2013 SCEC Project Report

Developing a statistical framework for earthquake rupture process for physics-based ground motion simulation

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1. Abstract

This project was funded in 2009, 2010, 2012, and 2013 by SCEC. The main research objective is to develop a statistical framework for quantifying the variability (aleatory uncertainty) of finite source process and to understand its relationship to near-source ground motion characteristics. We developed a stochastic model that governs the finite source process with 1-point and 2-point statistics of kinematic source parameters and developed a pseudo-dynamic rupture model generator (SongRMG, Ver 1.0). Especially in the project year, we investigated the effect of 1-point and 2-point statistics of kinematic source parameters on near-source ground motions by systematically perturbing 1-point and 2-point statistics of input source parameters (Song et al. 2014).

2. Technical Report

2.1. Pseudo-dynamic Rupture Model Generator (RMG)

We developed a physics-based (pseudo-dynamic) rupture model generator (SongRMG) with 1-point and 2-point statistics of kinematic source parameters. Song et al. (2009) and Song & Sommerville (2010) originally introduced the main idea and mathematical framework in the rupture model generator, and they were expanded and improved by following studies (Song & Dalguer 2013; Song et al. 2014). A set of spatial random fields model the spatial distribution of several key kinematic source parameters, such as slip, rupture velocity, and peak slip velocity. In other words, one random variable is assigned to every subfault patch for each source parameter. If we have three source parameters, there are 3 random fields. The number of random variables for each random field is equal to the number of subfault patches on the finite fault. The random field model is constrained by rupture dynamics and past events in the framework of 1-point and 2-point statistics. 1-point statistics is a marginal probability density function at a given point on the fault. If we assume the Gaussian distribution, mean and standard deviation are two main representative parameters. They control the possible range of values for each source parameter. For example, they control whether the rupture velocity is centered at a certain value with small variation, or has a wide range of variation with very low and high velocity, including supershear rupture. 2-point statistics is composed of both auto and cross-correlation. Autocorrelation controls the heterogeneity of each source parameters while cross-correlation controls coupling between source parameters.

Once we have target 1-point and 2-point statistics, we can generate a number of rupture scenarios by Monte Carlo sampling, assuming the multi-variate Gaussian distribution. We first construct a covariance matrix, given the target auto- and cross-correlation structures, and simulate the spatial distribution of source parameters that satisfy the target covariance matrix using the Cholesky factorization. Mean, standard deviation, and even the shape of marginal probability density function can be adjusted afterwards. Finally we combine the simulated spatial distribution of source parameters with a prescribed shape of slip velocity function, and produce a full description of finite source model. Song et al. (2014) provide the detailed description of the stochastic source modelling method.

```
% Coded by Song, S. (April. 2013)
% Basic input parameters to describe a finite source model

function [rup] = gen_src(rup)

% Basic information for an event
rup.outfl = ['rup_' rup.name '.mat'];

rup.target_Mw   = 6.73;

rup.num = 50;         % number of simulation

rup.elon = -118.515;  % longitude, top center of the fault plane in degree
rup.elat =   34.344;  % latitude,  top center of the fault plane in degree

rup.L    = 20;       % fault length (along-strike) in km
rup.W    = 25;       % fault width (along-dip) in km

rup.stk  = 122;      % strike in deg.
rup.dip  = 40;       % dip in deg.
rup.rak  = 105;      % rake in deg.

rup.dtop = 5.;       % depth to top of fault
rup.shyp = 6.0;      % along strike location (from top center) of hypocenter
rup.dhyp = 19.4;     % along dip location (from top edge) of hypocenter

rup.dx   = 0.2;      % grid size (along-strike) in km
rup.dz   = 0.2;      % grid size (along-dip) in km

rup.svf.type = 'pliu';   % currently 'tri','rec','pliu', 'etinti' available
rup.svf.dt   = 0.1;
%%% End of inputs~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
```

```
%%% Coded by Song, S. (April. 2013)
%%% Set up target 1-point and 2-point statistics

function [rup] = gen_stats(rup)

%%%           [slip Vr Vmax risT];
rup.p1.min = [0   0.5 1.0 0.1];
rup.p1.max = [500 6.0 500 10];

rup.lambda = 1; % min wavelength = 10 km
rup.fN = 6;

rup.p2.tag = 'positive_eigen';

%%% 1-point and 2-point statistics of source parameters
% mod_vec = [slip Vr Vmax]
rup.p1.mu = [100 3.0 200];
rup.p1.sig = [50 0.1 50];

rup.p2.ax = [10 10 10;nan 10 10; nan nan 10];
rup.p2.az = [6 6 6; nan 6 6; nan nan 6];

rup.p2.cc = [1 0.6 0.6; nan 1 0.6; nan nan 1];

rup.p2.RDx = [0 0 0; nan 0 0; nan nan 0];
rup.p2.RDz = [0 0 0; nan 0 0; nan nan 0];
```

Figure 1. Two input files required running the rupture model generator (RMG).

The RMG requires two input files. The first input file (left panel in Fig. 1) describes the location, geometry, and dimension of a finite source. The second input file (right panel in Fig. 1) defines target 1-point and 2-point statistics. The RMG produces two output files. The first one (left panel in Fig. 2) is a MATLAB data file that contains all relevant input, output, and control parameters in stochastic modelling. The second output file (right panel in Fig. 2) is an ASCII file that contains information about the spatio- and temporal evolution of slip velocity function in the standard rupture format (SRF). The SRF is initially designed by R. Graves (USGS) and is currently adopted by the SCEC Broadband Platform project. Therefore, finite source models generated by the rupture model generator can be directly implemented in the SCEC Broadband platform.

```
rup =

         name: 'Northridge'
        outfl: 'rup_Northridge.mat'
    target_Mw: 6.7300
          num: 50
         elon: -118.5150
         elat: 34.3440
            L: 20
            W: 25
          stk: 122
          dip: 40
          rak: 105
         dtop: 5
         shyp: 6
         dhyp: 19.4000
           dx: 0.2000
           dz: 0.2000
          svf: [1x1 struct]
           nx: 100
           nz: 125
           lx: [1x100 double]
           lz: [1x125 double]
          dis: [125x100 double]
           p1: [1x1 struct]
       lambda: 1
           fN: 6
           p2: [1x1 struct]
        eigen: [37500x1 single]
         slip: [1x1 struct]
           Vr: [1x1 struct]
          psv: [1x1 struct]
         risT: [1x1 struct]
           Mo: [1x50 single]
           Mw: [1x50 single]
         rupT: [1x1 struct]
         psv1: [1x1 struct]
```

```
1.0
PLANE 1
 -118.5150    34.3440     100      125      20.00      25.00
    122.00      40.00    5.00     6.00      19.40
POINTS   12500
  -118.6069    34.3906    5.06      122.00       40.00 4.000000e+08   15.30  0.1000
    105.00     101.79     54         0.00       0         0.00       0
5.109870e-07   1.007300e+01   2.622403e+01   4.557582e+01   6.432134e+01   7.860106e+01
8.540586e+01   8.370083e+01   7.497781e+01   6.141723e+01   4.631845e+01   3.334252e+01
2.561125e+01   2.411675e+01   2.361993e+01   2.306275e+01   2.244832e+01   2.178009e+01
2.106183e+01   2.029754e+01   1.949153e+01   1.864831e+01   1.777262e+01   1.686936e+01
1.594360e+01   1.500055e+01   1.404548e+01   1.308375e+01   1.212077e+01   1.116193e+01
1.021262e+01   9.278151e+00   8.363775e+00   7.474619e+00   6.615677e+00   5.791756e+00
5.007492e+00   4.267273e+00   3.575258e+00   2.935326e+00   2.351073e+00   1.825768e+00
1.362364e+00   9.634604e-01   6.312920e-01   3.677249e-01   1.742358e-01   5.191322e-02
1.440472e-03   0.000000e+00   0.000000e+00   0.000000e+00   0.000000e+00   0.000000e+00
  -118.6051    34.3896    5.06      122.00       40.00 4.000000e+08   15.69  0.1000
    105.00     105.29     43         0.00       0         0.00       0
6.784940e-07   1.876937e+01   4.918079e+01   8.195019e+01   1.062245e+02   1.137158e+02
1.038529e+02   8.184709e+01   5.640268e+01   3.753912e+01   3.212290e+01   3.127864e+01
3.030314e+01   2.920540e+01   2.799558e+01   2.668485e+01   2.528532e+01   2.380992e+01
2.227229e+01   2.068664e+01   1.906761e+01   1.743017e+01   1.578945e+01   1.416061e+01
1.255868e+01   1.099850e+01   9.494457e+00   8.060457e+00   6.709759e+00   5.454828e+00
4.307274e+00   3.277688e+00   2.375597e+00   1.609326e+00   9.859614e-01   5.112598e-01
1.896062e-01   2.397730e-02   0.000000e+00   0.000000e+00   0.000000e+00   0.000000e+00
0.000000e+00
```

Figure 2. Two output files. (a) MATLAB file, (b) ASCII file (Standard Rupture Format)

2.2. Sensitivity of Ground Motions to Source (Correlation) Statistics

One of the strengths of the newly developed rupture model generator is that it is based on a consistent statistical framework (i.e., 1-point and 2-point statistics). We can perturb 2-point correlation statistics systematically as shown in Fig. 3 and investigate its effect on near-source ground motions. We used a full set of correlation structures in pseudo-dynamic source modeling (Fig. 3a), or removed certain components of cross-correlation structures (Fig. 3b, 3c, and 3d). In particular, we removed all cross-correlations in Fig. 3d. Fig. 4 shows near-source ground motion characteristics obtained by pseudo-dynamic source models with 8 different sets of correlation structures. As we clearly observe in the left panel, the full correlations in pseudo-dynamic source models (blue line) produce much stronger ground motions in peak ground velocity than no correlations (black). More interestingly, once we include correlations between slip and rupture velocity (red and magenta), pseudo-dynamic source models produce stronger ground motions, getting closer to the full correlation model (blue), while pseudo-dynamic source models without this pair of correlation (green and cyan) produce weaker ground motions, getting closer to the no correlation model (black). This may imply that correlations for a certain pair of source parameters may be more dominant in determining ground motion intensities. The right panel in Fig. 4 indicates that the full correlation model produces less randomness (smaller sigma) in ground motion predictions.

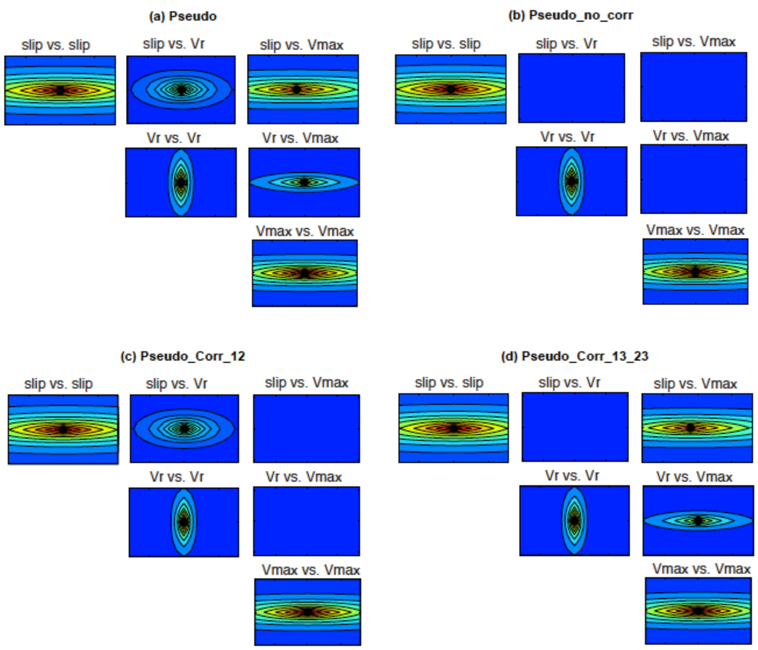


Figure 3. Perturbation of 2-point statistics. 3 off-diagonal blocks are perturbed sequentially (Song et al. 2014).

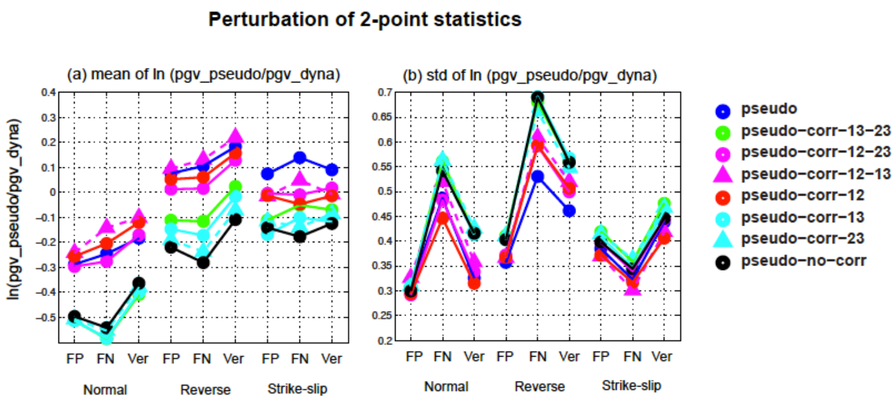
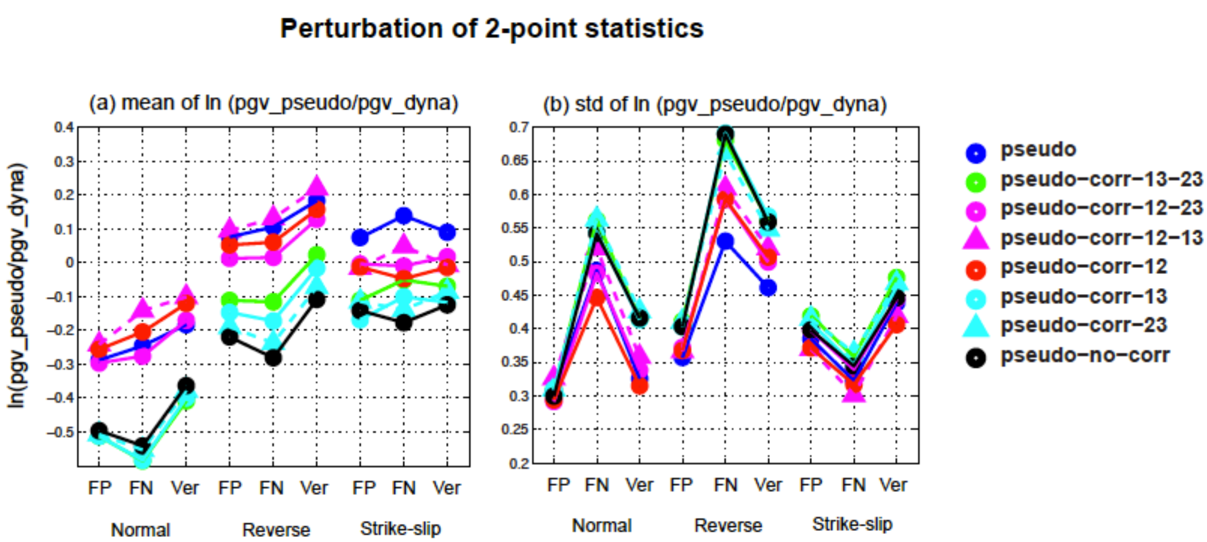


Figure 4. Comparison of pseudo-dynamically generated ground motions against dynamically generated ground motions after perturbing a certain element of 2-point statistics in pseudo-dynamic source models. (a) Mean of ln(pgv_pseudo/pgv_dyna) for 168 stations, (b) Standard deviation of ln(pgv_pseudo/pgv_dyna) for 168 stations. Mean and standard deviation are also averaged for 30 events (Song et al. 2014).

3. Exemplary Figure



[Caption] Ground motion residuals from pseudo-dynamic models (compared to dynamic models) for different levels of source correlations. Simulations show that source correlations produce stronger ground motions, and appropriate correlation in source modeling leads to less randomness in ground motion predictions (Song et al. 2014, GJI)

4. Intellectual Merit & Broader Impacts

Rupture dynamics enables us to understand earthquake rupture process in a physics-based way. We can study many interesting and complicated features of earthquake rupture by dynamic modeling. On the other hand, earthquake statistics enables us to quantify the variability of earthquake rupture for future events. We aim to develop a stochastic model for finite source process with simple correlation structures. This is an exciting research work because we can simulate finite source models by stochastic modeling. Seismologists and earthquake engineers can use stochastic finite source modeling tools developed in this project and generate a number of rupture scenarios for simulating ground motions. They can also study the effect of finite source process on near-source ground motion characteristics in a systematic sense.

5. Publications

5.1 Relevant Publications (peer-reviewed)

S. Song, L.A. Dalguer, and P.M. Mai (2014). Pseudo-dynamic source modeling with 1-point and 2-point statistics of earthquake source parameters, *Geophys. J. Int.*, 196, 1,770-1,786.

S. Song, and L.A. Dalguer (2013). Importance of 1-point statistics in earthquake source modeling for ground motion simulation, *Geophys. J. Int.*, 192, 1,255-1,270.

S. Song, P. Somerville (2010). Physics-based earthquake source characterization and modeling with Geostatistics, *Bull. Seism. Soc. Am.* 100, 482-496.

S. Song, A. Pitarka, and P. Somerville (2009). Exploring spatial coherence between earthquake source parameters, *Bull. Seism. Soc. Am.* 99, 2,564-2,571.

5.2 Conference Presentations

Song, S., L.A. Dalguer, and P.M. Mai, Pseudo-dynamic source modeling with 1-point and 2-point statistics of earthquake source parameters, fall meeting of American Geophysical Union (AGU), San Francisco, California, 2013.

Song, S., L.A. Dalguer, and P.M. Mai, Pseudo-dynamic source modeling with 1-point and 2-point statistics of earthquake source parameters, annual meeting of the Southern California Earthquake Center (SCEC), Palm Springs, California, USA, 2013.

Song, S., L.A. Dalguer, and P.M. Mai, Developing a statistical framework that governs finite earthquake source process, 8th Statistical Seismology Workshop, Beijing, China, 2013.

Song, S., L.A. Dalguer, and P.M. Mai, Developing a physics-based rupture model generator (RMG) with 1-point and 2-point statistics of source parameters, IASPEI, Gothenburg, Sweden, 2013.

Song, S., and L.A. Dalguer, Propagation of 1-point and 2-point statistics from dynamic source through kinematic to ground motions, annual meeting of Seismological Society of America (SSA), Salt Lake City, Utah, USA, 2013.

Song, S., P.M. Mai, and L.A. Dalguer, Pseudo-dynamic source modeling with 1-point and 2-point statistics of earthquake source parameters, annual meeting of European Geosciences Union (EGU), Vienna, Austria, 2013.