Shear-wave velocity (Vs) to over 2 km depth as characterized through the krSPAC microtremor array method: case study from the Seattle basin, Washington


Summary

We acquired microtremor array data at 11 sites in the Seattle basin, Washington State, and applied the wavenumber-normalized SPAC method (krSPAC) to obtain Vs to over 2000 m depth. In the krSPAC approach, we transform observed coherency-versus-frequency spectra to coherency-versus-kr (where k and r are wavenumber and station separation, respectively) prior to Vs modeling. Through this transformation, the requirement for array symmetry is eased. We deployed seven-sensor nested irregular triangular arrays, with nominal interstation separations that varied from ~300 m to 2000 m. Comparison of krSPAC Vs results to a previous interpretation from ambient noise tomography suggests a broadly comparable Vs structure in the 250 to 1000 m depth range and improved resolution at shallower depth. At each site, we interpret a high-velocity Quaternary boundary where Vs increases above 900 m/s. Using this boundary as the reference horizon, we calculate ground motion amplification of a factor of up to 2 from the overlying Quaternary sediments between 0.3 and 7 Hz.

Introduction

Shear-wave velocity (Vs) profiling methods have increased dramatically in the past 20 years through the development of ambient noise techniques that include SPAC (Aki, 1957; Bettig et al. 2001; Okada, 2003) and tomographic methods as utilized at global and mid-crustal scales (Bensen et al., 2007; Ekstrom et al., 2009). More recently, shallow crustal Vs models have been developed through advances in noise tomographic methods (Lin et al., 2013), seismic interferometry (Nakata et al., 2011), and frequency wavenumber beam-forming methods (Foti et al., 2011; Poggi et al., 2017).

Advances in SPAC Methods

Traditionally, SPAC practitioners analyze the vertical seismic wavefield acquired by sensors in a symmetric circular or quasi-circular array for Rayleigh wave dispersion. Modern implementations have seen numerous advances (Okada, 2003), including nontraditional array designs (Cho et al., 2004; Chavez-García et al., 2006), three-component wavefield analysis (Köhler, et al., 2007; Lamb et al., 2014), and other applications extending beyond Aki’s (1957) original theoretical foundations. The wavenumber normalized spatially-averaged coherency method (krSPAC) described by Asten et al. (2015) is one such implementation. This method differs from many SPAC implementations (such as Picozzi and Albarello (2007) and Di Giulio et al. (2012)) by making use of direct fitting of averaged interstation coherency spectra for layered-earth models rather than the more common approach of extracting phase-velocity dispersion curves followed by inversion for a layered-earth model.

Seattle Basin

The Seattle basin was first defined with gravity data (Danes et al., 1965), and it was subsequently delineated from aeromagnetic (Blakely et al., 2002) and active-source seismic imaging investigations (e.g., Johnson et al. 1994, Pratt et al., 1997; Brocher et al., 2001). Borehole data compiled by Jones (1996) delineate the general shape of the base of unconsolidated sediments within the Seattle basin most commonly interpreted as representing the base of Quaternary deposits (Johnson et al., 1999; Figure 1). However, these data do not impose strong constraints on the basin shape nor provide insight into the Vs structure beneath the city of Seattle at depths of 800 m or greater (deeper than many common Vs profiling methods typically image).
krSPAC basin-scale $V_s$ imaging

characterization of earthquake ground shaking and seismic hazard assessment in these areas is difficult. Previous studies within the Seattle basin have documented earthquake ground motion effects, such as amplification, caused by the 3D geometry and geologic layering of the basin (Hartzell et al., 2000; Frankel and Stephenson, 2000; Frankel et al., 2009).

We characterize $V_s$ with the krSPAC method from microtremor array data acquired in the Seattle basin, using seven-sensor arrays with up to 2000 m nominal interstation spacing at 11 sites. We investigate if these large-scale datasets can both characterize $V_s$ at depths over 1000 m and delineate the Quaternary-Tertiary boundary within the basin for use in earthquake ground motion studies.

**krSPAC Microtremor Array Method**

The krSPAC modeling method implements a wavenumber normalization scheme to increase the usable wavelengths and spectral bandwidth for extending dispersion analysis of ambient noise array data (Asten et al., 2015). The method, which is an extension of the MMSPAC approach of Asten (2006), relies on the use of a multi-sensor array, but the sensor array geometry can be significantly. By adhering to a multi-sensor analysis scheme, the method takes advantage of the spatial averaging inherent with conventional SPAC techniques that mitigates bias introduced by incomplete knowledge of the ambient noise source locations and propagation directions.

The concept of azimuthal averaging of coherencies for a plane wave passing multiple pairs of stations can be expressed, following Aki (1957), in the form

$$\rho(f) = \int e^{i k r \cos \theta} d \theta = J_0(kr)$$

where $\rho$ is the coherency spectrum, $k = 2 \pi f / C(f)$ is the wavenumber, $f$ is frequency, $C(f)$ is the phase velocity dispersion curve, $r$ is a constant station separation, $\theta$ is azimuthal angle of a station pair relative to the plane wave vector, and $J_0$ is the Bessel function of zero order. When performing interpretation via direct fitting of SPAC spectra, we use Equation 1 with a known value of $r$ and a forward model dispersion curve $C(f)$ to compute a model SPAC spectrum that is fit to the observed azimuthally averaged SPAC spectrum. The direct fitting is achieved by iterative forward modelling. The quality of the fit over a given bandwidth is measured objectively by the standard deviation of the fit, and variables in a layered earth model ($V_s$, and thickness $h$) are varied to achieve a best fit via a least-squares criterion. In our current implementation, uncertainty in layer thickness and velocity is captured through extremal analysis.

The need for array symmetry has been an historical limitation when inverting $V_s$ profiles from SPAC coherency spectra because of the loss of information at high wavenumbers during azimuthal-averaging. With krSPAC, we interpolate each spectrum to coherency-versus-kr instead of averaging sets of coherency-versus-frequency spectra and then fitting to an average SPAC spectrum, where $r$ may be different for each pair of stations. For fundamental mode Rayleigh-wave energy, the modeled SPAC spectrum reduces to $J_0(kr)$. The normalization process changes with each modeling iteration because $k$ is a function of frequency and phase velocity, and thus is updated with every change of the $V_s$ profile. The krSPAC approach has been tested against both boreholes and other ambient noise modeling methods and has been successful in these comparisons (Asten et al., 2015).

One of the important advantages of the krSPAC approach is that it can permit modeling to higher kr space (i.e., higher wavenumber, higher frequency, and better model resolution) with asymmetric sensor spacing. We use percent difference in the interstation distances among the three legs of a given analyzed array as a measure of array asymmetry, as given by the equation

$$\text{diff} = \frac{|r_{\text{max}} - r_{\text{min}}|}{(r_{\text{max}} + r_{\text{min}})/2} \times 100\%$$

where $r_{\text{max}}$ and $r_{\text{min}}$ are the longest and shortest interstation distance among any three sensors, respectively. For our analysis, we calculate coherency between three sensors at an average interstation distance ($r_{\text{avg}}$). In Figure 2, we compare sites RD08 and UW06, which have $r_{\text{avg}}$ asymmetry measures that are 2% to 18% and 14% to 102%, respectively.

![Figure 2: Examples of krSPAC coherency curves versus traditional curves. (a) Site RD08 has ~18% asymmetry on large array ($r_{\text{avg}} = 968$ m). Both observed $p(\theta)$ and $p(f)$ fit well overall, but $p(\theta)$ at $r_{\text{avg}} = 303$ m is a better fit to $4^\text{th}$ peak of predicted coherency. (b) Site UW06 large array (black solid and dashed lines) has high asymmetry, with $r_{\text{avg}} = 465$ m and 827 m of 102% and 42%, respectively. Both observed $p(\theta)$ and $p(f)$ fit for $r_{\text{avg}}$ of symmetric small array (gray solid and dashed lines), with $r_{\text{avg}} = 184$ m and](image-url)
krSPAC basin-scale Vs imaging

319 m. The fit for $\rho(kr)$ is better than $\rho(f)$ for the asymmetric triangles.

For site RD08 (Figure 2a), three of the four average interstation distance coherencies used in the forward modeling are presented. The interstation average ($r_{avg}$) of 175 m has an asymmetry measure ($r_{diff}$) of ~8%, and the observed $\rho(f)$ and $\rho(kr)$ coherency curves are nearly identical. At $r_{avg} = 303$ m, the $\rho(kr)$ coherency shows an improvement of fit through the third peak. The greatest improvement at this site occurs at $r_{avg}$ of 968 m between the second and third coherency peak; at this interstation spacing the measure of asymmetry was ~18%.

For site UW06 (Figure 2b), asymmetry was significantly greater, with $r_{diff}$ between ~14% and 102%. The $\rho(kr)$ coherency curves were not markedly improved over the $\rho(f)$ curves at $r_{avg} = 184$ and 319 m, even though asymmetry was relatively high (>10%). However, the improvement was dramatic for both $r_{avg} = 465$ m and 827 m, where interpretation could be extended past the second coherency peak in $\rho(kr)$, whereas the curve was not interpretable to even the first minimum in $\rho(f)$ space. Among all sites, we estimate that asymmetry varies from less than 1% to as much as 120% based on the $r_{diff}$ metric.

Seattle Basin krSPAC Microtremor Array Analysis

We acquired microtremor array data at 11 sites in the Seattle basin, including locations within the city of Seattle (Figure 1). All sites had seven sensors collecting 0.0083 to 100 Hz bandwidth data deployed on nested triangular arrays, using arrays with 300 m and 1000 m or 1000 m and 2000 m nominal interstation separations (i.e., $r$ values in Equations 1, and 2). The one exception was site NW, where a third array with ~300 m interstation spacing was acquired to complement 1000 and 2000 m arrays. Optimal sensor locations were selected prior to field deployment to approximate fully symmetric arrays; however, in-the-field deployment impediments, such as accessibility problems and highly localized noise sources (i.e., construction or excessive traffic), required sensor deployment at locations that were up to 200 m from the optimal location. Despite efforts to minimize the effect of near-field urban noise at sensor locations, some sensors showed insufficient coherency for use in krSPAC analysis.

We recorded roughly six hours of microtremor data at 5 ms sample rate. The data were pre-processed with amplitude debiasing, linear de-trending, bandpass filtering (0.05 - 20 Hz), and time synchronization prior to calculation of interstation cross coherency calculations [e.g., Asten, 2006]. Each of the 11 sites required a unique array analysis based on which interstation pairings had the highest coherencies and provided azimuthal averaging. Some sites, such as site SN07 had stations that were incoherent relative to other stations in the array across the frequency band of interest. Such sites commonly were at or near highly localized and energetic noise sources (e.g., heavy construction sites). In general, we calculated the interstation coherency for each sensor pair, then preferred interstation pairs were grouped into two asymmetric triangles with a central sensor for two $kr$-coherency curves per array. For each site, we thus use up to four averaged coherency curves for model fitting.

Delorey and Vidale (2011; henceforth D&V11) developed a three-dimensional Vs model across the Seattle basin between 250 m and 3500 m depth from ambient noise tomography. The D&V11 model was based on the analysis of Rayleigh wave dispersion between 0.1 and 0.5 Hz recorded on a regional array as part of the SHIPS experiment (Brocher et al., 2001). In Figure 3, each of the krSPAC final models is compared to the nearest D&V11 profile (between 580 m and 1600 m apart). In the majority of these comparisons, the krSPAC model captures the general gradient of the ambient noise tomographic Vs model in the 250 m to 1 km depth range while providing significantly greater model resolution above 250 m. The krSPAC models required less than 6 hours of noise recordings for Vs analysis, as compared to the three months of noise used for D&V11 modeling approach.

Figure 3: Comparison of krSPAC Vs models with profiles from three-dimensional ambient noise tomography Vs model (Delorey and Vidale, 2011). Overall trends in krSPAC Vs at depths greater than 250 m are in agreement with the noise tomography Vs. The krSPAC models demonstrate improved resolution in upper the 250 m.
krSPAC basin-scale Vs imaging

The depth to the $V_s > 900$ m/s layer defines a surface within the Seattle basin that we compare to the inferred base of Quaternary (Johnson et al., 1999), as shown in Figure 4. This surface is poorly constrained by borehole and seismic reflection data, but it is considered the standard for representing the thickness of unconsolidated materials in this region. Two of the interpreted depths from the krSPAC models differ by ~2% from the existing surface, while nine display greater variation from the inferred base of Quaternary surface. However, when taking uncertainty in the interpreted depths into account, nominally at ± 20% based on extremal analysis, the interpreted depths are consistent with the surface as inferred from previous investigations.

Figure 4: Comparison of base of Quaternary from Jones et al. (1996) and Johnson et al. (1999) to interpreted depth of $V_s > 900$ m/s from krSPAC models. Uncertainty in model depths at ± 20% shown by vertical bars with black “+” endpoints. Within uncertainty of profile depths, the best-fit models map out a horizon comparable to the previously inferred base of Quaternary, at depths to over 800 m.

Predicted Basin Amplification

We calculate the theoretical 1D linear-elastic spectral response from the interpreted krSPAC $V_s$ models using a SH transfer function approach (program NRAT TLE of Boore, 2000). The amplification curves presented in Figure 5 each are modeled with the interpreted base of Quaternary as the reference horizon. Although the predicted amplification is, by definition, relative to the reference (half-space) parameters, we use the half-space $V_s$ determined through krSPAC, and thus some variability may be due to differences in the reference $V_s$ from site to site. The mean amplification across the study region is between 1.5 and 2 between about 0.3 Hz and 7 Hz.

Based on simple-spectral-ratio analysis of three earthquakes, Pratt and Brocher (2006) estimated a comparable amplification level (2+) at two stations in the Seattle urban area, between roughly 1.6 and 10 Hz. Differences in the frequency range of observed amplification can be attributed in part to assumptions in the transfer function modeling and parameters as well as uncertainty introduced by a paucity of earthquake observations; however, the consistency of the broad amplification range and amplification level suggests that the krSPAC models are reasonably predicting observed amplification due to the unconsolidated Quaternary deposits in this region.

Figure 5. Predicted linear amplification for 11 krSPAC sites from a 1-D transfer function. Amplification curves shown in gray; solid black curve is the mean amplification of all sites; red dashed curves are ±1 standard deviation. Cyan and blue curves are simple spectral ratio (SSR) curves from nearby stations that recorded three earthquakes (Pratt and Brocher, 2006). The mean curve suggests broad amplification from the Quaternary deposits of up to 2 in the region of this study.

Conclusions

We use the krSPAC ambient noise method to obtain $V_s$ to over 2000 m depth within the Seattle basin. Comparison of krSPAC $V_s$ models to a previous interpretation from ambient noise tomography suggests a broadly comparable $V_s$ structure in the 250 to 1000 m depth range with improved resolution at shallower depth. We characterize $V_s$ at depths capable of delineating the Quaternary and upper Tertiary sedimentary deposits within the basin and interpret an important boundary where $V_s$ increases above 900 m/s. Using this boundary as the reference horizon, we calculate ground motion amplification of up to a factor of up to 2 from the Quaternary sediments between 0.3 and 7 Hz.

Acknowledgments

This work was supported by funding from the USGS Earthquake Hazards Program. Special thanks to David Worley for critical technical support during data acquisition and data processing. Any use of trade, product, or firm names is for descriptive purposes only and does not imply endorsement by the U.S. Government.