# Generating Broadband Seismograms for a suite of San Andreas Earthquakes

Mourhatch, R. (ramses@caltech.edu), Krishnan, S. (krishnan@caltech.edu)

## Introduction

We examines a method for generating broadband ground motions for a suite of San Andreas earthquakes ($M_w$ 6.0-8.0) using a hybrid of empirical & deterministic methods of ground motion simulations. We use finite source models from past earthquakes resampled to a 0.5 km x 0.5 km grid to generate the earthquakes. The low frequency content (< 0.5Hz) of the ground motions are generated using a wave propagation software package called SPECFEM3D. This package incorporates the regional 3D-velocity structure (SCEC,CVM-H) with its resolution enabling the software to accurately propagate waves with periods greater than 2 seconds. The results for this period range have been extensively validated in previous studies. The low frequency will be superposed with high frequency ground motions determined using empirical green's function (EGF) approach. The basic principle involving the EGF method is generating ground motions using seismograms from smaller earthquakes (sub-events) as green's functions for a large earthquake. The high-frequency motion for a given San Andreas earthquake scenario is generated using the following steps taken to best capture the path & local site effects:

1.Seismograms from actual historic events in the magnitude range 2.5-5.0 that have occurred along the entire rupture length of the given scenario are assigned to each subfault

2.For a given analysis site of interest, the seismogram recorded at the seismic station that is closest in distance is used.

3.Each of the seismograms is scaled by the ratio of assigned sub-fault moment to the sub-event moment.

4.The effect of geometric spreading & the delay in arrival of the waves is accounted by additional scaling and shifting.

5.The earthquake records corresponding to the rupture of all the sub-faults participating in the given earthquake scenario are combined after due scaling and shifting.

The key advances in this work are the use of rupture scenario-specific events as EGFs & the utilizing of the data from small magnitude earthquakes for generating high frequency synthetics for large magnitude earthquakes. We are also examining the best possible EGF for ground motions simulations. The main challenge is the low signal-to-noise ratio of the seismic waveforms from small magnitude earthquakes at large distances. The approach is being validated against recorded ground motions from the 2004 Parkfield ($M_w$ 6.0) & the 1992 Landers ($M_w$ 7.3) Earthquakes.

## High Frequency Ground Motion

### Background

The high frequency content (frequencies > 0.5 Hz) of the ground motions are being generated using Empirical Green's Functions method. The idea of Empirical Green's function method is based on estimating ground motions for large earthquakes using the records from smaller earthquakes as the Green's function (Empirical Green's Functions, EGF) for the site to source response (Hartzell 1978).

### Method

Our procedure for simulation of the suite of San Andreas earthquakes consist of following steps:

1. Event Selection: For simulating ground motion at a particular site (Target Station) we assign a record from historic earthquake catalogue to every subfaults. The selection process is done through an automated process that best match the path between subfault and target station. (Figure 6)
2. Summation Procedure: The record from each subfault are scaled and summed such that the results are consistent with Brune's 1970 spectral scaling law (Omega Square). We will be following a new variation of empirical green's function method (EQ 1).
3. Corrections: The records used as Green's functions are scaled by the ratio of the station-subfault distance ($R_{ij}$) to small event-record distance ($R_{EGF}$) (Figure 6) to account for geometric spreading. The records are shifted in time to adjust the arrival times for cases that the EGF's travel path is different from the subfault-station travel path. Additionally the records are shifted randomly in time to remove any periodicity that can occur due to the rupture propagation pattern.

### Analysis of EGF Selection

Traditionally the magnitudes of the selected EGFs is kept within 2-3 units of the Target events. We are exploring the possibility of using lower magnitude EGFs($M_w$ 2-5) for simulating large earthquakes ($M_w$ 8). This can ultimately unable a better utilization of the data available in the low magnitude range for ground motion simulation purposes.

Additionally, we are studying the performance of the use of different EGFs in simulation of ground motions with the goal of answering the following questions: "Given a magnitude of target event, the location of the station and the frequency band of interest, what is the best EGF to use?" Should we be using very low magnitude events with a perfect path representation or use the EGFs from different location but with magnitude closer to the target event?

We are currently developing methods to quantify the performance of each EGF for ground motion simulations. The preliminary plan is to analyze the performance of the simulations at various (a) distances, (b) frequency bands (c) and magnitudes of target events. The duration of the events, peak values, arrival time of the peak values (envelope of the time series) and the amplitude spectrum are the possible metrics of comparison for this study.

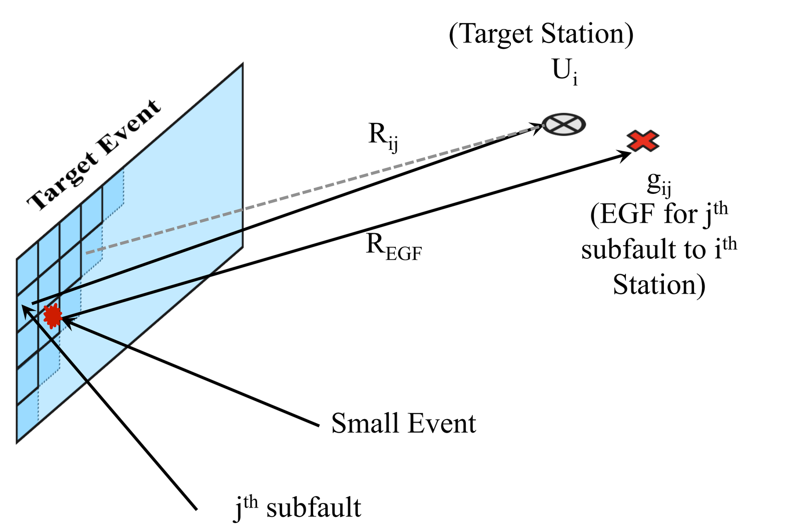



**Figure 6:** Choosing EGFs based on the location of subfault, small event, available record and the station of interest.

**EQ 1:**

$$U_i(t) = \sum_{j=1}^{N}\sum_{l=1}^{K_j}\left(\frac{R_{EGF}}{R_{ij}}\right)\left(\frac{M_{oj}}{K_j M_{oEGF}}\right)G_{ij}\left(x,t,t-t^j_{rup}-\frac{(l-1)\times t^j_{rise}}{K_j}-t_{rnd}\right)$$

N=Number of Subfaults

$K_j$=Number of EGFs needed to match the moment with the subfault

$t_{rup}^j$=Rupture time for the j^th subfault

$t_{rise}^j$=Rise time for j^th subfault

$t_{rnd}$= Random variable for removing periodicities of rise and rupture time

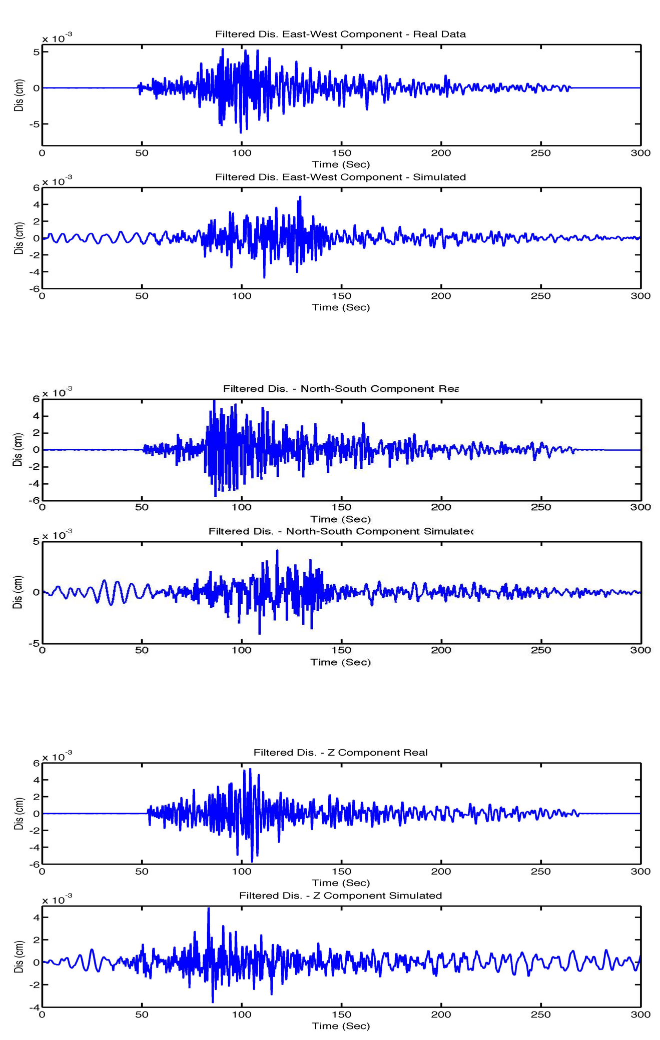


**Figure 7:** Example of a preliminary Ground motion simulations for a Parkfield 2004 earthquake. Figures illustrate the displacement time series of real and simulated data filtered for frequency band of 0.5 to 5 Hz.

## Low Frequency Ground Motion

### Source Model Generation

**Selection Criteria:** Selected source models (Table 1) are based on finite source models inferred from past earthquakes on vertically dipping right-lateral strike slip faults ($M_w$ 6.0-8.0)

**Resampling:** To ensure that the source models are capable of generating a 2s wave, they are resampled to a finer resolution (0.5 km X 0.5 km or lower). (Figure 1: resampled $M_w$ 7.89 Denali Earthquake)

**Mapping and Directivity:** The resampled source models are then mapped to 5 equally spaced segments of the southern San Andreas fault. For each location, two unilateral rupture directivities are considered (north-to-south & south-to-north). (Figure 2)

### Ground Motion Simulations

Ground motions are generated at 450 sites located on a roughly 7 km X 7 km (1/16 degree) grid using SPECFEM3D. Figure 3 illustrates the east-west component of the peak ground displacement maps for the scenarios shown in Figure 2. (Data valid for frequencies < 0.5 Hz)

### Data Analysis

The ground motions obtained from our simulations are used to examine the effects of parameters such as magnitude, distance, and directivity on ground motion intensity measures.

The data are compared against well studied ground motion prediction equations (GMPE) such as the ones developed by PEER.

Figure 4, illustrates a preliminary study on the variations in peak ground velocities (PGV) against distance for $M_w$ 7.28 earthquake (Data used in this analysis are obtain from SPECFEM3D). Additionally, in the same figure we have compared the results to the values obtained from GMPE (Campbell & Bozorgnia).

Figure 5, illustrates the PGV values against Magnitude for stations located at roughly 80 km from the earthquake and the results are compared against attenuation relations.

**Table 1:** Finite Source Models Selected for the San Andreas Study

| | Earthquake | Year | $M_w$ | Length (km) | Width (km) | Source Modeler |
|---|---|---|---|---|---|---|
| 1 | Parkfield | 2004 | 6.00 | 34 | 15.5 | Dreger et al |
| 2 | Imperial Valley | 1979 | 6.58 | 42 | 10.4 | Hartzell and Heaton |
| 3 | Tottori | 2000 | 6.73 | 32 | 20 | Semmane et al |
| 4 | Kobe | 1995 | 6.89 | 50 | 20 | Ide et al |
| 5 | Landers | 1992 | 7.08 | 83 | 18 | Cohee and Beroza |
| 6 | Hector Mine | 1999 | 7.17 | 54 | 16 | Ji et al |
| 7 | Landers | 1992 | 7.28 | 78 | 15 | Wald and Heaton |
| 8 | Izmit | 1999 | 7.44 | 141 | 23.3 | Sekiguchi and Iwata |
| 9 | Izmit | 1999 | 7.56 | 173 | 22.5 | Delouis et al |
| 10 | Denali | 2002 | 7.89 | 292 | 20 | Ji et al |

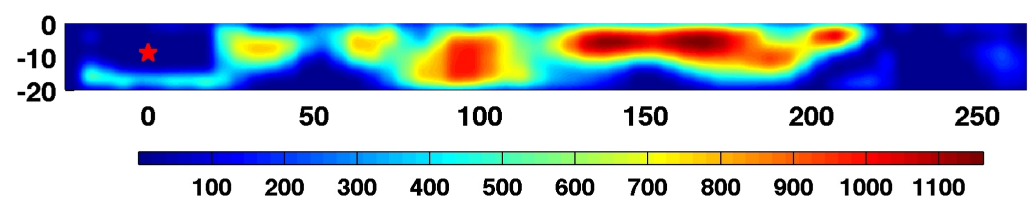


**Figure 1:** Slip distribution of the 2002 Mw = 7.9 Denali Earthquake (Chen Ji)

**Figure 2:** Magnitude 7.9 mapped to southern San Andreas Fault ,north-to-south rupture

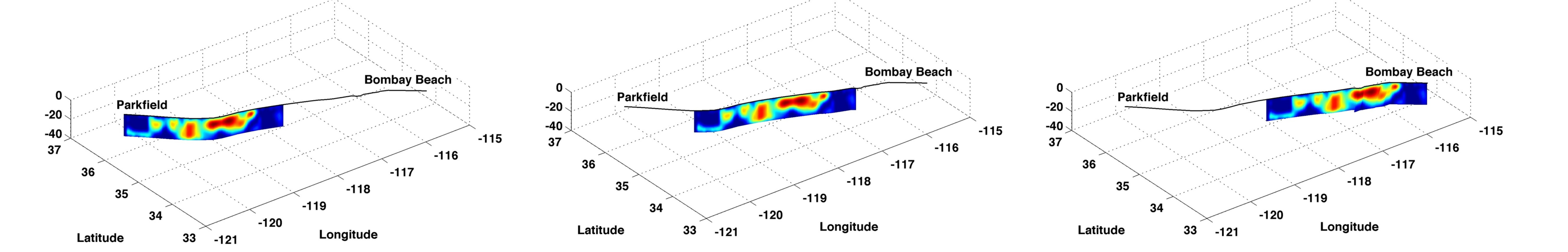
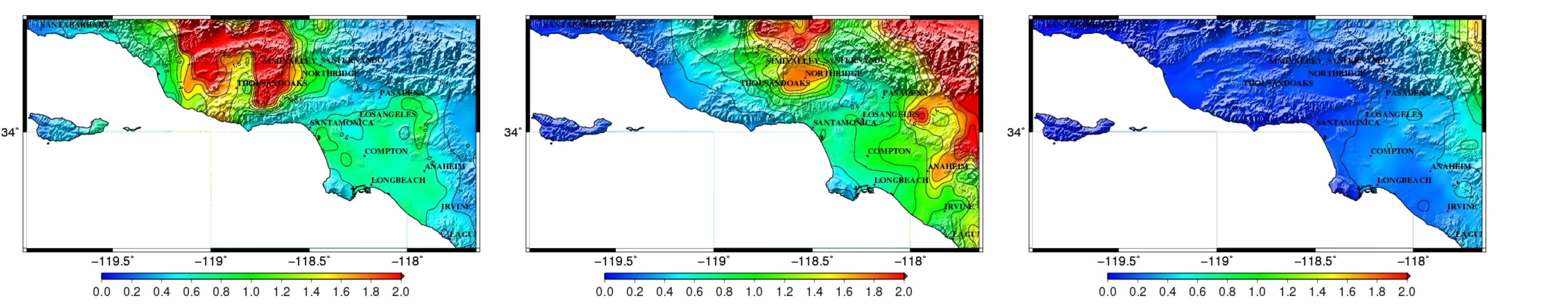



**Figure 3:** Peak Ground Displacement (East-West component) for hypocenter locations shown in Figure 2.



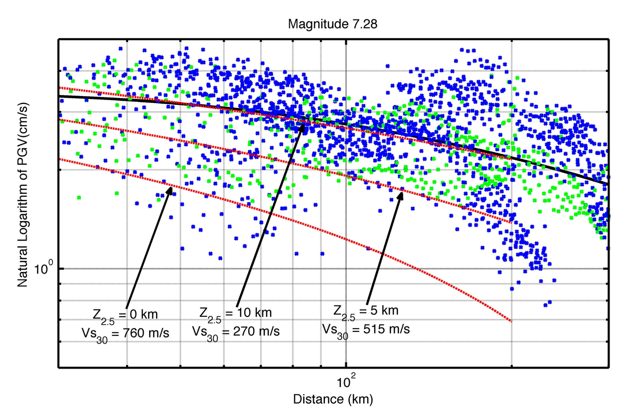


**Figure 4:** PGV Vs. Distance for $M_w$ 7.28 Earthquake. Green= Station in mountains, Blue=Stations in Valleys, Red Line = Attenuation Relations (Campbell & Bozorgnia) , Black Line= Best fit to Simulation Data

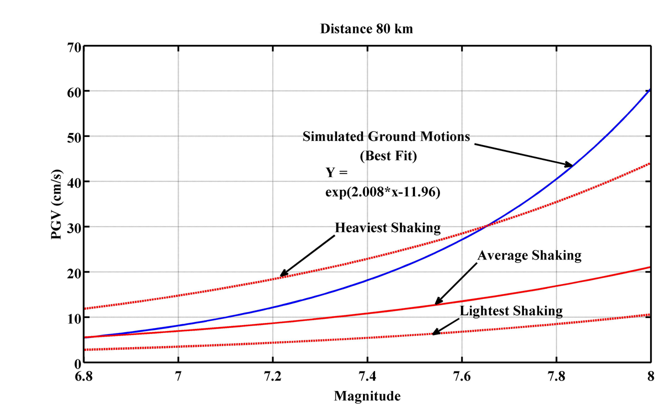



**Figure 5:** PGV Vs. Magnitude for stations located at a distance of 80 km from fault. Red Lines=Attenuation Relations (Campbell & Bozorgnia), Blue = Best Fit to Simulation Data.

## Acknowledgment

We thank Chen Ji (UCSB) and Martin Mai (ETHZ & KAUST) for providing source models; and Dimitri Komatitsch (University of Pau, France), Jean-Paul Ampureo (Caltech- GPS) and Carl Tape (UAF) for their insights into SPECFEM3D; Thomas Heaton(Caltech) and Robert Graves (USGS – Pasadena) for their insight into Empirical Green's Function Method.
We gratefully acknowledge the funding provided by the National Science Foundation (NSF Award No.0926962)

## References

(1) Hartzell, S. H. (1978). Earthquake aftershocks as Green's functions, *Geophys. Res. Lett.* **5**,1-4
(2) Joyner, W. B. and D. M. Boore (1986). On simulating large earthquakes by Green's function addition of smaller earthquakes, Earthquake Source Mechanics, *American Geophysical Monograph* **37**, Vol. 6, 269-274
(3) D. Komatitsch and J. P. Vilotte. The spectral-element method: an efficient tool to simulate the seismic response of 2D and 3Dgeological structures. *Bull. Seismol. Soc. Am.*, **88**(2):368-392, 1998
(4) Frankel, A. (1995). Simulating strong motions of large earthquakes using recording of small earthquakes: The Loma Prieta mainshock as a test case, *Bull. Seismol. Soc. Am.* **85**, 1144-1160