Review of BP1/BP2 Outcomes


*SCEC SEAS Workshop, Jan. 9, 2020*
1\textsuperscript{st} benchmarks
BP1 and BP2:

2D anti-plane shear motion. The fault is a vertical strike-slip fault in a homogeneous half-space. Friction is regularized rate-and-state friction with the aging law.

$L_x$ denotes fault-perpendicular extent of computational domain.

$L_z$ denotes down dip extent of computational domain.
**2D anti-plane problem:** a homogeneous, isotropic linear elastic half-space

$$0 = \frac{\partial \sigma_{xy}}{\partial x} + \frac{\partial \sigma_{yz}}{\partial z}, \quad \sigma_{xy} = \mu \frac{\partial u}{\partial x}; \quad \sigma_{yz} = \mu \frac{\partial u}{\partial z}$$

**Boundary condition:** free surface on the top of the model domain

$$\sigma_{yz}(x, 0, t) = 0.$$  

**Interface conditions:**

$$\sigma_{xy}(0^+, z, t) = \sigma_{xy}(0^-, z, t), \quad \tau = F(V, \theta),$$

**Friction laws on fault:**

$$F = \sigma_n f(V, \theta), \quad f(V, \theta) = a \sinh^{-1} \left[ \frac{V}{2V_0} \exp \left( \frac{f_0 + b \ln(V_0 \theta / D_c)}{a} \right) \right], \quad \frac{d\theta}{dt} = 1 - \frac{V \theta}{D_c},$$

**Initial conditions:** uniform slip rate $V_{init}$ and uniform prestress $\tau^0$

$$\tau^0 = \sigma_n a_{max} \sinh^{-1} \left[ \frac{V_{init}}{2V_0} \exp \left( \frac{f_0 + b_0 \ln(V_0 / V_{init})}{a_{max}} \right) \right] + \eta V_{init}.$$
# Codes used in BP1 and BP2

Table 1: Details of participating SEAS codes and modeling groups.

<table>
<thead>
<tr>
<th>Code Name</th>
<th>Type</th>
<th>Modeler Name &amp; Group Members</th>
<th>References</th>
</tr>
</thead>
</table>
| SCycle    | FDM  | abraham (Abrahams/Allison/Dunham) | Erickson et al. (2014)  
Allison and Dunham (2018)  
https://github.com/kali-allison/SCycle |
| FDCycle   | FDM  | erickson (Erickson/Mckay)       | Erickson and Dunham (2014)  
https://github.com/brittany-erickson/FDCycle |
| QDESDG    | DG-FEM | kozdon (Kozdon)               | https://github.com/jkozdon/QDESDG |
| Unicycle  | BEM  | barbot (Barbot)               | Barbot (2019) |
| FDRA      | BEM  | cattania (Cattania/Segall)     | Segall and Bradley (2012), Bradley (2014) |
| BICycleE  | BEM  | jiang (Jiang)  
lambert (Lambert/Lapusta)  
xma (Elbanna/Ma) | Lapusta et al. (2000), Lapusta and Liu (2009) |
| QDYN      | BEM  | luo (Ampuero/Idini/Luo/  
van den Ende)         | Luo and Ampuero (2017)  
https://github.com/ydluo/qdyn |
| ESAM      | BEM  | liu (Liu)  
wei (Shi/Wei)   | Liu and Rice (2007) |

**NAMING CONVENTION:** Note that the modeler name refers to the member of the modeling group who uploaded the data to the platform for simulations done by the group.
Benchmark BP1/BP2 Participation:

Total submissions:

11 modelers

>70 model runs

different B.C.

different cell sizes

different domain sizes
## Parameters used in BP1 and BP2

### Table 1: Parameter values used in the benchmark problem

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Definition</th>
<th>Value, Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rho$</td>
<td>density</td>
<td>2670 kg/m$^3$</td>
</tr>
<tr>
<td>$c_s$</td>
<td>shear wave speed</td>
<td>3.464 km/s</td>
</tr>
<tr>
<td>$\sigma_n$</td>
<td>effective normal stress on fault</td>
<td>50 MPa</td>
</tr>
<tr>
<td>$a$</td>
<td>rate-and-state parameter</td>
<td>variable (see Fig. 1)</td>
</tr>
<tr>
<td>$b$</td>
<td>rate-and-state parameter</td>
<td>variable (see Fig. 1)</td>
</tr>
<tr>
<td>$L$</td>
<td>critical slip distance</td>
<td>BP1: 0.008 m</td>
</tr>
<tr>
<td></td>
<td></td>
<td>BP2: 0.004 m</td>
</tr>
<tr>
<td>$V_p$</td>
<td>plate rate</td>
<td>$10^{-9}$ m/s</td>
</tr>
<tr>
<td>$V_{init}$</td>
<td>initial slip rate</td>
<td>$10^{-9}$ m/s</td>
</tr>
<tr>
<td>$V_0$</td>
<td>reference slip rate</td>
<td>$10^{-6}$ m/s</td>
</tr>
<tr>
<td>$f_0$</td>
<td>reference friction coefficient</td>
<td>0.6</td>
</tr>
<tr>
<td>$H$</td>
<td>depth extent of uniform VW region</td>
<td>15 km</td>
</tr>
<tr>
<td>$h$</td>
<td>width of VW-VS transition zone</td>
<td>3 km</td>
</tr>
<tr>
<td>$W_f$</td>
<td>width of rate-and-state fault</td>
<td>40 km</td>
</tr>
<tr>
<td>$\Delta z$</td>
<td>suggested cell sizes</td>
<td>BP1: 25 m</td>
</tr>
<tr>
<td></td>
<td></td>
<td>BP2: 25 m, 50 m, 100 m, 200 m, 300 m, 400 m, 800 m</td>
</tr>
<tr>
<td>$t_f$</td>
<td>final simulation time</td>
<td>BP1: 3000 years</td>
</tr>
<tr>
<td></td>
<td></td>
<td>BP2: 1200 years</td>
</tr>
<tr>
<td>$L_z$</td>
<td>depth of computational domain</td>
<td>not specified</td>
</tr>
<tr>
<td>$L_x$</td>
<td>off-fault distance of computational domain</td>
<td>not specified</td>
</tr>
</tbody>
</table>
The SCEC Sequences of Earthquakes and Aseismic Slip Project

**Benchmark Comparison Tool**

**Benchmark Descriptions**

**Downloads**

**Benchmark Comparison Tool**

- **Public Area**
- **Login to View Data**
- **Login to Upload Files**
- **Administrative Login**

*Exit to SEAS Project Home Page*
Time Series

fltst_dp000: $z = 0$ km (at the free surface)
fltst_dp025: $z = 2.5$ km
fltst_dp050: $z = 5$ km
fltst_dp075: $z = 7.5$ km
fltst_dp100: $z = 10$ km
fltst_dp125: $z = 12.5$ km
fltst_dp150: $z = 15$ km
fltst_dp175: $z = 17.5$ km
fltst_dp200: $z = 20$ km
fltst_dp250: $z = 25$ km
fltst_dp300: $z = 30$ km
fltst_dp350: $z = 35$ km
BP1 Results
Cumulative slip profiles from BP1:
Long-term behavior of BP1 models. (a) Shear stress and (b) slip rates at the depth of 7.5km in models with different outer boundary conditions (BC) and computational domain sizes. (c) Shear stress and (d) slip rates at depth of 7.5km in models with sufficiently large computational domain sizes. Legend labels indicate model names followed by information on BC and domain size, namely, \((L_x/L_z/BC)\) for FDM/FEM, and \((L_z/BC)\) or (HS, half-space) for BEM. BC1 and BC2 refer to the far-field free surface or displacement BC and BC3 refers to the periodic BC.
Coseismic behavior of BP1 models. Coseismic phase during the 8th event in Figure 5 is shown. Models with smaller computational domain sizes show discrepancies in (a) shear stresses at 12.5km depth and (b) slip rates at 7.5km depth. Models with sufficiently large computational domain sizes are compared for (c) shear stresses at 12.5km depth and (d) slip rates at 7.5km depth. Time series are aligned relative to the rupture initiation time at the depth of 12.5km in each model. Note that the halfspace solution luo is the same in (b) and (d) and serves as a reference. The surface reflection phase is marked by a black arrow.
Interevent times for model results reveal discrepancies attributable to computational domain size and far-field boundary condition type.
Take aways from code comparisons from BP1:

• Discrepancies among well-resolved models were significantly influenced by computational domain size, with larger domains yielding improvements in agreements, regardless of domain boundary conditions.

• Spin-up periods (time required for system to be independent of initial conditions) for well-resolved models was relatively short - approximately 2-3 events.

• Results on large domains agree well initially but still diverge over time, which was not unexpected due to accumulation of round-off errors and differences in computational techniques.
BP2 Results
Benchmark Problem BP2

**Similarity** - The problem set-up for this second benchmark is identical to that of the first benchmark problem (BP1), except for changes in some model parameters.

**Difference** - $L = 8\, \text{mm} \Rightarrow 4\, \text{mm}$, suggested cell size (node spacing), simulation time, and output format details.

**Objectives** - Understand complexity in simulated events and numerical resolution issues $\Rightarrow$ How to properly resolve 3D problems and interpret model results.
Important Physical Length Scales

**Process zone size**

\[ \Lambda_0 = C \frac{\mu D_c}{b\sigma_n} \]

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

**Nucleation zone size**

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

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

Suggested cell sizes: 25m, 50m, 100m, 200m, 300m, 400m and 800m. These correspond to three cases that resolve the process zone with 6, 3 and 1.7 grid points (\(h^*\) resolved with 40, 20, 10 grid points), and four cases that do not resolve it.
Slip Profiles

Lambert (BICycE; SBEM; $L_z=100$ km)
Comparison of best-resolved BP2 models (cell size of ∼25 m).
Increasing discrepancy in BP2 models due to an increased cell size of (a) 25 m, (b) 50 m, (c) 100 m, and (d) 200 m.
Effect of model resolution on earthquake patterns.
Effect of model resolution on seismic-aseismic slip partitioning over depth.
Effect of model resolution on recurrence intervals of large surface-breaching events.
Take aways from code comparisons from BP2:

• We observed qualitative similarities of bimodal events when the process zone was resolved by approximately 3 and 6 grid points, suggesting model convergence.

• A failure to resolve this length scale can lead to substantial differences in long-term fault behavior as well as earthquake statistics relevant to seismic hazard, such as frequency-size distributions and interevent times.

• Our initial benchmarks have a simple setup, comparison of results for tens of models have yielded some unexpected and important insights, affirming the importance of starting simple in a community code verification exercise.
Additional issues/questions:
• Motivation

• Results of slip profiles: general features and catalogue analysis

• Results of time series: long- and short-term behavior
Scientific Motivation for BP2

**microseismicity**

*Parkfield, CA*

**partial rupture**

2015 Ghorka EQ, Nepal

*Lapusta and Rice, 2003*

*Michel et al., 2017*
Comparison Strategy

Assess convergence/divergence of models in terms of different model characteristics for different cell sizes, within and across model groups.

**Slip Profiles**

- General model features
- Event catalogue analysis

**Time Series**

- Long-term & short-term evolution
- Depth-dependent conditions

```
fltst.dp000: z = 0.0 km (at the free surface)
fltst.dp024: z = 2.4 km
fltst.dp048: z = 4.8 km
fltst.dp072: z = 7.2 km
fltst.dp096: z = 9.6 km
fltst.dp120: z = 12.0 km
fltst.dp144: z = 14.4 km
fltst.dp168: z = 16.8 km
fltst.dp192: z = 19.2 km
fltst.dp240: z = 24.0 km
fltst.dp288: z = 28.8 km
fltst.dp360: z = 36.0 km
```