# SEAS Benchmark Problem BP4-QD

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Benchmark problem BP4 is for a three-dimensional (3D) extension of BP1 to a problem in a whole-space (quasi-dynamic approximation is still assumed), although some parameters are changed to make the computations more feasible. The model size, resolution, initial and boundary conditions, and model output are designed specifically for 3D problems.

## 1   3D Problem Setup

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

$$\mathbf{x} \in \mathbb{R}^3$$

with $x_3$ as positive downward. A vertical, strike-slip fault is embedded at $x_1 = 0$, see Figure 1. We assume 3D motion, letting $u_i = u_i(\mathbf{x}, t), i = 1, 2, 3$ denote the displacement in the $i$-direction. Motion is governed by the equilibrium equation

$$0 = \nabla \cdot \boldsymbol{\sigma} \tag{1}$$

in $\mathbb{R}^3$. Hooke's law relates stresses to strains by

$$\sigma_{ij} = K\epsilon_{kk}\delta_{ij} + 2\mu \left( \epsilon_{ij} - \frac{1}{3}\epsilon_{kk}\delta_{ij} \right) \tag{2}$$

for bulk modulus $K$ and shear modulus $\mu$. The strain-displacement relations are given by

$$\epsilon_{ij} = \frac{1}{2} \left[ \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right]. \tag{3}$$

## 2   Boundary and Interface Conditions

At $x_1 = 0$, the fault defines the interface and we supplement equations (1)–(3) with six interface conditions. We use the notation "+" and "−" to refer to the side of the fault with $x_1$ positive, and $x_1$ negative, respectively. We assume a "no-opening condition", namely that

$$u_1(0^+, x_2, x_3, t) = u_1(0^-, x_2, x_3, t), \tag{4}$$

and define the slip vector

$$s_j(x_2, x_3, t) = u_j(0^+, x_2, x_3, t) - u_j(0^-, x_2, x_3, t), \quad j = 2, 3, \tag{5}$$
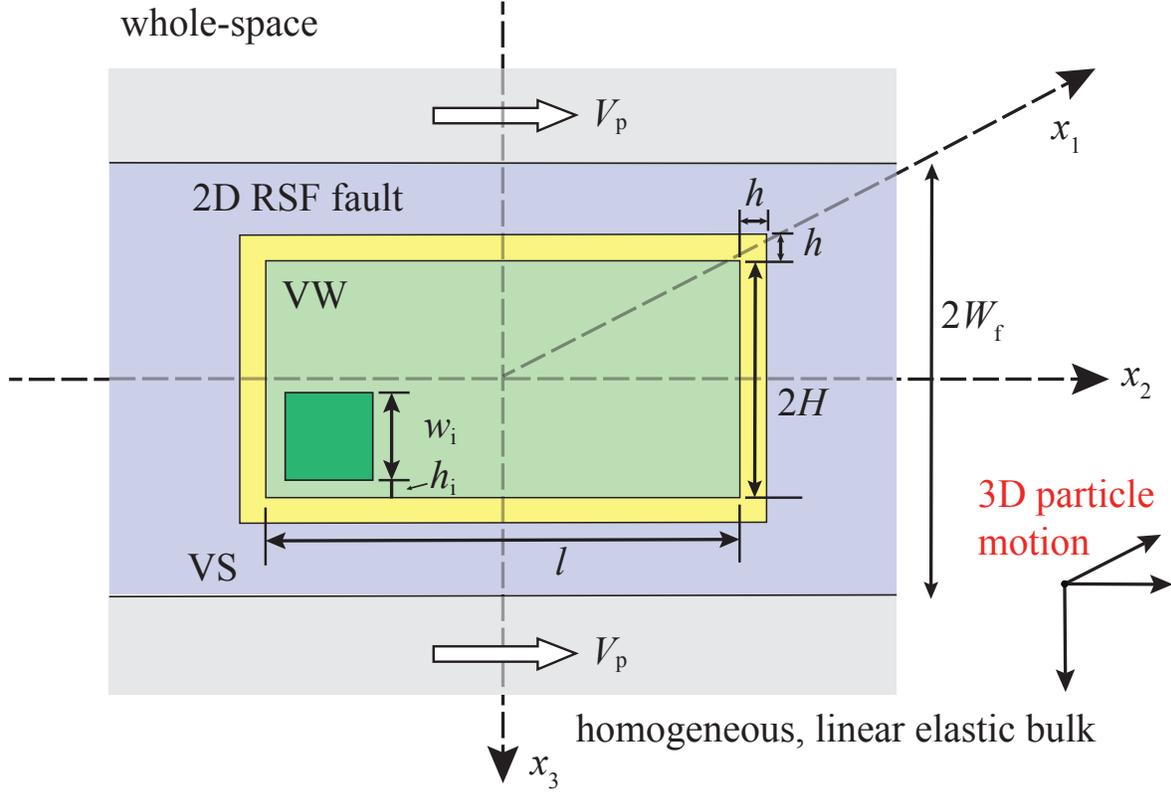
Figure 1: This benchmark considers 3D motion with a planar fault embedded vertically in a homogeneous, linear elastic whole-space. The fault is governed by rate-and-state friction in the region $-W_\mathrm{f} \le x_3 \le W_\mathrm{f}$ outside of which it creeps at an imposed constant horizontal rate $V_\mathrm{p}$. There is a velocity-weakening patch (green) in the rectangle $-H \le x_3 \le H, -l/2 \le x_2 \le l/2$, surrounded by a transition zone (yellow) of width $h$ to velocity-strengthening (blue).

i.e. the jump in horizontal and vertical displacements across the fault, with right-lateral motion yielding positive values of $s_2$. Positive values of $s_3$ occur when the $+$ side of fault moves in the positive $x_3$-direction and the $-$ side moves in the negative $x_3$-direction.

We require that components of the traction vector be equal and opposite across the fault, which yields the three conditions

$$-\sigma_{11}(0^+, x_2, x_3, t) = -\sigma_{11}(0^-, x_2, x_3, t), \tag{6a}$$
$$\sigma_{21}(0^+, x_2, x_3, t) = \sigma_{21}(0^-, x_2, x_3, t), \tag{6b}$$
$$\sigma_{31}(0^+, x_2, x_3, t) = \sigma_{31}(0^-, x_2, x_3, t), \tag{6c}$$

and denote the common values by $\sigma_\mathrm{n}$ (positive in compression), $\tau$ and $\tau_\mathrm{z}$ (respectively), i.e. the normal traction and two components of shear traction. Note that positive values of $\tau$ denote stress that tends to cause right-lateral faulting and positive values of $\tau_\mathrm{z}$ denote stress that tends to cause the $+$ side of the fault to move downward (in the positive $x_3$ direction) and the $-$ side to move in the negative $x_3$-direction.

In addition to conditions (4) and (6), the last two interface conditions are domain dependent. We define the slip velocity vector $\mathbf{V}$ in terms of the components

$$V_j = \dot{s}_j, \quad j = 2, 3, \tag{7}$$

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letting $V = ||\mathbf{V}||$ denote the norm of the vector. The vector of shear stresses due to quasi-static deformation is given by

$$\boldsymbol{\tau}^{\mathrm{qs}} = \begin{bmatrix} \tau \\ \tau_z \end{bmatrix}. \tag{8}$$

Within the domain $(x_2, x_3) \in \Omega_f = (-\infty, \infty) \times (-W_{\mathrm{f}}, W_{\mathrm{f}})$ we impose rate-and-state friction where shear stress on the fault is equal to fault strength $\mathbf{F}$, namely

$$\boldsymbol{\tau} = \mathbf{F}(\mathbf{V}, \theta), \tag{9}$$

where $\boldsymbol{\tau} = \boldsymbol{\tau}^0 + \boldsymbol{\tau}^{\mathrm{qs}} - \eta \mathbf{V}$ is the sum of the prestress, the shear stress 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 $c_{\mathrm{s}} = \sqrt{\mu/\rho}$ and density $\rho$. The fault strength

$$\mathbf{F} = \bar{\sigma}_{\mathrm{n}} f(V, \theta) \frac{\mathbf{V}}{V}, \tag{10}$$

where $\theta$ is the state variable and $\bar{\sigma}_{\mathrm{n}} = \sigma_n - p$ (the effective normal stress on the fault) for pore-pressure $p$. $\theta$ evolves according to the aging law

$$\frac{d\theta}{dt} = 1 - \frac{V\theta}{L}, \tag{11}$$

where $L$ (denoted $D_{\mathrm{c}}$ in BP1 and BP2) is the critical slip distance. The friction coefficient $f$ is given by a regularized formulation

$$f(V, \theta) = a \sinh^{-1} \left[ \frac{V}{2V_0} \exp\left( \frac{f_0 + b\ln(V_0\theta/L)}{a} \right) \right] \tag{12}$$

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 throughout $\Omega_f$ in order to define the velocity-weakening/strengthening regions (see Figure 1) as follows:

$$a(x_2, x_3) = \begin{cases} a_0, & (|x_3| \leq H) \cap (|x_2| \leq l/2) \\ a_{\max}, & (H + h \leq |x_3| < W_{\mathrm{f}}) \cup (l/2 + h \leq |x_2| < \infty) \\ a_0 + r(a_{\max} - a_0), & \text{else} \end{cases} \tag{13}$$

where $r = \max(|x_3| - H, |x_2| - l/2)/h$.

Outside the domain $\Omega_f$ (i.e. $|x_3| > W_{\mathrm{f}}$) the fault creeps horizontally at an imposed constant rate, given by the interface conditions

$$V_2(x_2, x_3, t) = V_{\mathrm{p}}, \tag{14a}$$
$$V_3(x_2, x_3, t) = 0, \tag{14b}$$

where $V_{\mathrm{p}}$ is the plate rate.

# 3  Initial Conditions and Simulation Time

Initial conditions on slip and the state variable are required. We consider that slip is initially zero everywhere in the domain, i.e.

$$s_j(x_2, x_3, 0) = 0, \quad j = 2, 3. \tag{15}$$

Since slip on a fault separating identical materials does not alter the normal traction, $\sigma_n$ remains constant. The initial state on the fault is chosen so that the model can start with a uniform slip velocity and pre-stress, given by

$$\mathbf{V} = \begin{bmatrix} V_{\text{init}} \\ V_{\text{zero}} \end{bmatrix}, \tag{16}$$

where $V_{\text{zero}}$ is chosen as $10^{-20}$ m/s to avoid infinite $\log(V_3)$ in data output, and

$$\boldsymbol{\tau}^0 = \tau^0 \cdot \mathbf{V}/V. \tag{17}$$

The scalar pre-stress $\tau^0$ corresponds to the steady-state stress at the slip rate $V_{\text{init}}$ within each region, namely

$$\theta(x_2, x_3, 0) = L/V_{\text{init}}. \tag{18}$$

and

$$\tau^0 = \bar{\sigma}_{\text{n}} a \sinh^{-1} \left[ \frac{V_{\text{init}}}{2V_0} \exp\left( \frac{f_0 + b\ln(V_0/V_{\text{init}})}{a} \right) \right] + \eta V_{\text{init}} , \tag{19}$$

To break the symmetry of the problem and facilitate comparisons of different simulations, we choose a square region with width $w_{\text{i}}$, at the lower-left corner of the VW region with an offset of $h_{\text{i}}$, as a favorable location for nucleation of the first seismic event. For this purpose, we impose a higher slip rate along the $x_2$-direction ($V_{\text{i}} = 1$ mm/s) within this region while keeping the state variable $\theta(x_2, x_3, 0)$ unchanged, which means that a higher pre-stress along the $x_2$-direction is also required: $\tau_{\text{i}}^0 = \bar{\sigma}_{\text{n}} a \sinh^{-1} \left[ \frac{V_{\text{i}}}{2V_0} \exp\left( \frac{f_0 + b\ln(V_0/V_{\text{init}})}{a} \right) \right] + \eta V_{\text{i}}$.

Equations (1)–(3), along with interface conditions (4), (6), (9), (14), and initial conditions (15), (16), (18), (19) are solved over the time period $0 \leq t \leq t_{\text{f}}$, where $t_{\text{f}}$ is a specified final simulation time. All necessary parameter values for this benchmark problem are given in Table 1.

Because computational efficiency for 3D problems demands a large cell size, we have changed some model parameters from BP1 in order to resolve relevant physical length scales. At a rupture speed of $0^+$, the quasi-static process zone, $\Lambda_0$, is expressed as:

$$\Lambda_0 = C\frac{\mu L}{b\bar{\sigma}_{\text{n}}}, \tag{20}$$

where C is a constant on the order of 1. Another important length scale, the nucleation zone size, $h^*$, is expressed as:

$$h^* = \frac{\pi}{2} \frac{\mu bL}{(b-a)^2 \bar{\sigma}_{\text{n}}}. \tag{21}$$

With the provided model values, the process zone $\Lambda_0$ and $h^*$ are nearly uniform within the VW region, with a size of $\approx 2.0$ km and $\approx 12.4$ km, respectively ($h^*$ is about 40% of the width of the VW zone).

We suggest using a cell size of $\Delta z = 500$ m for the simulations; results from simulations using smaller, if feasible, or larger cell sizes are welcome. For a cell size of 500 m, $\Lambda_0$ is resolved by $\sim$4 grid points and $h^*$ by $\sim$25 grid points. For methods that use multiple degrees of freedom along cell edges/faces, please take $\Delta z =$ edge length / number of unique degrees of freedom. For instance, for a high-order finite element method, if $h$ is the edge length and $N$ the polynomial order then $\Delta z = h/N$.

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Table 1: Parameter values used in this benchmark problem

| Parameter | Definition | Value, Units |
|:---:|:---:|:---:|
| $\rho$ | density | 2670 kg/m$^3$ |
| $c_{\mathrm{s}}$ | shear wave speed | 3.464 km/s |
| $\nu$ | Poisson's ratio | 0.25 |
| $a_0$ | rate-and-state parameter | 0.0065 |
| $a_{\mathrm{max}}$ | rate-and-state parameter | 0.025 |
| $b_0$ | rate-and-state parameter | 0.013 |
| $\bar{\sigma}_{\mathrm{n}}$ | effective normal stress | 50 MPa |
| $L$ | critical slip distance | 0.04 m |
| $V_{\mathrm{p}}$ | plate rate | $10^{-9}$ m/s |
| $V_{\mathrm{init}}$ | initial slip rate | $10^{-9}$ m/s |
| $V_0$ | reference slip rate | $10^{-6}$ m/s |
| $f_0$ | reference friction coefficient | 0.6 |
| $H$ | half-width of uniform VW region | 15 km |
| $l$ | length of uniform VW region | 60 km |
| $h$ | width of VW-VS transition zone | 3 km |
| $W_{\mathrm{f}}$ | half-width of rate-and-state fault | 40 km |
| $\Delta z$ | suggested cell size | 500 m |
| $t_{\mathrm{f}}$ | final simulation time | 1500 years |
| $w_{\mathrm{i}}$ | width of favorable nucleation zone | 12 km |
| $h_{\mathrm{i}}$ | distance of nucleation zone to SZ boundary | 1.5 km |

# 4 Benchmark Output

We request five types of data output for this benchmark:

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

(2) Source parameter time series (section 4.2)

(3) Earthquake catalog (section 4.3)

(4) Slip and stress evolution profile (section 4.4)

(5) Rupture time contour for first event (section 4.5)

The location information relevant to these outputs are shown in Fig. 2. Data files for (1), (2) and (5) are uploaded to the SCEC code verification web server:

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

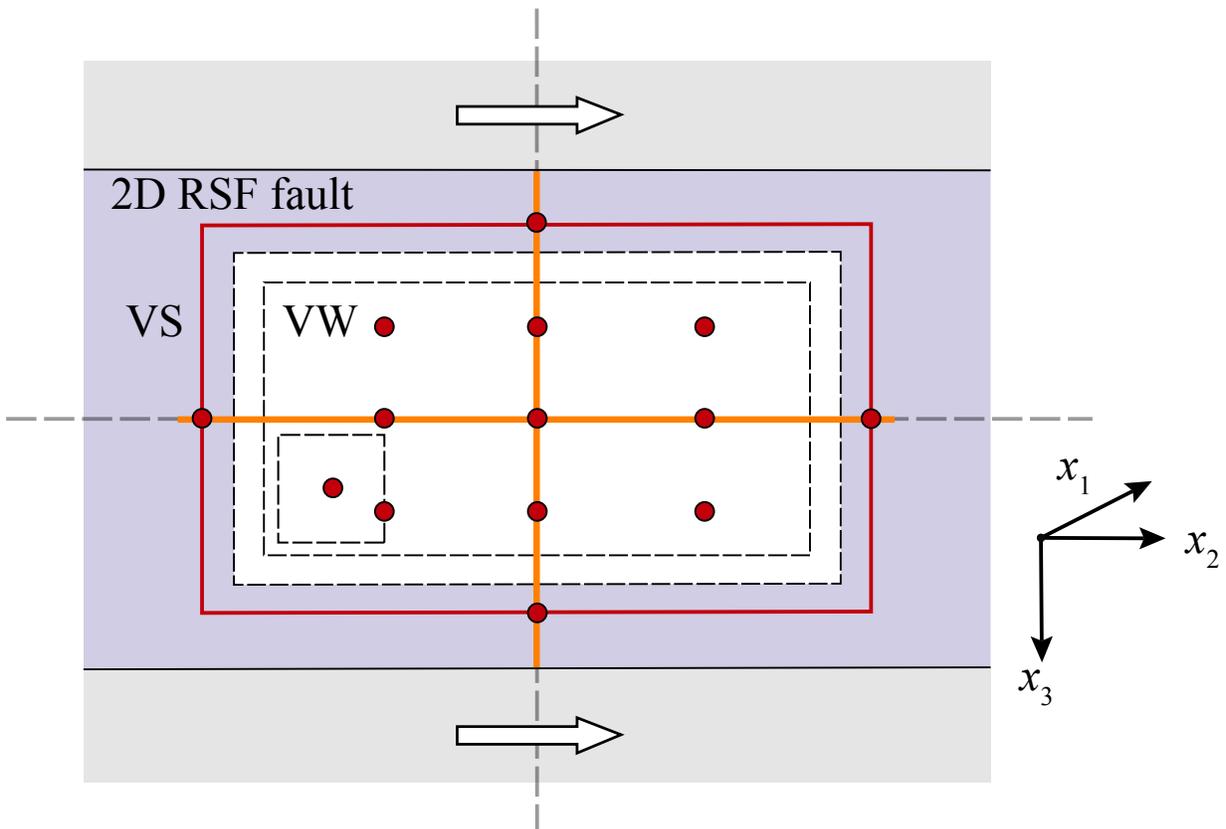Information on how to share output (3) and (4) is detailed in sections 4.3 and 4.4.



Figure 2: Observational points, lines, and region for model outputs. Local time series is output at on-fault observational points (red). Slip and stress evolution are output along two cross-section profiles (orange). The rectangular region outlined in red is used for estimating source parameter time series and rupture time contour. Dashed lines mark boundaries of different fault areas shown in Figure 1.

## 4.1 On-fault Time Series Output

You need to upload on-fault ($x_1 = 0$) time series files, which give slip components $s_2$ and $s_3$, base 10 log of the components of slip rate $V_2$ and $V_3$, base 10 log of the state variable (i.e. $\log_{10}(\theta)$), and shear stress components $\tau$ and $\tau_z$, 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 of the norm of the slip velocity vector over the entire fault) or seismic (when $\max(V) \geq 10^{-3}$ m/s). When outputting modeling results, use larger time intervals (e.g., ~0.1 yr) during aseismic periods and smaller time intervals (e.g., ~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 14 stations in total, as follows:

1. fltst_strk-360dp+000: $x_2 = -36.0, x_3 = +0.00$ km
2. fltst_strk-225dp-750: $x_2 = -22.5, x_3 = -7.50$ km
3. fltst_strk-165dp-120: $x_2 = -16.5, x_3 = -12.0$ km
4. fltst_strk-165dp+000: $x_2 = -16.5, x_3 = +0.00$ km
5. fltst_strk-165dp+120: $x_2 = -16.5, x_3 = +12.0$ km
6. fltst_strk+000dp-210: $x_2 = +0.00, x_3 = -21.0$ km
7. fltst_strk+000dp-120: $x_2 = +0.00, x_3 = -12.0$ km
8. fltst_strk+000dp+000: $x_2 = +0.00, x_3 = +0.00$ km
9. fltst_strk+000dp+120: $x_2 = +0.00, x_3 = +12.0$ km
10. fltst_strk+000dp+210: $x_2 = +0.00, x_3 = +21.0$ km
11. fltst_strk+165dp-120: $x_2 = +16.5, x_3 = -12.0$ km
12. fltst_strk+165dp+000: $x_2 = +16.5, x_3 = +0.00$ km
13. fltst_strk+165dp+120: $x_2 = +16.5, x_3 = +12.0$ km
14. fltst_strk+360dp+000: $x_2 = +36.0, x_3 = +0.00$ km

Each time series has 8 data fields, as follows.

| Field Name | Description, Units and Sign Convention |
|---|---|
| t | Time (s) |
| slip_2 | Horizontal component of slip (m). Positive for right-lateral motion. |
| slip_3 | Vertical component of slip (m). Positive for + side moving downward. |
| slip_rate_2 | $\log_{10}$ of the amplitude of the horizontal component of slip-rate ($\log_{10}$ m/s), which is positive for right-lateral motion. |
| slip_rate_3 | $\log_{10}$ of the amplitude of the vertical component of slip-rate ($\log_{10}$ m/s), which is positive for + side moving downward. |
| shear_stress_2 | Horizontal component of shear stress (MPa), which is positive for shear stress that tends to cause right-lateral motion. |
| shear_stress_3 | Vertical component of shear stress (MPa), which is positive for shear stress that tends to cause + side to move downward. |
| 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:<br>• Benchmark problem (No.4)<br>• Code name<br>• Code version (optional)<br>• Modeler<br>• Date<br>• Node spacing or element size<br>• Station location<br>• Minimum time step (optional)<br>• Maximum time step (optional)<br>• Number of time steps in file (optional)<br>• Anything else you think is relevant (optional)<br>• Descriptions of data columns (8 lines)<br>• Anything else you think is relevant |
| Field List | A single line, which lists the names of the 8 data fields, in column order, separated by spaces. It should be:<br>`t slip_2 slip_3 slip_rate_2 slip_rate_3 shear_stress_2 shear_stress_3 state` (all on one line).<br>The server examines this line to check that your file contains the correct data fields. |
| Time History | A series of lines. Each line contains 8 numbers, which give the data values for a single time step. The lines must appear in order of increasing time.<br>**Make sure to use double-precision when saving all fields.**<br>**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.<br>**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.4
# code=MYcode
# version=1.0
# modeler=A.Modeler
# date=2019/12/01
# element_size=500 m
# location= on fault, 0km along strike, 7.2km depth
# minimum_time_step=0.1
# maximum_time_step=3.157e6
# num_time_steps=2400
# Column #1 = Time (s)
# Column #2 = Slip_2 (m)
# Column #3 = Slip_3 (m)
# Column #4 = Slip_rate_2 (log10 m/s)
# Column #5 = Slip_rate_3 (log10 m/s)
# Column #6 = Shear_stress_2 (MPa)
```

```
# Column #7 = Shear_stress_3 (MPa)
# Column #8 = State (log10 s)
# The line below lists the names of the data fields
t slip_2 slip_3 slip_rate_2 slip_rate_3 shear_stress_2 shear_stress_3 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  Source Parameter Time Series Output

You need to upload a file named `global.dat`, which includes time series of two global source variables, maximum amplitude of slip rates

$$V_{\max} = \max_{(x_2, x_3) \in A} V$$

and moment rates

$$M_t = \int_A \mu V dA$$

for the domain $A$ that surrounds the velocity-weakening patch plus twice the transition zone width in every direction, i.e. $(|x_2| \leq l/2 + 2h) \cap (|x_3| \leq H + 2h)$ (shown in Fig. 2). Upload data corresponding to the same time steps you used for section 4.1.

Here is an example of a source parameter time-series file, with invented data.

```
# This is the file header:
# problem=SEAS Benchmark No.4
# code=MYcode
# version=1.0
# modeler=A.Modeler
# date=2019/12/01
# element_size=500 m
# location= VW patch + transition zone
# minimum_time_step=0.1
# maximum_time_step=3.157e6
# num_time_steps=2400
# Column #1 = Time (s)
# Column #2 = Max_slip_rate (log10 m/s)
# Column #3 = Moment_rate (N-m/s)
# The line below lists the names of the data fields
t max_slip_rate moment_rate
# Here is the time-series data.
0.000000E+00 0.000000E+00 -9.000000E+00
5.000000E-02 0.000000E+00 -9.000000E+00
```

```
1.000000E-01 0.000000E+00 -9.000000E+00
1.500000E-01 0.000000E+00 -9.000000E+00
# ...  and so on.
```

## 4.3   Earthquake Catalog Output

The earthquake catalog output file with a name `catalog.dat` is a single ASCII file that includes characteristics of all seismic events in the simulation. We define an event to start when the maximum slip rate exceeds $10^{-3}$ m/s, and to be over when maximum slip rate dips below $10^{-3}$ m/s for a time duration of at least 10 seconds (to avoid inaccurate estimate of event termination in the presence of slip rate fluctuation at the end of rupture). For each earthquake in the 1500-year simulation period, the file contains the event number, the event initiation time, event termination time, the total rupture area $R$, average stress in the rupture area $\tau_{\mathrm{avg}}$ at the beginning and end of the event (so stress drops can be computed from the two values), and the average coseismic slip in the rupture area $s_{\mathrm{avg}}$.

We consider the rupture domain $\Omega_R$ as those locations on the fault where slip rates have exceeded $10^{-3}$ m/s at any time during the event, with $R = |\Omega_R|$ being the total rupture area. We define $\tau_{\mathrm{avg}}$ as the amplitude of spatially averaged stress vector $\boldsymbol{\tau}$ within the rupture area:

$$\tau_{\mathrm{avg}} = \frac{1}{R} \Big| \int_{\Omega_R} \boldsymbol{\tau} \, d\Omega_R \Big|.$$

Similarly, we define $s_{\mathrm{avg}}$ as the amplitude of spatially averaged slip vector $\boldsymbol{s}$ within the rupture domain:

$$s_{\mathrm{avg}} = \frac{1}{R} \Big| \int_{\Omega_R} \mathbf{s} \, d\Omega_R \Big|.$$

**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 7 data fields, as follows:

| Field Name | Description, Units and Sign Convention |
|---|---|
| event_no | Event number. |
| t_start | Time event starts (s). |
| t_end | Time event ends (s). |
| rup_area | Rupture area (m$^2$). |
| avg_stress_start | Spatial average of stress within rupture area at t_start (MPa). |
| avg_stress_end | Spatial average of stress within rupture area at t_end (MPa). |
| avg_slip | Average slip in rupture area (m). |

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:<br>• Benchmark problem (No.4)<br>• Modeler<br>• Date<br>• Code<br>• Code version (if desired)<br>• Node spacing or element size<br>• Descriptions of data fields (1 line)<br>• Anything else you think is relevant (e.g. computational domain size) |
| Field List | One line listing the 7 data fields on one line, separated by spaces. It should be: `event_no  t_start  t_end  rup_area  avg_stress_start  avg_stress_end avg_slip` (all on one line). |
| Catalog | A series of lines.<br>**Make sure to use double-precision when saving all fields**.<br>**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.<br>**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. |

Here is an example of a catalog file, with invented data.

```
# This is the file header:
# problem=SEAS Benchmark No.4
# author=A.Modeler
# date=2019/12/01
# code=MyCode
# code_version=3.7
# element_size=500 m
# Column #1 = Event number
# Column #2 = Event start time (s)
# Column #3 = Event end time (s)
# Column #6 = Rupture area (m^2)
# Column #7 = Stress avg at start time (MPa)
# Column #8 = Stress avg at end time (MPa)
# Column #9 = Avg slip in rupture area (m)
# Computational domain size:  depth 100 km, distance off fault 100 km
# The line below lists the names of the data fields
event_no  t_start t_end rup_area avg_stress_start avg_stress_end avg_slip
# Here are the data
1 3.15500000E+07 3.15500200E+07 1.800000E+09 ...  5.000000E+00
2 4.70000000E+09 4.70000002E+09 1.800000E+09 ...  4.800000E+00
3 9.45000000E+09 9.45000002E+09 1.800000E+09 ...  4.820000E+00
# ...  and so on.
```

## 4.4 Slip and Stress Evolution Output

The slip and stress evolution output files with the names

```
slip_2_depth.dat
slip_2_strike.dat
stress_2_depth.dat
stress_2_strike.dat
slip_3_depth.dat
slip_3_strike.dat
stress_3_depth.dat
stress_3_strike.dat
```

are 8 ASCII files that record the spatial distribution of slip and stress (both horizontal and vertical components) on a subset of fault nodes at one-dimensional cross sections (either a specified distance along strike OR along depth), at representative time steps during the aseismic and seismic phases of the simulation. Data can be saved using representative time intervals of ~5 yr and ~1 s for results in aseismic and seismic phases, respectively, or with variable time steps. Either way, 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 nodes with a spacing of ~500 m (or larger for simulations with larger cells) either along depth (from $-W_\mathrm{f}$ to $W_\mathrm{f}$) or along strike (from $-l/2 - 7\,\mathrm{km}$ to $l/2 + 7\,\mathrm{km}$). The files should also contain the time series of maximum slip rate amplitude (taken over the entire fault), so that we can precisely differentiate aseismic and seismic phases. We request a total of 8 data files containing slip and stress data at two one-dimensional cross sections: one along-dip profile at $x_2 = 0\,\mathrm{km}$ and one along-strike profiles at $x_3 = 0\,\mathrm{km}$ (see the orange lines in Figure 2).

**NOTE**: Please upload this data to a Dropbox folder that will be shared with you (or send a request to bae@uoregon.edu).

Each data file has 4 data fields, as follows:

| Field Name | Description, Units and Sign Convention |
|---|---|
| x2 OR x3 | Strike (m) at ~500 m increments from $-37\,\mathrm{km}$ to $37\,\mathrm{km}$ OR Depth (m) at ~500 m increments from $-40\,\mathrm{km}$ to $40\,\mathrm{km}$ |
| t | Time (s). Nonuniform time steps. |
| max_slip_rate | The $\log_{10}$ of maximum amplitude of slip-rate (taken over the entire fault) ($\log_{10}$ m/s). |
| slip_2 OR slip_3 OR stress_2 OR stress_3 | Horizontal OR vertical component of slip (m) (positive for right-lateral motion OR for + side moving downward, respectively) OR horizontal OR vertical component of stress (in MPa). |

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:<br>• Benchmark problem (No.4)<br>• Modeler<br>• Date<br>• Code<br>• Code version (if desired)<br>• Node spacing or element size<br>• Descriptions of data fields (4 lines)<br>• Anything else you think is relevant (e.g. computational domain size) |
| Field List | Four lines. The first line lists either $x_2$ OR $x_3$. The next two lines lists the time steps and max slip rate (respectively). The last line lists which component of slip or stress. It should be:<br>`x2` OR `x3`<br>`t`<br>`max_slip_rate`<br>`slip_2` OR `slip_3` OR `stress_2` OR `stress_3` |
| Slip 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 distance along strike OR depth as you go across the row. Starting from the second row/line, each row/line contains time, maximum slip rate, and slip OR stress at all nodes at the time. These lines appear in order of increasing time (from top to bottom) and slip OR stress is recorded with increasing distance along strike or depth (from left to right). **Make sure to use double-precision when saving all fields**.<br>**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.<br>**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 $x_2$ or $x_3$ should appear in the first row, preceded by two zero numbers, for nodes with a spacing of $\sim$500 m. 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 or stress history (the remaining block) is represented by a two-dimensional array with time increasing as you go down the rows/lines, and either $x_2$ or $x_3$ increasing as you go across the columns ($\sim$149 and 161 columns, respectively). For example, the output in `slip_2_strike.dat` is a two-dimensional matrix of the form:

$$\begin{bmatrix} 0 & 0 & x_2 \\ T & \max(V) & \text{slip} \end{bmatrix}$$

The matrix should be of size $(N_t + 1, \sim151)$, where $N_t$ is the total number of time steps. This means that you output slip 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).

Here is an example of a slip-evolution file for `slip_2_strike.dat`, with invented data.

```
# This is the file header:
# problem=SEAS Benchmark No.4
```

```
# author=A.Modeler
# date=2019/12/01
# code=MyCode
# code_version=3.7
# element_size=500 m
# Row #1 = Strike (m) with two zeros first
# Column #1 = Time (s)
# Column #2 = Max slip rate (log10 m/s)
# Columns #3-83 = Horizontal slip along depth (Slip_2) (m)
# Computational domain size:  -100km < x1 < 100km, -100km < x2 < 100km, -100km < x3 < 100km
# The line below lists the names of the data fields
x2
t
max_slip_rate
slip_2
# Here are the data
0.000000E+00  0.000000E+00 -3.70000E+04 -3.65000E+04 ...  3.700000E+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
```

## 4.5   Rupture Time Contour Output

The rupture time contour output with a name `rupture.dat` is a single ASCII files that record the spatial distribution of arrival time of coseismic rupture front for the 1st earthquake in the simulation. We request the rupture time contour within a larger region that includes the VW zone, $(|x_2| \leq l/2 + 2h) \cap (|x_3| \leq H + 2h)$ (shown in Fig. 2). At each node, the rupture time value is chosen as the first time instance when local slip rate amplitude reaches 1 mm/s. This data needs to be uploaded to the web server.

Each data file has 3 data fields, as follows:

| Field Name | Description, Units and Sign Convention |
| --- | --- |
| x2 | Distance along strike (m). Positive means a location to the right of the origin. The values range from $-36\,\mathrm{km}$ to $36\,\mathrm{km}$. |
| x3 | Distance down-dip (m). Positive means a location below the origin. The values range from $-21\,\mathrm{km}$ to $21\,\mathrm{km}$. |
| t | Rupture time (s). This is the time at which slip rate first reaches a value greater than 1 mm/s. If this node never ruptures, use the value 1.0E+09. |

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:<br>• Benchmark problem (No.4)<br>• Modeler<br>• Date<br>• Code<br>• Code version (if desired)<br>• Node spacing or element size<br>• Descriptions of data fields (1 line)<br>• Anything else you think is relevant (e.g. computational domain size) |
| Field List | A single line, which lists the names of the 3 data fields on one line, separated by spaces. It should be:<br>x2 x3 t (on one line). |
| Rupture History | A series of lines. Each line contains three numbers, which give the (x2,x3) coordinates of a node on the fault surface, and the time t at which that node ruptures.<br>**Make sure to use double-precision when saving all fields**.<br>**C/C++ users:** We recommend using 21.13E or 21.13e floating-point format.<br>**Fortran users:** We recommend using E22.14 or 1PE22.13 floating-point format.<br>If a node never ruptures, the time should be given as 1.0E+09. |

**Note:** The nodes may appear in any order. The nodes do not have to form a rectangular grid, or any other regular pattern.

**Note:** When you upload a file, the server constructs the Delaunay triangulation of your nodes. Then, it uses the Delaunay triangulation to interpolate the rupture times over the entire fault surface. Finally, it uses the interpolated rupture times to draw a series of contour curves at intervals of 0.5 seconds.

Here is an example of a rupture time file, with invented data.

```
# This is the file header:
# problem=SEAS Benchmark No.4
# author=A.Modeler
# date=2019/12/01
# code=MyCode
# code_version=3.7
# element_size=500 m
# Column #1 = x2 (m)
# Column #2 = x3 (m)
# Column #3 = time (s)
# Computational domain size:  depth 100 km, distance off fault 100 km
# The line below lists the names of the data fields
x2 x3 t
# Here are the data
-3.60000E+04 0.000000E+04 0.000000E+00
```

```
-3.50500E+04 0.100000E+04 3.140000E+05
6.000000E+04 7.200000E+04 6.440000E+06
7.000000E+04 7.000000E+04 3.140000E+06
7.000000E+04 8.100000E+04 2.140000E+06
7.000000E+04 8.200000E+04 1.400000E+06
# ...  and so on.
```

# 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 whole-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. We prefer participants to use the cell size suggested in Table 1 and welcome results for different spatial resolutions. Each person can submit (at most) results from two different spatial resolutions and two different computational domain sizes.

As a sanity check for the simulation results, the total simulation time of 1500 years would consist of ~10 earthquakes. The first earthquake initiates instantaneously in the pre-chosen nucleation zone; later earthquakes nucleate spontaneously, at possibly different locations of the boundary of VW region, with a recurrence time of ~150 years and coseismic slip of ~5 m.