High Performance, Multidisciplinary Simulations for Regional Scale Earthquake Hazard and Risk (EQSIM)

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Understanding, and predicting, earthquake phenomenon is very challenging. Ground motions tend to be very site specific.
As a result of the complexities, empirical models have been utilized to analyze earthquake motions from many observed earthquakes (homogenized).
In the last 10 years, interest is growing in a simulation-based approach.

With an objective of answering key fundamental questions…

• How do earthquake ground motions vary across a region and how does this impact risk to infrastructure?
• How do incident ground motion waveforms interact with a particular facility?
Our application development is building a simulation framework for hazard and risk.
We are advancing and coupling codes for geophysics and infrastructure modeling.

**Earthquake Hazard**

**SW4 – 4th order finite difference geophysics code for wave propagation**

**Earthquake Risk**

**NEVADA & MSESSI – finite deformation, inelastic Finite Element codes for structures and soils**

**Weak Coupling**

**Strong Coupling**
Coupling geophysics and engineering simulations for risk assessments

- **Geophysics Simulation**
- **Engineering Simulation**

**Weak coupling**
- Diagram showing weak coupling between geophysics and engineering simulations.

**Strong coupling**
- Diagram illustrating strong coupling with a waveform chart showing acceleration (m/s²) vs. time (s) for seismic events.

The diagram compares weak and strong coupling scenarios, emphasizing the integration of geophysical and engineering simulations for risk assessments.
A multidisciplinary team is essential – a National Laboratory scale problem

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The Exascale big lift - regional ground motion simulations at “engineering” frequencies

Doubling the frequency resolution = 16X computational effort!
Our Exascale tasks

- Run much bigger models much faster
  - Very large models at higher frequency
  - Many realizations to account for uncertainties (e.g. fault rupture)

- Representation of fine-scale geology
  - Waveform data inversion
  - Stochastic geology

Base geology from data

Base + stochastic geology
Our simulation goal - the ability to resolve high frequencies and run many scenarios

Regional scale model (SFBA)

Application Performance

Remove computations as a barrier to scientific discovery and practical earthquake hazard and risk analysis
Our Figure of Merit (FOM) measures both science and application progress. For the representative fixed SFBA domain, the Figure of Merit is given by:

\[
(Freq)^4 \times \text{Wall Clock Time} \times 7.6
\]

How long does an earthquake scenario simulation take?

What frequency is being resolved?
SW4

Starting from a sound foundational code

- Advanced algorithms
- Platform optimization
- Exascale readiness
The SW4 code solves the time dependent 3D seismic wave equation

- **Seismic wave equation**
  - Isotropic visco-elastic materials
    - Generalized Maxwell solid
  - Kinematic (many) source model
    - Grid independent locations
  - Realistic topography with curvilinear grid
    - Built-in parallel mesh generator

- **Accurate & stable numerical method**
  - 4$^{th}$ order summation-by-parts finite differences
    - Energy stable on Cartesian + curvilinear grids
    - Fundamentally different from staggered FDTD
  - Explicit Newmark predictor + corrector
    - 4$^{th}$ order, CFL $\leq$ 1.3 Efficient!
  - Local mesh refinement
    - Hanging node interfaces

- **Implemented in C++ using MPI+OpenMP**
  - Makefile and Cmake; Python testing
    - MMS, Energy conservation, Analytical solutions
  - Open source distributed by CIG

\[
\rho \frac{\partial^2 \mathbf{u}}{\partial t^2} = \nabla \cdot \mathbf{T} + \mathbf{f}
\]
Next - developing a full waveform inversion approach for improving the material model

- Improve model using mismatch between data and simulated waveforms
  - 9x9 receiver grid
  - 3 component motion in time

- Minimize norm of mismatch
  - Constrained optimization
  - Gradient by solving adjoint wave equation

- Initial layered material model (Vs)
The San Francisco Bay Area region is our “numerical laboratory”

USGS 3D geologic model

Significant earthquake data
We have recently completed our 2018 science demonstration calculation (to 5 Hz)

- Simulation on CORI Phase II (2018 KPP baseline)
  - 8,192 nodes (85% of CORI)
  - 524,288 cores
  - 9 hour wall clock time
Ground Motion Simulation for a Magnitude 7.0 Earthquake on the Hayward Fault, eastern San Francisco Bay Area, northern California
Comparison of the simulation model with empirical data for an Oakland site

Computed response in Oakland adjacent to the Hayward Fault (black circles, line) agrees well with four (4) **Ground Motion Models (GMM)** from empirical data (colored squares, lines) with uncertainties (colored dotted lines)
Substantial progress in increasing the frequency resolution of our regional models

As frequency content increases, acceleration amplitudes increase and simulations are more consistent with observations.
NEVADA (weak coupling) & MSESSI (strong coupling)

- Implicit time integration
- Finite deformation
- Nonlinear materials
  (Structures and soils)
Developing thousands of building response simulations for near-field motions

Earthquake hazard

2048 nodes

Surface motions from regional geophysics simulation

~ 2000 nonlinear building response history simulations

Earthquake risk

50 nodes

Distribution of building peak interstory drift

Peak interstory drift of 40 story building for M7.0 Hayward fault/parallel motion

Elastic Behavior
Limited Permanent Distortion
Moderate Permanent Distortion
Large Permanent Distortion

Rupture hypocenter

SW4
At each location on the ground, the demand on the building system is determined.

Interstory drift is a fundamental measure of earthquake demand on a building structure.
Resulting distribution of risk to three story steel frame buildings (M=7 Hayward event)

Peak interstory drift for a 3 story steel moment frame

- Essentially elastic: Behavior – no damage
- Limited permanent distortion: repairable damage
- Moderate permanent distortion: minimal damage
- Large permanent distortion short of collapse: significant damage

DOE standard 1020 limit states
Progress to-date in the FOM from our science demonstration runs

Figure of Merit (FOM)

\[
(Freq)^4 \times \text{Wall Clock Time} \times 7.6
\]