Incorporating Full Elastodynamic Effects and Dipping Fault Geometries in Community Code Verification Exercises for Simulations of Earthquake Sequences and Aseismic Slip (SEAS)

SUPPLEMENTARY MATERIAL

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1 Self-convergence Studies

We ascertain self-convergence of BICyclE (for BP1-FD) and Unicycle (for BP3-QD) codes used to compute reference solutions by computing the L^2-norm error (in space) of final slip (at time t_f) against results on the finest grid (6.25 m for BP1-FD and 12.5 m for BP3-QD). Namely, we define the relative error via

$$\mathrm{err}_{\Delta z} = \frac{||\delta_{\mathrm{ref}} - \delta_{\Delta z}||}{||\delta_{\mathrm{ref}}||} \tag{1}$$

where the norm is the L^2-norm, defined for a fault variable g at final time t_f by $||g||^2 = \int_0^{W_f} |g(z', t_f)|^2 dz'$. Here the dummy variable z' ranges over the frictional portion of the fault $(0, W_f)$. Fault slip on the fine grid (reference solution R_1 for BP1-FD and R_2 for BP3-QD) is restricted to the same grid for the comparative solution $\delta_{\Delta z}$ which uses a cell size Δz, and the integral is approximated using trapezoidal quadrature. Table 1 shows $\mathrm{err}_{\Delta z}$ monotonically decreasing with cell size. In addition, for BP1-FD we ensure that the reference solution uses a sufficiently large domain size by successively increasing L_z (L_x is infinite by design) and computing

$$\mathrm{err}_{L_z} = \frac{||\delta_{\mathrm{ref}} - \delta_{L_z}||}{||\delta_{\mathrm{ref}}||} \tag{2}$$

using a reference solution with largest L_z (240 km in this case), denoted R_3. Here the cell size is fixed at $\Delta z = 12.5$ m in order to isolate the effects of domain size. As seen in Table 1, err_{L_z} also decreases monotonically with increasing L_z.

Table 1: Relative errors in self-convergence tests

BP1-FD		BP1-FD		BP3-QD	
Δz	$\mathrm{err}_{\Delta z}$	L_z	err_{L_z}	Δz	$\mathrm{err}_{\Delta z}$
100 m		120 km	3.03×10^{-3}	100 m	2.40×10^{-3}
50 m	5.12×10^{-5}	160 km	1.09×10^{-3}	50 m	1.24×10^{-3}
25 m	2.93×10^{-5}	200 km	3.68×10^{-4}	25 m	2.38×10^{-4}
12.5 m	9.29×10^{-6}				

2 Remaining cases for BP3-QD

Figures 1–4 contain remaining cases not shown in main text. Figure 1 show cumulative slip profiles and interevent times for the normal faulting cases. Results across codes exhibit good agreements. For the higher dip angle of 60°, the normal faulting case yields one characteristic event occurring every ∼95 years, which coincides with the interevent time of the largest event in the corresponding thrust faulting scenario (shown in main text), and yet no smaller event types emerge. For the 30° normal faulting case, two characteristic events emerge, similar to its thrust faulting counterpart (main text), but at longer interevent times of ∼75 and 110 years.

Figure 2 shows long-term time series for remaining cases not shown in main text (i.e. 90° thrust, 60° normal and 30° thrust) which show good agreements except in a few cases and outliers (FDCycle in 60° normal fault case and sbplib in 30° thrust fault).

In Figure 3 we plot the total normal stress at the down-dip distance $x_d = 7.5$ km, associated with each of the non-vertical dipping fault cases (those in which changes in normal stress occur) to better assess overall matching of code results. The overall changes in normal stress at this distance down-dip are only a few percent (our initial effective normal stress was taken to be 50 MPa), however discrepancies in peak values across participating codes are also evident and coincide with the outliers already mentioned here and in the main text. For the best-matching results however, thrust and normal faulting are accompanied with positive and negative normal stress changes, respectively, with larger changes associated with smaller dip angles.

Figure 4 shows remaining cases of off-fault surface stations, namely for the 30° thrust/normal faulting scenarios which further showcase asymmetries across the fault trace.

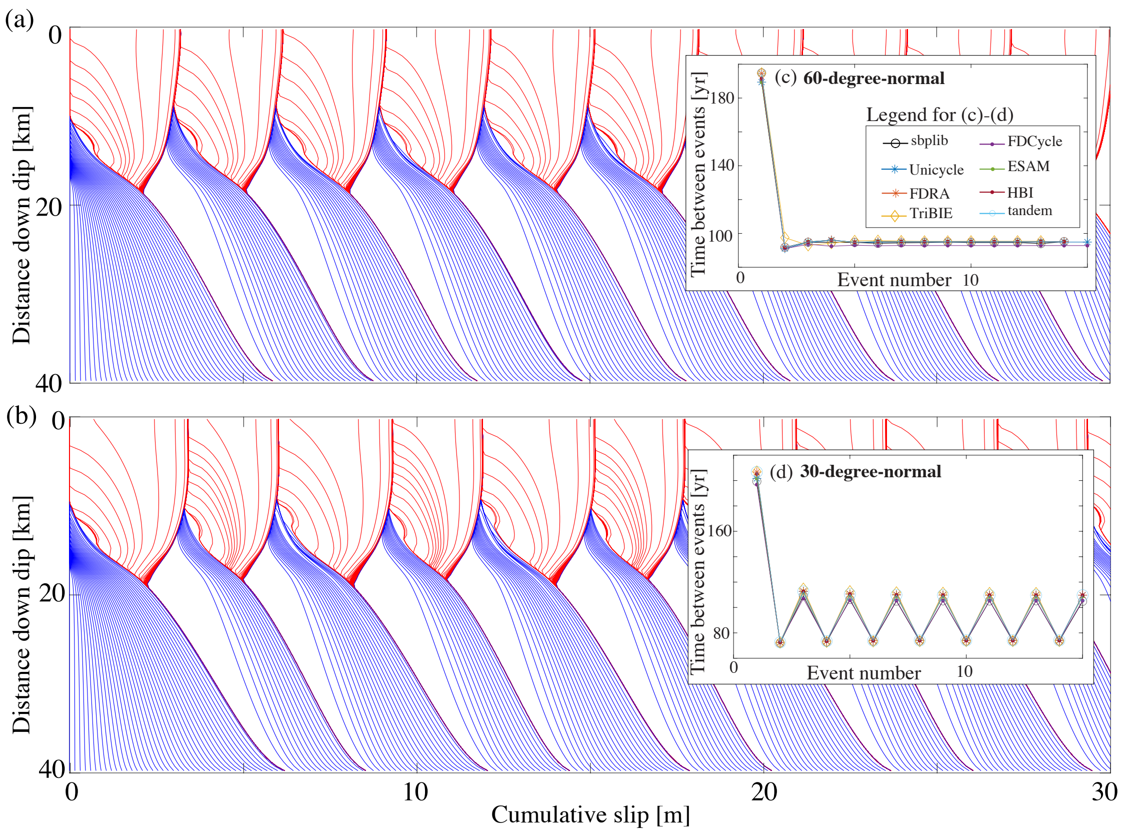

Figure 1: Cumulative slip profiles for BP3-QD normal-faulting simulations from the FDRA code (with slip multiplied by -1) with dip angles (a) 60° and (b) 30° plotted in blue contours every 5 years during the interseismic phases and in red every second during coseismic rupture. Interevent times for corresponding simulations across all participating codes shown in (c) for 60°, where characteristic events emerge every ∼95 years; (d) for 30°, where two distinct event types emerge every ∼75 and 110 years.

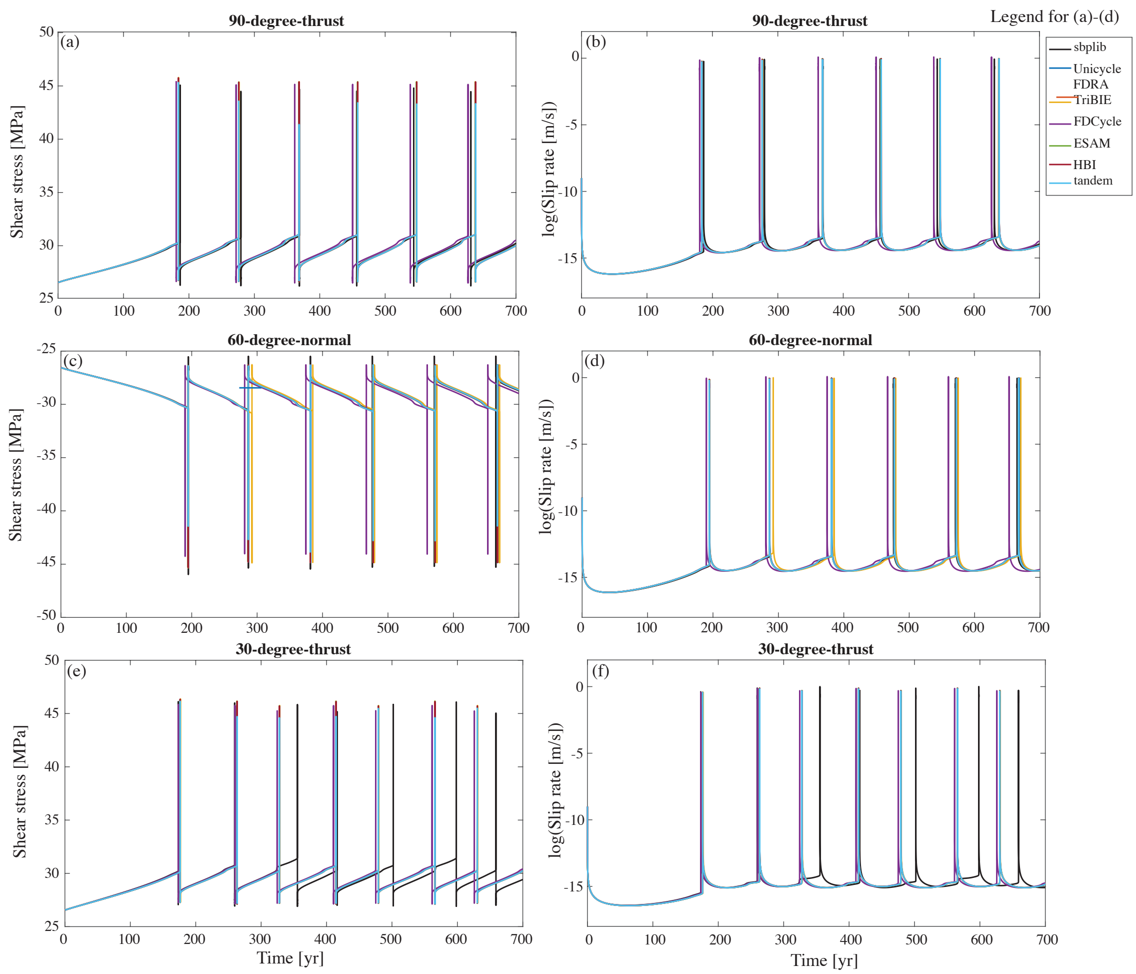

Figure 2: Long-term time-series of shear stress and slip rate for remaining BP3-QD faulting scenarios at $x_d = 7.5$ km for (a)-(b) 90° thrust, (b)-(c) 60° normal and (e)-(f) 30° thrust faulting cases.

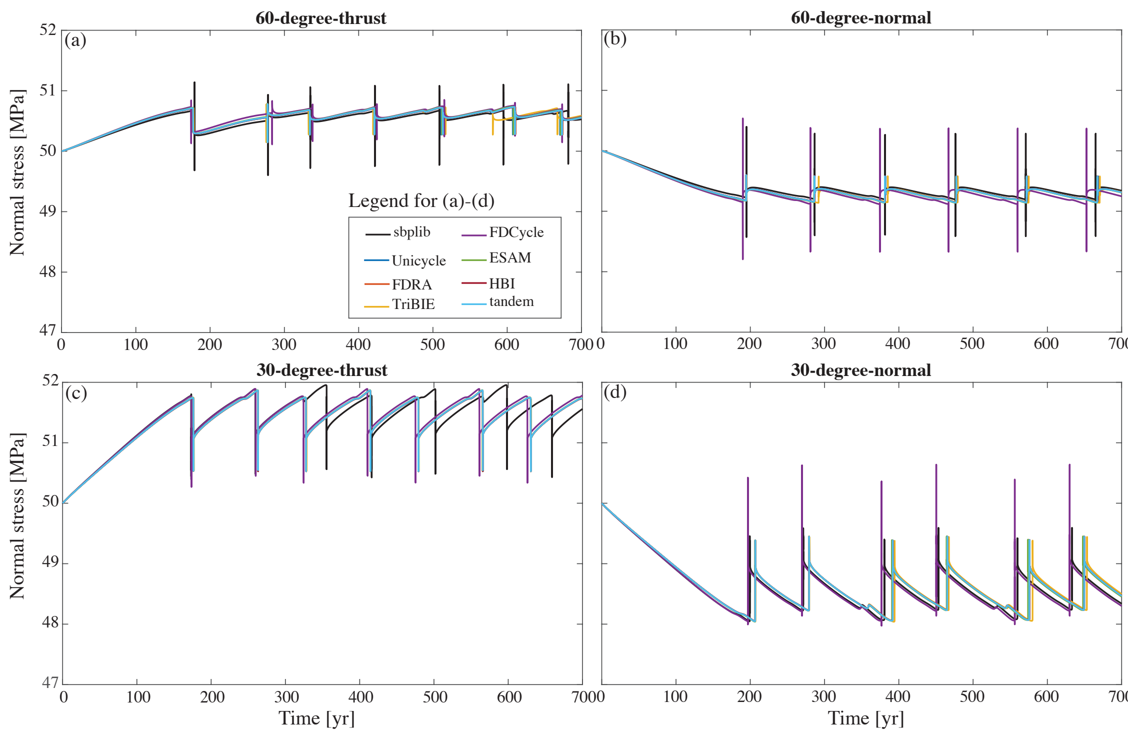

Figure 3: Long-term time-series of normal stress for BP3-QD thrust faulting scenarios at $x_d = 7.5$ km for (a)-(b) 60° thrust and normal faulting and (c)-(d) 30° thrust and normal faulting.

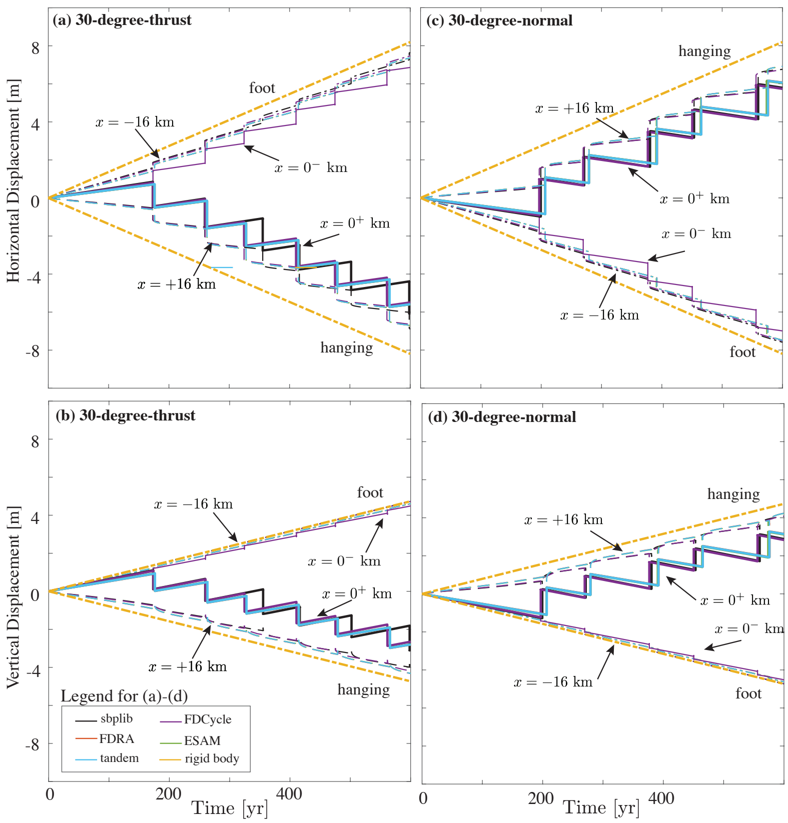

Figure 4: Horizontal and vertical components of surface displacement across a subset of codes at surface stations $x = 0^+, x = \pm 16$ km for remaining cases not shown in main text(a)-(b) 30° thrust and (c)-(d) 30° normal faulting cases. Also shown is surface station at $x = 0^-$ (not solicited by benchmark description) from FDCycle code for reference, and the rigid body (far field) translation (in yellow) where the text indicates motion on either the hanging or foot wall.

SEAS Benchmark Problem BP1-FD

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The problem set-up for benchmark BP1-FD is identical to that of the first benchmark problem (BP1/BP1-QD) except for the use of full elastodynamics instead of radiation damping to approximate the inertia effects. The total simulation time is reduced, but all other parameters are unchanged. Locations for time series output are same as BP1.

1 2D Problem Setup

The medium is assumed to be a homogeneous, isotropic, linear elastic half-space defined by

$$(x, y, z) \in (-\infty,\ \infty) \times (-\infty,\ \infty) \times (0,\ \infty),$$

with a free surface at $z = 0$ and z as positive downward. A vertical, strike-slip fault is embedded at $x = 0$, see Figure 1. We assume antiplane shear motion, letting $u = u(x, z, t)$ denote the displacement in the y-direction. Motion is governed by the momentum balance equation

$$\rho \frac{\partial^2 u}{\partial t^2} = \frac{\partial \sigma_{xy}}{\partial x} + \frac{\partial \sigma_{yz}}{\partial z}, \tag{1}$$

in the domain $(x, z) \in (-\infty, \infty) \times (0, \infty)$, where ρ is the material density. Hooke's law relates stresses to strains by

$$\sigma_{xy} = \mu \frac{\partial u}{\partial x}; \quad \sigma_{yz} = \mu \frac{\partial u}{\partial z} \tag{2}$$

for shear modulus μ.

2 Boundary and Interface Conditions

We supplement equations (1)–(2) with one boundary condition and two interface conditions. A free surface lies at $z = 0$, where all components of the traction vector equal 0. Mathematically, this condition is given by

$$\sigma_{yz}(x, 0, t) = 0. \tag{3}$$

At $x = 0$, the fault defines the interface. Superscripts "+" and "−" refer to the side of the fault with x positive, and x negative, respectively. We define slip by $\delta(z, t) = u(0^+, z, t) - u(0^-, z, t)$, i.e. the jump in displacement across the fault, with right-lateral motion yielding positive values of δ. We require that components of the traction vector be equal and opposite, which reduces in antiplane shear to the condition

$$\sigma_{xy}(0^+, z, t) = \sigma_{xy}(0^-, z, t), \tag{4}$$

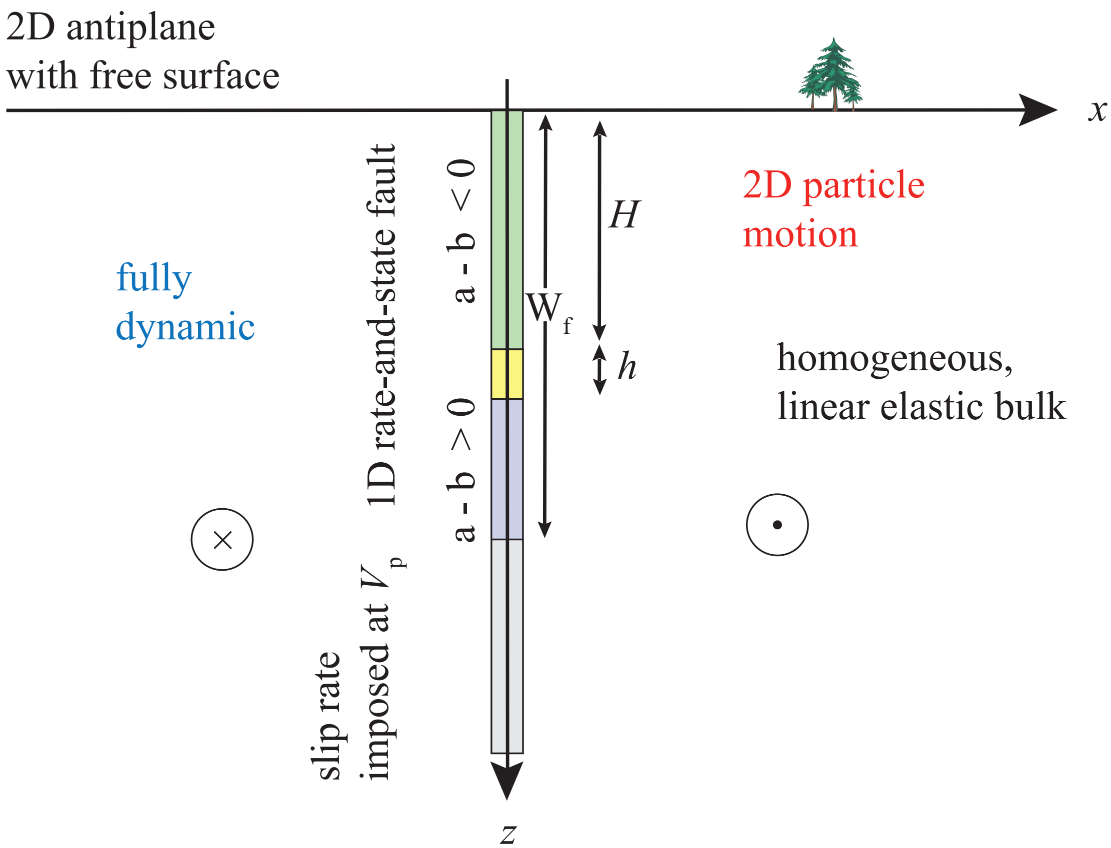

Figure 1: This initial benchmark considers a planar fault embedded in a homogeneous, linear elastic half-space with a free surface. The fault is governed by rate-and-state friction down to the depth W_f and creeps at an imposed constant rate V_p down to the infinite depth. The simulations will include the nucleation, propagation, and arrest of earthquakes, and aseismic slip in the post- and inter-seismic periods.

and denote the common value by $\Delta\tau$ (shear stress perturbation due to antiplane deformation). Note that positive values of $\Delta\tau$ denotes stress that tends to cause right-lateral motion.

The second interface condition is depth dependent. Down to a depth of W_{f}, we impose rate-and-state friction, namely, that shear stress on the fault be equal to fault strength F, namely

$$\tau = F(V, \theta), \tag{5}$$

where $\tau = \tau^0 + \Delta\tau$ is the sum of the prestress, and the shear stress perturbation. The fault strength $F = \sigma_{\mathrm{n}} f(V, \theta)$, where $V = \frac{\partial u}{\partial t}(0^+, z, t) - \frac{\partial u}{\partial t}(0^-, z, t)$ is the slip rate, and θ is the state variable. σ_{n} is the effective normal stress on the fault. For this first benchmark problem we assume σ_{n} is constant, given in Table 1. θ evolves according to the aging law

$$\frac{d\theta}{dt} = 1 - \frac{V\theta}{L}, \tag{6}$$

where L (denoted D_{c} is previous benchmarks) is the critical slip distance. The friction coefficient f is given by a regularized formulation

$$f(V, \theta) = a \sinh^{-1}\left[\frac{V}{2V_0} \exp\left(\frac{f_0 + b\ln(V_0\theta/L)}{a}\right)\right] \tag{7}$$

for reference friction coefficient f_0, reference slip rate V_0, and rate-and-state parameters a and b. For this benchmark, b is constant as b_0 and a varies with depth (insert in Figure 1) as follows:

$$a(z) = \begin{cases} a_0, & 0 \le z < H \\ a_0 + (a_{\max} - a_0)(z - H)/h, & H \le z < H + h \\ a_{\max}, & H + h \le z < W_{\mathrm{f}} \end{cases} \tag{8}$$

Below depth W_{f}, the fault creeps at an imposed constant rate, given by the interface condition

$$V(z, t) = V_{\mathrm{p}}, \quad z \ge W_{\mathrm{f}}, \tag{9}$$

where V_{p} is the plate rate.

3 Initial Conditions and Simulation Time

Initial conditions on particle displacement and velocity are required, as well as on the state variable. We assume that displacements are initially zero everywhere in the domain, i.e.

$$u(x, z, 0) = 0. \tag{10}$$

Particle velocities are given by

$$v(x^+, z, t) = V_{\mathrm{init}}/2 \tag{11}$$
$$v(x^-, z, t) = -V_{\mathrm{init}}/2 \tag{12}$$

where V_{init} is specified.

Table 1: Parameter values used in first benchmark problem

Parameter	Definition	Value, Units
ρ	density	2670 kg/m^3
c_s	shear wave speed	3.464 km/s
σ_n	effective normal stress on fault	50 MPa
a_0	rate-and-state parameter	0.010
a_max	rate-and-state parameter	0.025
b_0	rate-and-state parameter	0.015
L	critical slip distance	0.008 m
V_p	plate rate	10^{-9} m/s
V_init	initial slip rate	10^{-9} m/s
V_0	reference slip rate	10^{-6} m/s
f_0	reference friction coefficient	0.6
H	depth extent of uniform VW region	15 km
h	width of VW-VS transition zone	3 km
W_f	width of rate-and-state fault	40 km
Δz	suggested cell size	25 m
t_f	final simulation time	1500 years

The initial state on the fault is chosen to be consistent with a uniform slip rate and pre-stress at constant values V_init and τ^0, respectively. The pre-stress τ^0 corresponds to the steady-state stress with slip rate V_init at the depth of W_f, namely

$$\tau^0 = \sigma_\mathrm{n} a_\mathrm{max} \sinh^{-1}\left[\frac{V_\mathrm{init}}{2V_0}\exp\left(\frac{f_0 + b_0 \ln(V_0/V_\mathrm{init})}{a_\mathrm{max}}\right)\right]. \tag{13}$$

To be consistent with slip rate and pre-stress everywhere, the initial state is variable with depth and not necessarily at the steady state:

$$\theta(z,0) = \frac{L}{V_0}\exp\left\{\frac{a}{b}\ln\left[\frac{2V_0}{V_\mathrm{init}}\sinh\left(\frac{\tau^0}{a\sigma_\mathrm{n}}\right)\right] - \frac{f_0}{b}\right\}. \tag{14}$$

Equations (1)–(2), along with boundary condition (3), interface conditions (4)–(5) and (9), and initial conditions (10), (11) and (14) are solved over the time period $0 \le t \le t_\mathrm{f}$, where t_f is a specified final simulation time. All necessary parameter values for this benchmark problem are given in Table 1.

4 On-fault Time Series Output

Files are uploaded to the SCEC code validation web server at this address:

`http://scecdata.usc.edu/cvws/cgi-bin/seas.cgi`

You need to upload on-fault ($x = 0$) time series files, which give slip δ, base 10 log of the slip rate V, base 10 log of the state variable (i.e. $\log_{10}(\theta)$), and shear stress τ, for each on-fault station at representative time steps. We define the simulation periods as either aseismic (when $\max(V) < 10^{-3}$ m/s, where $\max(V)$ is the maximum slip rate over the entire fault) or seismic (when $\max(V) \geq 10^{-3}$ m/s). When outputting modeling results, use larger time intervals (e.g., $\sim$0.1 yr) during aseismic periods and smaller time intervals (e.g., $\sim$0.1 s) during seismic periods. More variable time steps are OK. Please keep the total number of time steps in the data file on the order of 10^4–10^5.

Time series data is supplied as ASCII files, one file for each station. There are 12 stations in total, as follows:

`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

Each time series has 5 data fields, as follows.

Field Name	Description, Units and Sign Convention
`t`	Time (s)
`slip`	Out-of-plane slip (m). Positive for right-lateral motion.
`slip_rate`	$\log_{10}$ of the out-of-plane slip-rate ($\log_{10}$ m/s). Positive for right-lateral motion.
`shear_stress`	Shear stress (MPa). Positive for shear stress that tends to cause right-lateral motion.
`state`	$\log_{10}$ of state variable ($\log_{10}$ s).

The on-fault time series file consists of three sections, as follows:

File Section	Description
File Header	A series of lines, each beginning with a # symbol, that give the following information: • Benchmark problem (No.3) • Code name • Code version (optional) • Modeler • Date • Node spacing or element size • Station location • Minimum time step (optional) • Maximum time step (optional) • Number of time steps in file (optional) • Anything else you think is relevant (optional) • Descriptions of data columns (5 lines)
Field List	A single line, which lists the names of the 5 data fields, in column order, separated by spaces. It should be: `t slip slip_rate shear_stress state` (all on one line). The server examines this line to check that your file contains the correct data fields.
Time History	A series of lines. Each line contains 5 numbers, which give the data values for a single time step. The lines must appear in order of increasing time. **Make sure to use double-precision when saving all fields**. **C/C++ users:** We recommend using 21.13E or 21.13e floating-point format for the time field and 14.6E or 14.6e format for all other data fields. **Fortran users:** We recommend using E22.14 or 1PE22.13 floating-point format for the time field and E15.7 or 1PE15.6 format for other data fields. The server accepts most common numeric formats. If the server cannot understand your file, you will see an error message when you attempt to upload the file.

Here is an example of an on-fault time-series file, with invented data.

```
# This is the file header:
# problem=SEAS Benchmark No.3
# code=MYcode
# version=1.0
# modeler=A.Modeler
# date=2018/10/01
# element_size=35 m
# location= on fault, 7.2km depth
# minimum_time_step=0.1
# maximum_time_step=3.157e6
# num_time_steps=2400
# Column #1 = Time (s)
# Column #2 = Slip (m)
# Column #3 = Slip rate (log10 m/s)
# Column #4 = Shear stress (MPa)
# Column #5 = State (log10 s)
#
```

```
# The line below lists the names of the data fields
t slip slip_rate shear_stress state
# Here is the time-series data.
0.000000E+00 0.000000E+00 -9.000000E+00 3.000000E+01 7.000000E+00 ...
5.000000E-02 0.000000E+00 -9.000000E+00 3.000000E+01 7.000000E+00 ...
1.000000E-01 0.000000E+00 -9.000000E+00 3.000000E+01 7.000000E+00 ...
1.500000E-01 0.000000E+00 -9.000000E+00 3.000000E+01 7.000000E+00 ...
# ...  and so on.
```

5 Slip and Stress Evolution Output

The slip and stress evolution output files, with the names

`slip.dat` and `stress.dat`

are two ASCII files that record the spatial distribution of slip and shear stress τ, respectively, on a subset of fault nodes at representative time steps during the aseismic and seismic phases of the simulation. Data can be saved using representative time intervals of approximately 5 yr and 1 s for results in aseismic and seismic phases, respectively, or with variable time steps. Data will be interpolated to plot slip every 5 yr during the aseismic phase, and every 1 s during the coseismic phase. The data should include a subset of nodes (e.g., with a spacing of ∼500 m) down to a depth of 40 km (the width of rate-and-state frictional fault, W_f). The file also contains the time series of maximum slip rates (taken over the entire fault), so that we can precisely differentiate aseismic and seismic phases.

NOTE: Please upload this data to a Dropbox folder that will be shared with you (or send request to bae@uoregon.edu). Please ensure that the file is ∼10s of MBs or less.

The data file has 4 data fields, as follows:

Field Name	Description, Units and Sign Convention
`z`	Depth (m) at approximately 500 m increments, down to 40 km. Positive for all depths.
`t`	Time (s). Nonuniform time steps.
`max_slip_rate`	The $\log_{10}$ of maximum out-of-plane slip-rate (taken over the entire fault) ($\log_{10}$ m/s). Positive for right-lateral motion.
`slip OR stress`	Out-of-plane slip (m) OR stress (MPa). Positive for right-lateral motion.

The data output consists of three sections, as follows:

File Section	Description
File Header	A series of lines, each beginning with a # symbol, that give the following information: • Benchmark problem (No.3) • Modeler • Date • Code • Code version (if desired) • Node spacing or element size • Descriptions of data fields (3 lines) • Anything else you think is relevant (e.g. computational domain size)
Field List	Two lines. The first line lists z. The second lists the names of the 3 other data fields on one line, separated by spaces. It should be: `z` `t max_slip_rate slip` OR `stress` (last three fields on one line).
Slip OR Stress History	A series of lines that form a 2-dimensional array of rows and columns. The first row/line lists the numbers 0, 0 (to maintain a consistent array size), followed by the spatial nodes with increasing depth as you go across the row. Starting from the second row/line, each row/line contains time, maximum slip rate, and slip of all nodes at the time. These lines appear in order of increasing time (from top to bottom) and slip is recorded with increasing depth (from left to right). **Make sure to use double-precision when saving all fields**. **C/C++ users:** We recommend using 21.13E or 21.13e floating-point format for the time field and 14.6E or 14.6e format for all other data fields. **Fortran users:** We recommend using E22.14 or 1PE22.13 floating-point format for the time field and E15.7 or 1PE15.6 format for other data fields.

Note that z should appear in the first row, preceded by two zero numbers, for nodes with a spacing of approximately 500 m down to a depth of 40 km (width of rate-and-state frictional fault). Time and maximum slip rate should appear as two single columns that start on the second row, with time increasing as you go down. Slip/stress history (the remaining block) is represented by a two-dimensional array with time increasing as you go down the rows/lines, and z increasing as you go across the columns (approximately 81 columns). The entire output array should be of size $(N_\mathrm{t}+1, \sim 83)$, where N_t is the total number of time steps. This means that you output slip/stress at selected nodes at one time step and move on to the next time step. (To keep the file on the order of 10s of MB, N_t should be on the order of 10,000).

The two-dimensional array should therefore be of the form: $\begin{bmatrix} 0 & 0 & z \\ T & \max(V) & \text{slip/stress} \end{bmatrix}$

Here is an example of a slip-evolution file for `slip.dat`, with invented data.

```
# This is the file header:
# problem=SEAS Benchmark No.3
# modeler=A.Modeler
# date=2019/03/01
# code=MyCode
```

```
# code_version=3.7
# element_size=25 m
# Row #1 = Depth (m) with two zeros first
# Column #1 = Time (s)
# Column #2 = Max slip rate (log10 m/s)
# Columns #3-83 = Slip (m)
# Computational domain size:  depth 100 km, distance off fault 100 km
# The line below lists the names of the data fields
z
t max_slip_rate slip
# Here are the data
0.000000E+00  0.000000E+00 0.000000E+00 5.000000E+02 ...  4.000000E+04
0.000000E+00 -9.000000E+00 0.000000E+00 0.000000E+00 ...  0.000000E+00
3.140000E+05 -9.000000E+00 1.340000E-05 1.340000E-05 ...  3.140000E-05
1.227000E+07 -9.000000E+00 1.560000E-05 1.560000E-05 ...  1.220000E-02
4.690000E+07 -9.000000E+00 1.580000E-05 1.580000E-05 ...  4.680000E-02
...
9.467078E+10 -4.500000E-01 9.050000E+01 9.050000E+01 ...  9.461000E+01
```

6 Using the Web Server

The web server lets you upload your modeling results (section 4). Once uploaded, you and other modelers can view the data in various ways.

6.1 Logging in and Selecting a Problem

To log in, start your web browser and go to the home page at:

`http://scecdata.usc.edu/cvws/cgi-bin/seas.cgi`

Click on "Upload Files," and then log in using your user name and password. Remember that passwords are case-sensitive. You are then presented with a list of code validation problems. Find the problem you want, and click the "Select" button. You will then see a list of files for the problem.

6.2 Navigating the Site

You navigate through the site by clicking buttons on the web pages. Avoid using your browser's Back or Forward buttons. If you use the Back or Forward buttons, you may get error messages from your browser.

6.3 Uploading Files

To upload a file, do the following steps:

- Find the file you want to upload, and click "Select." The server displays a page for you to upload the file.
- Select the data file on your computer. The exact method for file selection varies depending on operating system and web browser.
- Click on "Click Once to Upload." The file you selected is uploaded to the server.

When you upload a file, the web server immediately checks for correct formatting. There are three possible results:

- If the file is correctly formatted, the server displays a page noting the successful upload.
- If the file contains errors, the server displays an error log. The error log lists the errors that were detected in the file, each identified as specifically as possible.
- If the file is correctly formatted, but is questionable in some way (for example, a missing time step), then the server displays a warning log, which describes the problem.

When uploading time series files, the website may issue a warning that the time series cannot be filtered. Modelers should ignore this warning. After uploading a file, the file list shows the date and time that you uploaded the file. Remember that any file you upload will be visible to anyone who has access to the web site.

Additional help is available by clicking the “Help” link in the upper right corner of the webpage. Modelers who want to upload multiple versions of the benchmark (for example, using different element sizes), can do so using the “Change Version” feature of the website, which is described in the help screens. Direct further questions to Michael Barall.

6.4 Graphing, Viewing, and Deleting Files

After uploading a file, additional functions become available. These functions let you graph, view, or delete the uploaded file.

Graphing: To graph a file, find the file you want and click “Graph.” For a time-series file, the server displays graphs of all the data fields in the file. At the bottom of each graph page, there is a box you can use to adjust graphing preferences. Graphing a file is a good way to check that the server is interpreting your data as you intended.

Viewing: To view the text of a file, find the file you want and click “View.”

Deleting: To delete a file from the server, find the file you want and click “Delete.” The server displays a page asking you to confirm the deletion.

7 Benchmark Tips

Numerical boundary conditions (to truncate the half-space when defining the computational domain) will most likely change results at least quantitatively, or even qualitatively. We suggest extending these boundaries until you see results appear independent of the computational domain size.

Other aspects that could influence results are the switching of solvers/time stepping schemes between seismic/aseismic phases (e.g. the technique for choosing when to switch between quasi-static and dynamic codes depending on the regime and/or differences in boundary conditions for the different regimes). We suggest exploring these criteria to find robust results that do not differ (at least qualitatively) on when this switch occurs. We prefer participants to use the cell-size suggested in Table 1 and welcome results for different spatial resolutions.

SEAS Benchmark Problems BP3-QD and BP3-FD

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The problem set-up for benchmark BP3 (-QD: quasi-dynamic; -FD: fully dynamic) is that for 2D plane-strain motion, with a planar, dipping fault and a free surface. Many of the elastic and frictional parameters are identical to those used in the first benchmark problem (BP1). For BP3-QD, radiation damping is used to approximate the inertia effects.

1 2D Problem Setup

The medium is assumed to be a homogeneous, isotropic, linear elastic half-space defined by

$$(x, y, z) \in (-\infty,\ \infty) \times (-\infty,\ \infty) \times (0,\ \infty),$$

with a free surface at $z = 0$ and z as positive downward. We assume plane-strain motion, letting $[u, w] = [u(x, z, t), w(x, z, t)]$ denote the vector of in-plane displacements, with u in the (horizontal) x-direction and w in the (vertical) z-direction (with positive values of w downward). The displacements and strains are defined with respect to a prestressed, equilibrium reference state that exists at $t = 0$, as explained below. A planar fault is embedded in the material, dipping at ψ degrees from horizontal, see Figure 1. We assume $0 \leq \psi \leq 90°$. The fault plane is given by $x = z\cot(\psi)$ and partitions the domain into two sub-domains defined by superscripts "+" and "−", namely, $\Omega^+ = \{(x, z) : \quad x \geq z\cot(\psi)\}$ (the right side of the fault in Fig. 1) and $\Omega^- = \{(x, z) : \quad x \leq z\cot(\psi)\}$ (the left side of the fault in Fig. 1). For BP3-FD, motion in each sub-domain is governed by the momentum balance equation

$$\rho\frac{\partial^2 u}{\partial t^2} = \frac{\partial \sigma_{xx}}{\partial x} + \frac{\partial \sigma_{xz}}{\partial z}, \tag{1a}$$

$$\rho\frac{\partial^2 w}{\partial t^2} = \frac{\partial \sigma_{xz}}{\partial x} + \frac{\partial \sigma_{zz}}{\partial z}, \tag{1b}$$

where ρ is the material density. For BP3-QD, inertia is neglected and we solve the equilibrium equation.

The solution to 1 can be expressed as the superposition of the following three solutions:
1. A rigid body translation with zero associated stress changes, denoted $\left[u^{\text{rigid}}, w^{\text{rigid}}\right]$. This rigid body translation is different for the two sub-domains, and the discontinuity in that translational motion across the fault is the long-term slip.
2. An equilibrium, prestressed reference configuration with initial stress tensor given by

$$\boldsymbol{\sigma}^0 = \begin{bmatrix} \sigma^0_{xx} & \sigma^0_{xy} & \sigma^0_{xz} \\ \sigma^0_{xy} & \sigma^0_{yy} & \sigma^0_{yz} \\ \sigma^0_{xz} & \sigma^0_{yz} & \sigma^0_{zz} \end{bmatrix}. \tag{2}$$

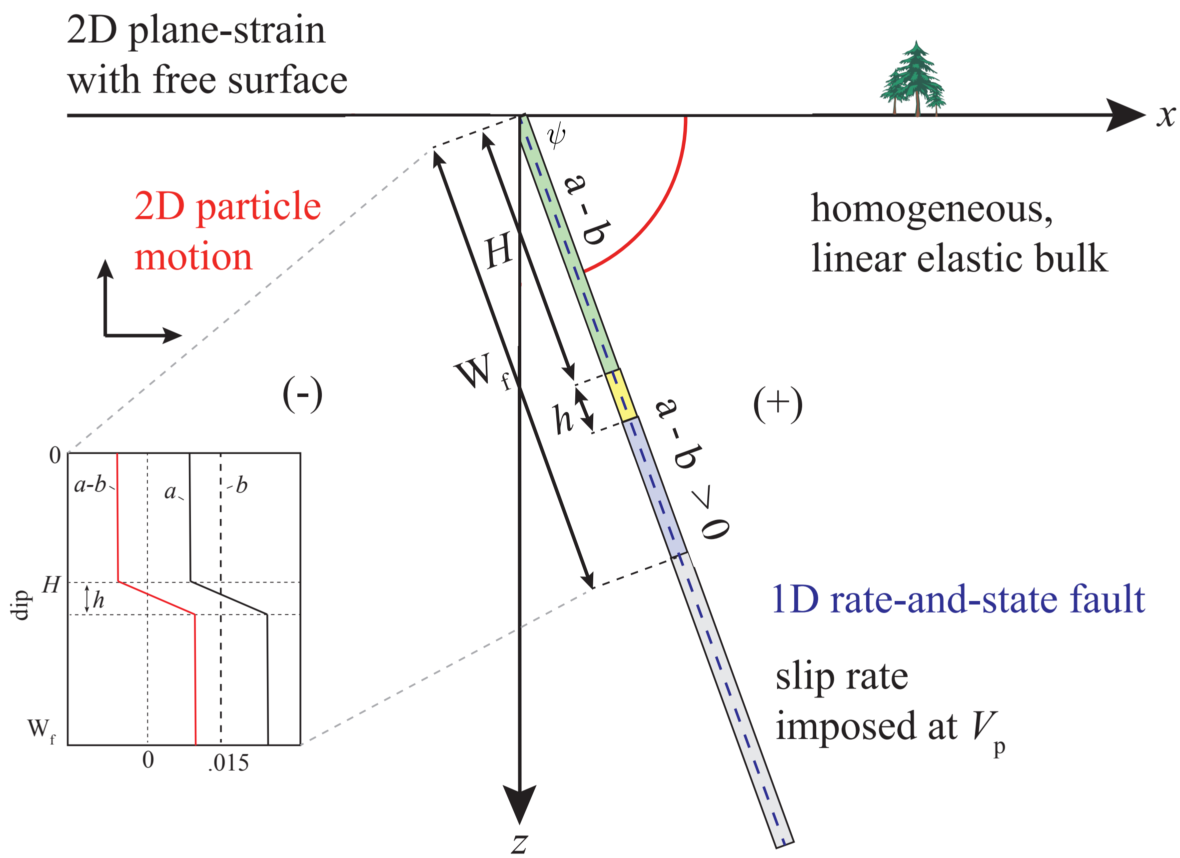

Figure 1: BP3-FD and BP3-QD consider a planar, dipping fault embedded in a homogeneous, linear elastic half-space with a free surface where motion is plane-strain. The fault is governed by rate-and-state friction down dip to a distance W_f and creeps at an imposed constant rate V_p down to the infinite dip distance. The simulations will include the nucleation, propagation, and arrest of quasi-dynamic (BP3-QD) and fully-dynamic (BP3-FD) earthquakes, and aseismic slip in the post- and inter-seismic periods. The left and right sides of the fault are labeled with "(-)" and "(+)", respectively.

The assumption of linear elastic response means that $\boldsymbol{\sigma}^0$ does not directly influence the medium response. However, the fault tractions associated with $\boldsymbol{\sigma}^0$ do influence fault slip through the friction law. For this reason, only those fault tractions are specified in this benchmark.
3. Displacements, strains, and stress changes due to fault slip differing from the steady slip provided by the rigid body translation.

The stresses are given by $\sigma_{ij} = \sigma^0_{ij} + \Delta\sigma_{ij}$, namely, the sum of the initial stress and the elastic stress change. Hooke's law relates stresses to strains by

$$\sigma_{xx} = \sigma^0_{xx} + (\lambda+2\mu)\frac{\partial u}{\partial x} + \lambda\frac{\partial w}{\partial z}; \quad \sigma_{xz} = \sigma^0_{xz} + \mu\left(\frac{\partial u}{\partial z} + \frac{\partial w}{\partial x}\right); \quad \sigma_{zz} = \sigma^0_{zz} + \lambda\frac{\partial u}{\partial x} + (\lambda+2\mu)\frac{\partial w}{\partial z} \tag{3}$$

for shear modulus μ and Lamé's first parameter λ.

2 Boundary and Interface Conditions

This semi-infinite domain problem requires conditions at infinity. For the quasi-dynamic BP3-QD we require that stress changes $\Delta\sigma_{ij}$ and displacement changes (from rigid body translation), $u - u^{\mathrm{rigid}}$ and $w - w^{\mathrm{rigid}}$, vanish at infinity ($x \to \pm\infty, z \to \infty$). For the fully dynamic BP3-FD, we permit only outgoing waves through the Sommerfeld radiation condition at infinity [Eringen and Suhubi, 1975, Bonnet, 1999]. The rigid body translation we specify as

$$u^{\pm,\mathrm{rigid}}(t) = \mp\frac{V_p t}{2}\cos\psi \tag{4a}$$

$$w^{\pm,\mathrm{rigid}}(t) = \mp\frac{V_p t}{2}\sin\psi \tag{4b}$$

where V_{p} is the plate rate.

A free surface lies at $z = 0$, where all components of the traction vector equal 0. Mathematically, this generates the two boundary conditions

$$\sigma^{\pm}_{xz}(x, 0, t) = 0 \tag{5a}$$

$$\sigma^{\pm}_{zz}(x, 0, t) = 0. \tag{5b}$$

In addition, we define slip on the fault by

$$\delta(z,t) = [u^-(X(z),z,t) - u^+(X(z),z,t)]\cos(\psi) + [w^-(X(z),z,t) - w^+(X(z),z,t)]\sin(\psi), \tag{6}$$

i.e. the jump in tangential displacement across the fault. Thrust (reverse) faulting yields positive values of δ, while normal yields negative values. We also define the "opening"

$$\gamma(z,t) = [u^-(X(z),z,t) - u^+(X(z),z,t)]\sin(\psi) - [w^-(X(z),z,t) - w^+(X(z),z,t)]\cos(\psi), \tag{7}$$

i.e. the jump in the normal component of displacement.

In the rest of this section, we refer to traction by omitting its evaluation at the fault for notational ease. The traction vector on each side of the fault is denoted with a superscript corresponding to the side of the fault and given by $T^{\pm} = T^{\pm}_0 + \Delta T^{\pm}$ where

$$T^{\pm}_0 = [\mp\sin(\psi)\sigma^{0,\pm}_{xx} \pm \cos(\psi)\sigma^{0,\pm}_{xz},\ \mp\sin(\psi)\sigma^{0,\pm}_{xz} \pm \cos(\psi)\sigma^{0,\pm}_{zz}], \tag{8}$$

$$\Delta T^{\pm} = [\mp\sin(\psi)\Delta\sigma^{\pm}_{xx} \pm \cos(\psi)\Delta\sigma^{\pm}_{xz},\ \mp\sin(\psi)\Delta\sigma^{\pm}_{xz} \pm \cos(\psi)\Delta\sigma^{\pm}_{zz}], \tag{9}$$

i.e. $T_0^{\pm}$ are the background tractions (prestress resolved on the fault) and $\Delta T^{\pm}$ are the changes in fault tractions associated with the displacement field. We require that components of the traction vector on either side of the fault be equal and opposite, namely, $-T^+ = T^-$. Since the background tractions satisfy $-T_0^+ = T_0^-$ (the common value we denote T^0), we require $-\Delta T^+ = \Delta T^-$ (the common value we denote ΔT), namely,

$$\sin(\psi)\left(\Delta\sigma_{xx}^+ - \Delta\sigma_{xx}^-\right) - \cos(\psi)\left(\Delta\sigma_{xz}^+ - \Delta\sigma_{xz}^-\right) = 0, \tag{10a}$$

$$\sin(\psi)\left(\Delta\sigma_{xz}^+ - \Delta\sigma_{xz}^-\right) - \cos(\psi)\left(\Delta\sigma_{zz}^+ - \Delta\sigma_{zz}^-\right) = 0. \tag{10b}$$

The remaining interface conditions are as follows: We assume a "no-opening" condition, namely,

$$\gamma(z,t) = 0, \tag{11}$$

and an additional condition that is depth dependent. First we note T^0 and ΔT can be further decomposed into shear and normal components, which must be continuous across the fault. These common values are denoted

$$\tau^0 = \sin(\psi)\cos(\psi)[-\sigma_{xx}^0 + \sigma_{zz}^0] + (\cos^2(\psi) - \sin^2(\psi))\sigma_{xz}^0, \tag{12a}$$

$$\sigma^0 = -\sin^2(\psi)\sigma_{xx}^0 + 2\sin(\psi)\cos(\psi)\sigma_{xz}^0 - \cos^2(\psi)\sigma_{zz}^0, \tag{12b}$$

and

$$\Delta\tau = \sin(\psi)\cos(\psi)[-\Delta\sigma_{xx} + \Delta\sigma_{zz}] + (\cos^2(\psi) - \sin^2(\psi))\Delta\sigma_{xz}, \tag{13a}$$

$$\Delta\sigma = -\sin^2(\psi)\Delta\sigma_{xx} + 2\sin(\psi)\cos(\psi)\Delta\sigma_{xz} - \cos^2(\psi)\Delta\sigma_{zz}. \tag{13b}$$

with normal stress positive in compression.

Down-dip to a distance W_{f}, we impose rate-and-state friction, namely, that shear stress on the fault be equal to fault strength F:

$$\tau = F(V, \theta, \sigma_{\mathrm{n}}). \tag{14}$$

For BP3-QD, $\tau = \tau^0 + \Delta\tau - \eta V$ is the sum of the prestress, the shear stress change due to quasi-static deformation, and the radiation damping approximation to inertia, where $\eta = \mu/2c_{\mathrm{s}}$ is half the shear-wave impedance for shear wave speed $c_{\mathrm{s}} = \sqrt{\mu/\rho}$. For BP3-FD, $\tau = \tau^0 + \Delta\tau$, namely the sum of the prestress and (dynamic) stress change.

The fault strength $F = \bar{\sigma}_{\mathrm{n}} f(|V|, \theta)\frac{V}{|V|}$, where $V = \frac{\partial\delta}{\partial t}$ is the slip rate, and θ is the state variable.

$$\bar{\sigma}_{\mathrm{n}} = (\sigma^0 - p^0) + \Delta\sigma \tag{15}$$

is the effective normal stress (which takes into account changes in normal stress induced by slip on the fault), where $\bar{\sigma}_{\mathrm{n}}^0 = \sigma^0 - p^0$ is the initial effective normal stress and changes in pressure are neglected. θ evolves according to the aging law

$$\frac{d\theta}{dt} = 1 - \frac{|V|\theta}{L}, \tag{16}$$

where L (denoted D_{c} is previous benchmarks) is the critical slip distance. The friction coefficient f is given by a regularized formulation

$$f(V,\theta) = a\sinh^{-1}\left[\frac{V}{2V_0}\exp\left(\frac{f_0 + b\ln(V_0\theta/L)}{a}\right)\right] \tag{17}$$

for reference friction coefficient f_0, reference slip rate V_0, and rate-and-state parameters a and b. For this benchmark, b is constant as b_0 (given in Table 1) and a varies with distance down-dip $x_d = z/\sin(\psi)$ (see insert in Figure 1):

$$a(x_d) = \begin{cases} a_0, & 0 \leq x_d < H \\ a_0 + (a_{\max} - a_0)(x_d - H)/h, & H \leq x_d < H + h \\ a_{\max}, & H + h \leq x_d < W_\mathrm{f} \end{cases} \tag{18}$$

Below down-dip distance W_f, the fault creeps at an imposed constant rate, given by the interface condition

$$V(x_d, t) = V_\mathrm{L}, \quad x_d \geq W_\mathrm{f}, \tag{19}$$

where V_L is an imposed fault slip rate.

3 Initial Conditions and Simulation Time

We solicit results from both thrust and normal faulting scenarios. Initial conditions for both scenarios are provided below, with differences specified by model parameters given in Table 1. Please be aware of notable sign differences: Thrust faulting corresponds to positive values in slip, slip rate, and shear traction, with negative values for normal faulting. Table 1 also provides values for the initial effective normal stress $\bar{\sigma}_\mathrm{n}^0$.

For BP3-FD initial values for displacements and velocities must be specified. We assume these are initially zero everywhere in the domain (i.e. we assume displacements are measured with respect to the prestressed equilibrium configuration), namely,

$$u(x, z, 0) = \dot{u}(x, z, 0) = 0, \tag{20}$$

$$w(x, z, 0) = \dot{w}(x, z, 0) = 0. \tag{21}$$

In addition, for BP3-FD we must specify τ^0 and an initial value for the state variable. τ^0 is set to the steady-state stress at slip rate V_init at the depth of W_f (given in Table 1), namely,

$$\tau^0 = \sigma_\mathrm{n}^0 a_{\max} \sinh^{-1}\left[\frac{V_\mathrm{init}}{2V_0} \exp\left(\frac{f_0 + b_0 \ln(V_0/|V_\mathrm{init}|)}{a_{\max}}\right)\right] \tag{22}$$

and the state variable is set to

$$\theta(z, 0) = \frac{L}{V_0} \exp\left\{\frac{a}{b} \ln\left[\frac{2V_0}{V_\mathrm{init}} \sinh\left(\frac{\tau^0}{a\sigma_\mathrm{n}^0}\right)\right] - \frac{f_0}{b}\right\}. \tag{23}$$

For BP3-QD, we must specify an initial value for slip, which we take to be zero, namely

$$\delta(z, t) = 0. \tag{24}$$

In addition we set τ^0 equal to steady-state stress at slip rate V_init at the depth of W_f, namely

$$\tau^0 = \sigma_\mathrm{n}^0 a_{\max} \sinh^{-1}\left[\frac{V_\mathrm{init}}{2V_0} \exp\left(\frac{f_0 + b_0 \ln(V_0/|V_\mathrm{init}|)}{a_{\max}}\right)\right] + \eta V_\mathrm{init}\,, \tag{25}$$

such that the actual shear stress on the fault initially is consistent with the desired initial slip rate V_init. And finally, the initial state for BP3-QD is variable with depth:

$$\theta(z, 0) = \frac{L}{V_0} \exp\left\{\frac{a}{b} \ln\left[\frac{2V_0}{V_\mathrm{init}} \sinh\left(\frac{\tau^0 - \eta V_\mathrm{init}}{a\sigma_\mathrm{n}^0}\right)\right] - \frac{f_0}{b}\right\}. \tag{26}$$

Table 1: Parameter values used in BP3. Plus/minus signs refer to thrust/normal faulting, respectively.

Parameter	Definition	Value, Units
ψ	dip angle	$30°, 60°$, and $90°$
ρ	density	2670 kg/m^3
ν	poisson's ratio	0.25
c_s	shear wave speed	3.464 km/s
$\bar{\sigma}_n^0$	initial effective normal stress on fault	50 MPa
a_0	rate-and-state parameter	0.010
a_{max}	rate-and-state parameter	0.025
b_0	rate-and-state parameter	0.015
L	critical slip distance	0.008 m
V_p	plate rate	$\pm 10^{-9}$ m/s
V_L	fault slip rate	$\pm 10^{-9}$ m/s
V_{init}	initial slip rate	$\pm 10^{-9}$ m/s
V_0	reference slip rate	10^{-6} m/s
f_0	reference friction coefficient	0.6
H	depth extent of uniform VW region	15 km
h	width of VW-VS transition zone	3 km
W_f	width of rate-and-state fault	40 km
Δz	suggested cell size	25 m
t_f	final simulation time	1500 years

Equations (1)–(3), along with boundary condition (5), interface conditions (10), (11), (14) and (19), and initial conditions ((20 - 23) for BP3-FD and (24-26) for BP3-QD) are solved over the time period $0 \leq t \leq t_f$, where t_f is a specified final simulation time. All necessary parameter values for this benchmark problem are given in Table 1.

4 Benchmark Output

We request three types of data output for this benchmark:

(1) On-fault time series (section 4.1)

(2) Off-fault time series (section 4.2)

(3) Slip and stress evolution profile (section 4.3)

When you upload your data to the platform and the Dropbox folder, please specify (either in the file description or by appending the filename) whether the results are for thrust or normal faulting scenarios.

4.1 On-fault Time Series Output

Files are uploaded to the SCEC code validation web server at this address:

`https://strike.scec.org/cvws/cgi-bin/seas.cgi`

Note that as of 09/02/2020, if you have been using the Perl script to upload files, you will need to obtain a new version of it (available in the download section of the website). You need to upload on-fault time series files, which give slip δ, base 10 log of the slip rate V, base 10 log of the state variable (i.e. $\log_{10}(\theta)$), and shear stress τ, for each on-fault station at representative time steps. We define the simulation periods as either aseismic (when $\max(V) < 10^{-3}$ m/s, where $\max(V)$ is the maximum slip rate over the entire fault) or seismic (when $\max(V) \geq 10^{-3}$ m/s). When outputting modeling results, use larger time intervals (e.g., $\sim$0.1 yr) during aseismic periods and smaller time intervals (e.g., $\sim$0.1 s) during seismic periods. More variable time steps are OK. Please keep the total number of time steps in the data file on the order of 10^4–10^5.

Time series data is supplied as ASCII files, one file for each station. There are 12 stations in total, defined by distance down-dip (not depth) as follows:

`fltst_dp000`: $x_d = 0$ km (at the free surface)
`fltst_dp025`: $x_d = 2.5$ km
`fltst_dp050`: $x_d = 5$ km
`fltst_dp075`: $x_d = 7.5$ km
`fltst_dp100`: $x_d = 10$ km
`fltst_dp125`: $x_d = 12.5$ km
`fltst_dp150`: $x_d = 15$ km
`fltst_dp175`: $x_d = 17.5$ km
`fltst_dp200`: $x_d = 20$ km
`fltst_dp250`: $x_d = 25$ km
`fltst_dp300`: $x_d = 30$ km
`fltst_dp350`: $x_d = 35$ km

Each time series has 5 data fields, as follows.

Field Name	Description, Units and Sign Convention
`t`	Time (s)
`slip`	Slip (m). Positive for fault normal motion.
`slip_rate`	$\log_{10}$ of the slip-rate ($\log_{10}$ m/s). Positive for fault normal motion.
`shear_stress`	Shear stress (MPa). Positive for shear stress that tends to cause fault-normal motion.
`normal_stress`	Normal stress (MPa).
`state`	$\log_{10}$ of state variable ($\log_{10}$ s).

The on-fault time series file consists of three sections, as follows:

File Section	Description
File Header	A series of lines, each beginning with a # symbol, that give the following information: • Benchmark problem (BP3-QD or BP3-FD) • Code name • Code version (optional) • Modeler • Date • Node spacing or element size • Station location • Minimum time step (optional) • Maximum time step (optional) • Number of time steps in file (optional) • Anything else you think is relevant (optional) • Descriptions of data columns (5 lines)
Field List	A single line, which lists the names of the 5 data fields, in column order, separated by spaces. It should be: `t slip slip_rate shear_stress normal_stress state` (all on one line). The server examines this line to check that your file contains the correct data fields.
Time History	A series of lines. Each line contains 5 numbers, which give the data values for a single time step. The lines must appear in order of increasing time. **Make sure to use double-precision when saving all fields**. **C/C++ users:** We recommend using 21.13E or 21.13e floating-point format for the time field and 14.6E or 14.6e format for all other data fields. **Fortran users:** We recommend using E22.14 or 1PE22.13 floating-point format for the time field and E15.7 or 1PE15.6 format for other data fields. The server accepts most common numeric formats. If the server cannot understand your file, you will see an error message when you attempt to upload the file.

Here is an example of an on-fault time-series file, with invented data.

```
# This is the file header:
# problem=SEAS Benchmark BP3-QD or BP3-FD
# code=MYcode
# version=1.0
# modeler=A.Modeler
# date=2020/10/01
```

```
# element_size=35 m
# location= on fault, 7.2km down-dip distance
# minimum_time_step=0.1
# maximum_time_step=3.157e6
# num_time_steps=2400
# Column #1 = Time (s)
# Column #2 = Slip (m)
# Column #3 = Slip rate (log10 m/s)
# Column #4 = Shear stress (MPa)
# Column #5 = Normal stress (MPa)
# Column #6 = State (log10 s)
#
# The line below lists the names of the data fields
t slip slip_rate shear_stress normal_stress state
# Here is the time-series data.
0.000000E+00 0.000000E+00 -9.000000E+00 3.000000E+01 7.000000E+00 ...
5.000000E-02 0.000000E+00 -9.000000E+00 3.000000E+01 7.000000E+00 ...
1.000000E-01 0.000000E+00 -9.000000E+00 3.000000E+01 7.000000E+00 ...
1.500000E-01 0.000000E+00 -9.000000E+00 3.000000E+01 7.000000E+00 ...
# ...  and so on.
```

4.2 Off-fault Time Series Output

You need to upload off-fault (surface) time series files (i.e. $x_d = z = 0$), which give two components of displacement u and w and of velocity $\dot{u}$ and $\dot{w}$ for each off-fault surface station at representative time steps. Please use the same time steps for outputting the on-fault and off-fault time series.

Time series data is supplied as ASCII files, one file for each station. There are 7 observational points on the surface with a distance from the fault trace, as follows:

1. `srfst_fn-32`: $x = -32$ km
2. `srfst_fn-16`: $x = -16$ km
3. `srfst_fn-08`: $x = -8$ km
4. `srfst_fn+00`: $x = 0^+$ km
5. `srfst_fn-00`: $x = 0^-$ km
6. `srfst_fn+08`: $x = 8$ km
7. `srfst_fn+16`: $x = 16$ km
8. `srfst_fn+32`: $x = 32$ km

Each time series has 7 data fields, as follows.

Field Name	Description, Units and Sign Convention
`t`	Time (s)
`disp_1`	Horizontal (u) component of displacement (m). Positive for moving in $x-$ (right) direction.
`disp_2`	Vertical (w) component of displacement (m). Positive for motion in $z-$ (downward) direction.
`vel_1`	horizontal component of velocity (m/s).
`vel_2`	vertical component of velocity (m/s).

The off-fault time series file consists of three sections, as follows:

File Section	Description
File Header	A series of lines, each beginning with a # symbol, that give the following information: • Benchmark problem (BP3-QD) • Code name • Code version (optional) • Modeler • Date • Node spacing or element size • Station location • Minimum time step (optional) • Maximum time step (optional) • Number of time steps in file (optional) • Anything else you think is relevant (optional) • Descriptions of data columns (7 lines)
Field List	A single line, which lists the names of the 5 data fields, in column order, separated by spaces. It should be: `t disp_1 disp_2 vel_1 vel_2` (all on one line). The server examines this line to check that your file contains the correct data fields.
Time History	A series of lines. Each line contains 5 numbers, which give the data values for a single time step. The lines must appear in order of increasing time. **Make sure to use double-precision when saving all fields**. **C/C++ users:** We recommend using 21.13E or 21.13e floating-point format for the time field and 14.6E or 14.6e format for all other data fields. **Fortran users:** We recommend using E22.14 or 1PE22.13 floating-point format for the time field and E15.7 or 1PE15.6 format for other data fields. The server accepts most common numeric formats. If the server cannot understand your file, you will see an error message when you attempt to upload the file.

Here is an example of an on-fault time-series file, with invented data.

```
# This is the file header:
# problem=SEAS Benchmark BP3-QD
# code=MYcode
# version=1.0
# modeler=A.Modeler
# date=2019/12/01
# element_size=100 m
# location= on surface, +8km distance off-fault
```

```
# minimum_time_step=0.1
# maximum_time_step=3.157e6
# num_time_steps=2400
# Column #1 = Time (s)
# Column #2 = Displacement_1 (m)
# Column #3 = Displacement_2 (m)
# Column #4 = Velocity_1 (m/s)
# Column #5 = Velocity_2 (m/s)
# The line below lists the names of the data fields
t disp_1 disp_2 vel_1 vel_2
# Here is the time-series data.
0.000000E+00 0.000000E+00 0.000000E+00 -9.000000E+00 -2.000000E+01
0.000000E+00 0.000000E+00 -2.000000E-01 0.000000E-09 -2.000000E-01
0.000000E+00 0.000000E+00 -2.000000E+01 0.000000E-09 -2.000000E+01
# ...  and so on.
```

4.3 Slip and Stress Evolution Output

The slip and stress evolution output files, with the names

`slip.dat`, `shear_stress.dat` and `normal_stress.dat`

are three ASCII files that record the spatial distribution of slip δ, and shear and normal stress τ and σ, respectively, on a subset of fault nodes at representative time steps during the aseismic and seismic phases of the simulation. Data can be saved using representative time intervals of approximately 5 yr and 1 s for results in aseismic and seismic phases, respectively, or with variable time steps. Data will be interpolated to plot slip every 5 yr during the aseismic phase, and every 1 s during the coseismic phase. The data should include a subset of nodes (e.g., with a spacing of ∼500 m) down dip to a distance of 40 km (the width of rate-and-state frictional fault, W_{f}). The file also contains the time series of maximum slip rates (taken over the entire fault), so that we can precisely differentiate aseismic and seismic phases.

NOTE: Please upload this data to a Dropbox folder that will be shared with you (or send request to bae@uoregon.edu). Please ensure that the file is ∼10s of MBs or less.

The data file has 4 data fields, as follows:

Field Name	Description, Units and Sign Convention
`x_d`	Distance down dip (m) at approximately 500 m increments, down to 40 km. Positive for all distances down dip.
`t`	Time (s). Nonuniform time steps.
`max_slip_rate`	The $\log_{10}$ of maximum slip-rate (taken over the entire fault) ($\log_{10}$ m/s). Positive for fault-normal motion.
`slip` OR `shear_stress` OR `normal_stress`	Slip (m) OR stress (MPa). Positive for fault-normal motion.

The data output consists of three sections, as follows:

File Section	Description
File Header	A series of lines, each beginning with a # symbol, that give the following information: • Benchmark problem (BP3-QD or BP3-FD) • Modeler • Date • Code • Code version (if desired) • Node spacing or element size • Descriptions of data fields (3 lines) • Anything else you think is relevant (e.g. computational domain size)
Field List	Two lines. The first line lists x_d. The second lists the names of the 3 other data fields on one line, separated by spaces. It should be: `x_d` `t max_slip_rate slip` OR `stress` (last three fields on one line).
Slip OR Stress History	A series of lines that form a 2-dimensional array of rows and columns. The first row/line lists the numbers 0, 0 (to maintain a consistent array size), followed by the spatial nodes with increasing down-dip distance as you go across the row. Starting from the second row/line, each row/line contains time, maximum slip rate, and slip of all nodes at the time. These lines appear in order of increasing time (from top to bottom) and slip is recorded with increasing down-dip distance (from left to right). **Make sure to use double-precision when saving all fields**. **C/C++ users:** We recommend using 21.13E or 21.13e floating-point format for the time field and 14.6E or 14.6e format for all other data fields. **Fortran users:** We recommend using E22.14 or 1PE22.13 floating-point format for the time field and E15.7 or 1PE15.6 format for other data fields.

Note that x_d should appear in the first row, preceded by two zero numbers, for nodes with a spacing of approximately 500 m down to a down-dip distance of 40 km (width of rate-and-state frictional fault). Time and maximum slip rate should appear as two single columns that start on the second row, with time increasing as you go down. Slip/stress history (the remaining block) is represented by a two-dimensional array with time increasing as you go down the rows/lines, and z increasing as you go across the columns (approximately 81 columns). The entire output array should be of size ($N_{\mathrm{t}} + 1, \sim 83$), where N_{t} is the total number of time steps. This means that you output slip/stress at selected nodes at one time step and move on to the next time step. (To keep the file on the order of 10s of MB, N_t should be on the order of 10,000).

The two-dimensional array should therefore be of the form: $\begin{bmatrix} 0 & 0 & x_d \\ T & \max(V) & \text{slip/stress} \end{bmatrix}$

Here is an example of a slip-evolution file for `slip.dat`, with invented data.

```
# This is the file header:
# problem=SEAS Benchmark BP3-QD
# modeler=A.Modeler
# date=2020/10/01
# code=MyCode
# code_version=3.7
# element_size=25 m
# Row #1 = Distance down dip (m) with two zeros first
# Column #1 = Time (s)
# Column #2 = Max slip rate (log10 m/s)
# Columns #3-83 = Slip (m)
# Computational domain size:  depth 100 km, distance off fault 100 km
# The line below lists the names of the data fields
x_d
t max_slip_rate slip
# Here are the data
0.000000E+00  0.000000E+00 0.000000E+00 5.000000E+02 ...  4.000000E+04
0.000000E+00 -9.000000E+00 0.000000E+00 0.000000E+00 ...  0.000000E+00
3.140000E+05 -9.000000E+00 1.340000E-05 1.340000E-05 ...  3.140000E-05
1.227000E+07 -9.000000E+00 1.560000E-05 1.560000E-05 ...  1.220000E-02
4.690000E+07 -9.000000E+00 1.580000E-05 1.580000E-05 ...  4.680000E-02
...
9.467078E+10 -4.500000E-01 9.050000E+01 9.050000E+01 ...  9.461000E+01
```

5 Using the Web Server

The web server lets you upload your modeling results (section 4). Once uploaded, you and other modelers can view the data in various ways.

5.1 Logging in and Selecting a Problem

To log in, start your web browser and go to the home page at:

```
http://scecdata.usc.edu/cvws/cgi-bin/seas.cgi
```

Click on "Upload Files," and then log in using your user name and password. Remember that passwords are case-sensitive. You are then presented with a list of code validation problems. Find the problem you want, and click the "Select" button. You will then see a list of files for the problem.

5.2 Navigating the Site

You navigate through the site by clicking buttons on the web pages. Avoid using your browser's Back or Forward buttons. If you use the Back or Forward buttons, you may get error messages from your browser.

5.3 Uploading Files

To upload a file, do the following steps:

- Find the file you want to upload, and click "Select." The server displays a page for you to upload the file.
- Select the data file on your computer. The exact method for file selection varies depending on operating system and web browser.
- Click on "Click Once to Upload." The file you selected is uploaded to the server.

When you upload a file, the web server immediately checks for correct formatting. There are three possible results:

- If the file is correctly formatted, the server displays a page noting the successful upload.
- If the file contains errors, the server displays an error log. The error log lists the errors that were detected in the file, each identified as specifically as possible.
- If the file is correctly formatted, but is questionable in some way (for example, a missing time step), then the server displays a warning log, which describes the problem.

When uploading time series files, the website may issue a warning that the time series cannot be filtered. Modelers should ignore this warning. After uploading a file, the file list shows the date and time that you uploaded the file. Remember that any file you upload will be visible to anyone who has access to the web site.

Additional help is available by clicking the "Help" link in the upper right corner of the webpage. Modelers who want to upload multiple versions of the benchmark (for example, using different element sizes), can do so using the "Change Version" feature of the website, which is described in the help screens. Direct further questions to Michael Barall.

5.4 Graphing, Viewing, and Deleting Files

After uploading a file, additional functions become available. These functions let you graph, view, or delete the uploaded file.

Graphing: To graph a file, find the file you want and click "Graph." For a time-series file, the server displays graphs of all the data fields in the file. At the bottom of each graph page, there is a box you can use to adjust graphing preferences. Graphing a file is a good way to check that the server is interpreting your data as you intended.

Viewing: To view the text of a file, find the file you want and click "View."

Deleting: To delete a file from the server, find the file you want and click "Delete." The server displays a page asking you to confirm the deletion.

6 Benchmark Tips

Numerical boundary conditions (to truncate the half-space when defining the computational domain) will most likely change results at least quantitatively, or even qualitatively. We suggest extending these boundaries until you see results appear independent of the computational domain size.

7 Acknowledgments

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References

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