Development and validation of stochastic representation of small-scale velocity and attenuation structure in SCEC CVMs

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Outreach during award period:

Participated and presented results from project at Joint SCEC-Japan workshop, 'Special Project for Reducing Vulnerability for Urban Mega Earthquake Disasters', Ichinobo, Matsushima, Japan, annual 2012 SCEC meeting in Palm Springs, and annual 2013 SSA meeting in Salt Lake City.

Funded PhD Student W. Savran at San Diego State University.

Summary

Small-scale, near-surface heterogeneities may affect ground motion estimates significantly, in particular as the highest frequency increases, and are currently not included in the SCEC Community Velocity Models (CVMs). Due to the variation over length scales of hundreds of meters, the density of current (and expected future) direct measurements of these heterogeneities, usually in terms of their S-wave velocity Vs (e.g., Vs30), is insufficient to capture their variation in sedimentary basins, such as those in southern California. Instead, we generate statistical models of near-surface velocity heterogeneities that occur in sedimentary basins, using available shallow S-wave measurements. Such statistical model can then be incorporated in the SCEC CVMs.

We collected more than 700 Vs30 measurements in the greater Los Angeles basin, with help from John Louie, Harold Magistrale and Alan Yong. We then generated semi-variograms for all the collected Vs30 measurements from the greater Los Angeles basin. The semi-variogram for the Vs30 measurements suggests a Hurst number of 0.25-0.43, or alternatively, a fractal dimension between 1.57 and 1.75.

We then simulated 0-2.5 Hz ground motions for the 2008 Mw5.4 Chino Hills, CA earthquake in a 56 km x 40 km x 28 km subset of the SCEC CVM 4.0. We assume a minimum Vs of 200 m/s, and the simulations are carried out with the finite difference code AWP-ODC. A fractal distribution of the near-surface heterogeneities with a Hurst exponent of 0.1 and standard deviation of 10% is added to the upper 800 m of the subset. We computed ground motions for a lossless model and for various linear relations between Qs and Vs. We find amplification/de-amplification of the peak ground velocities (PGVs) by up to a factor of 2, and that twice as large an area experiences de-amplified PGVs as compared to the area that experiences amplified PGVs. We find that the 'usual' Qs-Vs relation Qs=50Vs (km/s) grossly underpredicts the PGV from the data at this and other basin sites. Results using other Qs-Vs relations (in particular, higher Qs values, such as Qs=250Vs) provide better match to the PGV and duration of the data. This is expected, as the the small-scale heterogeneities substitute some of the effects from the intrinsic attenuation specified by the Qs-Vs relation.

Background

Several previous studies have laid the foundation for the research proposed here. Frankel and Clayton (1986) used 2-D finite-difference simulations of seismic scattering from random velocity fluctuations to model the attenuation in the Earth's crust. They found that Gaussian and Exponential distributions did not accurately reproduce travel-time anomalies and the seismic coda at high frequencies. O'Connell (1999) showed that stochastic variation of velocity variations in the upper crust can reproduce the observed log-normal dispersion of peak ground motions. His simulations of the 1994 Northridge earthquake also showed that observed, apparently nonlinear sediment responses can be explained by weakly heterogeneous random 3D crustal velocity variations. Mela and Louie (2001) showed that it is possible to extract statistical parameters such as correlation lengths and fractal dimensions from high-resolution seismic datasets. A similar statistical analysis applied to shallow Vs samples from the San Francisco Bay area estimated a spatial correlation distance of about 4 km for the upper 10 m of soils (Thompson et al., 2007).

Inspired by the earlier studies mentioned above, Olsen and Jacobsen (2011) began to analyze the amplification effects of shallow velocity heterogeneities on ground motions. They generated a 25 km by 25 km by 15 km (depth) 1D crustal model based on a representative deep sediment site from the Los Angeles basin with Vs as low as 250 m/s. This reference model was then augmented with fractal distributions of inhomogeneities for Vs<1500 m/s (<2km of depths). In three dimensions, these distributions show high wave-number decay of the power spectrum P(k) as:

$$P(k) = P_0 \left(1 + \left(k \Big/ k_{corner} \right)^2 \right)^{-(1.5+H)}$$

where H is the Hurst number, k_{corner} is a wave number below which the spectrum is approximately constant, and P_o is a constant. Frankel and Clayton (1986) favored a self-similar (von Karman) distribution with a Hurst number of 0 (power spectral decay of $1/k^3$) in their 2-D analysis of crustal scattering effects. Olsen and Jacobsen's 3-D study adopted the recommendation of H=0 and compared the results to those for H=-0.5 (power spectral decay of $1/k^2$) as proposed by O'Connell (1999) in his 3-D scattering model, and H=0.5 (power spectral decay of $1/k^4$). They also introduced pattern anisotropy in their models by generating horizontal and vertical length scales of the inhomogeneities of 1250 m and 250 m, respectively (see Figure 1). The fractal inhomogeneities were incorporated with standard deviations (s) of up to 10%, the range considered by Frankel and Clayton (1986).

Olsen and Jacobsen (2011) used their fractal models to simulate linear visco-elastic wave propagation using a fourth-order 3D staggered-grid finite difference (FD) method (Olsen et al., 2009). 0-2 Hz SH-wave sources were initiated in unison on a vertical plane extending to a depth of 5 km, 3.75 km from the edge of a 15 km by 15 km area including the fractal inhomogeneities. The simulations represented wavelengths as low as 125 m in the 3D model. Their resulting ground motions included prevailing bands of amplification aligned in the primary direction of the waves, larger for increasing Hurst value from -0.5 to 0.5 (see Figure 2). These bands are likely in part an artifact of the highly simplified earthquake source designed to isolate the scattering effects of the shallow heterogeneities. Nevertheless, the results show that even simple and rather weak fractal inhomogenieties can imply significant variations in ground motion amplifications (up to a factor of four).

The results by Olsen and Jacobsen (2011) also have implications for the attenuation of seismic amplitudes in the ground motion models. Recent 3D ground motion simulations using the SCEC CVMs have (somewhat ad-hoc) defined the (frequency-independent) Qs as a fraction of the local Vs. For example, Graves et al. (2008) and Olsen et al. (2009) used Qs=50*Vs (Vs in km/s), a relationship that has been found to generate long-period (0-~1Hz) amplitude decay with distance of the ground motions in general agreement with observations. However, the CVMs used in these simulations did not include an adequate variation of the shallow crustal heterogeneities. Olsen and Jacobsen (2011) showed that, when fractal heterogeneities are included in the shallow part of the CVM, the Qs=50*Vs relation seems to generate much too strong attenuation of the seismic amplitudes. Thus, the currently applied Qs relations may have to be reconsidered, if more realistic variation of the near-surface velocities is included.

Results form This SCEC Award:

Task 1: Gather existing near-surface velocity information for the southern California basins.

We collected more than 700 Vs30 measurements in the greater Los Angeles basin, see Figure 1, with help from John Louie, Harold Magistrale and Alan Yong.

Task 2: Analyze the shallow velocity measurements statistically.

We then generated semi-variograms for all the collected Vs30 measurements from the greater Los Angeles basin (Figure 1), using the method:

$$\tilde{\gamma}(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} \left[Z(x_i) - Z(x_i + h) \right]^2$$

where $Z(x_i)$ is the field value, h is the lag distance, and N(h) are the number of bins involved. The semi-variogram for the Vs30 measurements suggests a Hurst number of 0.25-0.43, or alternatively, a fractal dimension between 1.57 and 1.75.

Task 3: Simulate ground motion in southern California for the 2008 Mw5.4 Chino Hills earthquake in versions of the 3D CVM with and without the statistical model of the shallow heterogeneities.

We simulated 0-2.5 Hz ground motions for the 2008 Mw5.4 Chino Hills, CA earthquake in a 56 km x 40 km x 28 km subset of the SCEC CVM 4.0 (see Figure 3). We assume a minimum Vs of 200 m/s with a grid spacing of 16 m in all directions. The simulations are carried out with the finite difference code AWP-ODC (Cui et al., 2010). The source function used in the simulations includes some observational constraints up to 2.5 Hz or higher (Taborda and Bielak, 2012). A fractal distribution of the near-surface heterogeneities with a Hurst exponent of 0.1 and standard deviation of 10% is added to the upper 800 m of the subset. We computed ground motions for a lossless model and for various linear relations between Qs and Vs.
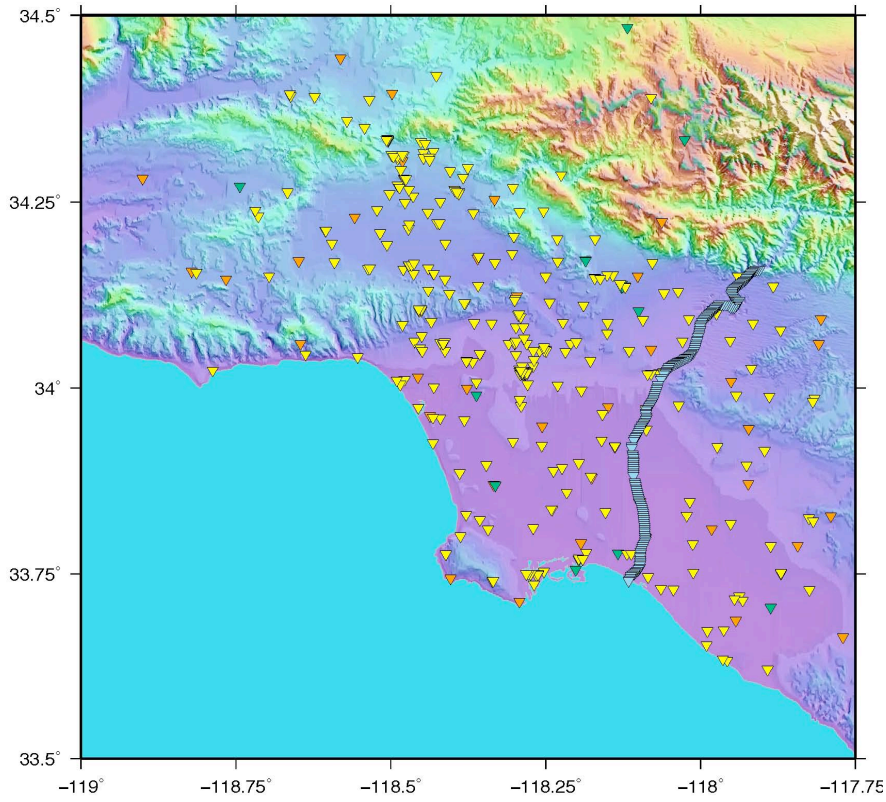
Figure 1. Location of Vs30 measurements collected for this study. John Louie provided the San Gabriel River (SGRiv) transect shown in teal trending approximately northeast, as well as various other ReMi[TM] measurements shown in orange. Data included in the SCEC CVM 4.0 compiled by Harold Magistrale and others are shown as yellow triangles. Other indirect Vs30 measurements provided by Alan Yong are shown as green triangles.
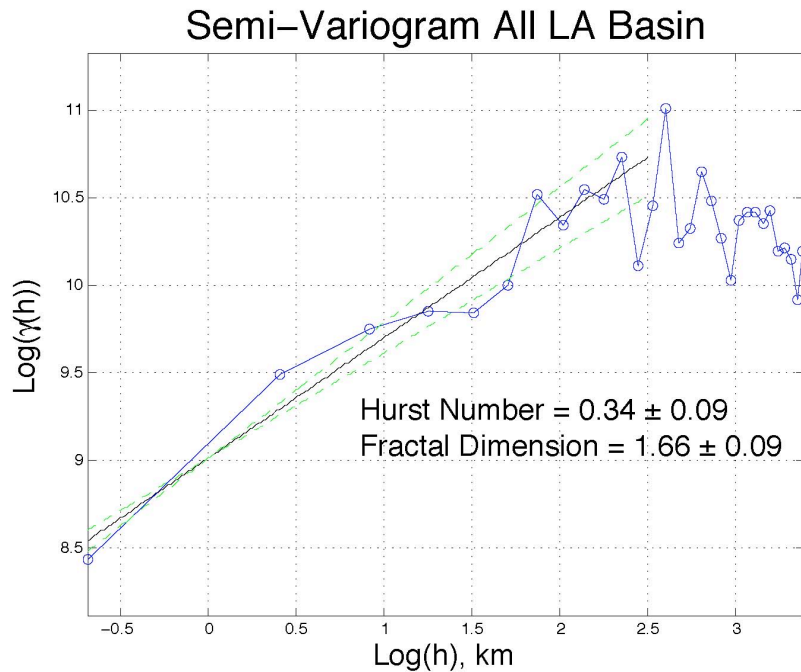

Figure 2. Semi-variogram in log-log space for all Vs30 measurements collected in Los Angeles basin.

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Some of the general conclusions from the simulations includes amplification/de-amplification of the peak ground velocities (PGVs) by up to a factor of 2, and that twice as large an area experiences de-amplified PGVs as compared to the area that experiences amplified PGVs.

Figure 4 shows a comparison of 0-2.5Hz data and synthetics at station LTP (deep LA basin, white triangle in SW model area). It is clear from the comparison that the simulation without the statistical model and the 'usual' Qs-Vs relation Qs=50Vs (km/s) grossly underpredicts the PGV from the data at this station. Results using other Qs-Vs relations (in particular, higher Qs values, such as Qs=250Vs) provide better match to the PGV and duration of the data. This is expected, as the the small-scale heterogeneities substitute some of the effects from the intrinsic attenuation specified by the Qs-Vs relation.
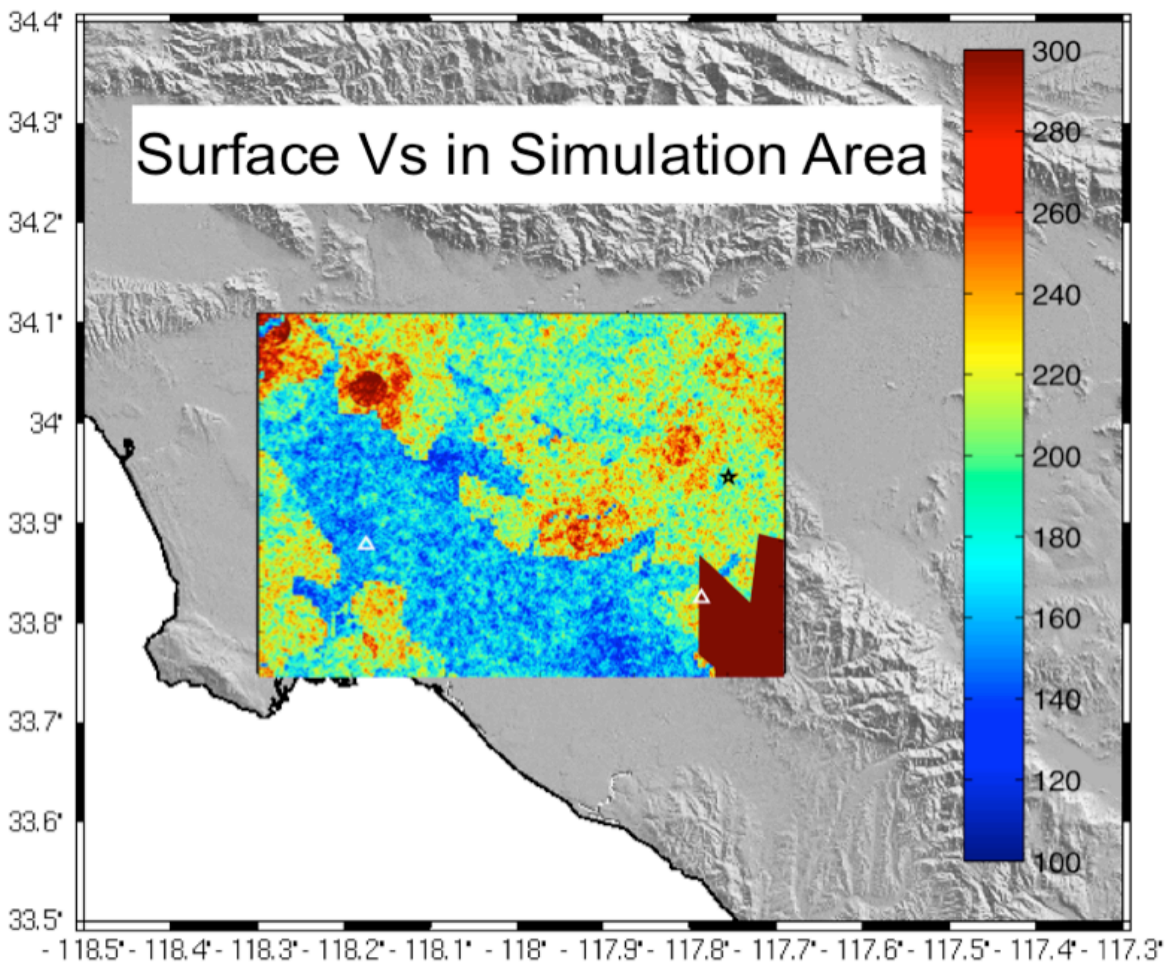

Figure 3. Surface Vs of the CVM 4.0 with the statistical model. The statistical model is included to a depth of 800 m within the model space. For the finite-difference simulations, the minimum Vs was truncated to 200 m/s.

E-W   N-S   UP

Velocity (m/s)

Data

Qs=50Vs (no inhomogeneities)

Elastic (inhomogeneities)

Qs=250Vs (inhomogeneities)

Qs=250Vs (inhomogeneities<1500 m/s)

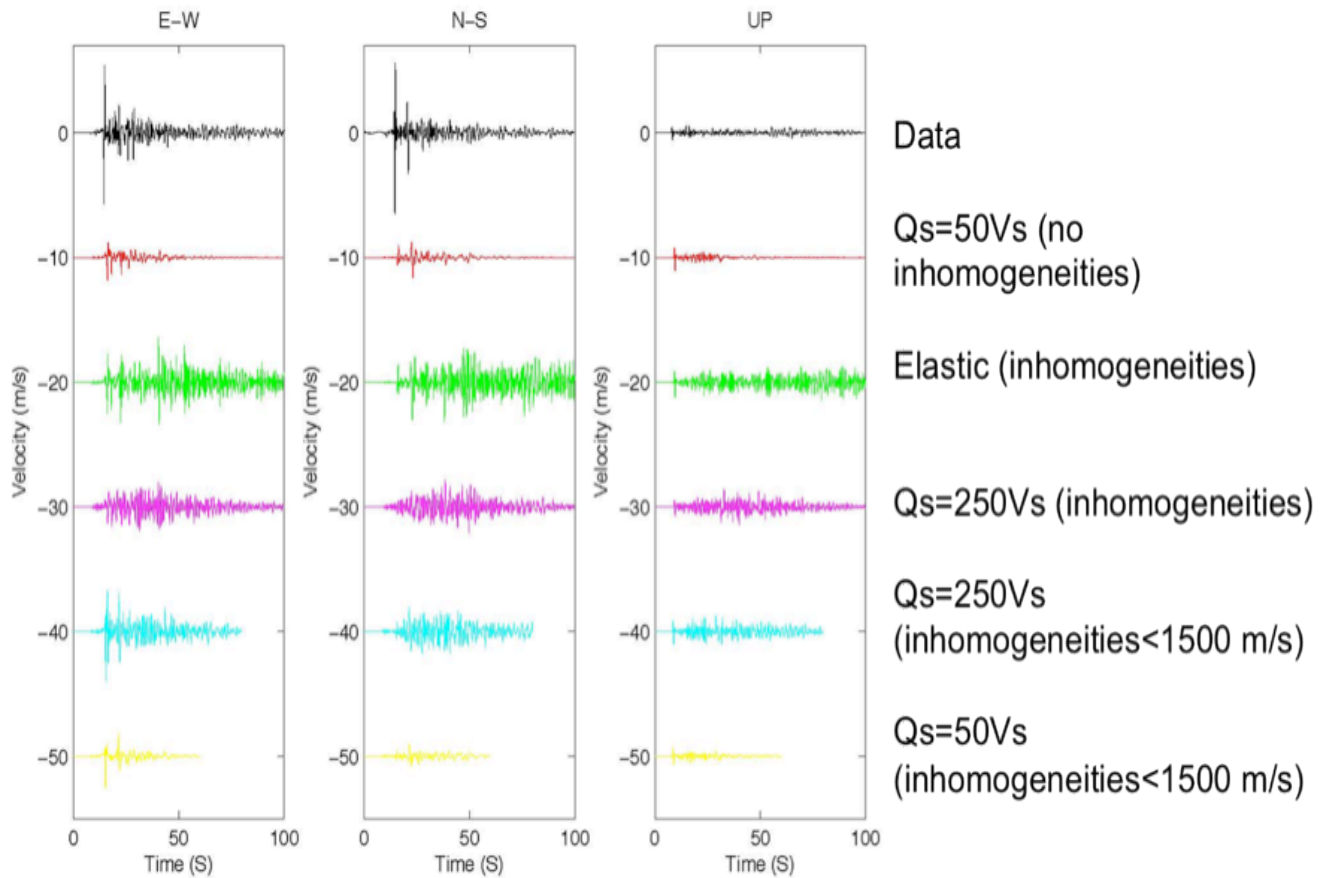Qs=50Vs (inhomogeneities<1500 m/s)

Time (S)

Figure 4. 0-2.5 Hz Data (black) and synthetics for various simulations of the 2008 Chino Hills earthquake at the deep basin site LTP (white triangle in SW area of the model shown in Figure 3).

Additional constraints on the statistical model was obtained from selected boreholes in the greater Los Angeles basin, provides by John Shaw. After correcting for cycle-skipping and detrending, we found Hurst numbers near 0.1, slightly lower than those from the Vs30 data. Continued work on the project during the SEISM award will further analyze the range of Hurst numbers from borehole logs.

Publications derived from this Award:

Olsen, K.B., W. Savran, and B.H. Jacobsen (2012). Ground motion prediction from low-velocity sediments including statistical models of inhomogeneities in southern California, in Proceedings of International Workshop 'Special project for Reducing Vulnerability for Urban Mega Earthquake Disasters', October 29-31, 2012, Ichinobo, Matsushima, Japan.

Olsen, K.B., W. Savran, and B.H. Jacobsen (2012). Spatial Variability of Shallow Velocity Measurements in the Los Angeles Area, William H. Savran, Kim B. Olsen, and Bo H. Jacobsen, procs of the 2012 SCEC annual meeting, Palm Springs, September 2012.

Olsen, K.B., W. Savran, and B.H. Jacobsen (2013). Ground motion prediction from low-velocity sediments including statistical models of inhomogeneities in southern California basins, Seism. Res. Letter, March 2013, p 334.

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