Perspectives from the SCEC Sequences of Earthquakes and Aseismic Slip (SEAS) Project

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Overview

• Introduction and motivation
  • Comparisons of earthquake models
  • SEAS project at SCEC
• Progress and results
  • Benchmark BP1: the simplest crustal faulting problem
  • Benchmark BP2: increased complexity in earthquake patterns
• Summary and Perspectives
Approaches to modeling earthquakes

**Spontaneous dynamic ruptures**
- Detailed single-event earthquake ruptures on fault segments and associated ground motion
- Successful code verification exercises and ongoing validation efforts
- Prestress conditions, nucleation procedures …

**Earthquake Simulators**
- Seismicity patterns over millennium time scales in large fault network systems
- Quasi-dynamic approximation, simplified interseismic loading …

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Dieterich and Richards-Dinger, 2010; Tullis, 2012

Harris et al., 2018
What are SEAS models?

**Sequences of Earthquakes and Aseismic Slip**

Distinct features:

1. Capture detailed earthquake rupture process
2. Interactions between earthquakes and aseismic slip over longer time scales
Interactions between fault creep, small and large earthquakes

- 3D models with a homogenous media
- Fully dynamic rupture
- Postseismic stress relaxation
- Microseismicity
- Interseismic fault coupling
- Compare with seismological, geodetic, and geological data

Jiang and Lapusta, Science, 2016; JGR, 2017
How rheology or structure influences earthquake patterns

- 2D antiplane models
- Quasi-dynamic earthquake ruptures
- Heterogeneous bulk material properties
- Off-fault plasticity
- Can further incorporate other inelastic rheology and fluid processes

Erickson and Dunham, JGR, 2014; Erickson et al., JMPS, 2017
SEAS (“seismic cycle”) models are now prevalent in earthquake research—addressing key SCEC objectives—but remain untested

Some outstanding questions

- Do our numerical models resolve the “true” fault behavior and its complexity?
- What model features may arise from numerical approximation and resolution issues?
- How do these physical factors influence the earthquake cycle? Do they matter?
- How to implement them with efficiency in 3D, larger scale simulations?

Verifying different computational codes is the first critical step

Community efforts are needed to address these issues
Progress in 2018–2019

Initiated the SEAS working group (10+ modeling groups; 40+ people on our email list)

1st SCEC workshop in April 2018

- 60 Participants (online & remote), half students & postdocs (jointly held with the dynamic rupture code validation group)
- Talks on science & codes, benchmark results & discussions
- Developed/completed benchmark problem BP1: a simple 2D antiplane problem
- Established online model-comparison platform (http://scecdata.usc.edu/cvws/seas/)

2nd SCEC workshop in November 2018

- 36 Participants (online & remote), over half students & postdocs
- Benchmark problem BP2: a simple 2D antiplane problem with increased event complexity
- First group publication in preparation (Erickson, Jiang, et al.)
Benchmark problems BP1 & BP2

Benchmark design guidelines
- Start simple
- Incrementally increase complexity
- Maximize participations

Problem setup
- 2D anti-plane problem
- 1D vertical strike-slip fault in a homogeneous half-space
- Rate-and-state friction with the aging evolution law
- Quasi-dynamic earthquakes
- Define a mathematical problem, leaving computational implementation up to modelers

Based on Rice, 1993
## Summary of Model Submissions for BP1/BP2

<table>
<thead>
<tr>
<th>Modeling Group Name and Members</th>
<th>Method (Code)</th>
<th>Time Stepping</th>
<th>Cell Size</th>
<th>Domain size at ((L_x, L_y))</th>
<th>B.C. at (L_x)</th>
<th>B.C. at (L_y)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abrahams (Abrahams/Allison/ Duhlain)</td>
<td>4th order FDM (Sycle)</td>
<td>RK4-5, [ED2014]</td>
<td>BP1: (dz = 25m, dx) var. BP2: (dz = 25/50/100/200/300/400/800m)</td>
<td>BP1: ((100km, 80km)) BP2: ((400km, 200km))</td>
<td>BP1: free/disp BP2: disp</td>
<td>traction free</td>
</tr>
<tr>
<td>Erickson (Erickson/Mckay)</td>
<td>2nd order FDM (FDcycle)</td>
<td>BP1: RK4-5, [ED2014] BP2: RK4-3, [ED2014]</td>
<td>BP1: (dz = 50m, dx) var. BP2: (dz = 50/100/200/300/400/800m, dx) var</td>
<td>BP1: ((80km, 80km)) BP2: ((80/160km, 80/160km))</td>
<td>BP1: free/disp BP2: disp</td>
<td>traction free</td>
</tr>
<tr>
<td>Kozdon (Dunham)</td>
<td>DG-FEM (beard)</td>
<td>RK4-5, [ED2014]</td>
<td>BP1: (dz = 25-50m) near fault. BP2: (dz = 50/100/200)m near fault.</td>
<td>BP1: ((160/800km, 80/400km)) BP2: ((80km, 160km))</td>
<td>BP1: free/disp BP2: disp</td>
<td>traction free</td>
</tr>
<tr>
<td>Barbot</td>
<td>BEM</td>
<td>RK adaptive</td>
<td>BP1: (dz = 25m) BP2: (dz = 25/50/100/200/300/400/800m)</td>
<td>((\infty, \infty))</td>
<td>N/A</td>
<td>disp.</td>
</tr>
<tr>
<td>Cattania (Segall/Cattania)</td>
<td>BEM (FDRA)</td>
<td>RK adaptive [B2014]</td>
<td>BP1: (dz = 25/19m) BP2: (dz = 25/50/100/200/300/400/800m)</td>
<td>BP1: ((\infty, \infty/160/640km)) BP2: ((\infty, \infty))</td>
<td>N/A</td>
<td>period. or disp.</td>
</tr>
<tr>
<td>Jiang</td>
<td>BEM (BICYCLE)</td>
<td>[L2000]</td>
<td>BP1: (dz = 25m) BP2: (dz = 25/50/100/200/300/400m)</td>
<td>BP1: ((\infty, 80/160km)) BP2: ((\infty, 160km))</td>
<td>N/A</td>
<td>period.</td>
</tr>
<tr>
<td>Lambert (Lambert/Lapusta)</td>
<td>BEM (BICYCLE)</td>
<td>[L2000]</td>
<td>BP1: (dz = 25/50m) BP2: (dz = 25/50/100/200/300/400m)</td>
<td>BP1: ((\infty, 50/80km)) BP2: ((\infty, 100km))</td>
<td>N/A</td>
<td>period.</td>
</tr>
<tr>
<td>Ma (Ma/Elbanna)</td>
<td>BEM (BICYCLE)</td>
<td>[L2000]</td>
<td>BP1: (dz = 25/50m) BP2: (dz = 25/50/100/200/300m)</td>
<td>((\infty, 80km))</td>
<td>N/A</td>
<td>period.</td>
</tr>
<tr>
<td>Luo (Luo/Idini/Ampuero)</td>
<td>BEM (QDYN)</td>
<td>BP1: Bulirsch-Stoer BP2: RK adaptive</td>
<td>BP1: (dz = 19.53m) BP2: (dz = 19/39/78/156/312/625m)</td>
<td>((\infty, \infty))</td>
<td>N/A</td>
<td>disp.</td>
</tr>
<tr>
<td>Liu</td>
<td>BEM</td>
<td>RK adaptive</td>
<td>BP1: (dz = 25m) BP2: (dz = 25/50/100/200/300/400m)</td>
<td>((\infty, \infty), (720km))</td>
<td>N/A</td>
<td>disp.</td>
</tr>
<tr>
<td>Wei (Wei/Shi)</td>
<td>BEM</td>
<td>RK adaptive</td>
<td>BP1: (dz = 25m) BP2: (dz = 25/50/100m)</td>
<td>((\infty, \infty), (720km))</td>
<td>N/A</td>
<td>disp.</td>
</tr>
</tbody>
</table>

* “modeling group” is denoted by modeler who submitted results
* \(L_y = \infty\) unless otherwise specified.
* “period.” boundary condition indicates that problem is solved in spectral domain.
BP1: periodic large earthquakes

How to compare different models?

long-term evolution of local slip/rate/stress

Time evolution of slip profiles on fault

coseismic evolution of slip rate/stress

[Graphs and diagrams illustrating the evolution of slip profiles and seismic activity]

- How to compare different models?

- Time evolution of slip profiles on fault

- Coseismic evolution of slip rate/stress
Main factors to explain model discrepancies

- **Computational domain sizes:** $L_z = 80$ km, 160 km, $\infty$
- **Boundary conditions:** displacement, traction-free

Coseismic period during 30th event

Comp. domain size $\rightarrow$ stress buildup $\rightarrow$ prestress $\rightarrow$ rupture process
Main factors to explain model discrepancies

- **Computational domain sizes**: $L_z = 80$ km, 160 km, $\infty$
- **Boundary conditions**: displacement, traction-free

![coseismic period during 30th event](image)

- $z = 7.5$ km
- $L_z \geq 160$ km

aligned at first rupture
Summary on BP1 model agreements and discrepancy

- Excellent agreements in best models
- Major quantitative discrepancies
  - exist in interseismic loading, prestress, and coseismic rupture process
  - due to boundary conditions and computational domain sizes
- Minor discrepancies may be inevitable
  - due to volume vs. boundary methods and approximation of the half space
BP2: bimodal earthquake patterns

- Problem setup identical to BP1, except for some model parameters.
- Objective: Understand complexity in simulated events and numerical resolution issues
  - How to properly resolve 3D problems and compare/interpret model results
Scientific Motivation for BP2

microseismicity at rheological boundaries

seismicity patterns on the SAF at Parkfield, CA

2D fault models

Lapusta and Rice, 2003

partial rupture of large asperities

2015 Ghorka Earthquake, Nepal

3D fault models

Michel et al., 2017

Figure 1. Setting of the Mw 7.8 Gorkha earthquake and dynamic simulations presented in this study. (a) Distribution of coseismic slip, location, and timing of the sources of high-frequency radiations (0.5 – 2 Hz) and pattern of interseismic coupling on the Main Himalayan Thrust fault (isocontour of locking from 10% to 90%) [Avouac et al., 2015; Galetzka et al., 2015; Stevens and Avouac, 2015; Elliott et al., 2016]. (b) Our fault model, with the velocity-strengthening (VS) and velocity-weakening (VW) areas indicated by the white and pink areas, respectively. The fault is loaded by dip-slip motion (slip is parallel to the shorter dimension of the model). The solid black line and black star represent the rupture area and epicenter of event 12, respectively. The black dashed rectangle outlines the area shown in Figure 2. The black dots show the location of points A and B where slip and stress histories are shown in Figure 3. (c) Maximum slip rate as a function of time during the 2000 yearlong simulation. The dashed horizontal line shows the 0.1 m/s threshold above which slip is considered to be seismic. Magnitudes are indicated, with event 12 in red.
Important Physical Length Scales

Nucleation zone size

\[ h^* = \frac{2 \mu b L}{\pi (b - a)^2 \sigma} \]

critical size of area that allows for frictional instability (~1 km)

Cohesive zone size

\[ \Lambda_0 = C \frac{\mu L}{b \sigma} \]

critical length scale required for resolving rupture tip (~170 m)

Changes in BP2 compared to BP1

- Characteristic slip evolution distance \( L \) is halved
- Smaller nucleation sizes and additional smaller events in simulations
- A broader range of model resolutions

Compare different model resolutions

- we suggest 7 cell sizes, 25, 50, 100, 200, 300, 400, & 800 m for simulations.
- The seven cases resolve \( h^* \) with 40, 20, 10, 5, 3, 2 and 1 grid points
- The first three cases resolve \( \Lambda_0 \) with 6, 3, 2 grid points; others don’t
Model agreements in BP2

long-term evolution of stress

Best-resolved models (25 m) from all groups

coseismic period during 8th large event

z=7.2 km
The effect of resolution on model behavior

Jiang (BICycle; SBEM; $L_z=160$ km)

**Slip Profiles**

- $dz$: 25 m; events: 21
- $dz$: 50 m; events: 21
- $dz$: 200 m; events: 119
- $dz$: 300 m; events: 574

Seismic phases: $V \geq 0.01$ m/s
Earthquake size (moment) distribution

seismic moment release per unit length, $M = G \times s \times L$

Jiang (BICycle; SBEM; $L_z=160$ km)
Earthquake size (moment) distribution

Jiang (BICycle; SBEM; $L_z=160$ km)

Earthquake statistics sensitive to model resolutions
Total moment release

Jiang (BICycle; SBEM; \(L_z=160\) km)

linear y-axis scale

logarithmic y-axis scale
Total moment release

Jiang (BICycle; SBEM; $L_z=160$ km)

Cattania (FDRA; BEM; $L_z=\infty$)

Total moment release in major events varies due to model resolution
Recurrence times of large earthquakes

Minor difference due to computational domain size

$\Delta z = 25 \text{ m}$

$\Delta z = 50 \text{ m}$
Recurrence times of large earthquakes

\[ \Delta z = 100 \text{ m} \]
\[ \Delta z = 200 \text{ m} \]
Recurrence times of large earthquakes

Poorly resolved models produce large events with more variable recurrence times

\[ \Delta z = 300 \text{ m} \]

\[ \Delta z = 400 \text{ m} \]
Lessons learned from BP1/BP2

- Different models (BEM/FDM/FEM) are in excellent agreements when (1) computational domain sizes are sufficiently large (BP1), (2) boundary conditions are consistent (BP1), and (3) important physical length scales are sufficiently resolved (BP2).

- Complex interactions between interseismic loading and earthquake nucleation/rupture/statistics

- Some model observables are more sensitive to model resolution than others
  - Small event numbers change dramatically
  - Moment release of major events have a systematic decrease
  - Recurrence times of largest events tend to be more variable (around the targeted values)
What’s next?

BP3 : BP1 + inertia effects

BP4 : 3D problem in a whole space

A SCEC workshop planned for 2019 Fall

**Important issues**

- How inertia affect model discrepancy
- How are nucleation sites, rupture style, recurrence times of earthquakes in 3D affected by modeling ingredients

**Future targets**

- Free surface effects in 3D
- Event complexity in 3D
- Heterogeneous frictional properties