

SCEC/USGS Dynamic Rupture Benchmarks TPV36 and TPV37: Shallow Dip Thrust Fault

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These 3D benchmarks use a fault dipping at 15 degrees in a linear elastic half-space. We are doing two benchmarks, as shown in the following table.

Benchmarks			
<i>Benchmark</i>	<i>Dimension</i>	<i>Rupture Type</i>	<i>Material Properties</i>
TPV36	3D	Rupture reaches the Earth's surface.	Linear elastic.
TPV37	3D	Rupture stops without reaching the Earth's surface.	Linear elastic.

We request that you run these benchmarks using 50 meter resolution on the fault.

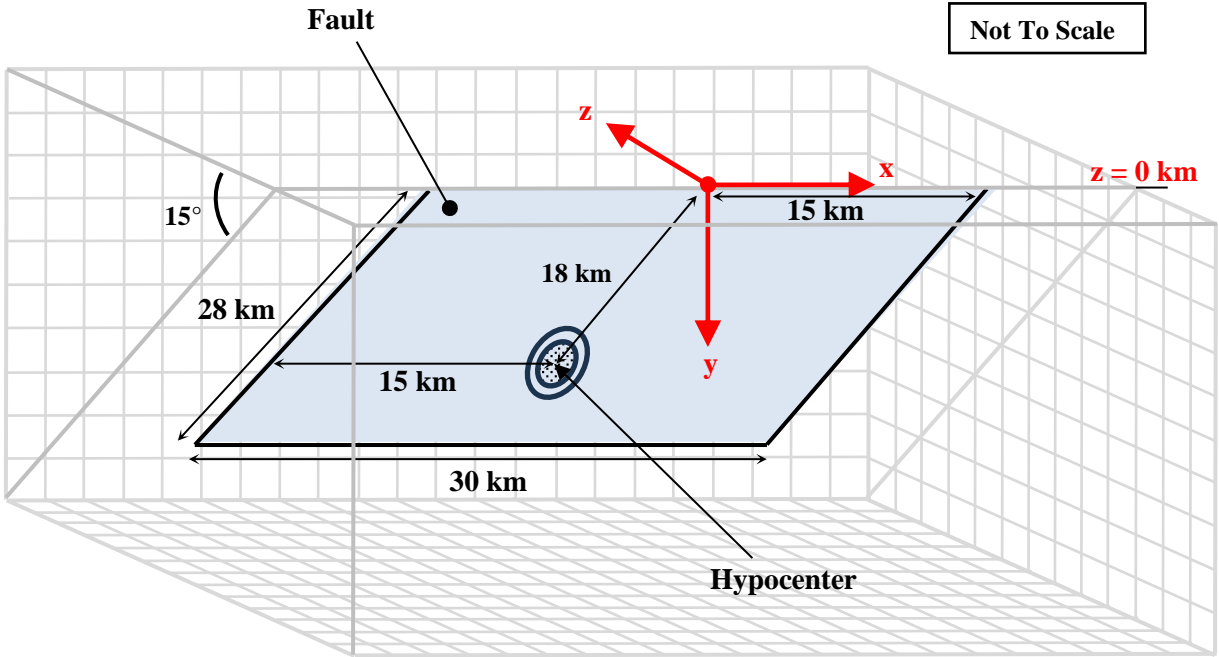
A few notes:

- We are introducing a new type of output file, which contains the final displacement at the Earth's surface. The web site is not equipped to accept this file, so we will send instructions for submitting the file in another way.
- The fault boundary condition is that slip goes to zero at the bottom and side borders of the fault. So, a node which lies precisely on the bottom or side border of the fault should *not* be permitted to slip.
- Nucleation is done using a smoothed forced rupture. The forced rupture is applied over an interval of 0.5 seconds (instead of being applied instantaneously as in some earlier benchmarks), and the forced rupture velocity varies with distance from the hypocenter.

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Part 1: Fault Geometry for TPV36 and TPV37



The model volume is a half-space. The fault is a planar thrust fault that dips at an angle of 15 degrees. The fault is a rectangle measuring 30000 m along-strike and 28000 m down-dip. The fault reaches the earth’s surface. The hypocenter is located in the center of fault along-strike, and 18000 m down-dip. Distance down-dip is measured downward from the fault trace along the sloping fault surface.

Introduce an (x, y, z) coordinate system, where x increases from left to right, y increases from top to bottom, and z increases from front to back. The origin is on the earth’s surface, in the center of the fault trace. In this coordinate system, the fault is:

$$\begin{aligned}
 -15000 \text{ m} &\leq x \leq 15000 \text{ m} \\
 0 \text{ m} &\leq y \leq (28000 \text{ m})(\sin 15^\circ) \\
 z &= y/(\tan 15^\circ)
 \end{aligned}$$

For these benchmarks, we are also calculating the final deformation of the Earth’s surface at the end of the simulation. The portion of the Earth’s surface where we are calculating the final deformation is:

$$\begin{aligned}
 -30000 \text{ m} &\leq x \leq 30000 \text{ m} \\
 y &= 0 \text{ m} \\
 -15000 \text{ m} &\leq z \leq 53000 \text{ m}
 \end{aligned}$$

Part 2: Description of the 3D Benchmarks

Fault Geometry

Fault geometry for TPV36 and TPV37 is shown in part 1. The planar fault surface dips at an angle of 15 degrees, and measures 30 km along-strike and 28 km along-dip.

The hypocenter is centered along-strike, and is 18 km down-dip. Allowing for a fault dip of 15 degrees, the hypocenter is at location $(x, y, z) = (0 \text{ m}, (18000 \text{ m})(\sin 15^\circ), (18000 \text{ m})(\cos 15^\circ))$ which is approximately $(x, y, z) = (0 \text{ m}, 4658 \text{ m}, 17387 \text{ m})$.

Slip goes to zero at the side and bottom borders of the fault. So, a node which lies precisely on the side or bottom border of the fault should not be permitted to slip.

Material Properties

In TPV36 and TPV37, the entire model volume is a linear elastic material, with the following parameters.

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

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

$$\text{Pressure-wave velocity } V_p = 6000 \text{ m/s}$$

Note that these are the same material properties used in benchmark TPV5 and several of our other SCEC/USGS Dynamic Rupture Group benchmarks.

Friction Parameters and Nucleation

We use a linear slip-weakening friction law, which has the following six parameters.

Friction Parameters		
<i>Symbol</i>	<i>Parameter</i>	<i>Unit</i>
μ_s	Static coefficient of friction.	Dimensionless
μ_d	Dynamic coefficient of friction.	Dimensionless
d_0	Slip-weakening critical distance.	Meter
C_0	Frictional cohesion.	Pascal
T	Time of forced rupture.	Second
t_0	Forced rupture decay time	Second

The operation of the slip-weakening friction law is described in detail later, in part 3.

The friction parameter values are as follows, where r denotes distance to the hypocenter, and r_{crit} denotes the radius of the nucleation zone:

$$\mu_s = 0.575$$

$$\mu_d = 0.450$$

$$d_0 = 0.18 \text{ m}$$

$$r_{\text{crit}} = 4000 \text{ m}$$

$$T = \begin{cases} \frac{r}{0.7 V_S} + \frac{0.081 r_{\text{crit}}}{0.7 V_S} \left(\frac{1}{1 - (r/r_{\text{crit}})^2} - 1 \right), & \text{if } r < r_{\text{crit}} \\ 1.0\text{E}+9, & \text{if } r \geq r_{\text{crit}} \end{cases}$$

$$t_0 = 0.50 \text{ s}$$

The variation in the value of T near the hypocenter causes the rupture to nucleate, in a manner that is described later, in part 4.

The two benchmarks, TPV36 and TPV37, differ in the frictional cohesion. Let w denote distance down-dip:

$$w \equiv y/(\sin 15^\circ)$$

For TPV36, the frictional cohesion is:

$$C_0 = \begin{cases} (0.0005 \text{ MPa/m})(8000 \text{ m} - w), & \text{if } w \leq 8000 \text{ m} \\ 0.0 \text{ MPa}, & \text{if } w \geq 8000 \text{ m} \end{cases}$$

For TPV37, the frictional cohesion is:

$$C_0 = \begin{cases} (0.001875 \text{ MPa/m})(8000 \text{ m} - w), & \text{if } w \leq 8000 \text{ m} \\ 0.0 \text{ MPa}, & \text{if } w \geq 8000 \text{ m} \end{cases}$$

The frictional cohesion C_0 is equal to 4.0 MPa at the Earth's surface in TPV36, and 15.0 MPa at the Earth's surface in TPV37, and tapers to zero at 8000 m down-dip. **The frictional cohesion is the only difference between TPV36 and TPV37.**

Initial Normal and Shear Stress on the Fault

The initial normal stress σ_{ini} , and the initial shear stress τ_{ini} , are proportional to distance down-dip:

$$\sigma_{\text{ini}} = (0.00424 \text{ MPa/m}) w$$

$$\tau_{\text{ini}} = (-0.00212 \text{ MPa/m}) w$$

in which $w \equiv y/(\sin 15^\circ)$ is equal to distance down-dip. The initial shear stress, τ_{ini} , is oriented along-dip and is negative. The negative value indicates that the far side the fault (the side in the $+z$ direction, that is, the hanging wall) is moving upward relative to the near side of the fault (the side in the $-z$ direction, that is, the footwall). In other words, a thrust fault.

For example, the hypocenter lies 18 km down-dip, and so $w = 18000$ m. By the above formulas, the initial normal and shear stress at the hypocenter are $\sigma_{\text{ini}} = 76.32$ MPa and $\tau_{\text{ini}} = -38.16$ MPa.

Running Time, Node Spacing, and Results

Run the model for times from **0.0 to 22.0 seconds after nucleation**.

Please submit results using **50 m node spacing** on the fault plane.

If you are unable to achieve 50 m node spacing on the fault plane, then you can use 100 m node spacing on the fault plane.

If you want to submit more than one set of results, you can use the “Change Version” function on the website to submit multiple sets of results.

The requested output files are:

- **On-fault time-series files**, which give slips, slip rates, and stresses for each on-fault station at each time step. These files are described in part 5.
- **Off-fault time-series files**, which give displacements and velocities for each off-fault station at each time step. These files are described in part 6.
- **A contour-plot file** which, for each node on the fault, gives the time at which the slip rate first changes from 0 to greater than 0.001 m/s. This file is described in part 7.
- **A surface deformation file** which, for each point on the Earth’s surface, gives the displacement of that point relative to its initial position, **at the end of the simulation**. The website is not equipped to permit uploading this file, and so instructions for submitting the file will be supplied separately. This file is described in part 8.

Part 3: Linear Slip-Weakening Friction

Benchmarks TPV36 and TPV37 use linear slip-weakening friction, with frictional cohesion and, in the nucleation zone, forced rupture. This friction law has the following parameters and variables:

Friction Parameters		
<i>Symbol</i>	<i>Parameter</i>	<i>Unit</i>
μ_s	Static coefficient of friction.	Dimensionless
μ_d	Dynamic coefficient of friction.	Dimensionless
d_0	Slip-weakening critical distance.	Meter
C_0	Frictional cohesion.	Pascal
T	Time of forced rupture.	Second
t_0	Forced rupture decay time	Second

Friction Variables		
<i>Symbol</i>	<i>Parameter</i>	<i>Unit</i>
σ_n	Normal stress acting on the fault, taken to be positive in compression.	Pascal
τ	Shear stress acting on the fault.	Pascal

When the fault is sliding, the shear stress τ at a given point on the fault is given by:

$$\tau = C_0 + \mu \max(0, \sigma_n)$$

The time-varying coefficient of friction μ is given by the following formulas, where D is the total distance the node has slipped, and t is the time since the start of the simulation:

$$\mu = \mu_s + (\mu_d - \mu_s) \max(f_1, f_2)$$

$$f_1 = \begin{cases} D/d_0, & \text{if } D < d_0 \\ 1, & \text{if } D \geq d_0 \end{cases}$$

$$f_2 = \begin{cases} 0, & \text{if } t < T \\ (t - T)/t_0, & \text{if } T \leq t < T + t_0 \\ 1, & \text{if } t \geq T + t_0 \end{cases}$$

The distance D that the node has slipped is path-integrated. For example, if the node slips 0.4 m in one direction and then 0.1 m in the opposite direction, the value of D is 0.5 m (and not 0.3 m).

The time of forced rupture T is used to nucleate the rupture, as described in part 4. At time $t = T$, the coefficient of friction begins to decrease, reaching its final dynamic value at time $t = T + t_0$. So, the node is forced to begin sliding somewhere in the interval $T < t < T + t_0$. Notice that because of the expression $\max(f_1, f_2)$, forcing has no effect if friction has already weakened due to the accumulated slip. If a given node does not undergo forced rupture, then the value of T is 1.0E9.

Tension on the fault: If you encounter tension on the fault, you should **treat tension on the fault the same as if the normal stress equals zero**. This is shown in the above formulas by the expression $\max(0, \sigma_n)$.

You should **constrain the motion of the 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.

Part 4: Nucleation

Nucleation is performed by forcing the fault to rupture, within a circular zone surrounding the hypocenter. Forced rupture is achieved by artificially reducing the friction coefficient, beginning at a specified time T . The parameter t_0 specifies how long it takes for the friction coefficient to be artificially reduced from its static value to its dynamic value. So, the friction coefficient reaches its dynamic value at time $T + t_0$. We reduce the friction coefficient gradually, over an interval of time, in order to smooth the nucleation process and reduce unwanted oscillations.

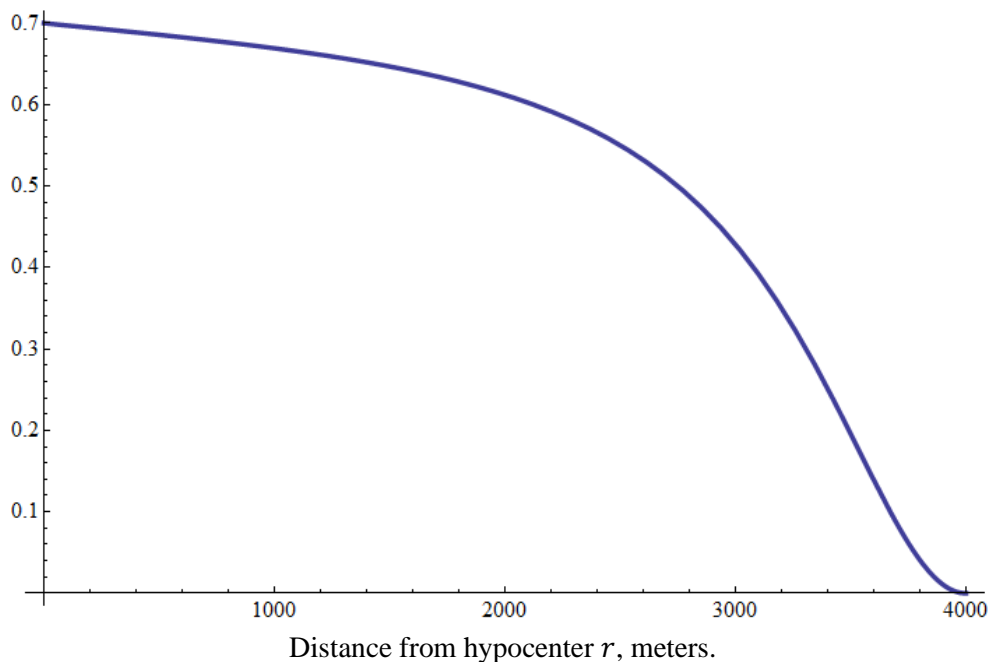
Recall that we selected $t_0 = 0.5$ s, and that the time of forced rupture is defined to be

$$T = \begin{cases} \frac{r}{0.7 V_S} + \frac{0.081 r_{\text{crit}}}{0.7 V_S} \left(\frac{1}{1 - (r/r_{\text{crit}})^2} - 1 \right), & \text{if } r < r_{\text{crit}} \\ 1.0\text{E}+9, & \text{if } r \geq r_{\text{crit}} \end{cases}$$

where r is distance from the hypocenter, and where $r_{\text{crit}} = 4000$ m is the radius of the nucleation zone. At the hypocenter, $T = 0$. The value of T then increases with distance from the hypocenter, which creates an expanding circular region of forced rupture.

The time T is computed so that the forced rupture expands at a variable speed. Near the hypocenter, the forced rupture expands at a speed of $0.7 V_S$. The speed decreases with increasing distance from the hypocenter, finally reaching a speed of zero at a distance of 4000 m from the hypocenter. The variable speed allows for a smooth transition between forced rupture and spontaneous rupture, because the spontaneous rupture should gradually overtake the ever-slowing forced rupture. The graph below shows the forced rupture speed $V_R \equiv dr/dT$ as a function of distance from the hypocenter.

Speed of forced rupture V_R/V_S .



Part 5: On-Fault Stations, and Time-Series File Format

The benchmarks use 22 stations on the fault, which are listed below. A diagrams of station locations appears following the table. You need to supply one time-series file for each station.

On-Fault Stations, for TPV36 and TPV37	
Station Name	Location
faultst000dp000	On fault, 0.0 km along strike, 0.0 km down-dip.
faultst000dp010	On fault, 0.0 km along strike, 1.0 km down-dip.
faultst000dp030	On fault, 0.0 km along strike, 3.0 km down-dip.
faultst000dp060	On fault, 0.0 km along strike, 6.0 km down-dip.
faultst000dp120	On fault, 0.0 km along strike, 12.0 km down-dip.
faultst000dp180	On fault, 0.0 km along strike, 18.0 km down-dip.
faultst000dp240	On fault, 0.0 km along strike, 24.0 km down-dip.
faultst040dp000	On fault, 4.0 km along strike, 0.0 km down-dip.
faultst040dp030	On fault, 4.0 km along strike, 3.0 km down-dip.
faultst040dp060	On fault, 4.0 km along strike, 6.0 km down-dip.
faultst040dp120	On fault, 4.0 km along strike, 12.0 km down-dip.
faultst040dp180	On fault, 4.0 km along strike, 18.0 km down-dip.
faultst080dp000	On fault, 8.0 km along strike, 0.0 km down-dip.
faultst080dp030	On fault, 8.0 km along strike, 3.0 km down-dip.
faultst080dp060	On fault, 8.0 km along strike, 6.0 km down-dip.
faultst080dp120	On fault, 8.0 km along strike, 12.0 km down-dip.
faultst080dp180	On fault, 8.0 km along strike, 18.0 km down-dip.
faultst120dp000	On fault, 12.0 km along strike, 0.0 km down-dip.
faultst120dp030	On fault, 12.0 km along strike, 3.0 km down-dip.

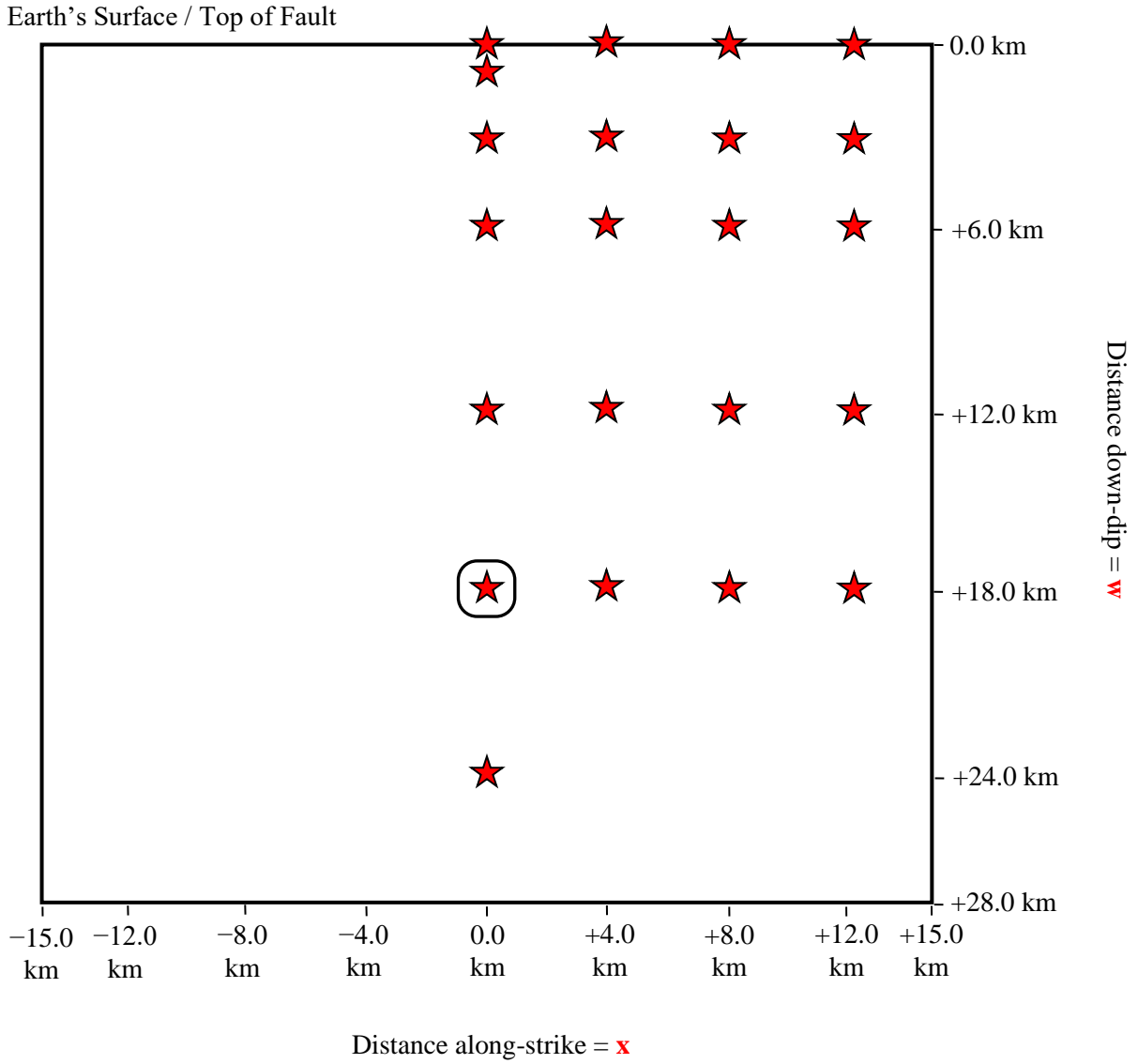
faultst120dp060	On fault, 12.0 km along strike, 6.0 km down-dip.
faultst120dp120	On fault, 12.0 km along strike, 12.0 km down-dip.
faultst120dp180	On fault, 12.0 km along strike, 18.0 km down-dip.

If you do not have a node at the location of a station, there are two options: (1) you can move the station to the nearest node, or (2) you can interpolate the data values from nodes near the station location.

Note: Location along-strike is measured relative to the origin of the (x, y, z) coordinate system. Positive locations are to the right of the origin. Because these benchmarks are symmetric, all stations are at non-negative coordinates along-strike.

Note: Recall that distance down-dip is defined to be $w \equiv y/(\sin 15^\circ)$, which is distance from the fault trace measured along the sloping fault plane.

Station Locations on Fault



There are 22 on-fault stations, at the following (x, w) coordinates, in km:

(0.0 km, 0.0 km)	(4.0 km, 3.0 km)	(8.0 km, 18.0 km)
(0.0 km, 1.0 km)	(4.0 km, 6.0 km)	(12.0 km, 0.0 km)
(0.0 km, 3.0 km)	(4.0 km, 12.0 km)	(12.0 km, 3.0 km)
(0.0 km, 6.0 km)	(4.0 km, 18.0 km)	(12.0 km, 6.0 km)
(0.0 km, 12.0 km)	(8.0 km, 0.0 km)	(12.0 km, 12.0 km)
(0.0 km, 18.0 km)	(8.0 km, 3.0 km)	(12.0 km, 18.0 km)
(0.0 km, 24.0 km)	(8.0 km, 6.0 km)	
(4.0 km, 0.0 km)	(8.0 km, 12.0 km)	

Note that location along-strike is measured relative to the origin of the (x, y, z) coordinate system
Positive locations are to the right of the origin.

Recall that distance down-dip is defined to be $w \equiv y/(\sin 15^\circ)$, which is distance from the fault trace measured along the sloping fault plane.

Each time series file is an ASCII file that contains 8 data fields on each line, as follows.

On-Fault Time Series Data Fields for TPV36 and TPV37	
Field Name	Description, Units, and Sign Convention
t	Time (s).
h-slip	Horizontal slip along-strike (m). Sign convention: Positive means right lateral slip.
h-slip-rate	Horizontal slip rate along-strike (m/s). Sign convention: Positive means right lateral motion.
h-shear-stress	Horizontal shear stress along-strike (MPa). Sign convention: Positive means shear stress that tends to cause right-lateral slip.
v-slip	Vertical along-dip slip (m). Sign convention: Positive means downward slip (that is, the far side of the fault moving downward relative to the near side of the fault). For TPV36 and TPV37, this is expected to be negative.
v-slip-rate	Vertical along-dip slip rate (m/s). Sign convention: Positive means downward motion (that is, the far side of the fault moving downward relative to the near side of the fault). For TPV36 and TPV37, this is expected to be negative.
v-shear-stress	Vertical along-dip shear stress (MPa). Sign convention: Positive means shear stress that tends to cause downward slip (that is, the far side of the fault moving downward relative to the near side of the fault). For TPV36 and TPV37, this is expected to be negative.
n-stress	Normal stress (MPa). Sign convention: Positive means extension .

The **near side** of a fault is in the front of the diagram (the $-z$ side of the fault).

The **far side** of a fault is in the back of the diagram (the $+z$ side of the fault).

The on-fault time series file consists of three sections, as follows.

On-Fault Time Series File Format for TPV36 and TPV37	
File Section	Description
File Header	<p>A series of lines, each beginning with a # symbol, that identifies the file. The following information is recommended:</p> <ul style="list-style-type: none"> • Benchmark problem (TPV36 or TPV37) • Author • Date • Code • Code version • Node spacing or element size • Time step • Number of time steps in file • Station location • Descriptions of data columns (7 lines) • Anything else you think is relevant
Field List	<p>A single line, which lists the names of the 8 data fields, in column order, separated by spaces. It should be:</p> <pre>t h-slip h-slip-rate h-shear-stress v-slip v-slip-rate v-shear-stress n-stress</pre> <p>(all on one line). The server examines this line to check that your file contains the correct data fields.</p>
Time History	<p>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.</p> <p>C/C++ users: For all data fields except the time, we recommend using 14.6E or 14.6e floating-point format. For the time field, we recommend using 20.12E or 20.12e format (but see the note on the next page).</p> <p>Fortran users: For all data fields except the time, we recommend using E15.7 or 1PE15.6 floating-point format. For the time field, we recommend using E21.13 or 1PE21.12 format (but see the note on the next page).</p> <p>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.</p>

Note: We recommend higher precision for the time field so the server can tell that your time steps are all equal. (If the server thinks your time steps are not all equal, it will refuse to apply digital filters to your data.) If you use a “simple” time step value like 0.01 seconds or 0.005 seconds, then there is no need for higher precision, and you can write the time using the same precision as all the other data fields. When you upload a file, the server will warn you if it thinks your time steps are not all equal.

Here is an example of an on-fault time-series file. This is an invented file, not real modeling data.

```
# Example on-fault time-series file.
#
# This is the file header:
# problem=TPV36
# author=A.Modeler
# date=2024/07/23
# code=MyCode
# code_version=3.7
# element_size=50 m
# time_step=0.005
# num_time_steps=2400
# location= 8.0 km along strike, 6.0 km down-dip
# Column #1 = Time (s)
# Column #2 = horizontal slip (m)
# Column #3 = horizontal slip rate (m/s)
# Column #4 = horizontal shear stress (MPa)
# Column #5 = vertical slip (m)
# Column #6 = vertical slip rate (m/s)
# Column #7 = vertical shear stress (MPa)
# Column #8 = normal stress (MPa)
#
# The line below lists the names of the data fields:
t h-slip h-slip-rate h-shear-stress v-slip v-slip-rate v-shear-stress n-stress
#
# Here is the time-series data.
# There should be 8 numbers on each line, but this page is not wide enough
# to show 8 numbers on a line, so we only show the first five.
0.000000E+00 0.000000E+00 0.000000E+00 7.000000E+01 0.000000E+00 ...
5.000000E-03 0.000000E+00 0.000000E+00 7.104040E+01 0.000000E+00 ...
1.000000E-02 0.000000E+00 0.000000E+00 7.239080E+01 0.000000E+00 ...
1.500000E-02 0.000000E+00 0.000000E+00 7.349000E+01 0.000000E+00 ...
2.000000E-02 0.000000E+00 0.000000E+00 7.440870E+01 0.000000E+00 ...
2.500000E-02 0.000000E+00 0.000000E+00 7.598240E+01 0.000000E+00 ...
# ... and so on.
```

Part 6: Off-Fault Stations, and Time-Series File Format

The benchmarks use the 22 off-fault stations listed below. All stations are at the earth's surface.

A diagram of station locations appears after the table. You need to supply one time-series file for each station.

Off-Fault Stations for TPV36 and TPV37	
Station Name	Location
body-090st000dp000	-9.0 km off fault (near side), 0.0 km along strike, 0 km depth.
body-090st100dp000	-9.0 km off fault (near side), 10.0 km along strike, 0 km depth.
body-090st200dp000	-9.0 km off fault (near side), 20.0 km along strike, 0 km depth.
body-030st000dp000	-3.0 km off fault (near side), 0.0 km along strike, 0 km depth.
body-010st000dp000	-1.0 km off fault (near side), 0.0 km along strike, 0 km depth.
body-010st100dp000	-1.0 km off fault (near side), 10.0 km along strike, 0 km depth.
body010st000dp000	1.0 km off fault (far side), 0.0 km along strike, 0 km depth.
body010st010dp000	1.0 km off fault (far side), 10.0 km along strike, 0 km depth.
body030st000dp000	3.0 km off fault (far side), 0.0 km along strike, 0 km depth.
body090st000dp000	9.0 km off fault (far side), 0.0 km along strike, 0 km depth.
body090st100dp000	9.0 km off fault (far side), 10.0 km along strike, 0 km depth.
body090st200dp000	9.0 km off fault (far side), 20.0 km along strike, 0 km depth.
body150st000dp000	15.0 km off fault (far side), 0.0 km along strike, 0 km depth.
body210st000dp000	21.0 km off fault (far side), 0.0 km along strike, 0 km depth.
body270st000dp000	27.0 km off fault (far side), 0.0 km along strike, 0 km depth.
body270st100dp000	27.0 km off fault (far side), 10.0 km along strike, 0 km depth.
body270st200dp000	27.0 km off fault (far side), 20.0 km along strike, 0 km depth.
body330st000dp000	33.0 km off fault (far side), 0.0 km along strike, 0 km depth.

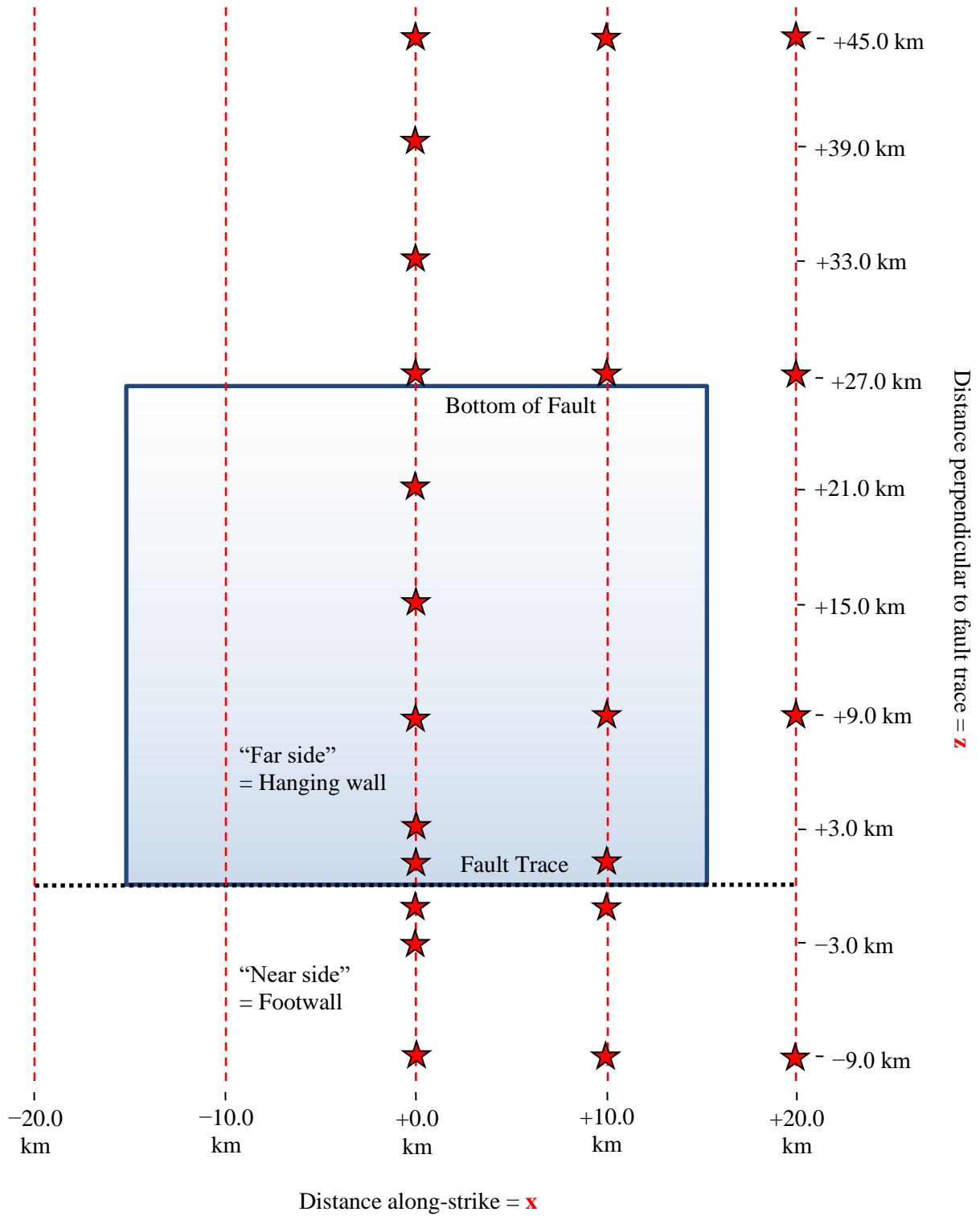
body390st000dp000	39.0 km off fault (far side), 0.0 km along strike, 0 km depth.
body450st000dp000	45.0 km off fault (far side), 0.0 km along strike, 0 km depth.
body450st100dp000	45.0 km off fault (far side), 10.0 km along strike, 0 km depth.
body450st200dp000	45.0 km off fault (far side), 20.0 km along strike, 0 km depth.

In the station names, the first number is the horizontal perpendicular distance from the station to the fault. A positive number means that the station is located on the **far side** of the fault.

If you do not have a node at the location of a station, there are two options: (1) you can move the station to the nearest node, or (2) you can interpolate the data values from nodes near the station location.

Note: Location along-strike is measured relative to the origin of the (x, y, z) coordinate system. Positive locations are to the right of the origin. Because these benchmarks are symmetric, all stations are at non-negative coordinates along-strike.

Off-Fault Station Locations



The diagram shows the Earth's surface, looking downwards in map view. The rectangle is the fault, projected vertically onto the Earth's surface.

There are 22 stations at the earth's surface, at the following (x, z) coordinates, in km:

(0.0 km, -9.0 km)	(0.0 km, 27.0 km)	(10.0 km, 27.0 km)
(0.0 km, -3.0 km)	(0.0 km, 33.0 km)	(10.0 km, 45.0 km)
(0.0 km, -1.0 km)	(0.0 km, 39.0 km)	(20.0 km, -9.0 km)
(0.0 km, 1.0 km)	(0.0 km, 45.0 km)	(20.0 km, 9.0 km)
(0.0 km, 3.0 km)	(10.0 km, -9.0 km)	(20.0 km, 27.0 km)
(0.0 km, 9.0 km)	(10.0 km, -1.0 km)	(20.0 km, 45.0 km)
(0.0 km, 15.0 km)	(10.0 km, 1.0 km)	
(0.0 km, 21.0 km)	(10.0 km, 9.0 km)	

The **near side** of the fault is in the front of the diagram (the $-z$ side of the fault). It is the footwall. The **far side** of the fault is in the back of the diagram (the $+z$ side of the fault). It is the hanging wall. **Positive** perpendicular distance from the fault means that the station is on the **far side**.

Note: In the diagram, the distance from the fault trace to the bottom of the fault appears to be less than 28 km because the fault is being viewed at an angle.

Each time series file is an ASCII file that contains 7 data fields, as follows.

Off-Fault Time Series Data Fields for TPV36 and TPV37	
Field Name	Description, Units, and Sign Convention
t	Time (s).
h-disp	Horizontal displacement, parallel to the fault strike (m). Sign convention: Positive means displacement to the right relative to the station's initial position (that is, in the $+x$ direction).
h-vel	Horizontal velocity, parallel to the fault strike (m/s). Sign convention: Positive means motion to the right (that is, in the $+x$ direction).
v-disp	Vertical displacement (m). Sign convention: Positive means displacement downward relative to the station's initial position (that is, in the $+y$ direction).
v-vel	Vertical velocity (m/s). Sign convention: Positive means motion downward (that is, in the $+y$ direction).
n-disp	Horizontal displacement, perpendicular to the fault strike (m). Sign convention: Positive means displacement away from the viewer, into the paper (away from near side of the fault and toward the far side of the fault) relative to the station's initial position. In other words, displacement in the $+z$ direction.
n-vel	Horizontal velocity, perpendicular to the fault strike (m/s). Sign convention: Positive means motion away from the viewer, into the paper (that is, away from near side of the fault and toward the far side of the fault). In other words, motion in the $+z$ direction.

The **near side** of the fault is in the front of the diagram (the $-z$ side of the fault).

The **far side** of the fault is in the back of the diagram (the $+z$ side of the fault).

The off-fault time series file consists of three sections, as follows.

Off-Fault Time Series File Format for TPV36 and TPV37	
File Section	Description
File Header	<p>A series of lines, each beginning with a # symbol, that identifies the file. The following information is recommended:</p> <ul style="list-style-type: none"> • Benchmark problem (TPV36 or TPV37) • Author • Date • Code • Code version • Node spacing or element size • Time step • Number of time steps in file • Station location • Descriptions of data columns (7 lines) • Anything else you think is relevant
Field List	<p>A single line, which lists the names of the 7 data fields, in column order, separated by spaces. It should be:</p> <pre>t h-disp h-vel v-disp v-vel n-disp n-vel</pre> <p>(all on one line). The server examines this line to check that your file contains the correct data fields.</p>
Time History	<p>A series of lines. Each line contains 7 numbers, which give the data values for a single time step. The lines must appear in order of increasing time.</p> <p>C/C++ users: For all data fields except the time, we recommend using 14.6E or 14.6e floating-point format. For the time field, we recommend using 20.12E or 20.12e format (but see the note on the next page).</p> <p>Fortran users: For all data fields except the time, we recommend using E15.7 or 1PE15.6 floating-point format. For the time field, we recommend using E21.13 or 1PE21.12 format (but see the note on the next page).</p> <p>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.</p>

Note: We recommend higher precision for the time field so the server can tell that your time steps are all equal. (If the server thinks your time steps are not all equal, it will refuse to apply digital filters to your data.) If you use a “simple” time step value like 0.01 seconds or 0.005 seconds, then there is no need for higher precision, and you can write the time using the same precision as all the other data fields. When you upload a file, the server will warn you if it thinks your time steps are not all equal.

Here is an example of an off-fault time-series file. This is an invented file, not real modeling data.

```
# Example off-fault time-series file.
#
# This is the file header:
# problem=TPV36
# author=A.Modeler
# date=2024/07/23
# code=MyCode
# code_version=3.7
# element_size=50 m
# time_step=0.005
# num_time_steps=2400
# location= 9.0 km off fault, 10.0 km along strike, 0.0 km depth
# Column #1 = Time (s)
# Column #2 = horizontal displacement (m)
# Column #3 = horizontal velocity (m/s)
# Column #4 = vertical displacement (m)
# Column #5 = vertical velocity (m/s)
# Column #6 = normal displacement (m)
# Column #7 = normal velocity (m/s)
#
# The line below lists the names of the data fields:
t h-disp h-vel v-disp v-vel n-disp n-vel
#
# Here is the time-series data.
# There should be 7 numbers on each line, but this page is not wide enough
# to show 7 numbers on a line, so we only show the first five.
0.000000E+00 0.000000E+00 0.000000E+00 0.000000E+00 0.000000E+00 ...
5.000000E-03 -2.077270E-85 -2.575055E-83 -2.922774E-86 -3.623018E-84 ...
1.000000E-02 -1.622118E-82 -2.005817E-80 -1.387778E-83 -1.713249E-81 ...
1.500000E-02 -9.020043E-80 -1.114231E-77 -4.402893E-81 -5.424313E-79 ...
2.000000E-02 -1.201684E-77 -1.467704E-75 -4.549845E-79 -5.533119E-77 ...
2.500000E-02 -1.528953E-75 -1.866265E-73 -4.126064E-77 -5.004886E-75 ...
# ... and so on.
```


Part 7: Contour-Plot File Format

There is one contour-plot file, as shown here:

Contour-plot file for TPV36 and TPV37	
File Name	Description
cplot	Rupture times for the fault.

The contour plot file lists the locations of all the nodes on the fault surface, and the time at which each node ruptures.

The contour plot file is an ASCII file that contains three data fields on each line, as follows.

Contour Plot Data Fields for TPV36 and TPV37	
Field Name	Description, Units, and Sign Convention
j	Distance along strike (m). Sign convention: Positive means a location to the right of the (x, y, z) origin. For TPV36 and TPV37, the value of j can range from -15000 to 15000 . (Note that j is equal to the x coordinate value.)
k	Distance down-dip (m), measured along the sloping fault surface. Sign convention: Zero is the earth's surface, and positive means underground . For TPV36 and TPV37, the value of k can range from 0 to 28000. (Note that k is equal to the y coordinate value divided by the sine of 15 degrees.)
t	Rupture time (s). This is the time at which fault slip-rate first changes from 0 to greater than 0.001 m/s. If this node never ruptures, use the value 1.0E+09.

A pair of numbers (j, k) denotes a point on the fault surface. It is equal to $(x, y/(\sin 15^\circ))$.

The contour plot file consists of three sections, as follows.

Contour Plot File Format for TPV36 and TPV37	
File Section	Description
File Header	<p>A series of lines, each beginning with a # symbol, that identifies the file. The following information is recommended:</p> <ul style="list-style-type: none"> • Benchmark problem (TPV36 or TPV37) • Author • Date • Code • Code version • Node spacing or element size • Descriptions of data columns (3 lines) • Anything else you think is relevant
Field List	<p>A single line, which lists the names of the 3 data fields, in column order, separated by spaces. It should be:</p> <p style="text-align: center;">j k t</p> <p>(all on one line). The server examines this line to check that your file contains the correct data fields.</p>
Rupture History	<p>A series of lines. Each line contains three numbers, which give the (j, k) coordinates of a node on the fault surface, and the time t at which that node ruptures.</p> <p>C/C++ users: We recommend using 14.6E or 14.6e floating-point format.</p> <p>Fortran users: We recommend using E15.7 or 1PE15.6 floating-point format.</p> <p>If a node never ruptures, the time should be given as 1.0E+09.</p> <p>Nodes may be listed in any order.</p>

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 contour-plot file. This is an invented file, not real modeling data.

```
# Example contour-plot file.
#
# This is the file header:
# problem=TPV36
# author=A.Modeler
# date=2024/07/23
# code=MyCode
# code_version=3.7
# element_size=50 m
# Column #1 = horizontal coordinate, distance along strike (m)
# Column #2 = vertical coordinate, distance down-dip (m)
# Column #3 = rupture time (s)
#
# The line below lists the names of the data fields.
# It indicates that the first column contains the horizontal
# coordinate (j), the second column contains the vertical
# coordinate (k), and the third column contains the time (t).
j k t
#
# Here is the rupture history
-6.000000E+02 7.000000E+03 3.100000E-02
-6.000000E+02 7.100000E+03 4.900000E-02
-6.000000E+02 7.200000E+03 6.700000E-02
-7.000000E+02 7.000000E+03 1.230000E-01
-7.000000E+02 7.100000E+03 1.350000E-01
-7.000000E+02 7.200000E+03 1.470000E-01
# ... and so on.
```

Part 8: Surface-Deformation File Format

There is one surface-deformation file, as shown here:

Surface-Deformation file for TPV36 and TPV37	
File Name	Description
surfdef	Final deformation at the Earth's surface at the end of the simulation.

The surface-deformation file lists the locations of nodes on the Earth's surface, and the final displacement of each node at the end of the simulation. It is recommended that the nodes span the portion of the Earth's surface defined by $-30000 \leq x \leq 30000$ and $-15000 \leq z \leq 53000$.

The surface-deformation file is an ASCII file that contains five data fields on each line, as follows.

Surface-Deformation Data Fields for TPV36 and TPV37	
Field Name	Description, Units, and Sign Convention
x	Distance along strike (m). This is equal to the x coordinate value. Sign convention: Positive means a location to the right of the (x, y, z) origin. For TPV36 and TPV37, the recommended range is $-30000 \leq x \leq 30000$.
z	Distance normal to the fault trace (m). This is equal to the z coordinate value. Sign convention: Positive means a location on the far side of the (x, y, z) origin. For TPV36 and TPV37, the recommended range is $-15000 \leq z \leq 53000$.
h-disp	Horizontal displacement, parallel to the fault strike, at the end of the simulation (m). Sign convention: Positive means displacement to the right relative to the node's initial position (that is, in the $+x$ direction).
v-disp	Vertical displacement, at the end of the simulation (m). Sign convention: Positive means displacement downward relative to the node's initial position (that is, in the $+y$ direction).
n-disp	Horizontal displacement, perpendicular to strike, at the end of the simulation (m). Sign convention: Positive means displacement away from the viewer, into the paper (away from near side of the fault and toward the far side of the fault) relative to the node's initial position. In other words, displacement in the $+z$ direction.

The surface-deformation file consists of three sections, as follows.

Surface-Deformation File Format for TPV36 and TPV37	
File Section	Description
File Header	<p>A series of lines, each beginning with a # symbol, that identifies the file. The following information is recommended:</p> <ul style="list-style-type: none"> • Benchmark problem (TPV36 or TPV37) • Author • Date • Code • Code version • Node spacing or element size • Descriptions of data columns (5 lines) • Anything else you think is relevant
Field List	<p>A single line, which lists the names of the 5 data fields, in column order, separated by spaces. It should be:</p> <pre style="margin-left: 40px;">x z h-disp v-disp n-disp</pre> <p>(all on one line). This line verifies that your file contains the correct data fields.</p>
Surface Deformation	<p>A series of lines. Each line contains five numbers, which gives the (x, z) coordinates of a node on the Earth's surface, and the displacement of the node in the x-direction, y-direction, and z-direction.</p> <p>C/C++ users: We recommend using 14.6E or 14.6e floating-point format.</p> <p>Fortran users: We recommend using E15.7 or 1PE15.6 floating-point format.</p> <p>Nodes may be listed in any order.</p>

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

Note: If a node lies exactly on the fault trace, there is an ambiguity in the displacement, because the displacement can be different on the two sides of the fault. You can choose how to resolve the ambiguity. Possible resolutions include: reporting the displacement on one side of the fault, either hanging wall or footwall; reporting the average of the two displacements; or omitting the node from the file.

Note: The website is not equipped for uploading the surface displacement file. Instructions for submitting the file will be sent separately.

Here is an example of a surface-deformation file. This is an invented file, not real modeling data.

```
# Example surface-deformation file.
#
# This is the file header:
# problem=TPV36
# author=A.Modeler
# date=2024/07/23
# code=MyCode
# code_version=3.7
# element_size=50 m
# Column #1 = horizontal coordinate, distance along strike (m)
# Column #2 = horizontal coordinate, distance normal to strike (m)
# Column #3 = horizontal displacement (m)
# Column #4 = vertical displacement (m)
# Column #5 = normal displacement (m)
#
# The line below lists the names of the data fields.
# It indicates that the first two columns contain the coordinates
# x and z, and the last three columns contain the displacement
# in the x, y, and z directions.
x z h-disp v-disp n-disp
#
# Here is the surface deformation
-3.200000E+03 -6.400000E+03 6.797617E-03 -2.903994E-02 3.074923E-01
-3.700000E+03 2.000000E+02 -1.081587E-01 -4.731012E-01 -1.241150E+00
7.800000E+03 -5.800000E+03 -1.336606E-02 -2.354464E-02 2.670004E-01
9.400000E+03 1.100000E+04 2.051477E-01 -6.435952E-01 -1.477435E+00
-1.100000E+03 6.800000E+03 -3.641479E-02 -9.962978E-01 -2.123343E+00
1.500000E+04 4.340000E+04 -1.063315E-01 -1.009014E-01 -4.282110E-01
-1.800000E+03 3.140000E+04 3.629308E-02 3.064986E-01 -1.018972E+00
# ... and so on.
```