Generic Earthquake Simulator

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INTRODUCTION

Many of the papers in this topical issue concern earthquake simulators and their results. The goals and history of the project leading to this work are described in the preface to this topical issue. Earthquake simulators are computer programs that use physics of stress transfer and frictional resistance to describe earthquake sequences. Some are capable of generating long earthquake histories on many faults. They necessarily adopt a variety of simplifications to make computation feasible. The amount of detail computed within individual earthquakes depends on the simulator. None of those capable of generating long histories includes elastodynamics, but some make approximations of it. Nevertheless, seismic waves are not computed in any of the many-fault simulators focused on here. The faults are typically approximated by many rectangular elements, although the future use of triangles would allow more accurate representation of curved fault surfaces.

This paper briefly describes the features that are common to all of the earthquake simulators discussed in this topical issue of *SRL*. Following it are four papers (Pollitz, 2012; Richards-Dinger and Dieterich, 2012; Sachs *et al.*, 2012; Ward, 2012) authored by each of the groups, which present features of their simulator that go beyond this generic description. Results from using these simulators are not presented in those papers but are contained within a subsequent paper (Tullis *et al.*, 2012) that compares the results of using these five simulators on an all-California fault model, allcal2. A detailed description of this fault model can be found at http://scec.usc.edu/research/eqsims/, and the formats used for input and output by our group are described by Barall (2012).

EARTHQUAKE SIMULATOR INPUTS

Fault Geometry and Slip Rates

UCERF (Field *et al.*, 2008) calls the combination of fault geometry and slip rates a deformation model, and these are the relatively well-known inputs to an earthquake simulator. Our current version of an all-California deformation model, allcal2 (excluding Cascadia), is nearly the same as UCERF2 (Field *et al.*, 2008). In this volume, it is this deformation model that is used for the results (Tullis *et al.*, 2012). In the future, we plan to use other versions of California fault models, such as the UCERF3 deformation model.

Bulk Rheology

For most of the simulators in this volume, the medium in which the fault system is embedded is represented by a homogeneous linear elastic half-space. However, one simulator (Pollitz, 2012), ViscoSim, can include both viscoelastic behavior and layered elasticity.

Stresses

Absolute levels of stress are generally not needed by these simulations, although ViscoSim (Pollitz, 2012) needs absolute levels to have realistic flow rates in the viscoelastic regions. The sources of the stresses on each fault element at any time can be divided into two different classes that are handled fundamentally differently by the simulators: (1) slip on the explicitly modeled fault elements (including the element itself) and (2) all sources external to the fault model. The former are calculated by some appropriate boundary element method (e.g., Chinnery, 1963 or Okada, 1992). Sources of stress included in the latter class include far-field tectonic motions, possible viscoelastic flow in the lower crust and mantle (for simulators other than ViscoSim, which includes this source explicitly), and earthquakes that occur off of the explicitly modeled fault system. Even in the absence of any detailed knowledge of these external sources, simply enforcing that the stresses on the fault elements not diverge to infinity at long times and that the fault patches all slip on average at their prescribed long-term rates implies that the long-term averages of these external stressing rates must simply be equal to those that would result from slipping each fault element steadily at the negative of its prescribed long-term rate (Savage, 1983). Another way to think about backslip loading is that the stresses due to imposing backward slip on all the faults at their long-term rate eventually become large enough to make them slip forward, typically by earthquakes, to relax the stress. Thus, the simulators use the constant stressing rates that result from such a backslip calculation to represent the external sources of stress. Although the time averages of the external stressing rates will be correct with this method, it will miss possible time variations.

Fault Friction

The various simulators use different constitutive descriptions for fault friction. In Earth, the frictional strengths of faults presumably vary from point to point, but we have insufficient knowledge of their actual values and spatial variations. Laboratory friction measurements provide some idea of possible *in situ* friction values as a function of rock type and temperature, but our knowledge of the actual rock types along faults is woefully inadequate for applying friction values to each point on a fault. Most of the earthquake simulators assume some difference between static and dynamic friction, and in some cases, these may vary with slip or slip velocity. One simulator (Richards-Dinger and Dieterich, 2012) uses rate and state friction. Although there is a tendency to refer to the highest stress level reached in an earthquake cycle in the simulations as the fault strength, all that is really modeled are changes in strength, namely, strength drops. Depending on the friction law used, the actual stress drop during an event could be somewhat smaller than the strength drop. Ideally we would know the appropriate variation in strength drop to use from one fault section to another, but we have insufficient information to determine this well. Typically in this work, for most faults, we use relations such as area–magnitude scaling to estimate the stress drop associated with earthquakes of a typical size for each fault section and then set the strength drop equal to that. In the case of the simulator that does not specify a strength drop but uses rate- and state-dependent friction (Richards-Dinger and Dieterich, 2012), the stress drop is proportional to the product of the normal stress σ_n and the difference of the state and rate coefficients, a and b, that is, to $\sigma_n \times (b - a)$, and weakly (logarithmically) dependent on the recurrence time; thus, some experimentation with varying σ_n and/or $b - a$ is required to produce a given average stress drop. In some places where paleoseismic data provide recurrence intervals, we tune the strength drops to match those data. Thus, for example, by trial and error, each simulator increases or decreases the assigned strength drop to lengthen or shorten, respectively, the simulated recurrence intervals to match those determined paleoseismically. Because different simulators assume different frictional behavior and treat rupture weakening differently, each simulator must do this tuning separately, although the tuning for each begins from a common assumed starting strength-drop distribution.

EARTHQUAKE SIMULATOR OUTPUTS

The output of an earthquake simulator may be quite varied and can include any desired statistical or other measure of what occurred as a function of time and space during a long history of simulated events. We have created a variety of tools to create standard output plots so that all the simulators can be compared via identical processing. Some such plots are shown by Tullis *et al.* (2012), but many more have been created and still more could be generated in the future.

The tools themselves are written in the R language (e.g., R Development Core Team, 2012). They currently consist of several utility functions bundled together as an R package and 23 actual tools. Each tool is a stand-alone executable that can be called from the command line (via the Rscript mechanism), which reads in a simulator output file in the standard format (Barall, 2012), possibly reads in other files (e.g., a fault geometry file), performs some sort of analysis, and either generates a plot or writes an output file with the results of this analysis. Input filenames, output filenames, and parameters controlling the analysis are all specified via command-line arguments. As the simulator output files are ascii encoded, the initial parsing of these ascii files can dominate the run time of some of the tools. Thus, a parsed, binary version of the files can optionally be saved for faster loading by subsequent tools. Several examples of the kinds of plots produced by the tools are shown by Tullis *et al.* (2012) and include frequency–magnitude distributions, various scaling plots (e.g., magnitude vs. area), and recurrence time probability density functions.

In addition to being called individually, the tools can also be called jointly via a wrapper program called runtools. The behavior of runtools is controlled by a configuration file. In this file, sets of tool runs appropriate for various problem setups are defined so that an entire set of plots and output files can be produced for a given simulator output with a single command. In addition, runtools move a copy of the simulator output files (both the original standard ascii file and the parsed binary file) to an archive directory and place the output files in a directory accessible on the web.

DIFFERENCES BETWEEN SIMULATORS

Table 1 lists many of the differences between the simulators. A description of the meaning of the features listed in column 1 of the table follows.

The first three rows refer to different aspects of how friction is treated by each simulator, this being the biggest difference between many of them. Rate and state friction (Dieterich, 1972, 1978, 1979, 1981; Ruina, 1983; Dieterich and Conrad, 1984; Tullis, 1986, 1988, 1996; Dieterich and Kilgore, 1994; Marone, 1998) is used by only one simulator. Among other features, it incorporates both a velocity and a displacement dependence to friction, but velocity dependence and displacement dependence can also be incorporated in simpler ways, as is done by some of our other simulators. Radiation damping (Rice, 1993) introduces a resistance to rapid slip and represents the inertial forces that retard rapid acceleration. Thus, although it does not involve seismic radiation, it realistically prevents slip speeds from becoming unbounded. Rupture weakening is a feature that promotes the propagation of ruptures by making it easier for fault elements to slip when neighboring elements slip. It is intended to create effects on rupture propagation that are similar to

Table 1
Features of Each Earthquake Simulator Included in this Topical Issue of *SRL* See Text for Description of the Features

	ALLCAL	VIRTCAL	RSQSim	ViscoSim
Rate-state friction			Yes	
Velocity-dependent friction	Yes		Yes	
Displacement-dependent friction	Yes	Yes	Yes	Yes
Radiation damping			Yes	
Rupture weakening		Yes	Yes	
Details during event	Yes		Yes	
Stress propagation delay	Yes			
Viscoelastic stress transfer				Yes
Layered elasticity				Yes

what would occur in fully elastodynamic treatments in which dynamic stress concentrations occur at the tip of propagating ruptures. Details of what occurs during an event, for example, the progression of the amount of slip during the event on each fault element that eventually slips, are resolved by some simulators and not by others. The temporal delay of slip along a rupture that would occur due to finite-wave velocities is included in only one of the simulators. Viscoelastic transfer of stress due to flow in deeper layers is only treated by one simulator. Including layers with differing elastic properties, instead of assuming only an elastic half-space, is only done for one simulator. It is notable that none of the simulators contain all of the features listed in Table 1, in part a result of the computational difficulties of including them all. Nevertheless, the fact that the simulators all do a reasonable job of matching the statistical behavior of observed seismicity (Tullis *et al.* , 2012) suggests that for many purposes, including all of the known physics about earthquakes may not be necessary, especially when enough observational data exist to tune unknown parameters such as the spatial variations in strength drops.

It should be noted that other more detailed earthquake simulators exist that presently are not suited for generating long histories of earthquakes on a specified geographic collection of many faults, but that make fewer approximations than do those simulators used in the comparisons in this topical issue of *SRL*. For example, three other simulators have been used to make comparisons of earthquake simulator results for simpler single fault problems in which it is possible to make more detailed comparison of what occurs (Richards-Dinger *et al.*, 2008; Tullis *et al.*, 2009). Notable among these other simulators is the one by Nadia Lapusta that uses an FFT approach and includes both full elastodynamics and rate and state friction (Lapusta *et al.*, 2000; Lapusta and Rice, 2003). Others include the one by Bruce Shaw that includes full elastodynamics in 2D (Shaw, 2003) and 3D (Shaw and Wesnousky, 2008) and PARK that uses rate and state friction, both in an early version (Stuart and Tullis, 1995; Tullis, 1996) and in a more recent one that uses radiation damping as well as a fast multipole method to increase computation efficiency (Tullis *et al.*, 1999; Tullis, 2003; Tullis and Beeler, 2008).

SUMMARY

All of the simulators discussed in this topical issue of *SRL* use much of what is known about the physics of earthquakes and about the California fault geometry and slip rates, although true elastodynamics is not used, and off-fault seismicity is not currently included. More information is desirable about the faults than is known, especially how the stress drops associated with earthquakes vary from fault section to fault section. Consequently, estimates are made for stress drops in those places where information is lacking, and the constraint on them provided by paleoseismic recurrence interval data is used at locations where that is available. Each simulator makes a variety of simplifications to allow calculation of long earthquake histories on many faults. Representation of fault friction and whether or how to deal with approximations to elastodynamic behavior are among the differences between the simulators. The diversity of simulator assumptions and methods provides some idea of the influence that different assumptions have on the results, as is discussed by Tullis *et al.* (2012).

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