BASIN RESPONSE TO VIRTUAL EARTHQUAKES ON THE
SAN JACINTO FAULT AND ON THE ITOIGAWA-SHIZUOKA
FAULT
Report for SCEC Award #15036
Submitted March 4, 2016

Investigators: Marine Denolle (UCSD, now at Harvard University), Frank Vernon (UCSD)

I. Project Overview ........................................................................................................................................i
   A. Abstract ..................................................................................................................................................i
   B. SCEC Annual Science Highlights .........................................................................................................i
   C. Exemplary Figure ..................................................................................................................................ii
   D. SCEC Science Priorities .......................................................................................................................ii
   E. Intellectual Merit ....................................................................................................................................ii
   F. Broader Impacts .....................................................................................................................................ii
   G. Project Publications ...............................................................................................................................iii

II. Technical Report ........................................................................................................................................1
   A. Dominant modes of propagation in basins .............................................................................................1
   B. Wavefront curvature in laterally heterogeneous media ..........................................................................1
   C. Source kinematic simulator ...................................................................................................................3
   D. References ............................................................................................................................................4
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.)

Our project aims to construct Virtual M7 earthquakes on the San Jacinto Fault (SJF) and the Itoigawa-Shizuoka Tectonic Line (ISTL) and predict ground motion in the greater Los Angeles and Tokyo metropolitan areas using high-quality, multi-year stacks ambient seismic field Green’s functions. We have computed 3-year stacks in Japan of all 9 component of the Green tensor between virtual sources on the Itoigawa-Shizuoka Tectonic Line (ISTL) and all receivers in the Tokyo Metropolitan area. We are currently pre-processing the California data set for years 2010-2014.

The cross-correlations functions in Japan are unusual in that several modes of Love and Rayleigh waves are visible in the frequencies of interest. The virtual earthquake approach was developed based on the assumption that only surface-wave fundamental modes were present. We need to isolate all modes, decouple Rayleigh from Love waves on all 9 components of the Green’s function and isolate the fundamental and higher overtones of surface waves. We use well established kinematic simulator to construct realistic earthquake source scenario and will be able to investigate effects of source directivity onto strong ground motion in Kanto and Los Angeles sedimentary basins.

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) Seismology
   Tectonic Geodesy
   Earthquake Geology
   Computational Science
   Unified Structural Representation (USR)
   Fault and Rupture Mechanics (FARM)
   Earthquake Forecasting and Predictability (EFP)

(2) Ground Motion Prediction (GMP)
   Southern San Andreas Fault Evaluation (SoSAFE)
   Stress and Deformation Through Time (SDOT)
   Community Modeling Environment (CME)
   Working Group on California Earthquake Probabilities (WGCEP)
   Collaboratory for the Study of Earthquake Predictability (CSEP)
   Central California Seismic Project (CCSP)
   Ground Motion Simulation Validation (GMSV)
   Aseismic Transient Detection
   Source Inversion Validation (SIV)
   Dynamic Rupture Code Validation
   Earthquake Simulators
   Communication, Education, and Outreach
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](image)

Raw ambient seismic field Green’s function between stations SSGH and all MeSO-net stations for the ZZ, RR, and TT components. Constant seismic wavespeed move-outs are shown and interpreted based on our finding in Boué et al (2015, 2016).

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](https://www.scec.org/research/priorities) for list of SCEC research priorities. For example: 6a, 6b, 6c

6b

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?

The richness of the ambient seismic field Green’s function obtained from extensive stacking of ambient seismic noise cross-correlation functions has shown the dominance of the surface-wave higher modes in wave propagation in sedimentary basins. We are evolving the virtual earthquake approach to account for higher modes and ray bending. We use a realistic kinematic earthquake simulator to generate a suite of scenario sources that will enable statistical analysis of strong ground motion.

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?

This research has involved strong collaborations with other postdoctoral fellows, currently creates new research for undergraduate students (senior thesis) and collaboration between three U.S. institutions and one Japanese institution. It has been presented at national conferences (AGU), part of the results is submitted for peer reviewing, two other publications are in preparation.

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 Publications 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.


Boué P., M. Denolle, N. Hirata, S. Nakagawa, G. C. Beroza, “Beyond Basin Resonance: Characterizing Wave Propagation Using a Dense Array and the Ambient Seismic Field”, submitted to GJI, SCEC contribution number 6180
II. Technical Report

We (collaborator Pierre Boué and PI Marine Denolle) have prepared a complete data set of 3 components of all MeSO-net stations (296 shallow boreholes) and 250 Hi-net stations (deeper boreholes) in the user-friendly SAC data format downsampled from 100Hz and 200Hz to 20Hz. The data set reaches 15TB of disk space. For southern California, we (co-PI Frank Vernon and PI Marine Denolle) have prepared 2011-2014 a combined broadband and short period stations to sample each site from all permanent networks (CI, AZ, PB) and temporary deployments on the San Jacinto Fault. The data is compacted in miniseed format and down to 5TB.

A. Dominant modes of propagation in basins

The cross-correlations for all 9 components of the Green tensor between all Hi-net stations and all MeSO-net stations are about 80% complete. All 9-component Green’s functions between the ISTL stations and the Kanto basin are complete and highlight quite rich waveform content. PI Marine Denolle collaborated with Pierre Boué to identify the waveform content. We found that, in average, the dominant modes of propagation for both Rayleigh and Love waves are the fundamental and first overtone, the second overtone is sometimes visible, that their amplitude varies from one component to another. Based on this work, we have identified all surface-wave modes to perform the virtual earthquake methods and are developing appropriate methods to isolate the modes in individual traces using polarization arguments.

B. Wavefront curvature due to lateral heterogeneity

The first order effect of coupling of modes is the polarization of Rayleigh and Love waves. We use the station azimuths to rotate from North - East - up to radial(R) – transverse(T) – down (Z). Borehole instruments often have errors in the horizontal components orientation, and we correct both Hi-net stations (source in NEID website) and MeSO-net stations (Kano et al, 2015) based on published misalignment values. Strong lateral heterogeneities of seismic velocities induce ray bending. Rayleigh waves are polarized on the RZ plane and Love waves are polarized on the transverse axis such that, in the laterally homogeneous case, the cross term components RT, TR, ZT, TZ should be zero. We construct a simple optimization problem to find the best orientations that minimizes the energy in those term. The energy is taken as the L2 norm of the Green’s function, a dimensionless quantity in our study. This is a non-linear inverse problem with only 2 parameters to find, angle $\phi_1$ and $\phi_2$ that we illustrate in Figure 1. Variations in $\phi_2$, and in particular in $\phi_2+\pi/2$ indicates variations in wavefront curvature due to lateral heterogeneity. This approach is new and we are exploring further use of this optimization problem, such as adding this as a constraint to eikonal tomography.
Figure 1: (a) Geometry between both receivers, (b) angle $\phi_2$ at receivers in the Kanto basin overlaying the $V_s = 3.2$ km/s iso-surface (Koketsu et al., 2009). (c) Tracking the wavefront curvature by looking at spatial variations of $\phi_2 + \pi/2$, and overlaying a circular wavefront predicted from laterally homogeneous medium.

The cross-correlation functions clearly show rich and complex waveforms. Figure 2 illustrates this with the ZZ-RR-TT move-out plots between SSGH station and the MeSO-net stations. Based on our study (Boue et al., 2016), we interpret the slowest wavepacket as the fundamental mode, the second as the first overtone and it is possible to discern the second overtone or a body wave ahead of the wavefront. Once the modes are decoupled, we can use the virtual earthquake approach (Denolle et al., 2013) to correct for source mechanism and source depth.

Figure 2: Raw ambient seismic field Green’s function between stations SSGH and all MeSO-net stations for the ZZ,
RR, and TT components. constant seismic wavespeed move-outs are shown and interpreted based on our finding in Boué et. al (2015, 2016).

The surface-wave eigen-solver GESC (Denolle et al 2012) provides us with the fundamental and first overtone excitation functions (Fig. 3(a-b)) based on the velocity profiles underneath each station sources found extracted from the 3D velocity model of Koketsu et al (2009). Note that sites in the basin experience changes from retrograde to prograde Rayleigh-wave surface particle motion (Boue et al, 2015, 2016), which enters as a denominator in the virtual earthquake approach (Denolle et al 2013), but that this effect is not predicted for in the Itoigawa region.

C. Source kinematic simulator

We have created a suite of kinematic earthquake ruptures using the UCSB (Lui et al 2006, Crempien and Archuleta, 2014) kinematic source simulator. Our goal is to represent an M7.4 oblique thrust fault. The fault is planar of length 100 km, width, 20 km, dip of 70˚ to approximate the drastic change of dip from the northern segment to the southern segment. The source coordinates are (36.53N,137.85E; 36.01N,138E). We generated 54 kinematic sources. We will use a similar approach to represent the source on the San Jacinto Fault. In this study, we just look for a realistic kinematic source representation, but future work will involve dynamic sources. Figure 3(c-f) shows the finite fault kinematic representation with the spatially varying moment release (proportional to slip), the rupture propagation and a heterogeneous rise time. For point sources in between station receivers, we will interpolate using the surface-wave dispersion as in Denolle et al (2014). Heterogeneity on the kinematic rupture also trades off with the bandlimited ambient noise Green’s functions, and we will investigate to which degree it affects the strength of the shaking.
Figure 3: (a) Velocity profile underneath the 22 stations of the Itoigawa-Shizuoka Tectonic Line (ISTL) (b) fundamental and first overtone mode surface waves eigen-functions for the radial Rayleigh (blue), transverse Love (black), and vertical Rayleigh (red) at different 6-second period underneath N.SSWH. UCSB Kinematic source simulator (Liu et al 2006): map of the moment release (c), the rupture time (d), the rise time (c) and the total moment rate function (f).

Our ambient seismic field Green’s function preserves the relative amplitudes and we rely on occurrence of local earthquakes to calibrate the relative amplitude to an absolute amplitude levels. The M6.2 Nagano 2014 earthquake well recorded by the MeSO-net stations is a perfect candidate to calibrate the amplitudes. In Southern California, we are currently refining the results from Denolle et al (2013) as part of an undergraduate research project at Harvard and will use a series of well recorded M4.5+ to calibrate the prediction from a San Jacinto event to absolute amplitudes.

D. References


Boué P., M. Denolle, N. Hirata, S. Nakagawa, G. C. Beroza, “Beyond Basin Resonance: Characterizing Wave Propagation Using a Dense Array and the Ambient Seismic Field”, submitted to GJI


