ShakeOut Scenario Appendix A: Kinematic Rupture Model

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SoSAFE Kinematic Rupture Model

Brad Aagaard, Ken Hudnut, Lucy Jones

OVERVIEW

We constructed the rupture model in a 2-D planar coordinate system and mapped it onto the 3-D nonplanar geometry of the San Andreas fault as defined by the SCEC Community Fault Model version 3.0. The slip distribution combines a long length scale background distribution with short length scale random variations. The rake angles, while constant at a given location, vary in space. The rise time, peak slip rate, and rupture speed all vary with slip as described below. We use a wavefront propagation algorithm to propagate the slip initiation time from the hypocenter to the rest of the fault surface. The spatial resolution of the source model is currently 1.0 km.

Fault Geometry

We assemble the nonplanar geometry of the San Andreas fault from three surfaces in the SCEC Community Fault Model: cfma_san_andreas_coachella_alt2_complete, cfm_san_andreas_mojave_extruded_complete, and cfma_san_bernardino_san_andreas_complete. We translated the southern end of the Mojave section about 1 km west so that it lines up with the northern extent of the San Bernadino section. We import these surfaces into LaGriT (Los Alamos National Laboratory 2005), create a consistent orientation for the triangulate faces, merge the surfaces into a a simply connected surface, and refine/derefine the surfaces so that the nominal spatial resolution is 1.0 km, while limiting "damage" to the surface geometry to 0.1 km.

Slip Time Function

The kinematic rupture model uses the integral of Brune's far-field time function (Brune 1970),

$$D(t) = D_{final}(1 - e^{-t/t_0})(1 + \frac{t}{t_0}), \quad (1)$$

$$t_0 = \frac{D_{final}}{eV_{max}}, \quad (2)$$

$$V_{max}[m/s] = 1.5\sqrt{D_{final}[m]}, \quad (3)$$

where $D(t)$ is the slip as a function of time, D_{final} is the final slip at a point, and V_{max} is the peak slip rate.

The rise time (the time it takes for 95% of the slip to occur, t_{95}), which is given by

$$t_{95} = 1.745\frac{D_{final}}{V_{max}}, \text{ where} \quad (4)$$

$$D(t_{95}) = 0.95D_{final}, \quad (5)$$

is in the range of 1–2 seconds for slip in the range of 1–3 meters. Varying the peak slip rate with the square root of the final slip blends two common approaches for dealing with inadequate constraints on slip rise time and peak slip rate. The most common approach assumes a uniform rise time in a given event with the value based on an empirical relationship, such as the one developed by Somerville *et al.* (1999). In this approach peak slip rates are proportional to slip. A second approach assumes a uniform peak slip rate, which gives rise times within an event that are proportional to slip. Clearly, across a spectrum of event sizes, rise times should exhibit features present in both approaches.

Summary of Construction Workflow

The rupture model is constructed in a 2-D planar coordinate system and then mapped onto a 3-D nonplanar surface.

1. Construct source model in along-strike / down-dip coordinate frame (planar surface).
   (a) Construct slip distribution.

i. Set slip based on along-strike variation provided by background model.
ii. Add short length scale (currently 30 km) variations in slip using von Karman distribution (Mai and Beroza 2002). Parameters (Hurst exponent and correlation lengths) come directly from Mai and Beroza. Standard deviation in random slip distribution is 2.0, which results in a maximum slip about 3-4 times the average slip.
iii. Confine slip distribution to along-strike and down-dip extents of nonplanar geometry and apply linear tapers to bottom and northern edge. Taper distance along bottom edge if 5 km. Taper distance along northern edge if 10 km. Also taper southern edge (confined to 5 km along strike and 3 km down dip from surface).
iv. Scale slip to give Mw 7.8 event (assuming uniform shear modulus of 3.0e+10 Pa).
v. Randomize rake angles. Rake angles are normally distributed about -180.0 degrees (right-lateral motion) with a standard deviation of 10.0 degrees.

(b) Construct peak slip rate distribution.
i. $V_{max} = 1.2\sqrt{D[m]}$
ii. Apply linear taper to top and bottom of rupture area. Peak slip rate decreases by 50% over a distance of 5.0 km. This mimics longer rise times associated with ruptures encountering regions of stable sliding at the top and bottom of the seismogenic zone.
NOTE: This taper distance is different than the one for the rupture speed. We might want to make them the same for simplicity; decreasing the taper distance for peak slip rate to 3.0 km may lead to large ground velocities at close distances to the fault.

(c) Construct slip initiation time distribution.
i. Construct distribution of rupture speed.
A. Set background rupture speed to 85% Vs. Background is set to 3 km/s and then shaped according to Vs from SCEC CVM 4.0 (queried along 14 profiles with 1 km down-dip resolution).
B. Add local perturbations in rupture speed. Perturbations in rupture speed are linearly related to relative variations in slip. Maximum slip corresponds to a rupture speed of $\sqrt{2}$ Vs Vs; average slip corresponds to a rupture speed of 0.85 Vs; zero slip corresponds to a rupture speed of 0.2 Vs.
C. Apply linear taper to rupture speed at top and bottom of rupture area. Rupture speed decreases by 50% over a distance of 3.0 km.
ii. Set slip initiation times using iterative procedure that traces rupture front away from hypocenter assuming locally circular wavefronts. Similar to procedure outlined in Vidale (1988).

2. Massage CFM geometry into simply connected surface with spatially uniform nominal vertex spacing (currently 1 km)
(a) Aligned southern edge of Mojave section with northern end of San Bernadino section.
(b) Merged Coachella, San Bernadino, and Mojave sections.

3. Map source model in along-strike / down-dip coordinate frame to nonplanar surface.
(a) Compute along-strike and down-dip coordinates of each vertex in nonplanar geometry.
(b) Interpolate source model from planar geometry (along-strike / down-dip coordinate frame) using along-strike and down-dip coordinates of nonplanar geometry. Induces slight warping of source model but distortion is rather small.

SOURCE MODEL DATA FILES

The source model is distributed in via a VTK file (for easy visualization) and an HDF5 file (using a slight variation of the Reference Earthquake Digital Library Rupture Model format). Because many visualization packages (e.g., ParaView) can read VTK files, the VTK file provides the easiest way to visualize the source model. The HDF5 file provides the source model in a standard format that can be easy accessed via the HDF5 API for many different computer languages (C, C++, Fortran, Python).

Source Model VTK File

The source model is provided as a VTK legacy ASCII file (as opposed to the recently developed VTK XML files). The file contains both vertex and subfault based data for

- slip time (Time in seconds at which slip begins)
- slip_vector (Slip vector in meters in 3-D coordinate system associated with displacement on east side of fault)
- slip (Slip vector in meters in along-strike, up-dip, opening coordinate system)
- slip_rate (Peak slip rate in meters)
- rupture_speed (Rupture speed in meters/second)
- strike_dist (Distance along strike in meters from southeast end)
- dip_dist (Distance down dip in meters from top end)
- rise_time (Time in seconds for 95% of the slip to occur)

The file also contains the coordinates of the centroids of the subfaults. For both the vertices and coordinates of the subfault centroids, the horizontal coordinates are easting and northing in meters in the UTM Zone 11 projection using WGS84 as the horizontal datum, and the vertical coordinate is elevation in meters with respect to mean sea level.

Source Model HDF5 File

The HDF5 file conforms to the Reference Earthquake Digital Library Rupture Model format as closely as possible. The only significant departures involve specifying the analytical form for the slip time function via a string attribute, providing both vertex and subfault based rupture models in a single file, and including additional useful information.

The `h5dump` command (distributed with HDF5) provides a convenient way to examine the contents and hierarchy of an HDF5 file. Similarly, `h5ls` will list information about selected parts of an HDF5 file. For more information on how to use these programs, see the HDF5 documentation or run them with the `-h` flag. The recommended way to extract the data values from the HDF5 file is through the HDF5 API. The HDF5 file contains the topology information for the fault surface (coordinates of vertices and how the vertices are connected into triangular faces) and data specified at the vertices and at the center of the triangular faces (subfaults).

The topology information stores the coordinates of the vertices and how the vertices are connected to form fault segments (please see definitions below). The orientation at a location is defined by the local strike, dip, and rake angles. In general, these angles define the nominal slip direction. Rake rotations are handled by specifying slip rate time histories with three components (slip associated with the rake angle, slip in the direction perpendicular to the rake angle, and fault opening).

Glossary

Fault segment A simply connected surface making up part of a fault. Fault segments are composed of subfaults.

Subfault The smallest elements into which each fault segment is divided. These elements can be triangles or squares (as shown) or any other polygonal shape. The coordinates of the vertices define the geometry of the fault segment.

Vertex Each node point of a subfault (rectangular subfaults have 4 vertices and triangular subfaults have 3 vertices).

Vertex based rupture Rupture in which slip is defined at each vertex.

Subfault based rupture Rupture in which slip is defined on each subfault.

Conventions

- All arrays are 0 based, that is the index of the first entry is 0 (as opposed to 1).
- Vertex datasets are named ‘vertices’.
- Fault segment datasets are labeled with the name of the fault segment (e.g., ‘San Andreas’).

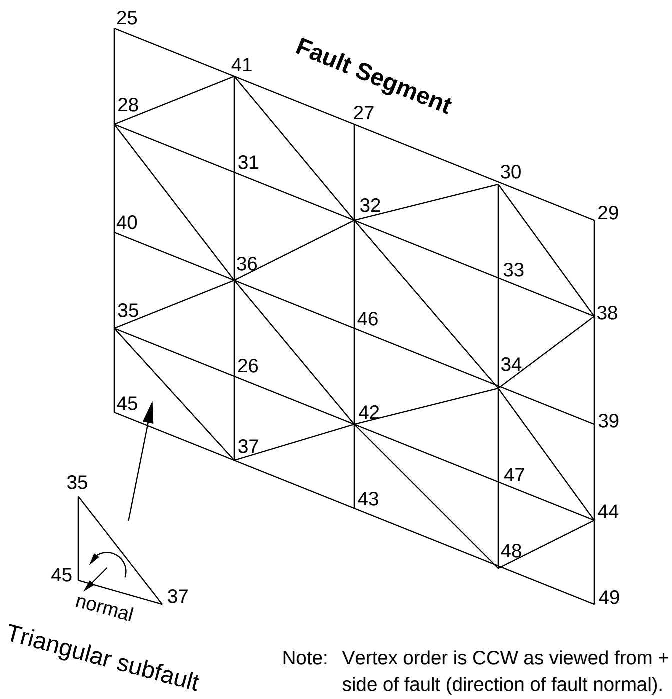

Figure 1: Fault segment divided into triangular subfaults. The vertices are numbered consecutively and the ordering for each subfault is counterclockwise as viewed from the positive side of the fault (direction to which fault normal points). Note that the direction of the ordering of vertices in each subfault must be consistent, but the vertices as a whole can be numbered in any order.

- The fault normal should be consistent across fault surfaces. The fault normal is defined by the cross product of the vector parallel to the rake direction and the vector perpendicular to the rake direction in the plane. The fault normal points from the footwall to the hanging wall (except when faults "roll over" and have dips greater than 90 degrees). This means that for a strike-slip fault, the rake-parallel slip is positive for left-lateral motion, the rake-perpendicular slip is positive for reverse motion, and the fault-opening displacement is positive for fault opening.

- Datasets may contain multidimensional arrays, but they are stored as one continuously indexed one-dimensional array. As a result, in multidimensional arrays it is important to know whether they are in column-major order or row-major order. In the specifications we explicitly show the order of the entries in multidimensional arrays to make the ordering clear.

Fault Orientation and Slip Vector

The orientation of the fault surface is defined by the strike and dip angles, ϕ and δ. The slip vector is defined by these two angles as well as the rake angle, λ. It is convenient to define axes rst as shown in figure 2 so that the r axis corresponds to the rake direction, the s axis corresponds to the in-plane rake-perpendicular direction, and the t axis points from the footwall to the hanging wall. The rake-perpendicular direction is chosen such that the rst axes are right-handed. The fault normal is points in a consistent direction with respect to the surface; with a consistent fault-normal direction, the dip angle will be greater than 90 degrees when the fault "rolls over". In general, this means that acceptable values for strike and dip range from 0 to 360 degrees.

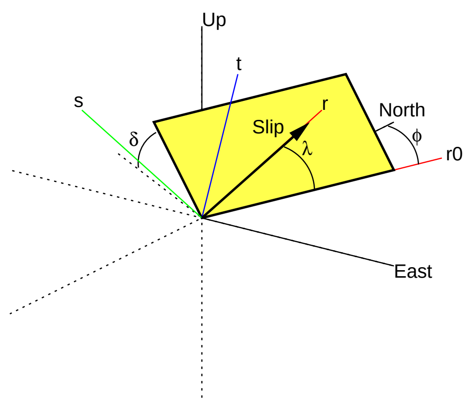

Figure 2: Fault orientation is defined by the strike and dip angles (ϕ and δ, respectively), and the slip vector is defined by the strike, dip, and rake angles (ϕ, δ, and λ, respectively).

This fault orientation convention leads to the convention that the slip components are positive for left-lateral, reverse, and fault opening dislocations. In this source model, we choose to set the rake angle to zero and let the three components of the slip define the rake angle. The rake angle is constant in time at each location but is not uniform over the fault surface

If we have a Cartesian coordinate system with $+x$ east, $+y$ north, and $+z$ up, then

$$\begin{pmatrix} r \\ s \\ t \end{pmatrix} = \begin{pmatrix} \sin\phi\cos\lambda - \cos\phi\cos\delta\sin\lambda & \cos\phi\cos\lambda + \sin\phi\cos\delta\sin\lambda & \sin\delta\sin\lambda \\ -\sin\phi\sin\lambda - \cos\phi\cos\delta\cos\lambda & -\cos\phi\sin\lambda + \sin\phi\cos\delta\cos\lambda & \sin\delta\cos\lambda \\ \cos\phi\sin\delta & -\sin\phi\sin\delta & \cos\delta \end{pmatrix} \begin{pmatrix} x \\ y \\ z \end{pmatrix}. \quad (6)$$

In many instances it is useful to be able to compute the strike, dip, and rake angles given the rst axes. First, we compute the vector $\vec{r_0} = (0,0,1) \times \vec{t}$, which is the r axis for a rake angle of zero. Using r_0, we can find the strike and dip angles using

$$\phi = \arctan\left(\frac{r_{0x}}{r_{0y}}\right) \text{ where } \phi = \begin{cases} \phi + 2\pi \text{ if } \phi < 0 \text{ and } r_{0y} > 0 \\ \phi + \pi \text{ if } \phi < 0 \text{ and } r_{0y} < 0 \\ \phi + \pi \text{ if } \phi > 0 \text{ and } r_{0y} < 0 \end{cases} \quad (7)$$

and

$$\delta = \arctan\left(\frac{\sqrt{t_x^2 + t_y^2}}{t_z}\right) \text{ where } \delta = \begin{cases} \delta + \pi \text{ if } \delta < 0 \text{ and } s_{0z} > 0 \\ \pi - \delta \text{ if } \delta < 0 \text{ and } s_{0z} < 0 \\ 2\pi - \delta \text{ if } \delta > 0 \text{ and } s_{0z} < 0 \end{cases} \text{ and } s_{0z} = t_x r_{0y} - t_y r_{0x}. \quad (8)$$

The rake angle is the angle between $\vec{r}$ and $\vec{r_0}$, so

$$\lambda = \arcsin(|\vec{r_0} \times \vec{r}|) \text{ where } \lambda = \pi - \lambda \text{ if } \vec{r_0} \cdot \vec{r} < 0. \quad (9)$$

Note that ϕ and δ need to be adjusted because $\arctan$ returns angles between $-\frac{\pi}{2}$ and $\frac{\pi}{2}$, and λ needs to be adjusted because the magnitude of the cross product will always be positive.

Hierarchy of HDF5 File

Each of the items in figure 3 is explained below using examples to indicate the contents of the groups and datasets.

root (/) The root group contains only one group- the *rupture_model* group.

rupture_model This is the main group for rupture model information and it contains three groups - *topology* (information defining the fault surface), *slip_summary* (information about the slip orientation and final slip), and *auxiliary* (auxiliary information that can be calculated from the other information).

The attribute for this group is *slip_type*, which specifies whether the model is vertex based or subfault based (permissible values = {‘vertices’, ‘subfaults’, ’both’}).

topology This group contains (1) a dataset with the coordinates of all vertices comprising the fault surfaces and (2) a group of *fault_segments*.

vertices This dataset stores the coordinates of the vertices in terms of longitude, latitude, and elevation. The array size is number of vertices × 3. This dataset might look something like:

Dataset: */rupture_model/topology/vertices*

	Lon (deg)	Lat (deg)	Elev (m)
Vertex 0	$^{(0)}$ -120.500	$^{(1)}$ 36.000	$^{(2)}$ 8.000
Vertex 1	$^{(3)}$ -120.195	$^{(4)}$ 36.015	$^{(5)}$ 7.990
⋮	⋮	⋮	⋮
Vertex N	$^{(3N)}$ -121.234	$^{(3N+1)}$ 35.836	$^{(3N+2)}$ 1.931

The attributes for this dataset are:

components Components of the coordinates (permissible value = {‘longitude, latitude, elevation’})

horizontal_datum Datum for longitude and latitude (permissible values = {‘WGS84’}),

horizontal_units Units for longitude and latitude (permissible values = {‘deg’}),

vertical_datum Datum for elevation (permissible values = {‘mean sea level’, ‘WGS84 ellipsoid’}),

geoid_model Geoid used to calculate mean sea level (useful if *vertical_datum* is ‘mean sea level’,

vertical_units Units for elevation {permissible values = ‘m’}).

fault_segments The *fault_segments* group is composed of a dataset for each simply connected fault surface (group size = number of fault segments). The datasets specify how the vertices are connected to form the geometric surface associated with the fault segment. The dataset array size is number of subfaults × number of subfault vertices. Each entry is the index of the vertex (first vertex has index 0). For example for ‘Fault Segment’ in figure 1, the number of subfaults is 25 and the number of vertices per subfault is 3. The ordering of vertices in each subfault *does* matter. The convention is that the order is counter-clockwise (CCW) as viewed from the side of the fault to which the normal points (generally the hanging wall). This is consistent with the convention that the CCW orientation defines the normal direction using the right hand rule. For example, the *Fault Segment* dataset would be:

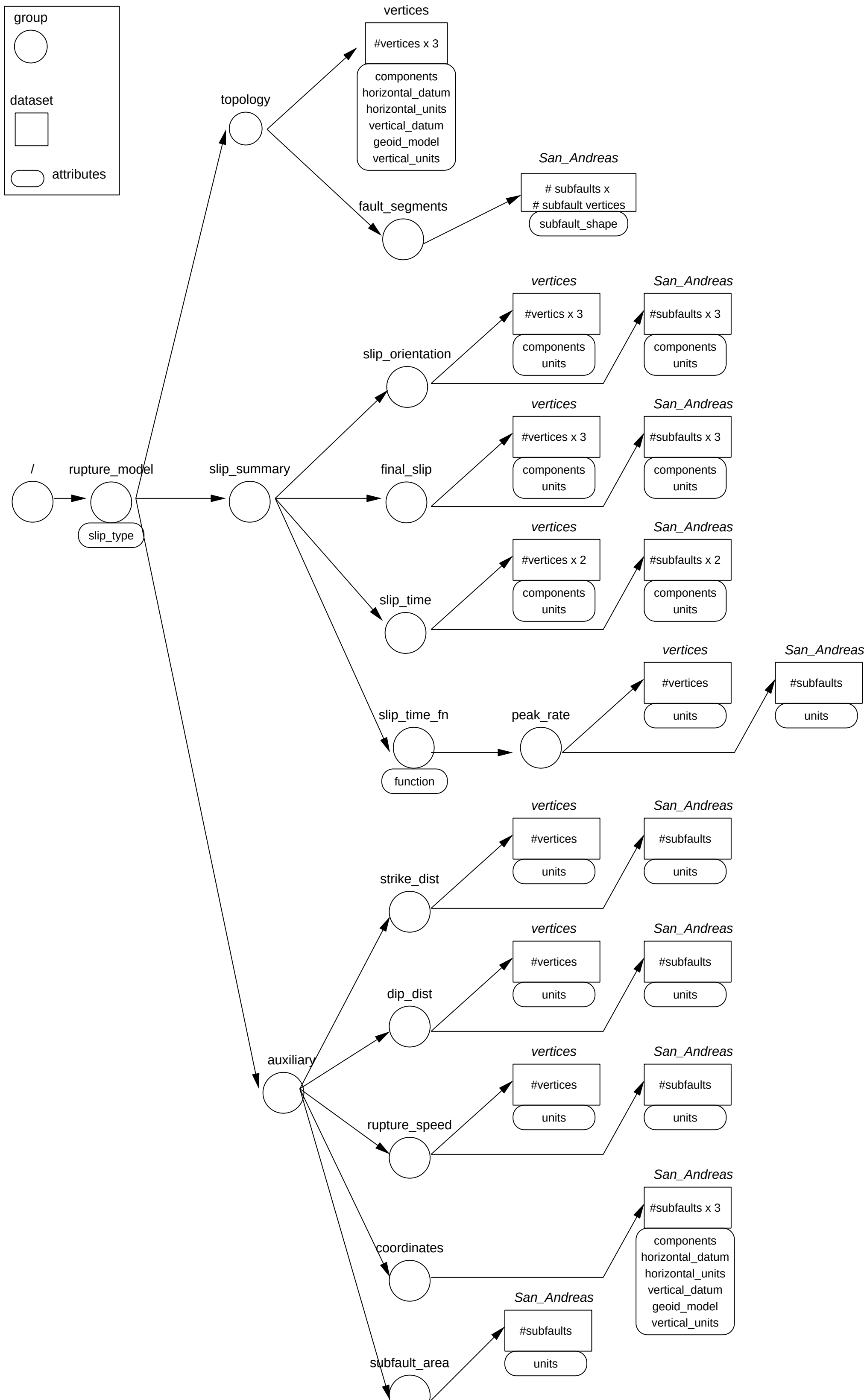

Figure 3: HDF5 hierarchy for rupture model.

Dataset: */rupture_model/topology/fault_segments/San_Andreas*

	index 0	index 1	index 2	index 3
Subfault 0	$^{(0)}$ 0	$^{(1)}$ 2	$^{(2)}$ 12	$^{(3)}$ 1
Subfault 1	$^{(4)}$ 1	$^{(5)}$ 12	$^{(6)}$ 7	$^{(7)}$ 5
Subfault 2	$^{(8)}$ 5	$^{(9)}$ 7	$^{(10)}$ 22	$^{(11)}$ 16
Subfault 3	$^{(12)}$ 16	$^{(13)}$ 22	$^{(14)}$ 9	$^{(15)}$ 10
Subfault 4	$^{(16)}$ 2	$^{(17)}$ 6	$^{(18)}$ 11	$^{(19)}$ 12
⋮	⋮	⋮	⋮	⋮

slip_summary This group summarizes the slip at each vertex. The *slip_summary* contains four groups: *slip_orientation*, *final_slip*, *slip_time*, and *slip_time_fn*. Each group contains both vertex based rupture model information in *vertices* datasets and subfault based rupture model information in *San_Andreas* datasets.

slip_orientation This group stores the orientation of the slip for each vertex using the local strike, dip, and rake angles. The slip orientation datasets are constant in time, so rake rotations are implemented by using 3 components for slip. Note that the fault normal must point in a consistent direction with respect to the fault surface, so strike, dip, and rake angles may each range between 0 and 360 degrees. The *vertices* dataset might be something like:

Dataset: */rupture_model/slip_summary/slip_orientation/vertices*

	Strike (deg)	Dip (deg)	Rake (deg)
Vertex 0	$^{(0)}$ 57.0	$^{(1)}$ 85.6	$^{(2)}$ 183.0
Vertex 1	$^{(3)}$ 57.1	$^{(4)}$ 85.8	$^{(5)}$ 175.1
⋮	⋮	⋮	⋮
Vertex N	$^{(3N)}$ 60.2	$^{(3N+1)}$ 75.3	$^{(3N+2)}$ 150.8

The attributes for these dataset are *components* to indicate the components in the dataset (permissible value = {‘strike, dip, rake’}) and *units* to indicate the units for the strike, dip, and rake angles (permissible values = ‘deg’).

final_slip This group stores the final slip in the rupture model. The final slip is given with 3 components: slip parallel to the rake direction, slip perpendicular to the rake direction, and fault opening. The *vertices* dataset might be something like:

Dataset: */rupture_model/slip_summary/final_slip/vertices*

	Rake $\|\|$ (m)	Rake $\perp$ (m)	Opening (m)
Vertex 0	$^{(0)}$ 0.24	$^{(1)}$ 0.03	$^{(2)}$ 0.0
Vertex 1	$^{(3)}$ 0.23	$^{(4)}$ 0.06	$^{(5)}$ 0.0
⋮	⋮	⋮	⋮
Vertex N	$^{(3N)}$ 0.35	$^{(3N+1)}$ -0.02	$^{(3N+2)}$ 0.0001

The attributes for these datasets are *components*, which specifies the components of the dataset (permissible value = {‘rake parallel, rake perpendicular, opening’}), and *units*, which specify the units for the slip (permissible values = ‘m’).

slip_time This dataset contains the time when slip begins and the time at which 95% of the final slip has accumulated relative to the origin time. If slip does not occur, then the slip begin and end times are set to 1.0e+6.

Dataset: */rupture_model/slip_summary/slip_time/vertices*

	Slip begin time (sec)	Slip end time (sec)
Vertex 0	$^{(0)}$ 0.44	$^{(1)}$ 1.27
Vertex 1	$^{(2)}$ 0.45	$^{(3)}$ 1.24
⋮	⋮	⋮
Vertex N	$^{(2N)}$ 8.35	$^{(2N+1)}$ 10.23

The attributes for these datasets are *components*, which indicate the components of the dataset (permissible value = {‘begin time, end time’}), and *units*, which indicate the units for the slip begin and end times (permissible values = ‘sec’).

slip_time_fn This dataset contains the information defining the slip time function. The analytical expression for the slip time function is given as the string attribute, *function*, for this group. This group contains the parameters for the slip time function, which is the peak slip rate for Brune's far-field time function.

peak_rate This group stores the peak slip rate as a scalar quantity. The *vertices* dataset might be something like:

Dataset: */rupture_model/slip_summary/slip_time_fn/peak_rate/vertices*

	Peak slip rate (m/s)
Vertex 0	$^{(0)}$ 1.67
Vertex 1	$^{(1)}$ 2.41
⋮	⋮
Vertex N	$^{(N)}$ 3.25

The attribute for these datasets is *units*, which indicate the units for peak slip rate (permissible value = {'m/s'}).

auxiliary This group contains auxiliary datasets. In most cases these values can be computed from the other values based on the fault geometry. The *auxiliary* group contains five groups: *strike_dist*, *dip_dist*, *rupture_speed*, *coordinates*, and *subfault_area*. The *strike_dist*, *dip_dist*, and *rupture_speed* groups contain both vertex based rupture model information in *vertices* datasets and subfault based rupture model information in *San_Andreas* datasets.

strike_dist This group stores the distance along strike of each vertex and subfault.

Dataset: */rupture_model/auxiliary/strike_dist/vertices*

	Dist. along strike (m)
Vertex 0	$^{(0)}$ 1004.4
Vertex 1	$^{(1)}$ 3646.4
⋮	⋮
Vertex N	$^{(N)}$ 54435.3

The attribute for these datasets is *units*, which indicate the units for distance (permissible value = {'m'}).

dip_dist This group stores the distance down dip of each vertex and subfault.

Dataset: */rupture_model/auxiliary/dip_dist/vertices*

	Dist. down dip (m)
Vertex 0	$^{(0)}$ 1456.2
Vertex 1	$^{(1)}$ 5645.4
⋮	⋮
Vertex N	$^{(N)}$ 8582.3

The attribute for these datasets is *units*, which indicate the units for distance (permissible value = {'m'}).

rupture_speed This group stores the rupture speed at each vertex and subfault.

Dataset: */rupture_model/auxiliary/rupture_speed/vertices*

	Peak slip rate (m/s)
Vertex 0	$^{(0)}$ 2890.2
Vertex 1	$^{(1)}$ 4323.4
⋮	⋮
Vertex N	$^{(N)}$ 2708.3

The attribute for these datasets is *units*, which indicate the units for peak slip rate (permissible value = {'m/s'}).

coordinates This group stores the coordinates of the centroid of each subfault.

Dataset: */rupture_model/auxiliary/coordinates/San_Andreas*

	Lon. (deg)	Lat. (deg)	Elev. (m)
Subfault 0	$^{(0)}$ -115.224	$^{(1)}$ -115.435	$^{(2)}$ -116.234
Subfault 1	$^{(3)}$ 34.842	$^{(4)}$ 35.235	$^{(5)}$ 36.554
⋮	⋮	⋮	⋮
Subfault N	$^{(3N)}$ -23458.3	$^{(3N+1)}$ -1235.3	$^{(3N+2)}$ -5238.3

The attributes are the same as those of the *vertices* dataset in the *topology* group.

subfault_area This group stores the area of each subfault.

Dataset: */rupture_model/auxiliary/subfault_area/San_Andreas*

	Area (m^2)
Subfault 0	$^{(0)}$ 34423.2
Subfault 1	$^{(1)}$ 23141.4
⋮	⋮
Subfault N	$^{(N)}$ 42342.3

The attribute for this dataset is *units*, which indicates the units for area (permissible value = {'m^2'}).

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