alternative simulation codes

Fully validated for spectral response

- 1.5 year validation project
- Multiple rounds of validation/improvements
- Independent review panel

Continuation of work in 2018

Used for large ground motion characterization projects
CyberShake: PSHA from Physics-Based Simulations

Earthquake Rupture Forecast (e.g. UCERF) + Kinematic source models + 3D velocity model (from F3DT) = Hazard Curves and fault disaggregation, M, R, ε disaggregation, Hazard maps
CyberShake Study 17.3, Central CA

- Calculations for 2 velocity models for each of 438 sites, 1 Hz simulations, 40,000+ earthquakes

- Used OLCF Titan and NCSA Blue Waters
  - Averaged 1295 nodes (CPU + GPU) for 31 days, maximum of 5374
  - 900,000 node-hours consumed (21.6M core-hours)
  - Pegasus, HTCondor, Globus used for workflows
  - Workflow tools scheduled 15,581 jobs to both systems
  - Transferred 308 TB of intermediate data between the two systems

- Generated 285 million two-component seismograms
- 43 billion intensity measures

- Workflow tools managed 777 TB of data
  - 10.7 TB of output data automatically staged back for archival storage
CyberShake Study 17.3 Results: Velocity Model Comparison

1D model

3D model
CyberShake Study 17.3 Results: CCA and LA

CyberShake

- First simulation-based PSHA model
- Used as database for machine-learning of California Earthquake Early Warning system
- Leading model in USGS Urban Seismic Hazard Mapping Project
- Source of new design maps under consideration by building code update
High-F Project

Pushing deterministic ground-motion simulations to higher frequencies (~10Hz) while

- Improving computational efficiency
- Adding more realistic physics:
  - fault roughness
  - near-fault plasticity
  - frequency-dependent attenuation
  - topography
  - small-scale near-surface heterogeneity
  - near-surface nonlinearity

Image: K. Olsen, Y. Cui, A. Chourasia

Image: Roten et al. 2015

Image: K. Olsen, Y. Cui, A. Chourasia
Including plasticity in near-fault material

3D Drucker-Prager plasticity with parameters from Hoek-Brown rock strength criterion include in AWP-ODC (GPU and CPU versions on BW)

\[ \sigma_1 = \sigma_2 = \sigma_3 \]

\( m_t \): tabulated by rock type, e.g.:
- slate, shale, siltstone: \( m_t \approx 7 \)
- sandstones, breccias, conglomerates: \( m_t \approx 17 \)
- diorite, gabbro, granite: \( m_t \approx 25 \)

\( GSI \): tables with range of values by rock type
- empirical equations (e.g., Chang, 2006)
- descriptive grades (Brown, 1981), field estimates

**GSI:** describes degree of fracturing and weathering
- value (0 - 100) assigned based on charts
- approximates 100 at large depth (> 1 km)

90 massive
75 blocky
60 disturbed
50 disintegrated
30 deformed, folded

Roten et al. (2014, 2015, 2016)
ShakeOut with Drucker-Prager Plasticity (Roten et al., 2016)
AWP-ODC

NVIDIA GPUs

- A first 4-Hz nonlinear M7.7 earthquake simulation on the southern San Andreas Fault conducted using 4,200 Blue Waters GPUs
- 100% of parallel efficiency achieved for both linear/ nonlinear versions of AWP-ODC up to 8,192 GPUs
- Accelerated time-to-solution from original nonlinear 0.68sec to 0.29sec per iteration
- Blue Waters PAID project provided additional support.

Intel Xeon Phi

- Mega Lattice Updates per Second (MLUPS): Xeon Phi KNL 7290 achieves 2x speedup over NVIDIA K20X, 97% of NVIDIA Tesla P100 performance
- Performance on 9,000 nodes of Cori-II equivalent to performance of over 20,000 K20X GPUs at 100% scaling
- Open Source: https://github.com/HPGeoC/awp-odc-os

6.5x Speedup of CyberShake SGT version on Cray XK7 compared to XE6 at node-to-node level
**AWP-ODC on Sunway TaihuLight**

- Tsinghua University/Wuxi SC Center ported open source AWP-ODC using Sunway OpenACC and fully optimized the code on TaihuLight
- Sustained 15-Pflop/s or 12.5% of the peak achieved, a ACM Gordon Bell Finalist in 2017
- 1976 Mw7.2 Tangshan earthquake scenario and high-fidelity simulation using 10 million cores
  - A spatial resolution of 25m
  - 320km x 320km x 60km
  - Frequency of up to 10Hz
  - Included non-linear near-fault physics

EDGE Achieved 10.4 DP-PFLOPs on Cori Phase 2

- Extreme-scale Discontinuous Galerkin Environment: Seismic wave propagation through DG-FEM
- Focus: Problem settings with high geometric complexity
- Fused simulations to explore inter-simulation parallelism
- Tuned for Haswell, Knights Landing, Skylake, and Knights Mill through LIBXSMM library
- Cori Phase 2 weak scaling: Sustained 10.4 DP-PFLOPs (38% of peak)
- Theta strong scaling: Sustained 3.4 DP-PFLOPs (40% of peak) for a 100x increase in node count
- Open Source: http://dial3343.org
- Collaboration of SDSC, Intel, and SCEC through Intel PCC program

(Breuer et al., ISC’17)
Takeaways

• Ground motions simulations on HPC are a great learning tool for scientific research
• Simulations are already impacting design, improved hazard will help us to reduce seismic risk
• Continuous development needed
• Collaboration is essential

What’s next?

• Replace ERF with earthquake simulator
• Go to up to higher frequencies, extend the range of applications
• Test and implement additional physics
• Formally evaluate uncertainties
• Use simple models as benchmarks in the evaluation of complex models
• Validate, validate, validate...
Earthquakes – not a question of if... but when.

Thank you!

Partial list of collaborators:
Not all damage is structural...

"Structurally, the building is fine. But sadly, the earthquake destroyed all of our art pieces."
“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…”

Team included USGS, CGS, FEMA, SCEC, and nearly 200 other partners in government, academia, emergency response, and industry.

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

“Los Angeles will have the nation's toughest earthquake safety rules” – LA Times
Not a question of “if”...

Future earthquakes in California constitute ~ 66% of the long-term national seismic risk

<table>
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<th>Magnitude (greater than or equal to)</th>
<th>Average repeat time (years)</th>
<th>30-year likelihood of one or more events</th>
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