Development of a broadband 3D pseudo-dynamic rupture generator for geometrically complex faults

Report for SCEC Award #15119
Submitted March 17, 2016

Investigators: Kim Olsen (SDSU)

I. Project Overview

A. Abstract

In the box below, describe the project objectives, methodology, and results obtained and their significance. If this work is a continuation of a multi-year SCEC-funded project, please include major research findings for all previous years in the abstract. (Maximum 250 words.)

We have used the Support Operator code to simulate ensembles of dynamic rupture models. We have used rough-fault parameters tuned by Shi and Day (2013), as well as elasto-plastic yielding. The simulations are carried out in simple 3-D velocity (halfspace or layered) models, using a grid spacing of 25 m to accurately resolve the break-down zone and wave propagation frequencies up to 10 Hz. We use slip-weakening and rate-and-state friction laws with depth dependent stresses. The dynamic rupture is inserted as a kinematic rupture in AWP-ODC, which allows us to include frequency-dependent anelastic attenuation and small-scale heterogeneities into the ground motion estimates. We compare the ground motion intensities to those from GMPEs, as well as matching the surface slip to the expected values from studies. We find residuals of slip (Δu), peak slip velocity (V_{peak}) and rupture velocity (V_{rup}) to be positively correlated with the initial friction (μ_0) implying that regions with higher stress-drop ($\Delta\tau$) produce larger Δu, V_{peak}, and V_{rup}, and vice versa. We also find that maximum correlation for V_{rup} occurs at a lag distance of ~100 m. This implies that changes in V_{rup} occur (shortly) after the rupture front has encountered changes in μ_0, whereas changes in Δu and V_{peak} occur instantaneously. We are on track to complete the rupture generator by the end of SCEC4.

B. SCEC Annual Science Highlights

Each year, the Science Planning Committee reviews and summarizes SCEC research accomplishments, and presents the results to the SCEC community and funding agencies. Rank (in order of preference) the sections in which you would like your project results to appear. Choose up to 3 working groups from below and re-order them according to your preference ranking.

1) Ground Motion Prediction (GMP)
2) Community Modeling Environment (CME)
3) Ground Motion Simulation Validation (GMSV)

C. Exemplary Figure

Select one figure from your project report that best exemplifies the significance of the results. The figure may be used in the SCEC Annual Science Highlights and chosen for the cover of the Annual Meeting Proceedings Volume. In the box below, enter the figure number from the project report, figure caption and figure credits.

Figure 4. (top) Cross-correlation coefficient between initial friction μ_0 and the peak sliprate (V_{peak}) residuals computed by removing a depth-dependent mean value for a model with rate-and-state friction law. (bottom) histogram of V_{peak} residual values for dynamic rupture simulation using rate-and-state friction and rough fault model. Credit: W.H.Savran.

D. SCEC Science Priorities

In the box below, please list (in rank order) the SCEC priorities this project has achieved. See *https://www.scec.org/research/priorities* for list of SCEC research priorities. *For example: 6a, 6b, 6c*

6e, 6b, 6c

E. Intellectual Merit

How does the project contribute to the overall intellectual merit of SCEC? *For example: How does the research contribute to advancing knowledge and understanding in the field and, more specifically, SCEC research objectives? To what extent has the activity developed creative and original concepts?*

SCEC aims to advance seismic hazard analysis to higher frequencies which requires transparent and efficient methods to generate kinematic source functions. Most current kinematic rupture generators have not been tested at the higher frequencies. The proposed rupture generator here includes the energy at the higher frequencies from data-constrained geometrical roughness of the fault, Q(f) and small-scale heterogeneities in the surrounding media.

F. Broader Impacts

How does the project contribute to the broader impacts of SCEC as a whole? *For example: How well has the activity promoted or supported teaching, training, and learning at your institution or across SCEC? If your project included a SCEC intern, what was his/her contribution? How has your project broadened the participation of underrepresented groups? To what extent has the project enhanced the infrastructure for research and education (e.g., facilities, instrumentation, networks, and partnerships)? What are some possible benefits of the activity to society?*

Immediate applications of the proposed kinematic rupture generator includes the SDSU Broadband Platform (BBP) method (currently sharing the Graves and Pitarka rupture generator), CyberShake and UCERF3. The project includes training of William Savran and support for his doctoral in the Joint Doctoral Program between SDSU and UCSD.

G. Project Publications

All publications and presentations of the work funded must be entered in the SCEC Publications database. Log in at http://www.scec.org/user/login and select the Publications button to enter the SCEC Pubications System. Please either (a) update a publication record you previously submitted or (b) add new publication record(s) as needed. If you have any problems, please email *web@scec.org* for assistance

2015 SCEC Annual Report

Development of a broadband 3D pseudo-dynamic rupture generator for geometrically complex faults

Report for SCEC Award 15119

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Publications and Reports:

Savran, W.H., and K.B. Olsen (2015). Toward a 3D kinematic rupture generator based on rough fault spontaneous rupture models, SCEC Annual Mtg, Palm Springs, Sept. 2015, Poster #011.

Savran, W.H., and K.B. Olsen (2016). Extracting the statistics of 3D rough fault dynamic rupture simulations for pseudo-dynamic source generation, Annual Mtg. of the Seismological Society of America, Reno, NV, Poster presentation on April 21, poster #84.

Introduction

We proposed to extend the 2D method by Trugman and Dunham (2014) who used the statistics emerging from ensembles of 2D plane strain dynamic rupture simulations on geometrically complex ('rough') faults to develop a 3D SCEC pseudo-dynamic Community Rupture Generator for broadband (0-10 Hz+) simulations. Trugman and Dunham found that the ground motions generated by their rupture generator displayed characteristic features (e.g., peak motion, spectral amplitude) similar to those from the underlying dynamic rupture simulations and to those from strong motion records (e.g., flat acceleration spectra at higher frequencies). Immediate applications of such method includes the SDSU Broadband Platform (BBP) method (currently sharing the Graves and Pitarka (2010, 2015) rupture generator), but other modules on the platform as well as CyberShake and UCERF3 will also be able to take advantage of the broadband rupture generator under development.

The proposed first year's effort was primarily to use a support operator code (SORD) to simulate a suite of 3D dynamic ruptures with fractal rough-fault geometry up to 10 Hz+ for events with magnitudes up to ~M7.2, and to start a search for parameter correlations, analyze source-time functions and fit them to an analytic expression usable by the rupture generator. We have made good progress on the proposed work, with preliminary work shown off at the 2015 SCEC annual meeting, and a summary in this report. A second year of funding has been awarded by SCEC, where we plan to generate, implement and validate a pseudo-dynamic model with the statistics learned from the dynamic rupture ensembles, which produces sources and ground motion distributions consistent with fully dynamic rough fault simulations.

Completed Work

Over the past year we have used the Support Operator code (SORD, Ely et al. 2009; extended by Shi and Day (2013) for rough-fault simulation capabilities) to simulate ensembles of dynamic rupture models. We have used rough-fault parameters tuned by Shi and Day (2013), e.g., Hurst number=1, amplitude-to-wavelength ratio α ~0.005 but with tests for a range of α values, as well as elasto-plastic yielding to limit stress concentrations in fault bends in the dynamic rupture. The simulations are carried out in simple 3-D velocity (halfspace or layered) models, using a grid spacing of 25 m to accurately resolve the break-down zone and wave propagation frequencies up to 10 Hz. Model discretizations amount to 5-20 billion grid points depending on the magnitude (currently up to ~M7.2, but larger magnitudes will be considered in the future) which require 1-5 wall clock hours per simulation using 5000-20000 processors for up to 45s of rupture propagation. The code shows strong scaling on supercomputers where SCEC has large allocations available on platforms such as Titan (ORNL) and Blue Waters (NCSA). We estimate a total need for 5-10 million service units on these platforms to complete the databases of dynamic rupture simulations, covered by current and planed requests for allocations.

Figure 1 (left) shows one of the rough-fault geometries used to build the database for the rupture generator, for a 60 km long by 20 km deep fault (slip primarily constrained to $\leq$ 16 km). We use slip-weakening and rate-and-state friction laws with depth dependent stresses, with representative parameters listed in Table 1. Velocity strengthening friction is emulated in the top part of the model to ensure that ground motions are realistic. The dynamic rupture is inserted as a kinematic rupture into the scalable finite-difference code AWP-ODC, which allows us to include frequency-dependent anelastic attenuation (Withers et al., 2016) and small-scale heterogeneities into the ground motion estimates (Savran and Olsen, 2016). We compare the ground motion intensities to those from GMPEs to make sure they are realistic (see Figure 2, left), as well as matching the surface slip to the expected values from studies, such as Wells and Coppersmith (1994) and Leonard (2010). An example from the rupture ensemble is shown in Fig. 3.

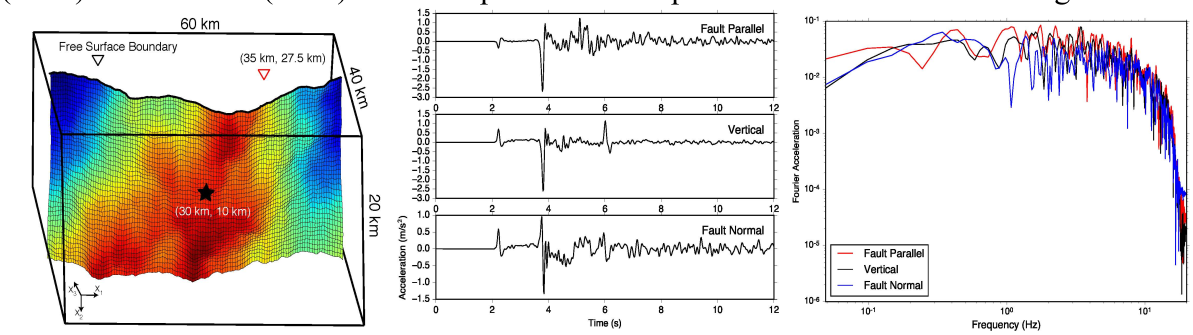

Figure 1. (left) One realization of rough fault geometry for a 60 km x 20 km fault, generating events with magnitudes up to about 7.2. 0-10Hz (center) accelerograms and (right) Fourier spectra at the station depicted by the red triangle on the left.

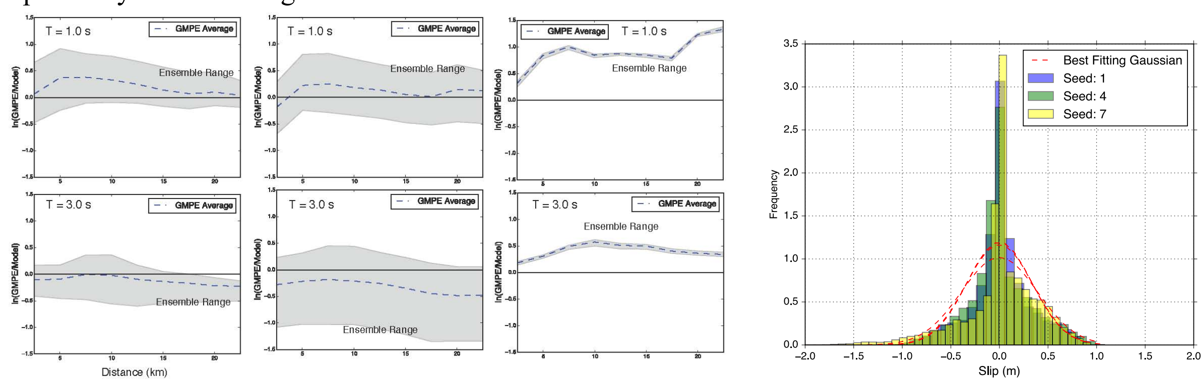

Figure 2. (left) Bias of SA-1s and SA-3s for a 5-realization rough-fault rupture ensemble relative to the range of leading GMPEs for roughness values (α) of (left) 0.0125, (middle) 0.005, and (right) 0.0005. Clearly, the comparisons are very sensitive to the roughness of the fault, with the largest bias obtained for the smoothest faults (underpredicted). (right) Preliminary 1-point statistics for slip with depth-dependent mean removed, for 3 rough-fault realizations.

We have started the analysis of the rupture simulation ensemble, which will be the basis for assembling the kinematic rupture generator (Fig. 2, right). A critical point is to understand how the spatial fields associated with the kinematic parameters, namely residuals of slip (Δu), peak slip velocity (V_{peak}) (see Fig. 4), and rupture velocity (V_{rup}) correlate to the fault roughness. We find all three kinematic parameters to be positively correlated with the initial friction (μ_0) implying that regions with higher stress-drop ($\Delta\tau$) produce larger Δu, V_{peak}, and V_{rup}, and vice versa. We also find that maximum correlation for V_{rup} occurs at a lag distance of ~100 m. This implies that changes in V_{rup} occur after the rupture front has encountered changes in μ_0, whereas changes in Δu and V_{peak} occur instantaneously. We will use these computed correlation coefficients to describe the correlation between the rough fault profile and the kinematic rupture fields. Also shown in Fig. 4 is a histogram of the V_{peak} residual values, where we find the residual values to be approximately normally distributed.

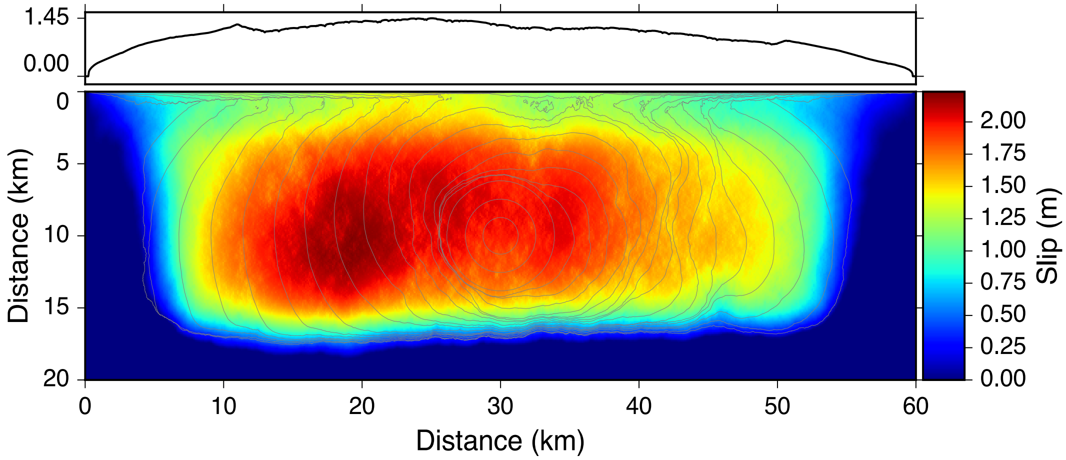

Figure 3. Example from the ~M7.2 rough-fault ensemble. Colors depict the final slip distribution and the contours show the rupture initiation times. The top graph shows the surface slip, which is compared to expected values for strike-slip earthquakes from Wells and Coppersmith (1994) and Leonard (2010).

Parameter		Value
Material Properties		
Compressional Wave Velocity	Vp	6000 m/s
Shear Wave Velocity	Vs	3464 m/s
Density	ρ	2700 g/cm^3
Cohesion	c	5 MPa
Internal Friction Coefficient	$\tan(\phi)$	0.75
Frictional Properties		
Direct-effect parameter	a	0.01 (Depth-dependent)
Evolution-effect parameter	b	0.014
Reference slip rate	V_0	1 μm/s
Steady-State coefficient at V_0	f_0	0.7
Evolution distance	L	0.2 m
Fully-weakened friction coefficient	f_w	0.2
Evolution distance of traction θ_{pc}	L_{pc}	0.2 m
Initial fault slip rate	V^{ini}	6 x 10^{-11} m/s
Inital Stresses		
Normal Stress	σ_0	$\sigma_0 = -(\rho_b - \rho_f) g\, x_2$
Shear Stress	τ_0	$\tau_0 = \lvert\sigma_0\rvert/3$
Fault Roughness		
Fault Roughness	α	(0.001, 0.01, 0.025)
Minimum wavelength	λ_{min}	200 m
Model Properties		
Spatial Discretization	dx	25 m
Time Discretization	dt	0.002 s
Simulation Time	nt	12.0 s
Model Size	nx_1, nx_2, nx_3	2401, 801, 1601

Table 1. Parameters used to generate the preliminary rough-fault rupture model database.

We have also started examining the shape of the sliprate functions obtained from the dynamic rupture simulation ensemble. This information will be used to provide guidelines for the kinematic rupture generator to calculate the generic shape of the rupture functions.

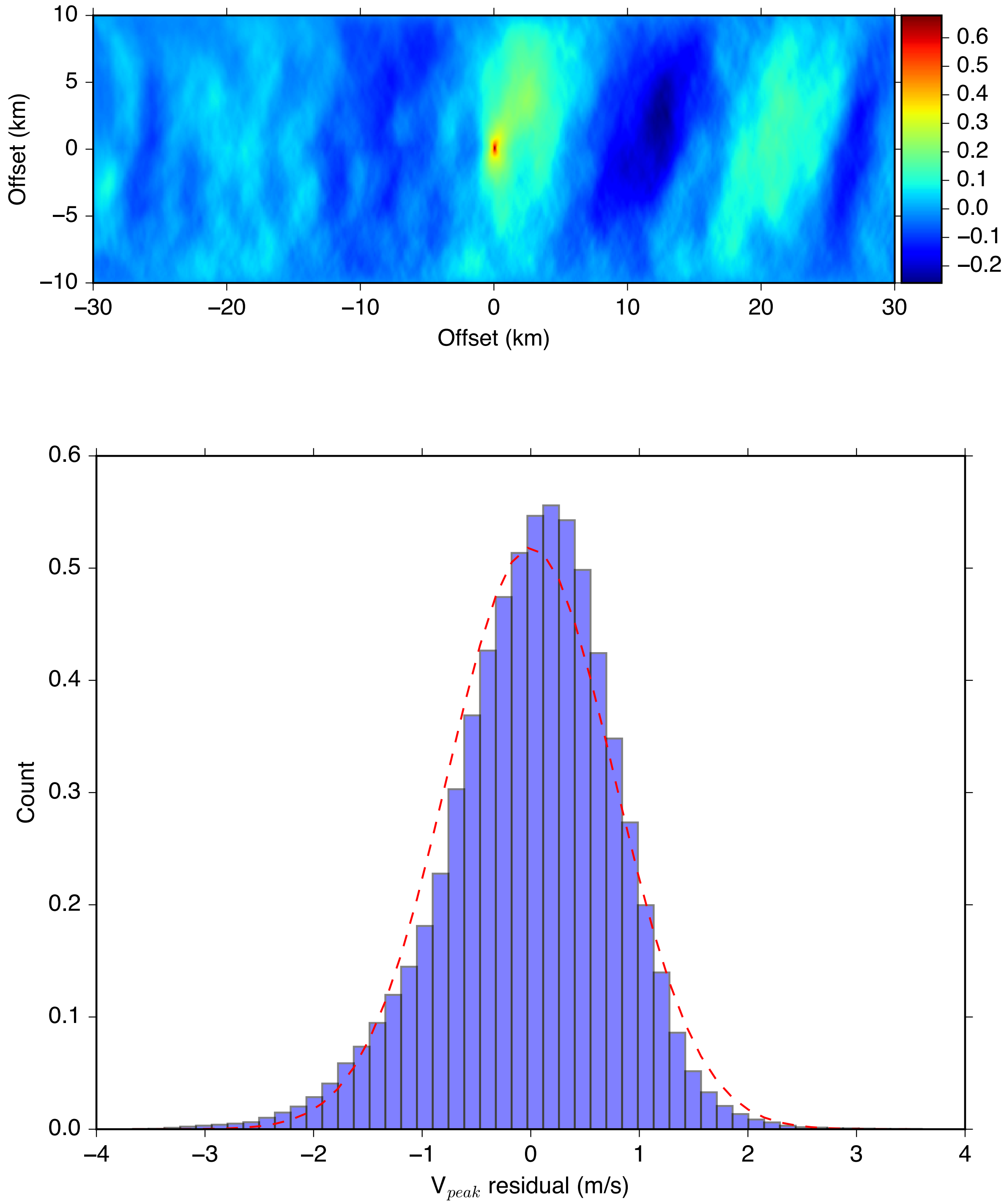

Figure 4. (top) Cross-correlation coefficient between initial friction μ_0 and the peak sliprate (V_{peak}) residuals computed by removing a depth-dependent mean value for a model with rate-and-state friction law. (bottom) histogram of V_{peak} residual values for dynamic rupture simulation using rate-and-state friction and rough fault model.

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