Fault Stepover Benchmarks
TPV22 and TPV23

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Right-lateral strike-slip faults in a linear elastic half-space:

Density $\rho = 2670 \text{ kg/m}^3$

Shear-wave velocity $V_s = 3464 \text{ m/s}$

Pressure-wave velocity $V_p = 6000 \text{ m/s}$
Linear slip-weakening friction.

Right-lateral faults.

Requested resolutions: 100 m and 50 m.
Issues in Dynamic Rupture Simulations of Fault Stepovers
Harris, Archuleta, and Day (1991) — 2D simulations.

- Maximum stepover distance ~ 5 km.
- Figure above shows Coulomb stress on a hypothetical parallel fault.
- Fault in the figure is left-lateral, so extensional side is on the top.
Stepover Distance — 3D is Different than 2D.

Harris and Day (1999) — 3D simulations (extensional stepover and subshear rupture).
- Maximum stepover distance ~ 1 km.
- Rupture on fault #2 begins at the earth’s surface.
Movie — Coulomb Stress Surrounding the End of a Fault, in 3D.

Movie shows where Coulomb stress on a hypothetical second fault would exceed a threshold value.

- The fault extends from the left edge to -5000 m along-strike.
- The compressional side is in back, the extensional side is in front.

(The movie is from a test run, which does not have the same parameters as TPV22-23).
Movie — Coulomb Stress Surrounding the End of a Fault, in 3D.

Movie shows where Coulomb stress on a hypothetical second fault would exceed a threshold value.
- The fault extends from the left edge to -5000 m along-strike.
- The compressional side is on top, the extensional side is on bottom.
(The movie is from a test run, which does not have the same parameters as TPV22-23).
Nucleation Follies on Fault #2.

Compressional Examples

Dilational Examples
Loss of Numerical Precision.

Compressional Stepover 1000 m

Compressional Stepover 1400 m

Finite Element (FaultMod) 100 m
Finite Element (FaultMod) 50 m
Finite Difference (DayFD) 100 m
Finite Difference (DayFD) 50 m
Complicated Slip-Time History.

“foreshock”

“mainshock”
TPV22-23 Design
Friction Parameters.

\[ \mu_s = 0.548 \]

\[ \mu_d = 0.373 \]

\[ d_0 = 0.30 \, \text{m} \]

\[ C_0 = \begin{cases} 
(0.0014 \, \text{MPa/m})(5000 \, \text{m} - \text{depth}), & \text{if depth} \leq 5000 \, \text{m} \\
0.0 \, \text{MPa}, & \text{if depth} \geq 5000 \, \text{m} 
\end{cases} \]

Cohesion tapers from 7.0 MPa at the earth’s surface, to 0 at depths of 5000 m or greater.

Cohesion in the upper 5 km suppresses the tendency of the rupture on fault #2 to nucleate at the earth’s surface.
Initial Stress.

\[ \sigma_{\text{ini}} = 60.00 \text{ MPa} \]

\[ \tau_{\text{ini}} = \begin{cases} 
29.38 \text{ MPa}, & \text{if depth \leq 15000 m} \\
29.38 \text{ MPa} - (0.002938 \text{ MPa/m})(\text{depth} - 15000 \text{ m}), & \text{if depth \geq 15000 m}
\end{cases} \]

Stresses are chosen to produce a supershear rupture, so the rupture is energetic enough to make the jump.

Initial shear stress tapers down from 29.38 MPa at a depth of 15000 m, to 14.69 MPa at the bottom of the fault at depth 20000 m.

Reducing the initial shear stress in the lower 5 km creates a “soft” barrier at the bottom of the fault, and prevents nucleation on fault #2 from occurring at the bottom of the fault.
On-Fault Stations.

Modelers are asked to submit slip, slip rate, and stress as a function of time, for 7 stations on fault #1 (top) and 11 stations on fault #2 (bottom).

In addition, modelers are asked to submit the time at which each point on the fault begins to slip, from which we construct rupture contour plots.
Off-Fault Stations.

Modelers are asked to submit displacement and velocity as a function of time, for 6 stations on the earth’s surface.

Distance along-strike = $x$

Distance perpendicular to fault #1 = $z$
TPV22 Results — 50 vs. 100 Meters
TPV22 Comparisons
(1600 m Extensional Stepover)
Distance down-dip (m)

Distance along strike (m)

barall.2 (Michael Barall - Finite Element - FaultMod - 50 m)
barall.4 (Michael Barall - Finite Difference - DayFD - 50 m)
duan (Benchun Duan - Finite Element - EQdyna - 100 m test)
kaneko.2 (Yoshihiro Kaneko - Spectral Element - SPECFEM3D - 50m)
ma (Shuo Ma - Finite Element - MAFE (100 m))
payne.2 (Ryan Payne - Finite Element - EQdyna - 50m)
somala.2 (Surendra Somala - Spectral Element - SESAME (50m))

Aagaard – PyLith 200 m
Fault #1

5 Hz low-pass filter applied to all time series.

aagaard (Brad Aagaard - PyLith v1.9.0a - Tet4 200m)
barall.2 (Michael Barall - Finite Element - FaultMod - 50 m)
barall.4 (Michael Barall - Finite Difference - DayFD - 50 m)
cruz-atienza (Tago/Cruz-Atienza - Discontinuous Galerkin - DGCrack - 200 m)
duan (Benchun Duan - Finite Element - E0dyna - 100 m test)
kaneko.2 (Yoshihiro Kaneko - Spectral Element - SPECFEM3D - 50m)
ma (Shuo Ma - Finite Element - MAFE (100 m))
payne.2 (Ryan Payne - Finite Element - E0dyna - 50m)
somala.2 (Surendra Somala - Spectral Element - SESAME (50m))
Fault #1

5 Hz low-pass filter applied to all time series.
Fault #1

5 Hz low-pass filter applied to all time series.
Fault #1

5 Hz low-pass filter applied to all time series.
5 Hz low-pass filter applied to all time series.
Fault #2

5 Hz low-pass filter applied to all time series.
5 Hz low-pass filter applied to all time series.
5 Hz low-pass filter applied to all time series.
5 Hz low-pass filter applied to all time series.
5 Hz low-pass filter applied to all time series.
5 Hz low-pass filter applied to all time series.
TPV23 Comparisons
(1000 m Compressional Stepover)
fault2st200dp100

Horizontal slip rate (m/s)

Time (s)

Fault #2

5 Hz low-pass filter applied to all time series.
Fault #2

5 Hz low-pass filter applied to all time series.
5 Hz low-pass filter applied to all time series.
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5 Hz low-pass filter applied to all time series.
Conclusions

Our stepover benchmarks are:
   TPV22 = Extensive 1600 m stepover.
   TPV23 = Compressional 1000 m stepover.

These multi-fault benchmarks must be carefully designed to avoid:
   • Loss of numerical precision, which may occur when shear stress is near the minimum required to sustain a rupture.
   • Nucleation at the top or bottom of fault #2, and other bad nucleation patterns.

Our stepover distances are relatively large for 3D dynamic rupture simulations, so we need supershear rupture conditions to get a jump.

Comparison of 50 m and 100 m results shows good agreement, indicating the benchmarks are well resolved at the requested resolutions.

Comparison between different codes shows good agreement.