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This is the 2006 SCEC Progress Report for SCEC Proposal # 06123. It is written by and submitted by the coordinating PI, Ruth Harris.

A Collaborative Project:
3D Rupture Dynamics, Validation of the Numerical Simulation Method

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* = No Cost to SCEC

The goal of our group is to compare and better understand the computer codes that are currently being used by SCEC scientists to simulate earthquake rupture dynamics. The results have significant ramifications for research findings in the SCEC science groups Earthquake Source Physics, Ground Motions, Fault Systems, Fault and Rock Mechanics, in the SCEC NGA project, and in the SCEC ITR projects Pathway3, TeraShake and Cybershake because all of these projects rely on the assumption that the numerical simulations are working similarly and correctly.

Code comparers in 2006 prepared for and participated in the February 2007 SCEC Code workshop, with 16 SCEC researchers, including postdocs and students, tackling our sixth and seventh benchmarks, The Problem, Version 6 (TPV6) and The Problem, Version 7 (TPV7). The definitions of these benchmarks and instructions to the modelers are attached as Appendix I.

The modelers included 16 people (15 U.S. SCEC scientists/postdocs/students and 1 scientist from Japan) who used 14 different computer codes to numerically simulate earthquakes in the code-validation exercise. In some cases a modeler used more than one code and in some cases modelers worked as a team, using one code. Included among the modelers were SCEC students, postdocs, faculty, USGS researchers, and 1 researcher who originally started participating in code validation while at a SCEC U.S. institution in 2004 but who is now working at AIST, in Japan. The list of modelers and their codes is Table 1.

The benchmarks tackled for the 2007 workshop were 3D simulations of spontaneous rupture propagation on a vertical strike-slip fault in a heterogeneous medium, with homogeneous initial stress conditions on the fault plane itself, within a 30 km long by 15 km deep fault surface. The fault intersected the earth's free surface. We examined the bimaterial case with two different material contrasts. The Problem, Version 6 had a higher contrast of shear modulus across the fault and The Problem, Version 7 had a lower contrast of shear modulus (see Appendix I). The idea was to test how the different codes responded to the bimaterial problem, since our previous benchmarks had been for a homogeneous medium.

These two benchmarks were also the unveiling exercises for our newly developed online web comparison tools developed by contract employee Michael Barall. In all previous benchmarks the comparisons were done manually by unlucky coordinating PI Harris, whereas for the first time, for this exercise the modelers were able to submit their results to the website, check to make sure that they were submitting results that made sense (e.g. sign-convention was correct, scale was correct), and also compare with the results of other SCEC modelers using different dynamic rupture codes.

Some Results:

Our main finding was that the new SCEC website is a huge plus compared to our previous labor-and time-intensive techniques, especially for the coordinating PI. Parts of the website will likely be borrowed by the SCEC CME project, if they haven't already been borrowed by the time of this writing.

Scientifically we learned that the bimaterial problem, with the parameters that we selected for TPV6 and TPV7 is a tricky case of needing to use finer grid spacing than some of the codes are capable of using at this time. We also learned that subsets of the codes produced similar results, whereas other codes produced different results, using the coarser 100 m spacing, but that it was difficult to tell which code was the most accurate due to the resolution issue. In particular, even for the "well-posed" TPV6, it is likely that the grid spacing would need to be on the order of 25-50 m for an accurate comparison. A conclusion from this exercise is that the results from each code should be examined with a convergence test to determine how fine a grid spacing is needed for each specific code.

We also had good discussions regarding the use of various types of regularization parameters in the spontaneous rupture codes, for the bimaterial problem. Some authors (SCEC and outside-of-SCEC) use various forms of regularization of the friction, whereas at least one SCEC code author uses viscous damping. How these different types of regularization affect the timing and amplitude of rupture on a highly detailed level may lead to slightly different results for the bimaterial problem, and so convergence seems a bit more challenging than our previous benchmarks where we were dealing with a homogeneous medium.

Table 1. Codes and Code Users for The February 12, 2007 Workshop

The Problem, Versions 6, 7
(January – February 2007)

(Results Submitted by February 8, 2007)

3D Code	Code User(s)	TPV6 Spacing (m)	TPV7 Spacing (m)	Code Description
EqSim	**Aagaard**	**100**	**100**	**Aagaard Finite Element**
AWM-Olsen	**Cruz Atienza/Olsen**	**100**	**100**	**Olsen Finite Difference**
dfm	**Dalguer/Day**	**100**	**100**	**Day Finite Difference**
dfm	**Day/Dalguer**	**50**	**50**	**Day Finite Difference**
EQdyna	**Duan**	**100**	**100**	**Duan Finite Element**
MDSBI	**Dunham**	**100**	**100**	**Dunham Spectral Bounday Integral**
SGFD	**Dunham2**	**100**	**100**	**Dunham Finite Difference**
SORD	**Ely**	**100**	**100**	**Ely Irregular-grid Support-Operator**
Kase	**Kase**	**100**	**100**	**Kase Finite Difference**
BI	**Liu/Lapusta**	**100**	**100**	**Lapusta/Liu Spectral Bounday Integral**
MAFE	**Ma**	**100**	**100**	**Ma Finite Element**
DYNA3D	**Oglesby**	**150**	**150**	**Oglesby Finite Element**
FDMSPLIT	**Pitarka**	**100**	**100**	**Pitarka Finite Difference**
ABAQUS	**Templeton/Bhat**	**100**	**100**	**ABAQUS Finite Element/Explicit**

Appendix 1. 10 page letter sent to modelers describing the benchmarks.

January 23, 2007

Dear SCEC Spontaneous Rupture Modeler,

We are tackling The Problem, Versions 6 and 7 for our upcoming spontaneous rupture code-validation (modelers) workshop. This workshop will be held on **Monday February 12, 2007 in the SCEC rooms at USC.** We're planning a 10:00 a.m. start time and anticipate being done by 5:00 p.m.

The specific goal for this meeting is to see if we can get a (comparative) handle on the The Problem, Versions 6 and 7, the vertical strike-slip fault bimaterial benchmarks.

For this workshop if your code has been modified significantly since our last exercise, please feel free to mention this at our meeting. We also have scheduled presentations from authors of 3 codes that we've not heard much about before, and, a general introduction to the bimaterial problem theory and methods.

The next pages have the description of The Problem, Versions 6 and 7.

TPV6 and TPV7 all use the same nucleation process as TPV3, and incorporate a free surface, intended to represent the earth's free surface.

We are using 100 m element size or node-spacing for all of these benchmarks.

For TPV6 and TPV7 we are starting a new system whereby modelers submit their results via Michael Barall's SCEC IT website. Information is arriving separately about how to send material to the website.

If you see any errors or omissions in any of the files of website directions or directions on these instructions here, please notify me and Michael Barall by email ASAP and we will work to change them, or, explain things better. This is our first run with the new submission system, and as you know I can always have typos in my directions, so all eagle-eye edits are welcome.

The deadline for submitting results to the website is ***February 5, 2007.***

Thanks!
Ruth

P.S. I need to give special thanks to code-validation volunteer Eric Dunham who put much thoughtful time and effort into how we should best do these bimaterial benchmarks. So if you see something on the upcoming pages that makes sense, please thank Eric and his group of collaborators.

Michael Barall is also greatly enhancing our code validation capabilities, with our new website. It will save me a huge amount of time and effort (and likely you too), so I also give my thanks to Michael.

Part I. Some definitions:

Displacement = motion relative to its initial position. Since all of the calculations start with this position at 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.

Please note that for TPV6 and TPV7 since we are looking at stations on each side of the fault, at each side of the split nodes, we will be considering displacement and velocity, rather than slip and slip-rate at the stations.

For the TPV6 and TPV7 contour plots, we will however be looking at slip-rate.

Part IIa. MODEL DESCRIPTION - THE PROBLEM, VERSION 6 (Jan. 12, 2007)

Please note that this is **THE 3D** model that we are investigating for **TPV6**. Although variations are of course interesting, our goal is to follow the description precisely. If the code you're using will not run with Version 6's parameters, please contact Ruth ASAP. *Please feel free to point out to me as soon as possible, if I 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.

TPV6 is intended to reside in the "well-posed" regime for bimaterial problems and so uses a very high shear modulus (density*vs*vs) contrast.
<u>Slip-weakening is the fracture criterion.</u>

1) Material properties are homogeneous within each side of the fault, but change when one traverses to the other side of the fault. This is the bimaterial problem.

a) On the far side of the fault plane, vp, vs, density = vp_1, vs_1, $density_1$

vp_1 = 6000/1.6 m/s = **3750 m/s**
vs_1 = 3464/1.6 m/s = **2165 m/s**
$density_1$ = 2670/1.2 kg/m^3 = **2225 kg/m^3**

b) On the near side of the fault plane, vp, vs, density = vp_2, vs_2, $density_2$

vp_2 = 6000 m/s
vs_2 = 3464 m/s
$density_2$ = 2670 kg/m^3

2) The fault within the three-dimensional medium is a vertical right-lateral strike-slip planar fault that reaches the Earth's surface.

3) The rupture is allowed within a rectangular area that is 30000 m long x 15000 m deep.

4) The bottom boundary of the allowed 30000m x 15000m rupture area is defined by a strength barrier*.

5) The right and left ends of the allowed 30000 m x 15000 m rupture area are defined by a strength barrier*.

6) The nucleation point is centered both along-dip and along-strike of the 30000m x 15000m rupture area, on the fault plane, at 15000m along-strike and 7500m depth.

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

length of 3000m. The square nucleation patch is centered on the nucleation point. The initial shear stress in this square area is equal to 81.6 MPa.

Within the entire 3000 m x 3000 m nucleation patch, at zero seconds:
Static coefficient of friction = 0.677
Dynamic coefficient of friction = 0.525
Initial shear stress in the along-strike-direction (at t = 0) = 81.6 MPa
Initial shear stress in the along-dip direction (at t = 0) = 0 MPa
Initial normal stress (at t = 0) = 120 Mpa
Initial static yield stress (at t = 0) = 0.677 x 120 MPa = 81.24 MPa
Initial dynamic friction stress (at t = 0) = 0.525 x 120 MPa = 63.00 Mpa
Initial stress drop (at t = 0) = 81.6 MPa – (0.525 x 120 MPa) = 18.6 Mpa
Slip-weakening critical distance = 0.40 m

10) Outside of the nucleation patch, friction is governed by the linear slip-weakening fracture criterion, but the initial shear stress is different.

Within the 30000 m x 15000 m faulting area, but outside of the 3000 m x 3000 m nucleation patch:

Static coefficient of friction = μ_s = 0.677
Dynamic coefficient of friction = μ_d = 0.525
Initial shear stress in the along-strike-direction (at t = 0) = 70 MPa
Initial shear stress in the along-dip-direction (at t = 0) = 0 MPa
Initial normal stress (at t = 0) = 120 MPa
Initial static yield stress (at t = 0) = 0.677 x 120 MPa = 81.24 MPa
Initial dynamic friction stress (at t = 0) = 0.525 x 120 MPa = 63.00 MPa
Initial stress drop (at t = 0) = 70 MPa – (0.525 x 120 MPa) = 7.00 MPa
Slip-weakening critical distance = d_0 = 0.40 m

11) *On the fault plane, but outside of the 30000 m x 15000 m faulting area, there is a strength barrier.
This is accomplished by setting the static coefficient of friction to the high value of 10000. so that the rupture is not able to propagate on the fault plane beyond 30000 m x 15000 m:

Static coefficient of friction = μ_s = 10000.
Dynamic coefficient of friction = μ_d = 0.525
Initial shear stress in the along-strike direction (at t = 0) = 70 MPa
Initial shear stress in the along-dip direction (at t = 0) = 0 MPa
Initial normal stress (at t = 0) = 120 MPa
Slip-weakening critical distance = d_0 = 0.40 m

----------------End of TPV6 Description-------------------

Part IIb. MODEL DESCRIPTION - THE PROBLEM, VERSION 7 (Jan. 12, 2007)

Please note that this is **THE 3D** model that we are investigating for **TPV7**. Although variations are of course interesting, our goal is to follow the description precisely. If the code you're using will not run with Version 7's parameters, please contact Ruth ASAP. *Please feel free to point out to me as soon as possible, if I 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.

TPV7 is intended to reside in the "ill-posed" regime for bimaterial problems and so uses a lower shear modulus (density*vs*vs) contrast than the previous benchmark, TPV6. Everything else is the same for TPV7 as it was for TPV6.
Please do not specifically modify your code (or friction) to do TPV7 - use whichever form of your code that you would use for our homogeneous material benchmarks.
Slip-weakening is the fracture criterion.

1) Material properties are homogeneous within each side of the fault, but change when one traverses to the other side of the fault. This is the bimaterial problem.

a) On the far side of the fault plane, vp, vs, density = vp_1, vs_1, $density_1$

vp_1 = 6000/1.2 m/s = **5000 m/s**
vs_1 = 3464/1.2 m/s = **2887 m/s**
$density_1$ = 2670 kg/m^3 = **2670 kg/m^3**

b) On the near side of the fault plane, vp, vs, density = vp_2, vs_2, $density_2$

vp_2 = 6000 m/s
vs_2 = 3464 m/s
$density_2$ = 2670 kg/m^3

2) The fault within the three-dimensional medium is a vertical right-lateral strike-slip planar fault that reaches the Earth's surface.

3) The rupture is allowed within a rectangular area that is 30000 m long x 15000 m deep.

4) The bottom boundary of the allowed 30000m x 15000m rupture area is defined by a strength barrier*.

5) The right and left ends of the allowed 30000 m x 15000 m rupture area are defined by a strength barrier*.

6) The nucleation point is centered both along-dip and along-strike of the 30000m x 15000m rupture area, on the fault plane, at 15000m along-strike and 7500m depth.

7) Nucleation occurs because the initial shear stress in a 3000 m x 3000 m square nucleation patch is set to be higher than the initial static yield stress in that patch. Failure occurs everywhere on the fault plane, including in the nucleation patch, following a linear slip-weakening fracture criterion. The square patch has a side-length of 3000m. The square nucleation patch is centered on the nucleation point. <u>The initial shear stress in this square area is equal to 81.6 MPa</u>.

Within the entire 3000 m x 3000 m nucleation patch, at zero seconds:

Static coefficient of friction = 0.677
Dynamic coefficient of friction = 0.525
Initial shear stress in the along-strike-direction (at t = 0) = 81.6 MPa
Initial shear stress in the along-dip direction (at t = 0) = 0 MPa
Initial normal stress (at t = 0) = 120 Mpa
Initial static yield stress (at t = 0) = 0.677 x 120 MPa = 81.24 MPa
Initial dynamic friction stress (at t = 0) = 0.525 x 120 MPa = 63.00 Mpa
Initial stress drop (at t = 0) = 81.6 MPa – (0.525 x 120 MPa) = 18.6 Mpa
Slip-weakening critical distance = 0.40 m

8) Outside of the nucleation patch, friction is governed by the linear slip-weakening fracture criterion, but the initial shear stress is different.

Within the 30000 m x 15000 m faulting area, but outside of the 3000 m x 3000 m nucleation patch:

Static coefficient of friction = μ_s = 0.677
Dynamic coefficient of friction = μ_d = 0.525
Initial shear stress in the along-strike-direction (at t = 0) = 70 MPa
Initial shear stress in the along-dip-direction (at t = 0) = 0 MPa
Initial normal stress (at t = 0) = 120 MPa
Initial static yield stress (at t = 0) = 0.677 x 120 MPa = 81.24 MPa
Initial dynamic friction stress (at t = 0) = 0.525 x 120 MPa = 63.00 MPa
Initial stress drop (at t = 0) = 70 MPa – (0.525 x 120 MPa) = 7.00 MPa
Slip-weakening critical distance = d_0 = 0.40 m

9) *On the fault plane, but outside of the 30000 m x 15000 m faulting area, there is a strength barrier.
This is accomplished by setting the static coefficient of friction to the high value of 10000. so that the rupture is not able to propagate on the fault plane beyond 30000 m x 15000 m:

Static coefficient of friction = μ_s = 10000.
Dynamic coefficient of friction = μ_d = 0.525
Initial shear stress in the along-strike direction (at t = 0) = 70 MPa
Initial shear stress in the along-dip direction (at t = 0) = 0 MPa

Initial normal stress (at t = 0) = 120 MPa
Slip-weakening critical distance = d_0 = 0.40 m

-----------------End of TPV7 Description--------------------

Part III. RESULTS TO PROVIDE BEFORE THE WORKSHOP

(Please send results to our SCEC website on or before February 5, 2007)

Note 1.
Results submission instructions are documented in separate files sent to you by Michael Barall.

Note 2.
The requested output files are (see Michael's instructions for the fomats):

1) Time-series files, in ascii format
2) Rupture time contours
   (for TPV6, TPV7 you won't email a pre-plotted file as we did in our previous benchmarks. Instead this time you'll be providing the website with the actual coordinates of the contours)

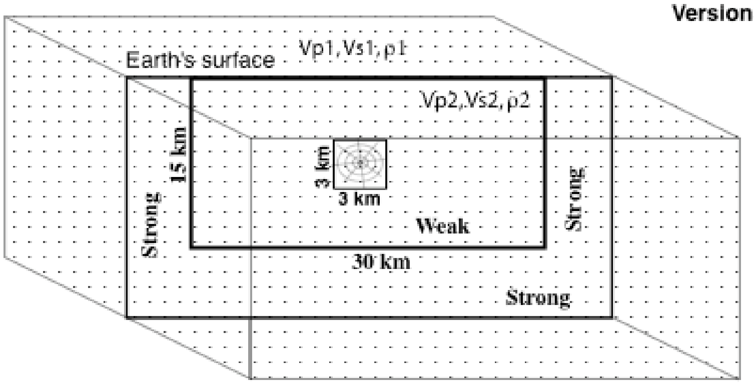
Note 3.
Please see the accompanying file *faultstationsTPV67.pdf* showing the locations of the stations, and the 3D bimaterial model.
There are 10 stations that are all along the fault, on each split node side, so that they occur at 5 different locations if one were looking at the fault plane in side view
6 (3) of the stations are at the earth's surface, and 4 (2) of the stations are at hypocentral depth.

Note 4.
The sign convention for the coordinate system and for the split-nodes are shown in the accompanying file *Signconvention3d.pdf*

Note 5.
Computations should be run using the following element-size/node-spacing
100m

Note 6.
Time series are to be run for 12 seconds

Overall view:



Vertical strike-slip fault is the boundary between two materials.
On the far side of the fault, Vp, Vs, density = Vp1,Vs1,ρ1
On the near side of the fault, Vp, Vs, density = Vp2, Vs2, ρ2

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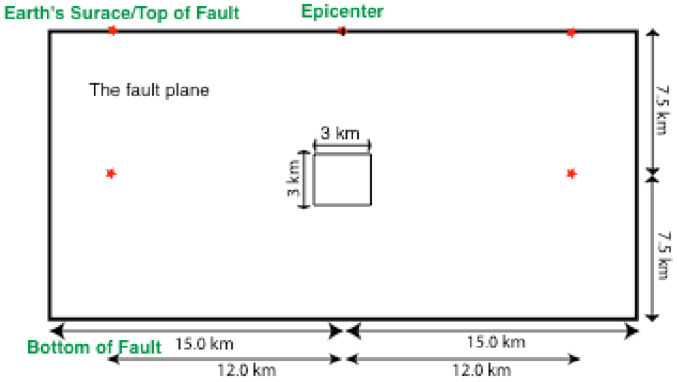
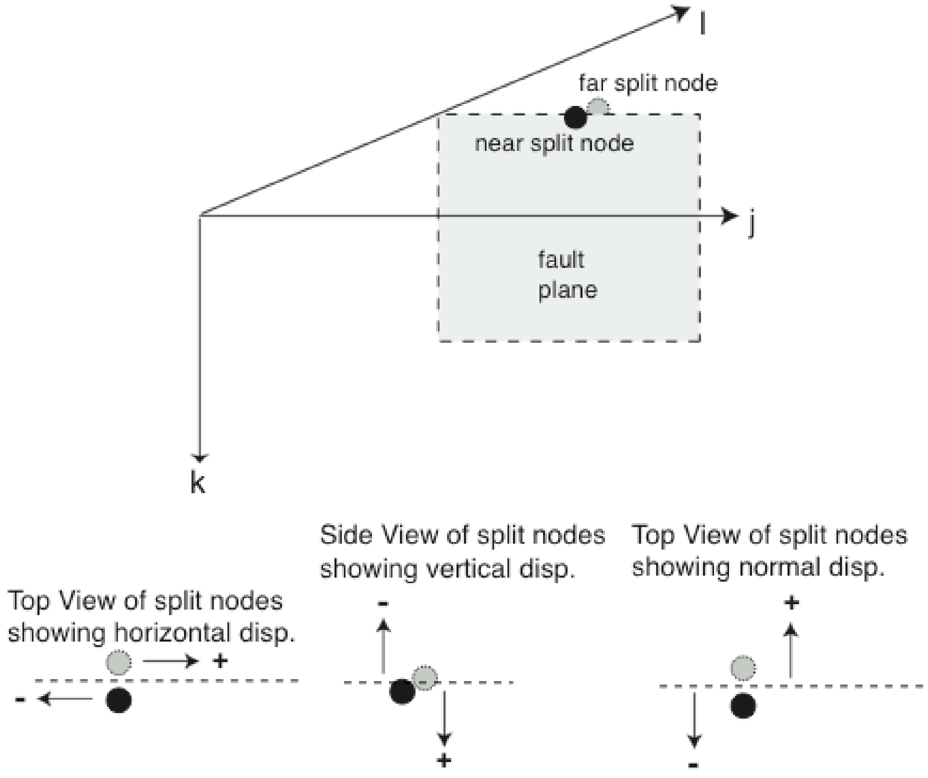
The fault plane (in a different scale from above), with stations immediately on the fault (**one station for each side of the split node**) are indicated by stars. Note that both sides of each split node are shown by one star, so that each star actually indicates two stations.

6 Stations on the Earth's surface (depth=0 km) are at
0 and +/-12.0 km along-strike distance from the epicenter.
4 Deeper Stations are at
+/-12.0 km along-strike distance from the hypocenter.





horizontal displacement of split node on far side of fault = $u(j,k,l^+)$
horizontal displacement of split node on near side of fault = $u(j,k,l^-)$
horizontal slip = $u(j,k,l^+) - u(j,k,l^-)$ (>0 for right-lateral strike-slip)

vertical displacement of split node on far side of fault = $v(j,k,l^+)$
vertical displacement of split node on near side of fault = $v(j,k,l^-)$
vertical slip = $v(j,k,l^+) - v(j,k,l^-)$ (>0 for downward slip)

normal displacement of split node on far side of fault = $w(j,k,l^+)$
normal displacement of split node on near side of fault = $w(j,k,l^-)$
normal slip = $w(j,k,l^+) - w(j,k,l^-)$ (>0 for extension)