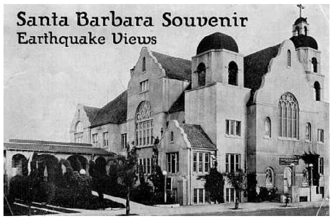

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SPATIAL VARIABILITY OF GROUND MOTION AMPLIFICATION FROM LOW-VELOCITY SEDIMENTS INCLUDING FRACTAL INHOMOGENEITIES WITH SPECIAL REFERENCE TO THE SOUTHERN CALIFORNIA BASINS

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ABSTRACT

Many state-of-the-art area-specific velocity models (e.g., the Southern California Earthquake Center (SCEC) Community Velocity Model (CVM) V.4.0) include a wealth of geophysical data, such as tomographc results, and gravity, reflection and well-log data. However, these CVMs usually poorly resolve near-surface small-scale amplification effects. Toward characterizing the variability of shallow sediment amplification, we have investigated the effects of inhomogeneities with fractal distributions augmented onto the shallow seismic velocity structure derived from the SCEC CVM V.4.0. Our analysis used linear 0-2 Hz 3D visco-elastic finite-difference wave propagation with grid spacings of 25 m or less. We find that even simple and rather weak fractal stochastic inhomogenities imply significant variations in ground motion amplifications (up to a factor of four), including bands of strong amplification aligned along the average ray path from a horizontally-propagating SH-wave source. We show that these patterns depend strongly on the incidence angle of the main wavefront. For vertically-incident planar SH-wave sources we find that the largest contribution to the site effects from small-scale heterogeneities arise from those included in the upper ~100 m of the sediment column. Finally, it is important to tune the statistical model (scattering Q) with anelastic attenuation (intrinsic Q), where a tradeoff appears to persist.

INTRODUCTION

The shaking from an earthquake can be dramatically amplified by local site effects, with prominent examples from the 1989 Loma Prieta earthquake in the Marina District of San Francisco and the 1985 Michoacan earthquake in Mexico City. The variation of the soil amplification over short distances (from tens to hundreds of meters) is important for design of lifelines such as bridges and pipelines, as these structures extend over considerable horizontal length. State-of-the-art area-specific Community Velocity Models (CVMs, e.g., the Southern California Earthquake Center (SCEC) CVM version 4.0 and CVM-H) resolve near-surface velocities on the order of kilometers. However, the resolution of small-scale amplification effects at about 2Hz, the approximate maximum frequencies in state-of-the-art ground motion (e.g., Cui et al., 2010) typically requires a resolution of the shallow sediment velocities on the order of 100 m or less. Due to the expensive acquisition of the data, it may not in the foreseeable future be feasible to capture the likely rapid spatial variation of the near-surface material by deterministic models.

A popular method to define the intrinsic attenuation (Qs and Qp) values in deterministic ground motion estimation studies is to use a function of the local shear-wave velocity Vs (see, e.g. Graves et al., 2008; Olsen et al., 2009), with calibration against strong motion data. However, this definition of the Q factors may be biased by the fact that the variation of the heterogeneities in the shallow sediments is un-physically smooth. When a more realistic distribution of shallow velocities is used, estimates of Qs (and Qp) are likely to increase, due to the added amount of scattering duration in the signal. Thus, it is likely that the refinement of shallow velocity heterogeneities will redefine the Q-velocity relations currently used in ground motion simulations.

This study aims at improving the understanding of how proposed statistical models of the near-surface sedimentary velocity variations affect ground motion amplification up to about 2 Hz. We have selected a suite of statistical models of the heterogeneities in the sediments, based on previous studies. 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).

VELOCITY MODELS AND 3D WAVE PROPAGATION

In this study we focus on the effects of inhomogeneities in the sediments, where we expect the highest degree of small-scale variation in the low-velocity material. For our analysis we generate 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 is then augmented with distributions of inhomogeneities with fractal distributions within a central area of dimensions 15 km by 15 km. The fractal inhomogeneities are included for either Vs<500 m/s (depths less than about 100 m), Vs<1000 m/s (depths less than about 500 m) or Vs<1500 m/s (depths less than about 2 km). We simulate 65 s of 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 are initiated in unison on either a vertical plane extending to a depth of 5 km, 3.75 km from the edge of the area including the fractal inhomogeneities (horizontally-propagating source), or on a horizontal plane at about 3 km depth below this area (vertically-incident source), as illustrated in Figure 1). Although somewhat simplified, this earthquake source is selected because it isolates the scattering effects. With Vs as low as 250 m/s and frequencies up to 2 Hz, we represent wavelengths as low as 125 m in the 3D model.

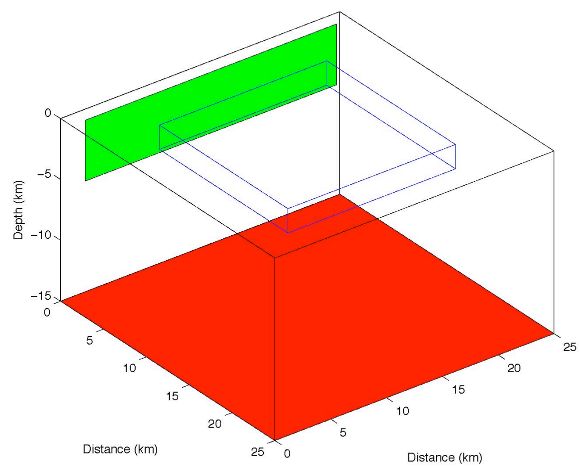

Fig. 1. Model and source geometry. Outer black box is the FD grid boundary, and the inner blue box is the volume augmented with inhomogeneities. The horizontally-incident sources are initiated on the green surface, and the vertically-incident sources are initiated on the red surface (here shown 12 km deeper than used in the simulations for convenience). The top boundary is a free surface, and the remaining boundaries are absorbing (Perfectly Matched Layers, PMLs, Marcinkovich and Olsen [2003]).

FRACTAL HETEROGENEITIES

In three dimensions, a fractal distribution has a high wave-number decay of the power spectrum P(k) as:

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

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 Shinozuka [1987]. 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. In our 3-D study we adopt the recommendation of H=0 and compare 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 to those for H=0.5 (power spectral decay of $1/k^4$). The models defined by Hurst numbers of -0.5, 0, and 0.5 represent a realistic range based on proposed models in the literature. We introduce pattern anisotropy in the model by horizontal stretching of an isotropic distribution by a factor of 5, generating horizontal and vertical length scales of the inhomogeneities of 1250 m and 250 m, respectively (or horizontal and vertical 'corner wavelengths' of 7.5 km and 1.5 km, respectively). The fractal inhomogeneities are incorporated with standard deviations (σ) of 5 or 10%, the range considered by Frankel and Clayton (1986). Figure 2 illustrates the variation of the considered velocity models as a function of depth and at the free surface. H=-0.5 represents the 'grainiest' distribution, with H=0.5 being the smoothest. While currently unknown, it is reasonable to expect that the actual distribution of heterogeneities in shallow sediments may be approximated by fractal distributions with a Hurst number between -0.5 and 0.5.

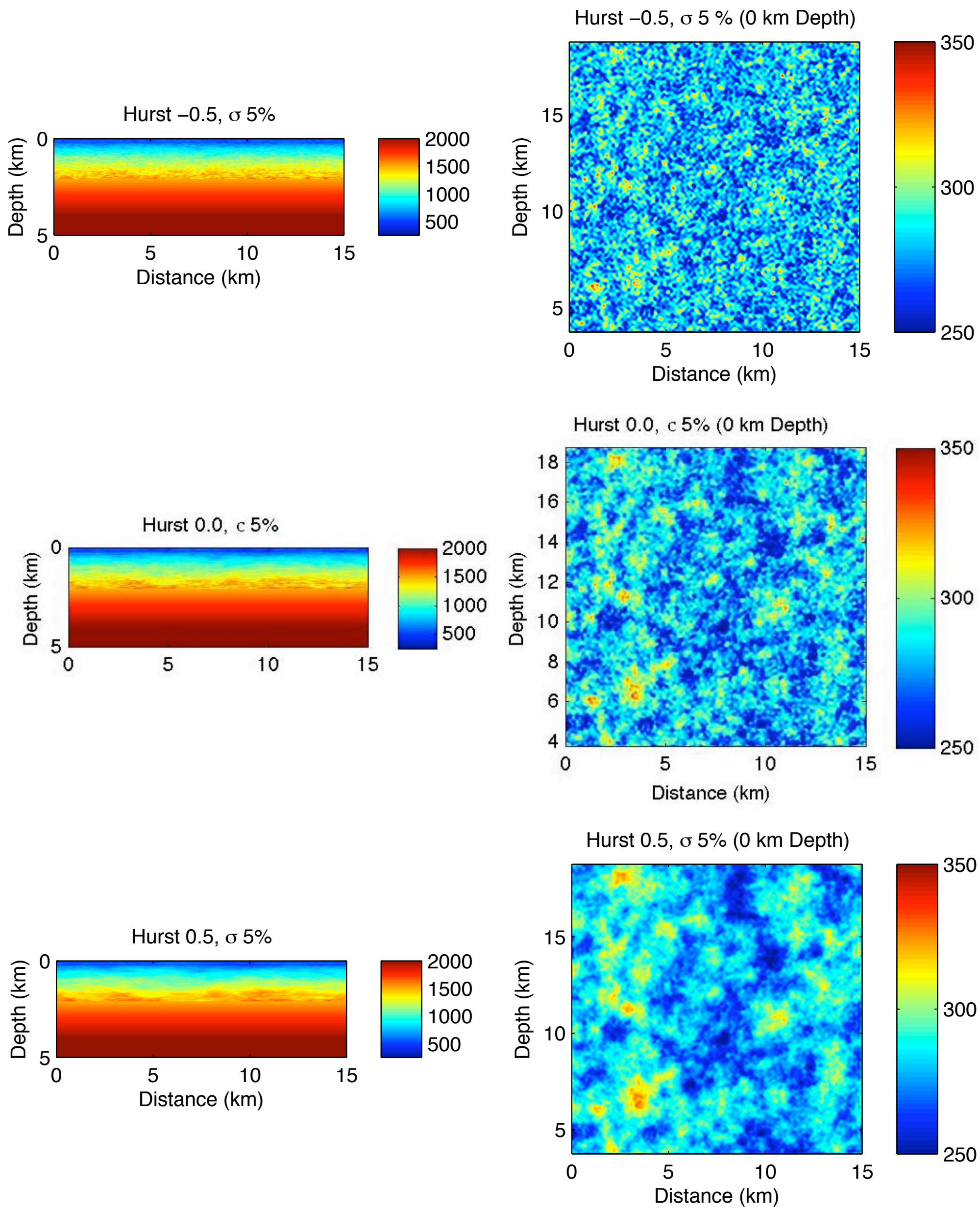

Fig. 2. (left) Vertical cross-sections along the center in the primary direction of the wave propagation and (right) horizontal slices at z=0 of the shear wave model, 5% σ, for (from top to bottom) Hurst=-0.5, 0.0, and 0.5. Fractal inhomogeneities are included for Vs<1500 m/s extending to a depth of about 2 km. Notice the more 'grainy' distribution for Hurst=-0.5, and the smoother distribution for Hurst=0.5. The velocity model is based on a 1D profile from the SCEC CVM V4.0 in the Los Angeles basin, with a minimum Vs of 250 m/s.

RESULTS FOR HORIZONTALLY-PROPAGATING SH-WAVE SOURCES

Figure 3 show snapshots of cumulated velocity vector magnitude, for a simulation in a sediment model including fractal inhomogeneities with a Hurst value of 0 and 10% σ, respectively. Notice the development of bands of large particle velocities aligned along the average ray path from the source as the SH/Love waves sweep through the inhomogeneities. These bands are clearly present in Figs. 4 (5% σ) and 5 (10% σ) showing the vector peak ground motion for models with fractal inhomogeneities included for Hurst values of -0.5, 0, and 0.5, relative to that for a (lossless) reference model without heterogeneities added. The bands of amplification increase in strength from the models with Hurst = -0.5, through Hurst = 0, to Hurst = 0.5, and (as expected) from 5% σ to 10% σ for the heterogeneities. These banded patterns depend strongly on the incidence angle of the main wavefront. While possibly in part controlled by the highly simplified earthquake source designed to isolate the scattering effects of the shallow heterogeneities, the results show that even simple and rather weak fractal inhomogeneties can imply significant variations in ground motion amplifications.

The amplification effects are summarized in Fig. 6, showing the peak ground velocities measured along left-right profiles for models with fractal inhomogeneities relative to those for the reference model (lossless, no inhomogeneities), as a function of distance in the primary propagation direction of the waves. Here, it is interesting to note that the 10% σ models show up to about 50% larger median of the peak velocity amplification than the 5% σ models at distances up to about 8 km from the source, while the values are more similar at larger distances from the source. The largest mean amplification (10% σ) reaches about 2, 2.7, and 3 for Hurst values of -0.5, 0 and 0.5, respectively, while the largest amplification for an individual model exceeds 6 (Hurst = 0.5, 10% σ). However, in addition to the areas of large amplification, notice also the areas of strong de-amplification (deep blue regions in Figs. 4 and 5), as the focusing of energy along the banded patterns generates energy sinks in the neighboring areas.

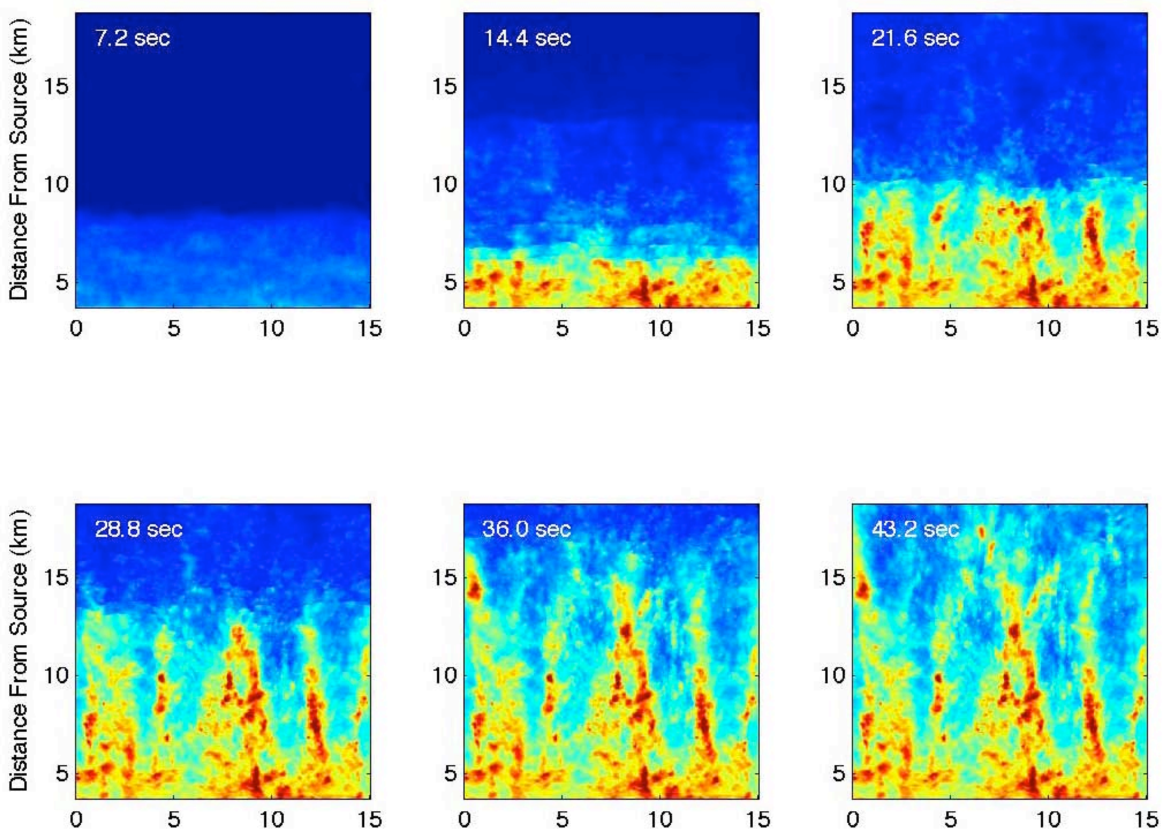

Fig. 3. Snapshots of cumulated velocity vector magnitude, for a simulation with fractal inhomogeneities with a Hurst value of 0 and 10% σ. Notice the development of bands of large velocities as the SH/Love waves sweep through the inhomogeneities. Scaling constant, arbitrary amplitude.

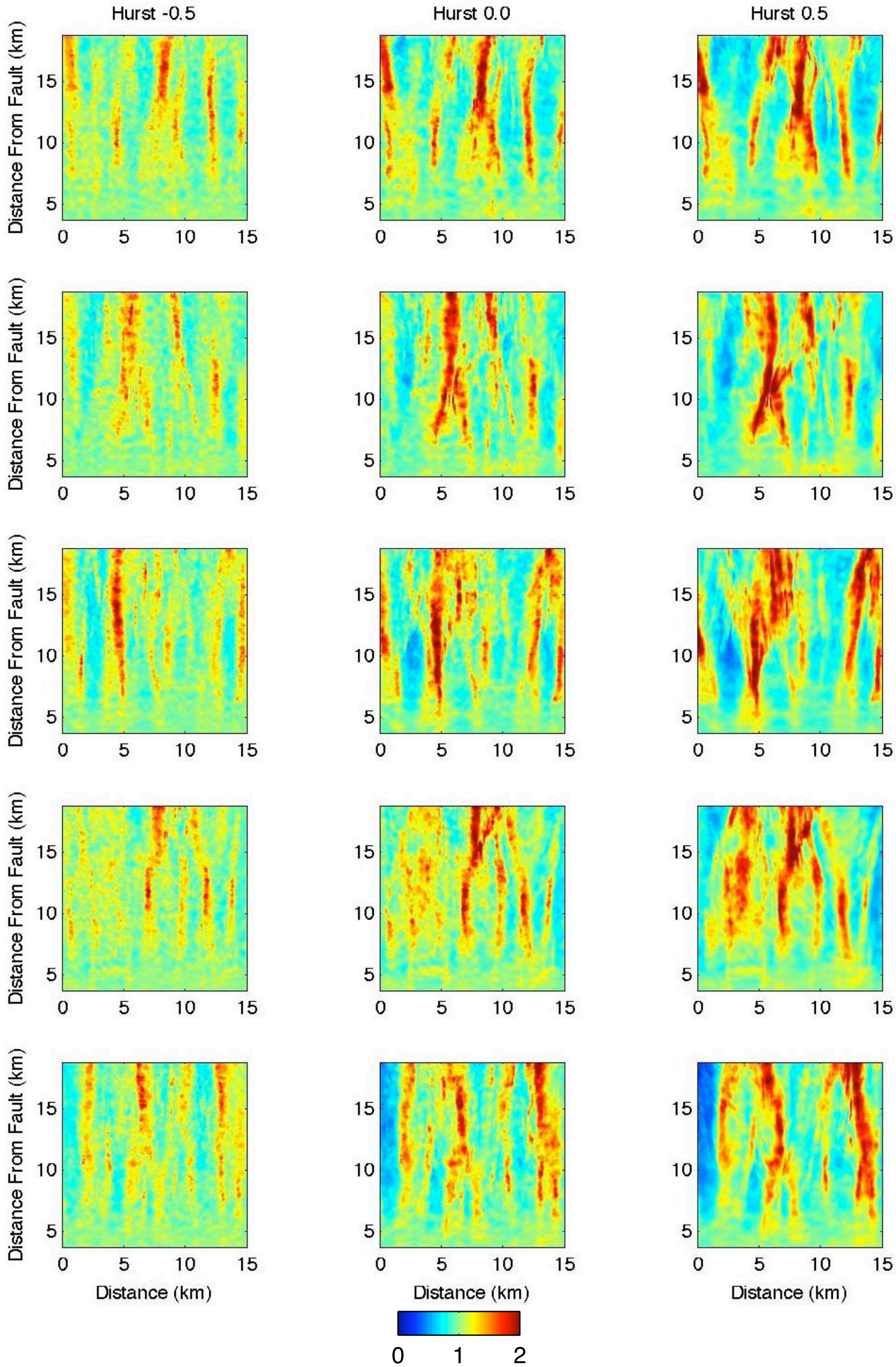

Fig. 4. Peak ground velocities for models with fractal inhomogeneities (included for Vs<1500 m/s) with 5% σ, relative to those for the reference model (lossless, no inhomogeneities). Each row represents a different seed for generating the inhomogeneities. Notice the prevailing bands of amplification aligned in the primary direction of the waves, stronger as the Hurst value increases.

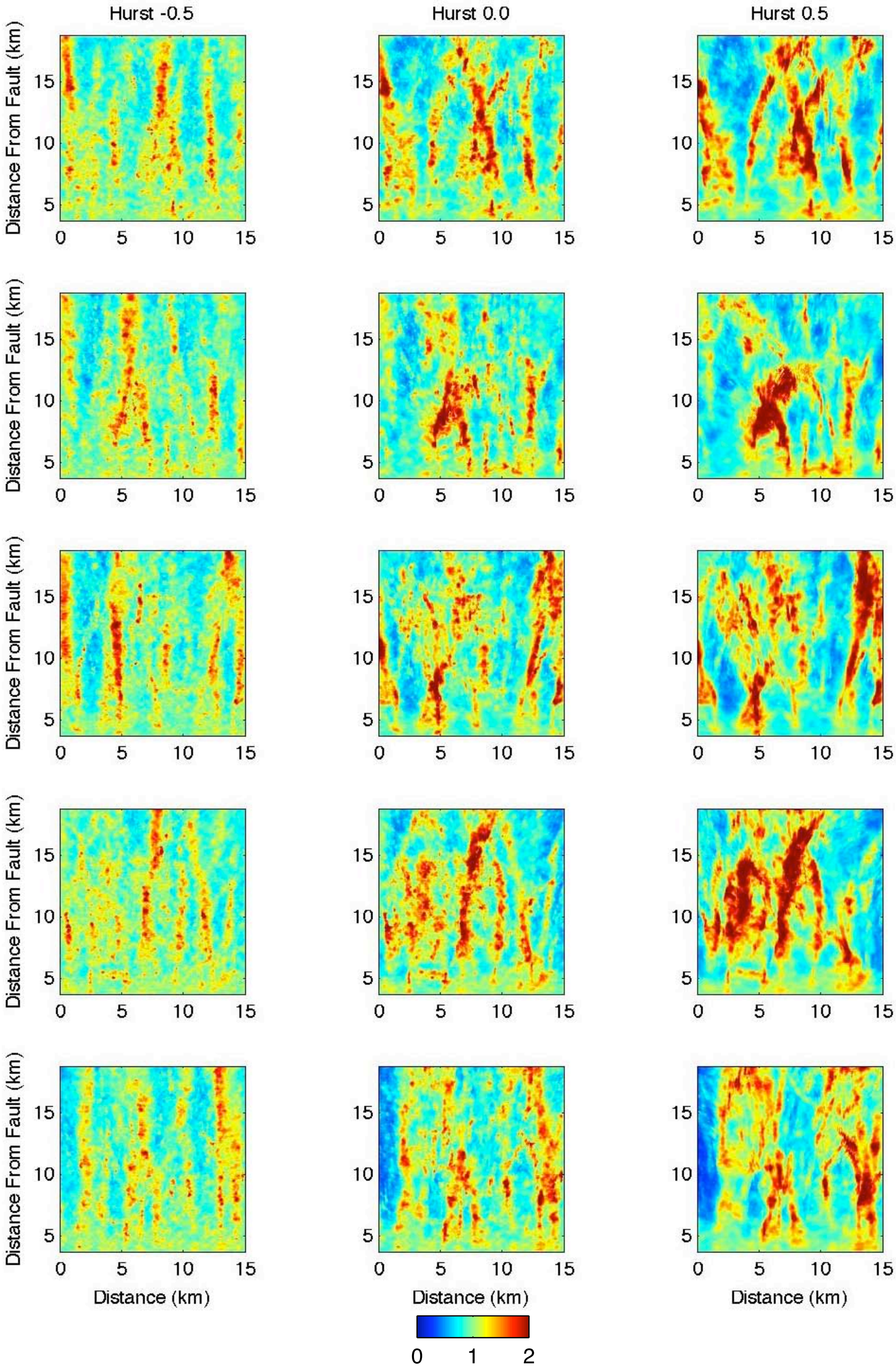

Fig. 5. Same as Fig. 4, but for 10% σ.

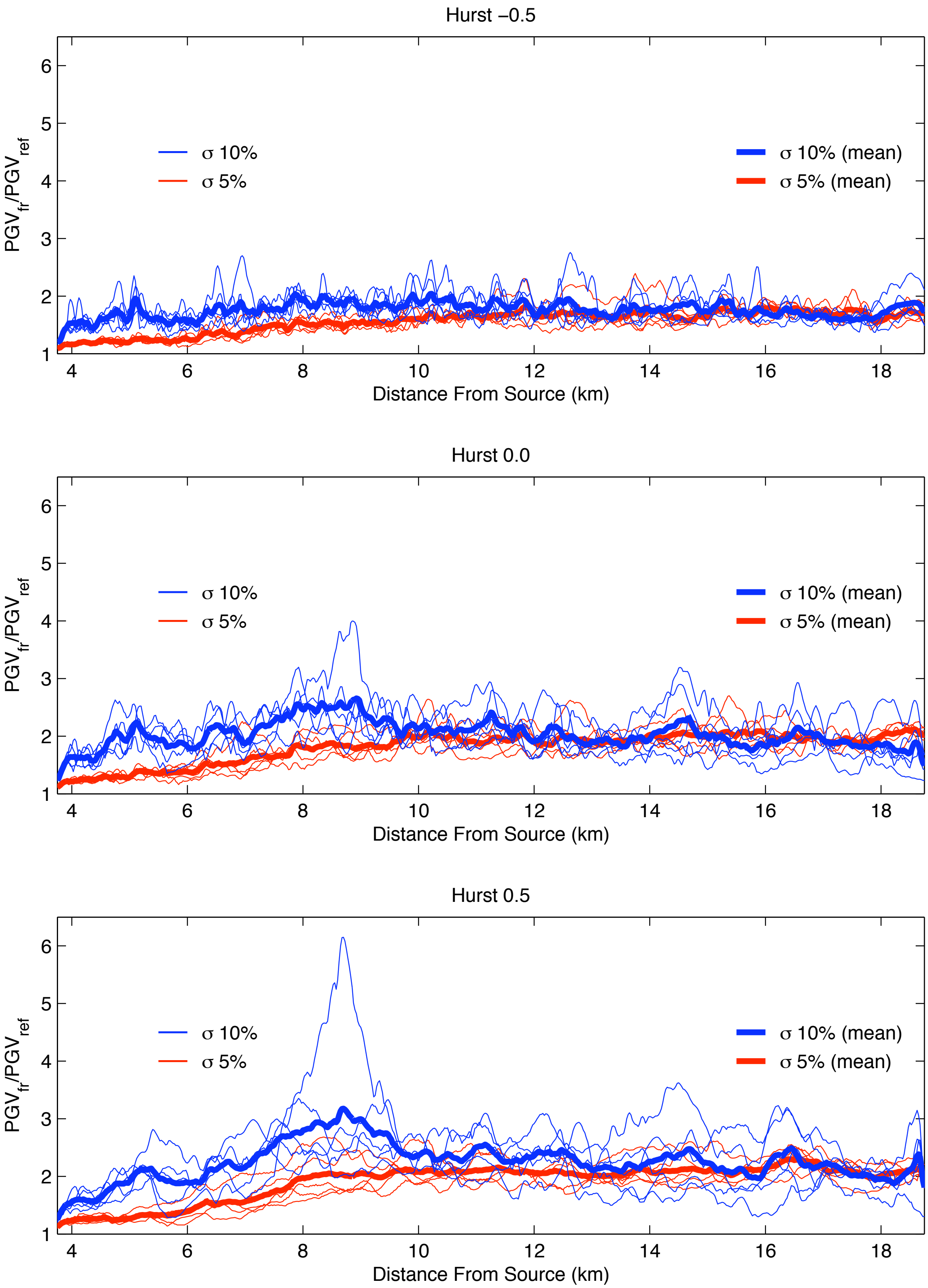

Fig. 6. Peak ground velocities measured along left-right profiles for models with fractal inhomogeneities relative to those for the reference model (lossless, no inhomogeneities), as a function of distance in the primary propagation direction of the waves. Notice that the 10% σ models show up to about 50% larger median of the peak velocity amplification than the 5% σ models at distances up to about 8 km from the source, while the values are more similar at larger distances from the source.

Figure 7 shows synthetic seismograms along the center of the (lossless) 3D model in the primary propagation direction of the waves in a model with fractal inhomogeneities characterized by a Hurst number of 0 and σ 5% and 10%. Note the decrease in coherency of the SH/Love wave train on the transverse component and increase in scattering amplitude on the radial and vertical components from σ 5% to σ 10%. This also illustrates how larger σ tends to increase the signal duration.

Our results 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 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. Figure 8 shows transverse-component synthetic seismograms along the center of the 3D model, including fractal inhomogeneities with H=0.0 and σ 10%, for a lossless model and models using Qs=500*Vs (km/s), Qs=200*Vs (km/s), and Qs=100*Vs (km/s). These results suggest 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.

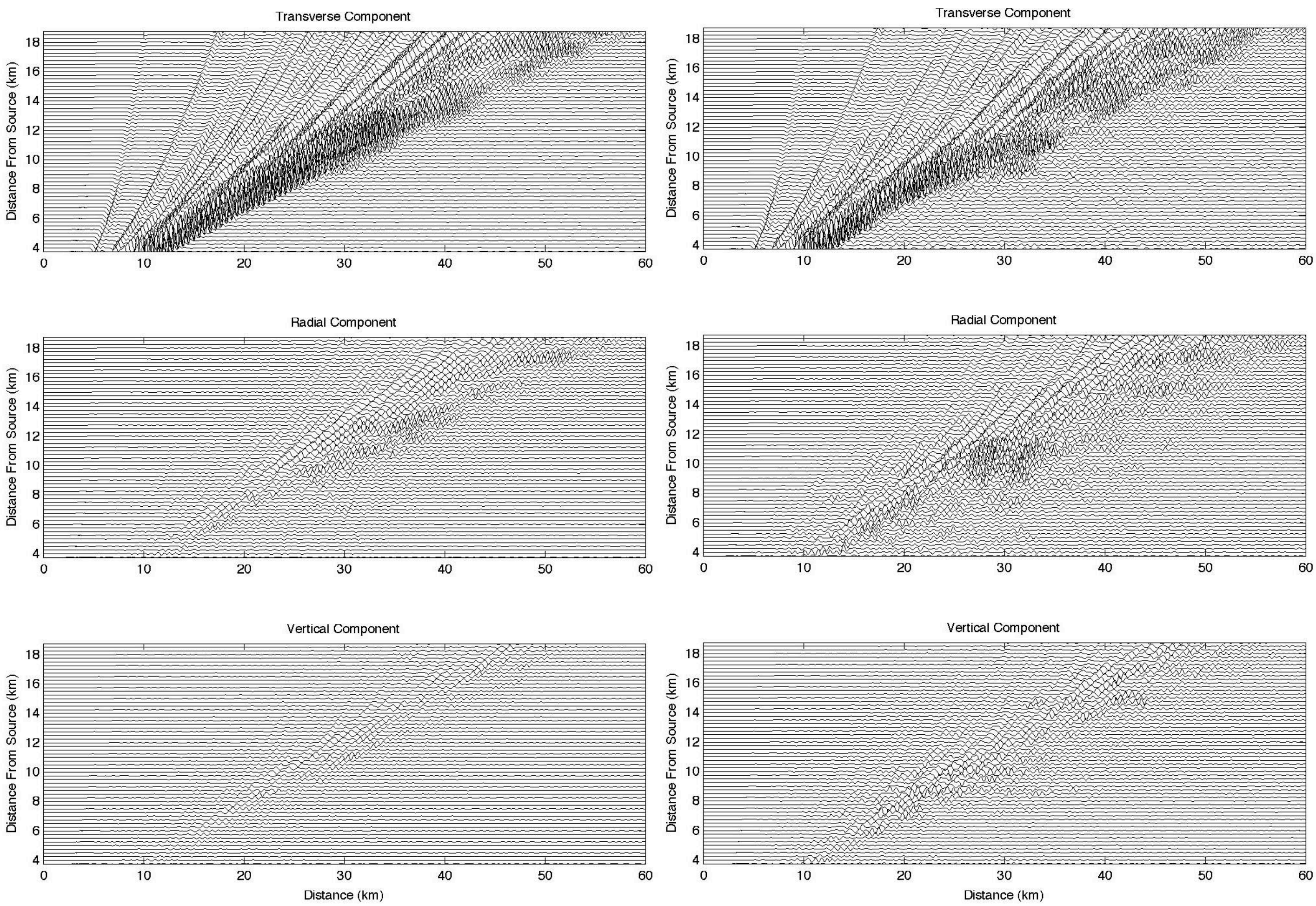

Fig. 7. Three-component synthetic seismograms along the center of the (lossless) 3D model in the primary propagation direction of the waves in a model with fractal inhomogeneities characterized by a Hurst number of 0 and (left) σ 5% and (right) 10%.

RESULTS FOR VERTICALLY-INCIDENT SH-WAVE SOURCES

Figure 9 shows peak ground velocities for models with fractal inhomogeneities, included for Vs<1500 m/s (M1500, to depths of about 2 km), Vs<1000 m/s (M1000, to depths of about 1 km), and Vs<500 m/s (M500, to depths of about 100 m) with 5% σ and Hurst=0.0, relative to those for the reference model, using a vertically-incident planar SH-wave source. Note that these amplification levels represent effects from the fractal inhomogeneities only. The mean of the largest amplification values for the five different seed values reaches 20% for the M1500 models, 19% for the M1000 models and 15% for the M500 models. This results suggests that while the inhomogeneties buried in deeper sediments increase the amplification, the largest contribution to the 0-2 Hz site effects are due to small-scale velocity (and density) variations included in the upper ~100 m of the sediment column. The primary contribution of the inhomogeneties included at deeper depths (down to about 2 km) is a slight increase in the corresponding amplification (and de-amplification) levels at the same locations as those observed for the M500 model.

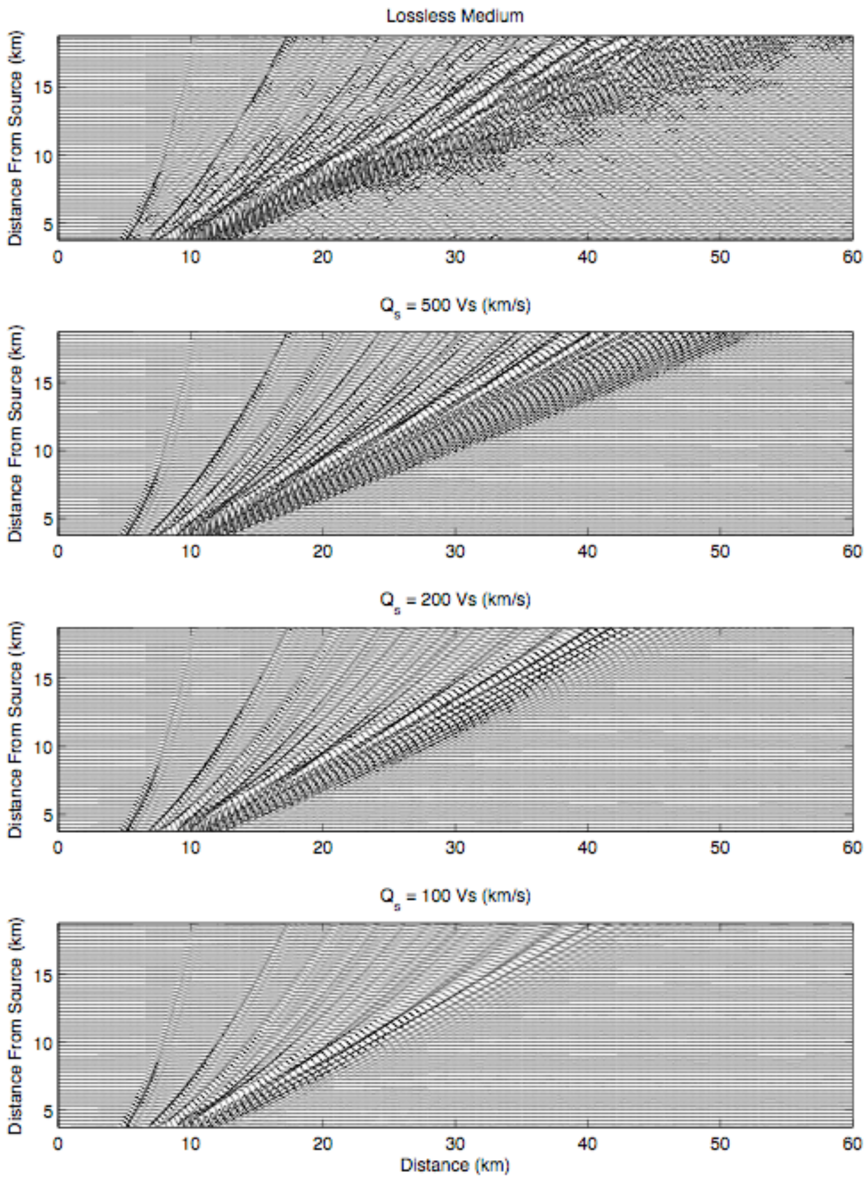

*Fig. 8. Transverse-component synthetic seismograms along the center of the 3D model, including fractal inhomogeneities with H=0.0 and σ 10%. From top to bottom: Lossless, Qs=500*Vs (km/s), Qs=200*Vs (km/s), and Qs=100*Vs (km/s).*

COMPUTATIONAL ASPECTS

The 3D fractal distributions are generated using optimized matlab scripts, requiring a few minutes of runtime for the 3D models. The wave propagation is carried out by a fourth-order staggered-grid visco-elastic finite-difference method in a 3D velocity model (Olsen et al., 2009). Each 3D simulation required about ½ hour wall-clock time using 3600 cores on Kraken at NICS. The computational parameters are summarized in Table 1.

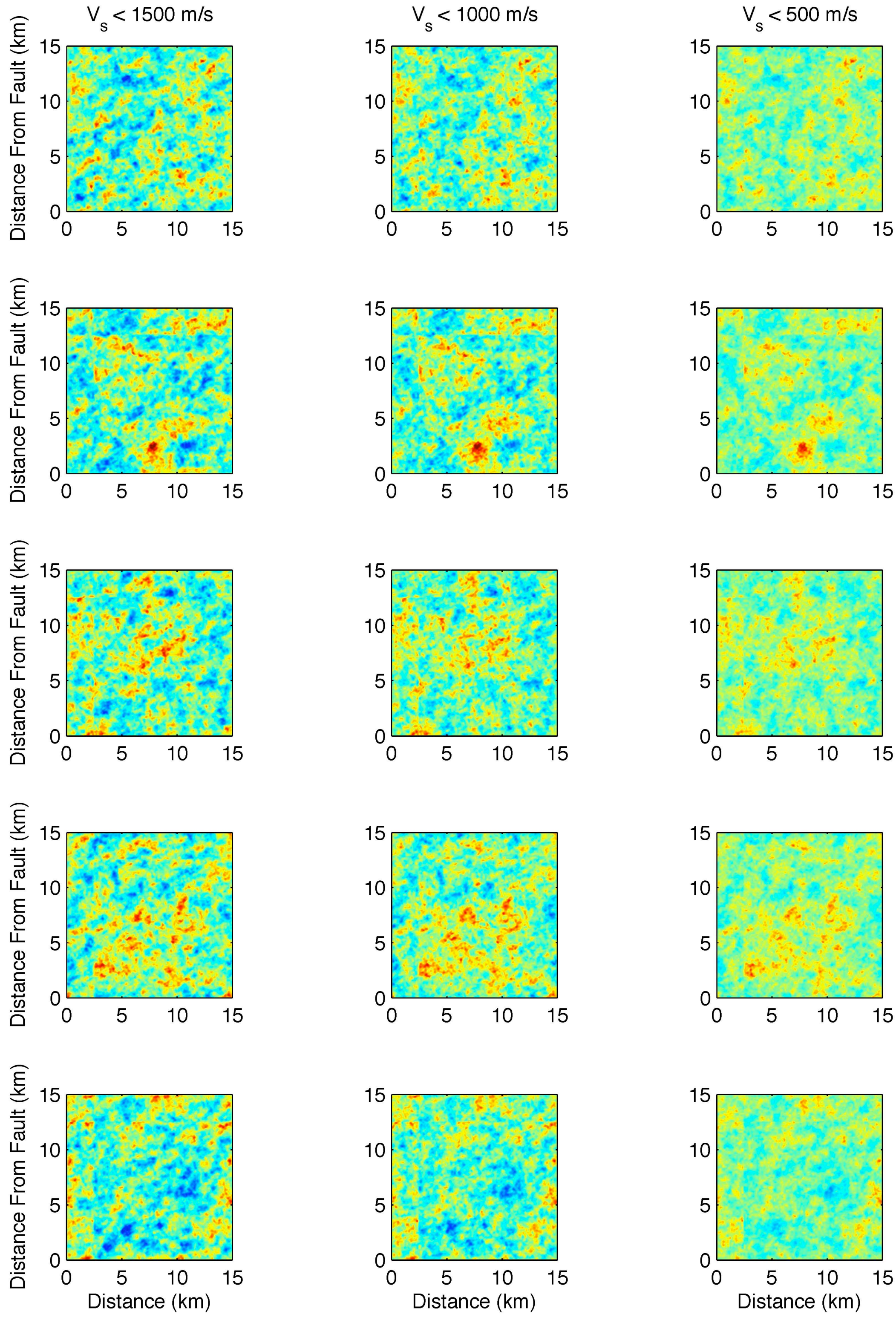

Fig. 9. Peak ground velocities for models with fractal inhomogeneities, included for (left) Vs<1500 m/s, (middle) Vs<1000 m/s, and (right) Vs<500 m/s with 5% σ and Hurst=0.0, relative to those for the reference model (lossless, no inhomogeneities), using a vertically-incident planar SH wave. Each row represents a different seed for generating the inhomogeneities.

Table 1. Computational Parameters

Parameter	Value
Number of grid points	600 million
Grid spacing	25 m
Time step	0.0018 s
Simulation time	65 s
Minimum S-wave velocity	250 m/s
Maximum frequency	2 Hz

DISCUSSION AND CONCLUSIONS

State-of-the-art area-specific velocity models do not resolve small-scale amplification effects in the near-surface sediments, possibly introducing bias in earthquake ground motion simulations, as the frequencies increase. Our preliminary analysis shows that even simple and rather weak fractal stochastic inhomogenities imply significant variations in ground motion amplifications (up to a factor of six) as well as de-amplification, including bands of strong amplification aligned along the average ray path from a 0-2 Hz horizontally-propagating SH-wave source. Simulations with vertically-incident planar SH-wave sources show that the small-scale heterogeneities included in the upper ~100m of the sediment column contribute more to the site effects, as compared to small-scale heterogeneities buried deeper in the sediments. A tradeoff is found for the statistical model (scattering Q) with anelastic attenuation, indicating that the latter needs to be tuned for models including the near-surface heterogeneities, as compared to existing, smoother velocity distributions.

It may be possible to establish a realistic statistical model of the near-surface inhomogeneities by comparison of earthquake ground motion simulations to data (e.g., O'Connell, 1999), and by directly mapping the statistical properties of shallow Vs (such as Vs30) estimates (e.g., Thompson et al., 2009; Thompson, 2010). Important constraints of such model include the effective depth extent to which the source of the scattering originates, and the fractal dimension of the inhomogeneities. If incorporated in the CVMs, such models may improve deterministic ground motion prediction as supercomputers allow the highest frequency to increase. Future efforts should also incorporate more realistic earthquake sources and 3D CVMs.

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