New Directions in Computational Earthquake Physics
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Extending SCEC’s expertise in computational science from large-scale scenario earthquake simulations to more sophisticated earthquake physics

- Small-scale fault-zone physics (in large-scale simulations)
- Multicycle dynamics (self-consistent initial conditions; role of slow slip)
- High frequency ground motion (geometrical complexities)
Source Processes Causing Incoherent High Frequency Ground Motion: Fault Roughness and Geometric Complexity

Fault-Normal Velocity Field

Model features naturally arising variations in slip and rupture velocity (spatially uniform initial stresses and friction law parameters)

[Dunham et al., 2010]
Frequency-Dependent Radiation Pattern and Directivity Effects
(In Far-Field Body Waves)

Caused by variations in local radiation pattern from nonplanarity
(can never be captured with standard method of heterogeneous stresses on planar faults)

[Cho and Dunham, work in progress, 2010]
Numerical Method: Simultaneous Solution of Elastodynamics and Friction Law

- Block-structured curvilinear meshes
- Artificial dissipation to control oscillations
- SBP+SAT finite differences
- Provably stable and high-order accurate

Parallelized FD code, currently in 2D with roughness wavelengths > 100 m (using ~100-500 cores routinely)

Main bottleneck now is lack of expertise visualizing large-scale simulation results

Method can be extended and coupled to unstructured finite volume mesh (for arbitrarily complex geometries) with provable stability and accuracy
Multicycle Dynamics

- Inertial dynamics as well as quasi-static loading (rate-and-state friction)
- Self-consistent initial conditions for single event simulations

Current methodologies limited to simplest geometries, linear elasticity
Computational challenge: quasi-static elasticity (equations are elliptic, not hyperbolic)
requires scalable parallel iterative solvers for volume-discretized (FD, FE, FV) codes

[Noda and Lapusta, 2010]
Physics-Based Description of Fault-Zone Processes

Fault strength governed by small-scale processes, many of which have only recently been introduced into dynamic rupture models (usually in idealized 2D geometries)

E显示方程式描述热和孔隙流体的传输，孔隙介质的热力学，摩擦等，尺度约为1-10 mm

fracturing and inelastic deformation in damage zone

slip accommodated by thin shear zone (frictional heating, melting?)

fluid-saturated fault gouge (thermal pressurization of pore fluids)

[Sibson, 2003]

[Chester and Chester, 1998]
Numerical Methodology:
couple elastodynamics with transport of heat and pore fluids within fault zone

$$h_{elast} \sim 1 \text{ mm}$$

$$h_{diff} \sim 1 - 10 \mu \text{m}$$
Earthquake Simulations with Dynamic Weakening

Only ~30 m propagation distance (magnitude 1-2, mapping 2D simulations to 3D) but no compromises in lab-based parameters

low initial stress

\[ 2w = 100 \ \mu m \]
\[ x = 8 \ m \]
\[ \tau^b = 0.2302\bar{\sigma}_0 \]

typical static friction \( f_s \sim 0.8 \) at nearly singular rupture front

low stress during slip (minimizes heat production)

Operation of mature faults (like SAF) at low stresses

[Noda, Dunham, and Rice, 2009]
Computational Challenges

Numerical methods: Multiphysics (diffusion + wave propagation)
Load balancing: Processors holding fault have significantly higher work loads

Imagine: Each fault grid point now has associated fault-zone grid with \(~10^2–10^3\) points

Terashake Domain Decomposition

No. of Procs = 12x10x2 = 240

[Olsen et al., 2006]
Resolution, Resolution, Resolution

Current state-of-the-art with marginally resolved rupture fronts on uniform grids

Fault Dimension

\[ \Delta x \]

1 mm 1 cm 0.1 m 1 m 10 m 100 m

~30 m (2D)  
~30 km (3D)

~30 km (2D) ~30 km (3D)

lab-based physics  artificially increased \(D_c\)

Grid Spacing

5 orders of magnitude difference!!!

Alternative approaches:
- Parameterization of unmodeled small-scale processes
- Adaptive Mesh Refinement (AMR) to resolve rupture front and wavefronts
Adaptive Mesh Refinement

resolve sharp wavefronts and nearly singular stress/velocity fields around rupture front

stress concentration at rupture front

propagation direction

actively slipping region (10 m)

2D domain (10 km by 10 km), smallest $\Delta x \sim 1$ mm:

- uniform mesh: $10^{14}$ grid points
- adaptive mesh: $10^8$ grid points
  (identical numerical error approximating spatial derivatives)
Adaptive Mesh Refinement

2D domain (200 km by 200 km), smallest $\Delta x \sim 5$ m:
- uniform mesh: 32,768 grid points in each direction
- adaptive mesh: few hours on 8-core Mac Pro (factor of 256 refinement)

[Kozdon and Dunham, work in progress, 2010]
High frequency ground motion

- Five causes:
  - Site/Path: (1) site effects, (2) scattering off material heterogeneities
  - Source: variations in (3) slip, (4) rupture velocity, (5) local radiation pattern
- Computational tasks: Select code (options: SORD, FEM, FDM with mapping)
  - Our FD code scales to 4096 cores (most tested), but needs optimization
  - Add roughness waves to scale of slip in 2D
  - Extend to 3D

Multicycle simulations (quasi-static loading, dynamic ruptures)

- Currently only in BIEM codes (flat faults in uniform whole-spaces)
- Extension to general geometries and material response with FEM/FDM/FVM
- Computational tasks:
  - Optimize BIEM codes (parallel FFT)
  - Scalable parallel iterative solver for volume-discretized methods

Dynamic weakening mechanisms and detailed fault-zone models

- Thermal pressurization, velocity-weakening friction, off-fault plasticity
- Computational tasks:
  - Load balancing or enlisting off-fault processes to help update fault physics
  - AMR to resolve nearly singular fields at rupture front