# Final Technical Report

# Refined Seismic Amplification Forecasting by Improved Basin-Structure imaging with noise correlation methods

USGS Grant No. G09AP00138

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The cities of Seattle and Tacoma lie largely atop deep sedimentary basins. These basins amplify and distort the seismic waves from nearby moderate and large earthquakes in ways that need to be understood if we are to anticipate the hazard from future earthquakes. Hazard maps are strongly dependent on the accuracy of basin shear wave velocity models and basin surfaces waves, converted from incident shear waves, are a particular hazard in the Seattle basin [Frankel, et al 2007].

We obtained the SHIPS dataset and used it to extract short-period Rayleigh waves in the Seattle basin using ambient noise techniques. The SHIPS dataset is augmented by nearby stations of the Pacific Northwest Seismic Network (PNSN) and Earthscope's Transportable Array (TA). We use ray theory and a Born approximation to forward model Rayleigh wave phase velocities and invert for the 2-D velocity structure at a range of frequencies.

Since the recording period of the SHIPS array was short (~40 days), many of the station pairs did not produce measurable surface waves. However, we were able to extract data from ~3000 paths over 7 periods between 2-10 seconds to constrain the upper few kilometers of the basin. Data coverage is excellent in the city of Seattle and some of the surrounding communities. Our Rayleigh wave phase velocity model clearly shows the location and magnitude of the Seattle fault and basin.

We developed a 3-D inverse method to calculate the shear wave velocity of the Seattle Basin using our Rayleigh wave phase velocity model [Delorey and Vidale, 2010]. Our forward calculation uses a normal mode method developed by Tekeuchi and Saito [1972]. Our results reveal greater detail in the upper 4 km than previous models. (Figure 1).

We collected data from two local earthquakes, a shallow crustal event and a deep Benioff Zone event. For these two events we run finite-difference simulations using our velocity model and the previous velocity model used in the development of the Seattle seismic hazard maps. The simulations using our new velocity model more closely predict the observations than simulations using the previous model for periods between 1-2 seconds (Figures 2 and 3). Both the data and the simulations demonstrate that levels of shaking are dependent upon a complex set of variables including basin structure, wave-guides, and soil types.

We are computing three-dimensional finite-difference seismograms incorporating velocity, density and attenuation variations, and constructing improved models for predicted ground shaking during various realistic earthquake scenarios (Figure 4). Then, working with Art Frankel we are using these improved models to help quantify the risk of strong shaking to the urban environment and critical infrastructure, as Art has already done with previous models.

We use ambient noise to directly observe the shear wave velocity structure of the Seattle Basin. The 3D structure of deep crustal basins has a significant impact on the propagation of seismic waves and seismic hazards in the cities that sit atop them. Our shear wave model of the Seattle Basin contains more detail than the previous model used in seismic hazard assessments and may help explain some of the unmodeled amplitude scattering observed in previous efforts. We have shown quantitatively that our new model makes better predictions than the previous model for two local earthquakes.

Our method’s strength is the resolving power of short period Rayleigh waves on shear wave velocity in the upper few kilometers without the need to precisely know Poisson’s ratio. We believe that our new model can be applied to predict levels of ground shaking with greater accuracy than the current seismic hazard maps for Seattle, as demonstrated by the two events we examined, due to more accurate modeling of shear wave velocities in the upper 3-4 km of the basin.

Further improvements in the Seattle Basin velocity model could be achieved using a more optimal station arrangement, more broadband instruments, a longer recording duration, and developing a joint inversion that explicitly includes geological information about sharp discontinuities such as faults and basin edges. However, using a limited, legacy dataset we were able to make measurable improvements to amplitude predictions for two local earthquakes at frequencies relevant to seismic hazard assessments.

Delorey, A. A. and Vidale, J. E. (2010), Seattle Basin shear-velocity model from noise correlation Rayleigh waves, *submitted Bul. Seis. Soc. Am*

Frankel, A.D., Stephenson, W.J., Carver, D.L., Williams, R.A., Odum, J.K, and Rhea, S., 2007, Seismic hazard maps for Seattle, Washington, incorporating 3D sedimentary basin effects, nonlinear site response, and rupture directivity: *U.S. Geological Survey Open-File Report* 2007-1175, 77 p., 3 pls.

Stephenson, W. J. (2007), Velocity and density models incorporating the Cascadia Subduction Zone for 3D earthquake ground motion simulation, *U.S. Geological Survey Open-File Report* 2007-1348.

Takeuchi, H., and M. Saito (1972), Seismic surface waves, *Methods Comput. Phys.*, 11, 217–295.

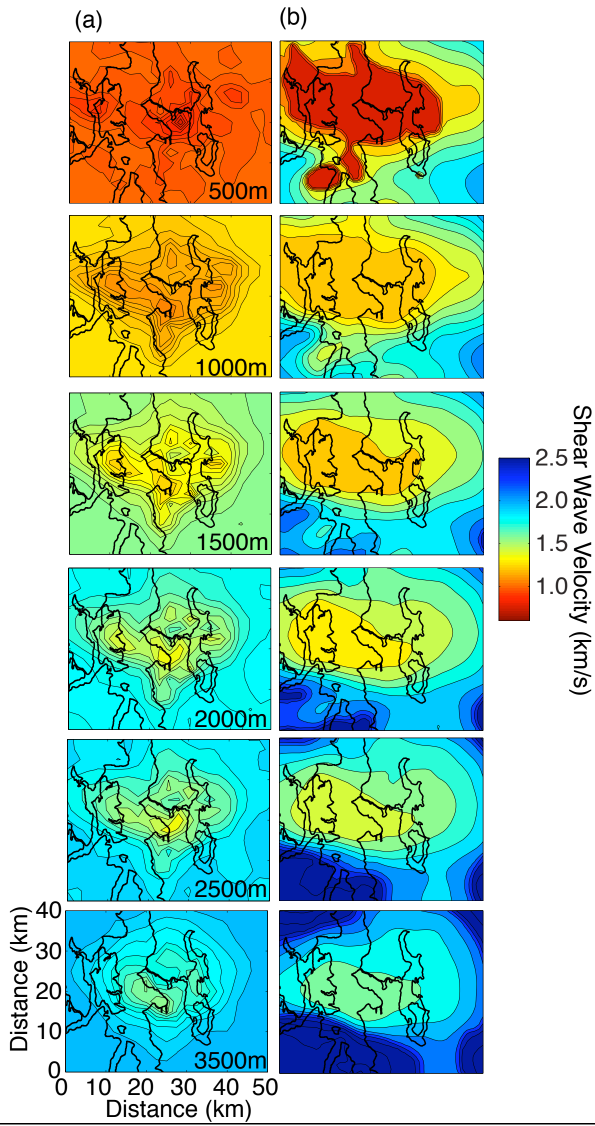


Figure 1. Shear wave velocity of the Seattle Basin from (a) this study and (b) Stephenson (2007)

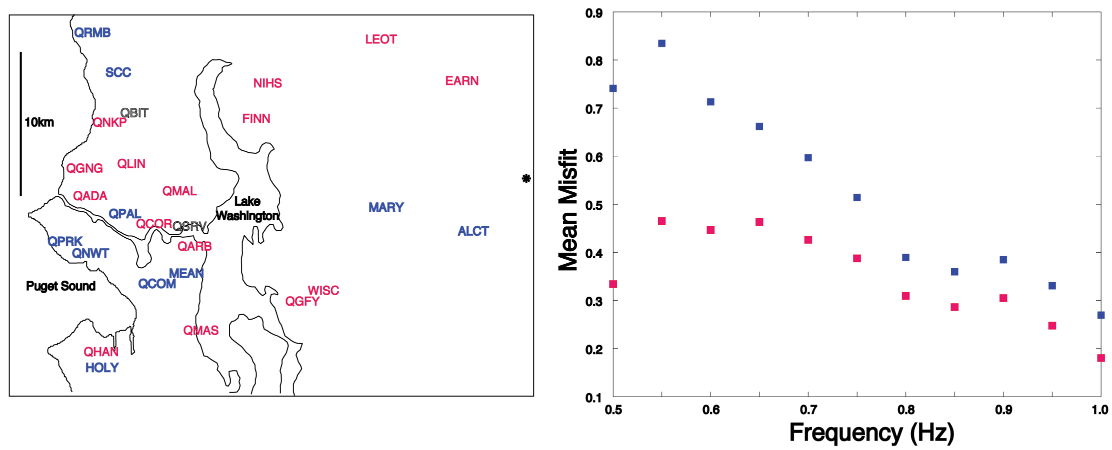


Figure 2. To the left is shown stations recording the event whose epicenter is indicated by the asterisk. Stations in red indicate locations in which our new model better predicts amplitudes than the previous model. Stations in blue indicate locations in which the previous model better predicts amplitudes than our new model. Black stations indicate locations where amplitude predictions were nearly identical. To the right is shown the average amplitude misfit for all station at a range of frequencies between 0.5-1 Hz; red squares indicate misfit for our new model and blue squares indicate misfit for the previous model.

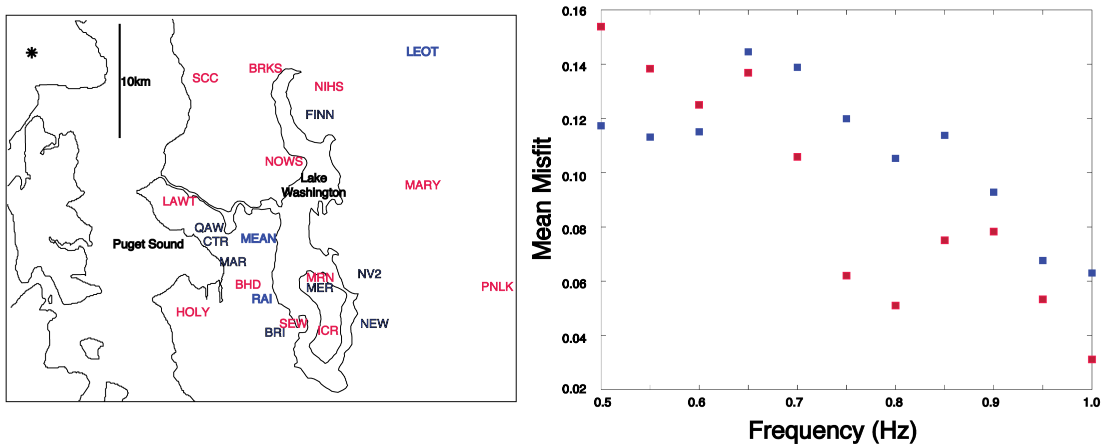


Figure 3. To the left is shown stations recording the event whose epicenter is indicated by the asterisk. Stations in red indicate locations in which our new model better predicts amplitudes than the previous model. Stations in blue indicate locations in which the previous model better predicts amplitudes than our new model. Black stations indicate locations where amplitude predictions were nearly identical. To the right is shown the average amplitude misfit for all station at a range of frequencies between 0.5-1 Hz; red squares indicate misfit for our new model and blue squares indicate misfit for the previous model.

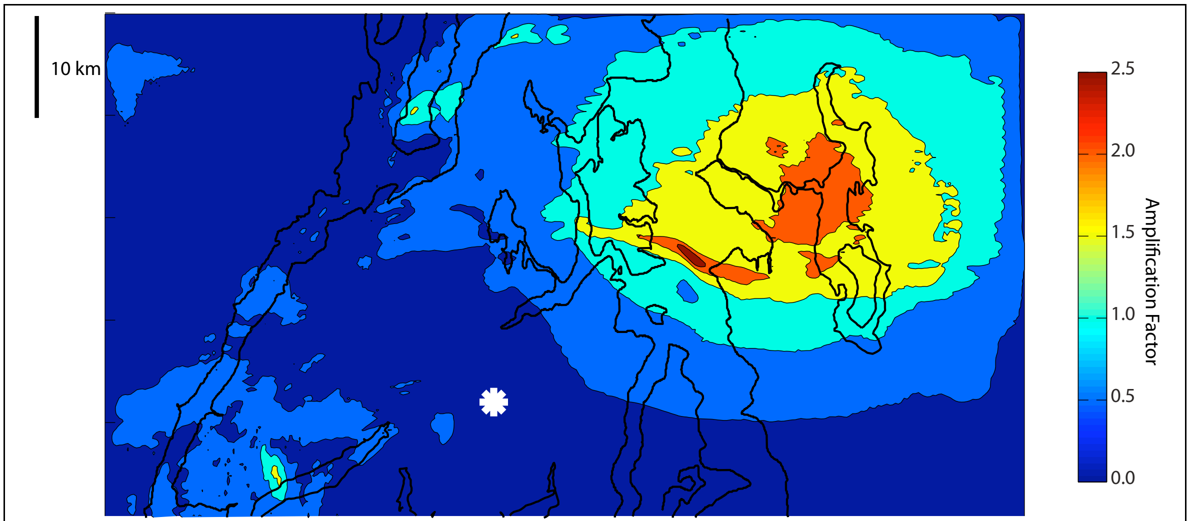


Figure 4. Amplification factors for a 51 km deep Benioff zone earthquake indicated by the white asterisk. The high amplitude factors to the southwest are caused by a wave-guide effect of the Seattle Fault and the other regions of high amplification are due to the effects of the Seattle Basin.