TPV10 and TPV11

Part I. SOME DEFINITIONS:

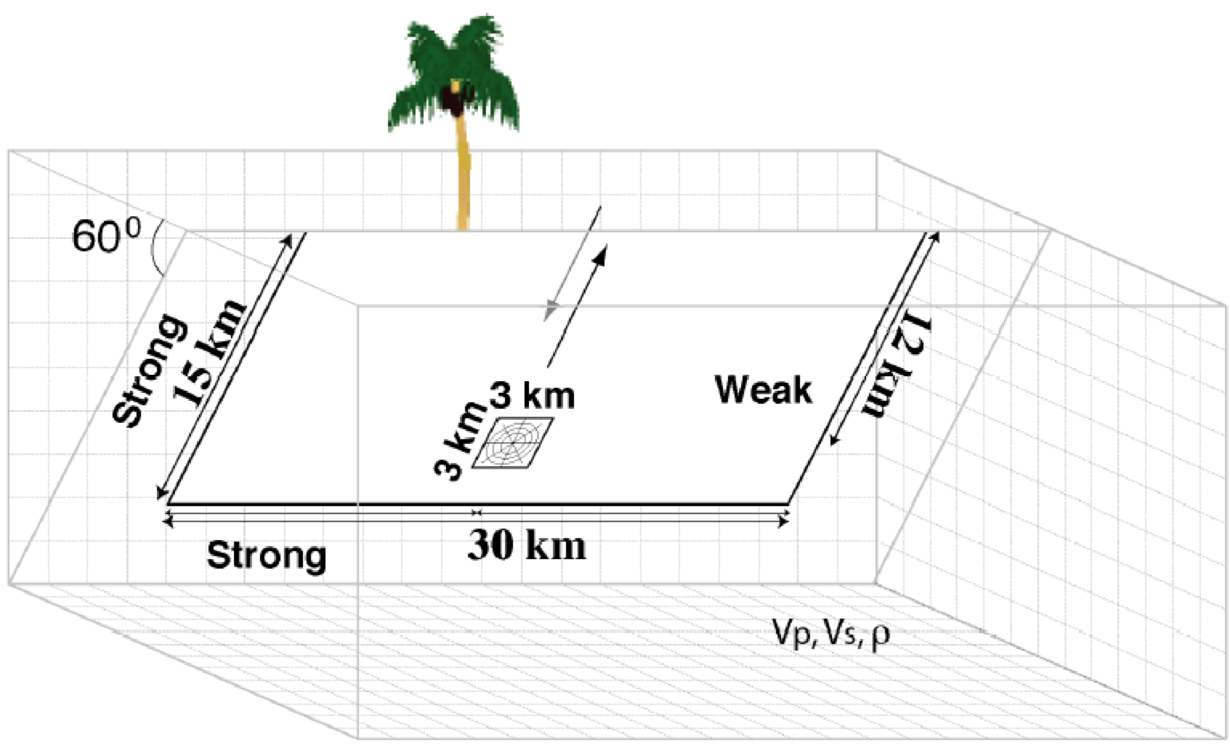
Displacement = motion relative to its initial position. Since all of the calculations start with an initial position of zero, Displacement = Absolute motion.

Velocity = Absolute motion with respect to time.

Slip = Relative motion across the fault plane (e.g., for split nodes).

Slip-Rate = Relative motion across the fault plane (e.g., for split nodes), with respect to time.

Rupture Front = Location of the leading edge of the rupture. Here we define this region as where (and when) slip-rate first changes from zero to greater than 1 mm/s.



Nov. 1, 2008

Part II. MODEL DESCRIPTION - THE PROBLEM, VERSIONS 10 AND 11

Please note that these are **THE 3D** models that we are investigating for TPV10 and TPV11. Although variations are of course interesting, our goal is to follow the description precisely. If the code you're using will not run with the Version 10 and 11 parameters, please contact us ASAP.

The only difference between TPV10 and TPV11 is the value of the static coefficient of friction. TPV10 is intended to have subshear rupture propagation, and TPV11 is intended to have supershear rupture propagation.

In these problems, you may encounter tension on the fault surface at shallow depths. Refer to the friction law description, later in this document, for instructions on how to handle tension.

Please feel free to point out to me as soon as possible, if we have omitted some critical details that you and others may need to run the simulations, or if there are any mistakes in the descriptions/requests.

Note: All units are in MKS.

1) Material properties are homogeneous throughout the medium and set to:
   vp = **5716**. m/s
   vs = **3300**. m/s
   density = **2700**. kg/m^3

2) The fault within the three-dimensional medium is a **60-degree dipping** planar **normal** fault that resides in a halfspace. The fault reaches the Earth's surface.

3) The rupture is allowed in a rectangular area that is 30000 m along-strike x 15000 m down-dip.

4) The regions below, to the left of, and to the right of the allowed 30000 m x 15000 m rupture area are defined by a strength barrier.

5) The nucleation patch (a square) is centered in the along-strike direction of the 30000 m x 15000 m rupture area. This nucleation patch is not in the middle of the fault plane along-dip, but instead is deeper on the fault so that its center-point is located on the fault plane at **12000 m** down-dip distance, which for this 60-degree dipping-fault case, is at approximately **10392 m** depth.

6) Nucleation occurs because the initial shear stress for the 3000-m x 3000-m square nucleation patch is set to be higher than the initial static yield strength in that patch. Failure occurs everywhere on the fault plane, including in the nucleation patch, following a linear slip-weakening fracture criterion.

7) For the entire 30000 m x 15000 m fault plane, including for the 3000 m x 3000 m nucleation patch, a slip-weakening fracture criterion is followed, and:

   Cohesion = **$0.2\text{x}10^6$ Pa**
   Dynamic coefficient of friction = **0.448**
   Slip-weakening critical distance = **0.50 m**

   For **TPV10**: Static coefficient of friction = **0.760**

   For **TPV11**: Static coefficient of friction = **0.570**

8) Outside the 30000 m x 15000 m fault plane, the fault is locked so that is it unable to slip. You may implement this locked area using any technique that is appropriate for your code. One possible technique is to follow slip-weakening in the locked area, but set the strength so high that the rupture cannot propagate beyond the faulting area, for example:

   Cohesion = **$1000.0\text{x}10^6$ Pa**
   Static coefficient of friction = **10000.**
   Dynamic coefficient of friction = **0.448**
   Slip-weakening critical distance = **0.50 m**

9) **For the entire fault plane, including the nucleation patch, both the initial (t=0) <u>fault-normal</u> stress and the initial (t=0) <u>dip-direction shear-stress</u> increase linearly with down-dip distance.**

For the entire fault plane,

Initial fault-normal stress (at t = 0) = 7378 Pa/m x meters-down-dip-distance

e.g., at 10 km down-dip distance, initial fault-normal stress
= 7378 x 10000 Pa = 73.78 x10^6 Pa

<u>**The initial dip-direction shear stress also increases linearly with the down-dip-distance on the fault, but its value depends on whether one is inside (or on the border of) or outside the nucleation patch**</u>:

Outside the nucleation patch,

Initial dip-direction shear stress (t=0) = 0.55 x initial normal stress

e.g., at 10 km down-dip distance, initial down-dip shear stress
= 0.55 x 73.78 x10^6 Pa = 40.579x10^6 Pa

Inside (and on the border of) the 3000 m x 3000 m nucleation patch, the initial dip-direction shear stress is higher than the static yield strength that includes cohesion.

Initial dip-direction shear stress (t=0)
= cohesion + ((static coefficient of friction + 0.0057) x initial normal stress)

e.g., for **TPV10** at 12 km down-dip distance inside the nucleation patch,
initial shear stress in the dip-direction
= 0.2x10^6 Pa + ((0.760 + 0.0057) x 7378 x 12000) Pa
= 0.2x10^6 Pa + 67.79 x10^6 Pa = 67.99 x10^6 Pa

e.g., for **TPV11** at 12 km down-dip distance inside the nucleation patch,
initial shear stress in the dip-direction
= 0.2x10^6 Pa + ((0.570 + 0.0057) x 7378 x 12000) Pa
= 0.2x10^6 Pa + 50.97 x10^6 Pa = 51.17 x10^6 Pa

<u>**Everywhere on the fault plane, the horizontal (along-strike) initial shear stress (at t=0) = 0**</u>

10) **Inside and on the border of the 30000m x 15000m faulting area, but outside the 3000m x 3000m nucleation patch at t=0 seconds**:

Linear slip-weakening is followed,
The initial fault-normal stress is a linear function of down-dip distance,
The initial dip-direction shear stress is a linear function of down-dip distance.

Cohesion = **0.2×10^6 Pa**
Dynamic coefficient of friction = **0.448**
Slip-weakening critical distance = **0.50 m**

For **TPV10**, static coefficient of friction = **0.760**
For **TPV11**, static coefficient of friction = **0.570**

Initial fault-normal stress (t=0)
= **7378 Pa x down-dip distance (in meters)**
Initial shear stress in dip-direction (t=0)
= **0.55 x 7378 Pa x down-dip distance (m)**

Initial horizontal (along-strike) shear stress (t=0) = **0 Pa**

For **TPV10**, initial static yield strength (t=0)
= **0.2×10^6 Pa + (0.760 x 7378 Pa x down-dip distance (m))**
For **TPV11**, initial static yield strength (t=0)
= **0.2×10^6 Pa + (0.570 x 7378 Pa x down-dip distance (m))**

Initial dynamic friction stress (t = 0)
= **0.2×10^6 Pa + (0.448 x 7378 Pa x down-dip distance (m))**
Initial stress drop (t=0)
= **-0.2×10^6 Pa + (0.102 x 7378 Pa x down-dip distance (m))**

11) **Inside and on the border of the 3000 m x 3000 m nucleation patch, at t=0 seconds**:

Linear slip-weakening is followed,
The initial normal stress is the <u>same</u> linear function of down-dip distance,
The initial dip-direction shear stress is a <u>different</u> linear function of down-dip distance, such that the initial dip-direction shear stress is greater than the static yield strength.

Initial horizontal (along-strike) shear stress (t=0) = **0 Pa**

Cohesion = **0.2×10^6 Pa**
For **TPV10**, static coefficient of friction = **0.760**
For **TPV11**, static coefficient of friction = **0.570**
Dynamic coefficient of friction = **0.448**
Slip-weakening critical distance = **0.50 m**
Initial fault-normal stress (t=0)
= **7378 Pa x down-dip distance (in meters)**

For **TPV10**, initial static yield strength (t=0)
= **0.2×10^6 Pa + (0.760 x 7378 Pa x down-dip distance (m))**
For **TPV11**, initial static yield strength (t=0)
= **0.2×10^6 Pa + (0.570 x 7378 Pa x down-dip distance (m))**

For **TPV10**, initial shear stress in dip-direction (t=0)
= **0.2×10^6 Pa + ((0.76 + 0.0057) x 7378 Pa x down-dip distance (m))**
For **TPV11**, initial shear stress in dip-direction (t=0)
= **0.2×10^6 Pa + ((0.57 + 0.0057) x 7378 Pa x down-dip distance (m))**

Initial dynamic friction stress (t = 0)
= **0.2×10^6 Pa + (0.448 x 7378 Pa x down-dip distance (m))**

For **TPV10**, initial stress drop (t=0)
= **0.3177 x 7378 Pa x down-dip distance (m)**
For **TPV11**, initial stress drop (t=0)
= **0.1277 x 7378 Pa x down-dip distance (m)**

12) On the fault plane but outside the 30000 m x 15000 m faulting area, there is a strength barrier that makes it impossible for the fault to slip. One possible technique for creating the strength barrier is to establish very large values for the cohesion and the static coefficient of friction, for example, cohesion = 1000 MPa and static coefficient of friction = 10000.

Summary of Parameters for TPV10 and TPV11		
Parameter	**Nucleation Area**	**Rupture Propagation Area**
Critical distance (d0)	0.5 m	0.5 m
Cohesion	0.2 MPa	0.2 MPa
Static coefficient of friction (mu_s)	TPV10: 0.760 TPV11: 0.570	TPV10: 0.760 TPV11: 0.570
Dynamic coefficient of friction (mu_d)	0.448	0.448
Initial normal stress (sigma_ini)	7378 (Pa/m) * down-dip distance (m)	7378 (Pa/m) * down-dip distance (m)
Initial shear stress along-dip	(mu_s + 0.0057) * sigma_ini + cohesion	0.55 * sigma_ini
Initial shear stress along-strike	0	0
Yield stress	mu_s * max (0, normal stress) + cohesion	mu_s * max (0, normal stress) + cohesion
Dynamic friction	mu_d * max (0, normal stress) + cohesion	mu_d * max (0, normal stress) + cohesion
Initial stress drop	(mu_s + 0.0057 - mu_d) * sigma_ini	(0.55 - mu_d) * sigma_ini - cohesion

End of TPV10 and TPV11 Description

Part III RESULTS TO PROVIDE

1) The requested output files are:

- A rupture time contour plot.

- Time-series files.

Please provide the results in raw form (no filtering). Don't worry about oscillations. The required file formats are posted on the website, as "*Required file formats, and instructions for uploading files, for TPV10 and TPV11*".

2) Computations should be run using **100 m node spacing** on the fault plane. If the code you are using cannot run with 100 m node spacing, due to memory/processor constraints, please let me know.

3) Please provide time series results for the times **0.0 to 15.0 seconds after nucleation**.

4) Please provide time series results for both on-fault and off-fault stations. The station locations are shown on the website as "*Diagram showing locations of on-fault stations, for TPV10 and TPV11*" and as "*Diagram showing locations of off-fault stations, for TPV10 and TPV11*".

5) Sign conventions are illustrated on the website as "*Diagram showing coordinate system and sign conventions, for TPV10 and TPV11*".

Part IV SLIP-WEAKENING FRICTION LAW

Benchmark problems TPV10 and TPV11 use linear slip weakening with cohesion.

This friction law has four parameters:

μ_s = static coefficient of friction
μ_d = dynamic coefficient of friction
d_0 = slip weakening distance
c = cohesion

Initially, the split node is locked. Failure occurs, and the node begins to slip, when:

shear stress > c + (μ_s × max (normal stress, 0))

When the split node has slipped a total distance d, the coefficient of friction is:

$\mu = \mu_s + (\mu_d - \mu_s) \times d / d_0$ if $d <= d_0$

$\mu = \mu_d$ if $d >= d_0$

While the split node is slipping, the shear stress on the fault is:

shear stress = c + (μ × max (normal stress, 0))

where μ is the slip-varying coefficient of friction given above.

Tension on the fault: You are likely to encounter tension on the fault at shallow depths. The procedure is to **treat tension on the fault the same as if normal stress equals zero**. This is shown in the above formulas by the expression "max (normal stress, 0)". In particular, notice that when the fault is in tension, the shear stress is equal to the cohesion (and *not* equal to zero).

We recommend that you **constrain the displacement of the split node so that the fault cannot open (that is, only permit sliding parallel to the fault), even when the fault is in tension**. During the time the fault is in tension, continue to accumulate the slip distance d as usual.

Backwards motion: You may encounter backwards motion on the fault at shallow depths. If this occurs, the slip distance d appearing in the formulas above is the total slip distance, not the net slip distance. For example, if the fault slips down 0.3 m and then slips up 0.1 m, the slip distance d is 0.4 m (and not 0.2 m).