Heterogeneous Initial Stress Benchmarks
TPV16 and TPV17

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Benchmark Description
TPV16-17 have a vertical, right-lateral, strike-slip fault with heterogeneous initial stress conditions.
Modelers are asked to submit displacement and velocity as a function of time, for 12 stations on the earth’s surface.

Since the fault is vertical, stations on the far side of the fault should have the same waveforms as the stations on the near side of the fault.
Modelers are asked to submit slip, slip rate, and stress as a function of time, for 6 stations on the fault.

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.
TPV16-17 Parameters

Density = 2670.0 kg/m³

\[ V_s = 3464.0 \text{ m/s} \]

\[ V_p = 6000.0 \text{ m/s} \]

\[ D_c = 0.40 \text{ m} \]

\[ \mu_s = 0.677 \]

\[ \mu_d = 0.373 \]

\[ \sigma_0 = 60.0 \text{ MPa} \]

Same as TPV5

Equivalent to TPV5 (same difference between yield stress and sliding stress)

Parameter selection follows our practice of reusing material from earlier benchmarks, so we build incrementally on prior work.
Linear Slip-Weakening Friction

When the fault is sliding, the shear stress $\tau$ at a given point on the fault is given by:

$$\tau = C + \mu \times \max(0, \sigma)$$

The time-varying coefficient of friction $\mu$ is given by:

$$\mu = \begin{cases} 
\mu_s + (\mu_d - \mu_s) \times D/D_c, & \text{if } D < D_c \text{ and } t < T \\
\mu_d, & \text{if } D \geq D_c \text{ or } t \geq T 
\end{cases}$$

where $D$ is the total distance the node has slipped, and $t$ is the time since the start of the earthquake. The effect is:

- The coefficient of friction declines linear from $\mu_s$ to $\mu_d$ as the fault slips by distance $D_c$.
- At time $T$, the coefficient of friction drops immediately to $\mu_d$ (if it is not already $\mu_d$). This only happens within a few hundred meters of the hypocenter.
Heterogeneous Initial Conditions
TPV16 Initial Stress

along-strike distance, m

depth, m

shear/normal stress

0 0.2 0.4 0.6
TPV16

Static Coefficient of Friction
TPV16

Time of Forced Rupture
TPV16

Slip Weakening Critical Distance
TPV16

Cohesion
TPV17 Initial Stress
TPV17

Static Coefficient of Friction
TPV17

Time of Forced Rupture
TPV17

Slip Weakening
Critical Distance
TPV17

Cohesion
Nucleation
Day (1982) obtained the following formula, which gives the minimum radius $R_D$ that a circular rupture must have, such that it is energetically favorable for the rupture to expand.

$$R_D = \frac{7\pi\mu (\tau_s - \tau_d) D_c}{24(\tau - \tau_d)^2}$$

For typical parameter values used in spontaneous rupture simulations, the Day radius is about 3 to 4 km.

The nucleation problem is that, somehow, we must impose an artificial mechanism to get the size of the rupture up to the Day radius, at which point the rupture can be self-sustaining.
Two-Stage Nucleation Method

All of today’s benchmarks use a new two-stage method of nucleation.

Because the Day radius is proportional to $D_C$, rupture propagation is energetically favorable once the rupture reaches the dotted blue circle.

**Zone of forced rupture**
Forced rupture propagates at $0.7V_S$ to dotted circle (720 m), then $0.35V_S$ to solid circle (900 m). Forced rupture immediately reduces friction coefficient to $\mu_d$.

(Distances shown are for TPV18-21.)

**Zone of reduced fracture energy**
$D_C$ is linearly tapered from 0.04 m at dotted circle (360 m), to 0.40 m at solid circle (3600 m).
Rupture Contours
TPV16 Rupture Contours

- aagaard.2 (Brad Aagaard - PyLith v1.7.0a - Tet4 75m)
- barall.2 (Michael Barall - Finite Element - FaultMod - Denser Mesh)
- cruz-atienza (Tago/Cruz-Atienza - 3D Discontinuous Galerkin Code - DGCrack)
- dalguer (Luis Dalguer - Finite Difference - DFM)
- duan (Benchun Duan - Finite Element - EQdyna)
- gabriel (Alice Gabriël - Finite Difference AWP-ODC)
- kaneko (Yoshihiro Kaneko - Spectral Element - SPECFEM3D)
- kase (Yuko Kase - Finite Difference)
- ma (Shuo Ma - Finite Element - MAFE)
- somala (Surendra Somala - Spectral Element - SEASME)
TPV16 Rupture Contours Compared to Initial Stress
TPV17 Rupture Contours Compared to Initial Stress
Waveform Comparisons for Stations and Realizations
All waveforms are filtered with a 3 Hz low-pass filter.
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Slip rate waveforms are filtered with a 3 Hz low-pass filter.
TPV16  Vertical Slip Rate  TPV17

Vertical slip rate (m/s)

Time (s)

(smaller scale)

Vertical slip rate (m/s)

Time (s)

(smaller scale)

Vertical slip rate (m/s)

Time (s)

(smaller scale)

Vertical slip rate (m/s)

Time (s)
Slip rate waveforms are filtered with a 3 Hz low-pass filter.
TPV16               Horizontal Shear Stress               TPV17
Waveform Comparisons for Codes
Waveform Comparison for Station 6 km Off-Fault

All waveforms are filtered with a 3 Hz low-pass filter.
TPV16 — Horizontal Velocity

TPV17 — Horizontal Velocity
Waveform Comparison for Station 0.2 km Off-Fault

All waveforms are filtered with a 3 Hz low-pass filter.
TPV16 — Horizontal Velocity

TPV17 — Horizontal Velocity
TPV16 — Normal Velocity

TPV17 — Normal Velocity
Waveform Comparison for Station On-Fault at Depth of 9.0 km

All waveforms are filtered with a 3 Hz low-pass filter.
TPV16 — Horizontal Slip Rate

TPV17 — Horizontal Slip Rate
TPV16 — Vertical Shear Stress

TPV17 — Vertical Shear Stress
TPV16 — Horizontal Slip

TPV17 — Horizontal Slip
Waveform Comparison for Station On-Fault at the Earth’s Surface

All waveforms are filtered with a 3 Hz low-pass filter.
TPV16 — Horizontal Slip Rate

TPV17 — Horizontal Slip Rate
TPV16 — Horizontal Shear Stress

TPV17 — Horizontal Shear Stress
Conclusion
Conclusion

TPV16-17 are designed to be like “TPV5 with random initial stress.”

The codes agree well in contour plots, waveforms, timing, and amplitudes.

The contours show the rupture responding to the random initial stress field.
Thank You