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Shear-wave structure of southern Sweden from precise phase-velocity measurements of ambient-noise data

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ABSTRACT

We analyze continuous recordings from 36 stations (630 station-pairs) over a year to build the first crustal shear-wave model based on the ambient-noise method in southern Sweden. Cross-correlations of vertical components between all the stations are computed, and phase-velocity dispersion curves measured. We invert cross-correlation envelopes for an azimuthal source distribution. We then estimate velocity measurement bias for each station pair by comparing synthetic cross correlations calculated with that source distribution and a uniform source distribution. Dispersion curves are corrected for the estimated bias before tomography. After constructing phase-velocity maps in different period ranges between 3 and 30 s, they are combined and inverted for shear velocity beneath each grid point. Anomalies in the model are interpreted in relation to intrusions and tectonic features of the region. The bias due to an uneven source distribution is generally small (< 1.2 %). The bias correction significantly reduces residual data variance at the longest periods where it is biggest.

Keywords: Ambient-noise tomography; Source distribution; Bias correction; Crustal structure.

INTRODUCTION

Ambient seismic noise is widely used to determine shear-velocity structures of the crust and uppermost mantle. The method does not depend on earthquakes and, therefore, it is ideal for regions with a low rate of seismicity such as Scandinavia. The method is justified by theoretical representations that relate the cross-correlation of random noise fields to the Green's function between two receivers (Lobkis &Weaver, 2001; Snieder, 2004). However, noise fields are not completely random which can result in velocity bias (Froment et al., 2010). This bias can be important in our region with small velocity variations (Sadeghisorkhani et al., 2017) and with an uneven source distribution (Köhler et al., 2011; Sadeghisorkhani et al., 2016). Therefore, precise velocity measurements and accounting for possible bias are necessary.

We have two objectives in this work. First, to investigate the effect of bias correction on the constructed tomographic maps at different periods. Second, three-dimensional (3-D) shear-velocity model of southern Sweden is obtained from the phase-velocity of Rayleigh waves.

METHODOLOGY

Vertical-component data from 36 stations of the Swedish National Seismic Network (SNSN) in 2012 are analyzed (**Figure 1a**). Before correlation, the mean and trend are removed from daily traces of each station, instrument response is corrected, traces are decimated to 2 Hz sampling frequency and one-bit normalized. Traces are cross-correlated and stacked for the whole year.

To measure phase-velocity dispersion curves, we developed a software package called GSpecDisp (Sadeghisorkhani et al., 2018). It measures phase velocity for each station pair in the spectral domain by matching zero crossings of the real part of the correlation spectrum with a Bessel function of the first kind. We select dispersion curves close to a regional average dispersion curve within the software.

As discussed, an uneven source distribution causes velocity bias and accounting for it can improve tomographic results. We use the method introduced by Sadeghisorkhani et al. (2016) to invert for the azimuthal source distributions in different period ranges based on the envelope amplitudes of all cross-correlations in the region. **Figure 1b** shows two examples of the source distribution in the secondary and primary microseismic bands. In the secondary microseismic band, energy mainly comes from northwesterly directions, whereas for the primary band it mainly comes from the northeast. We estimate the phase-velocity bias following the approach of Sadeghisorkhani et al. (2017). Two synthetic cross-correlations are computed for a uniform source distribution and the inverted source distribution. The time shift between the two is interpreted as bias. The phase-velocity dispersion curves are then corrected based on the estimated bias. Bias is substantial when the inter-station distance is small compared to a wavelength.

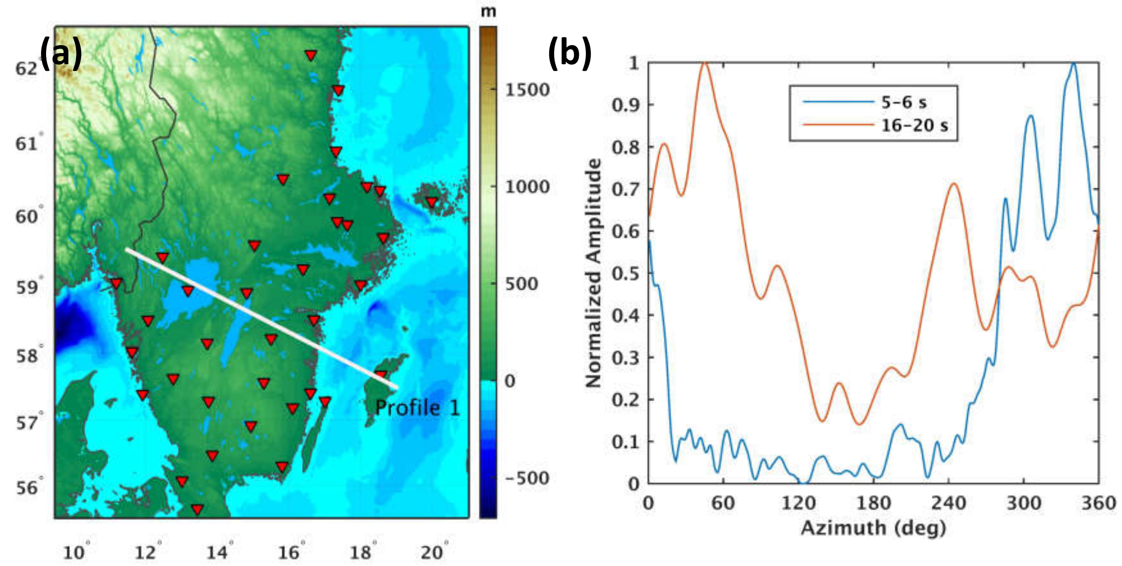

Figure 1. (a) Location of the 36 broadband stations that are used in this study on top of a topographic map of the region. The white line shows the location of the profile (cross-section) in **Figure 3c**. (b) Azimuthal source distribution of ambient noise at two period ranges as seen by stations in southern Sweden. The amplitude in each period range is normalized by its maximum.

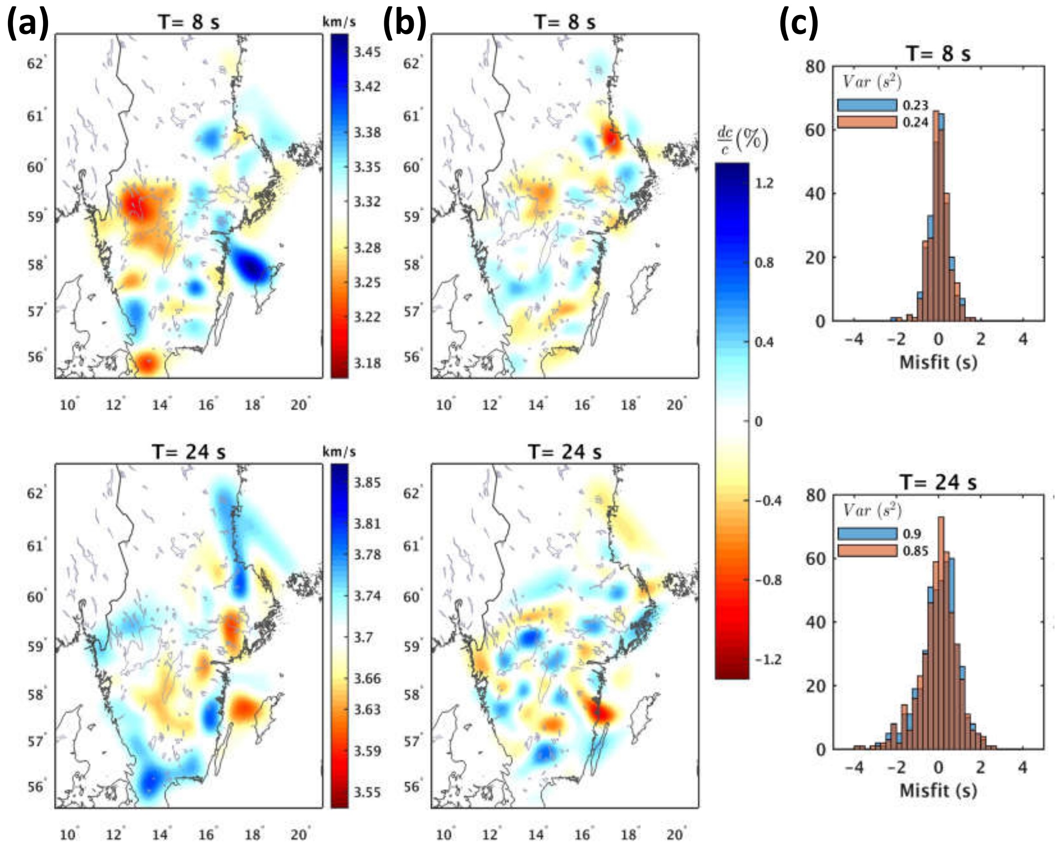

Figure 2. Column (a) shows phase-velocity maps at 8 and 24 s. Column (b) shows relative difference between the bias corrected and not corrected tomographic maps at these periods. Blue color (positive values) means the bias correction leads to higher phase velocities. Column (c) shows histograms of the post-inversion, travel-time residuals before the bias correction (blue) and after that (orange). Their variances are presented in s^2 in each case.

We use the Fast Marching Surface Tomography (FMST) package (Rawlinson, 2005) for tomography. Phase-velocity maps are constructed for periods between 3 and 30 s with a node spacing of 0.25° in latitude and 0.5° in longitude. This is roughly equivalent to 27 km grid spacing in our region. FMST solves the inverse problem iteratively. The starting model at each period is chosen to be homogenous and equal to the mean phase velocity of all station pairs. Inversions are regularized by damping and damping parameters are chosen based on the trade-off between data misfits and model roughness. **Figure 2a** shows phase-velocity maps at 8 and 24 s. The phase velocity variations are around 4%.

To investigate effects of the bias correction, we repeat the travel-time tomography with the same parameters, but without bias correction. Then, we calculate the difference between phase-velocity maps based on corrected and uncorrected data. Two examples of the difference are shown in **Figure 2b**. **Figure 2c** shows the histogram of travel-time residuals after tomography for the examples. Results imply that at the longer periods the bias correction improves the tomographic maps, but at shorter periods there is no significant difference between the two approaches. The bias for each measurement can be up to a few percent, but for nodes where many paths cross, their combined effect does not change node velocity significantly.

To obtain the shear-velocity model, a linearized one-dimensional (1-D) inversion of the local dispersion curve estimate is applied at each nodal point of the phase-velocity maps (Herrmann, 2013). We used different starting models at different nodes depending on independent estimates of Moho depth. Starting models are chosen based on grid searches of shear velocity with a fixed Vp/Vs ratio of 1.75 for the average phase-velocity dispersion curve of the region. We use the Moho-depth model of Europe provided by Grad & Tiira (2009).

We invert the local dispersion curve at each node fixing the Vp/Vs ratio using results from a receiver function study of the region (Olsson et al., 2008). Two depth slices at 12.5 and 22.5 km and a cross-section of the final model are shown in **Figure 3**. The most striking feature of the model is a high-velocity anomaly between Gotland and the mainland at 12.5 km depth that can be seen in the depth profile (**Figure 3c**). The anomaly is interpreted as relating to Rapakivi intrusions. The anomaly reverts to a slow anomaly at greater depth. A slow anomaly is located in the western part of the region beneath lake Vänern at 12.5 km depth. In the depth profile, it starts near the surface and deepens toward the west. This slow anomaly is co-located with a region with elevated seismicity rate.

CONCLUSION

We have built a shear-velocity model for southern Sweden based on surface waves recovered from vertical components of ambient noise. Corrections for measurement bias due to an uneven source distribution have little effect on the estimated phase-velocity maps, but reduce the residual data variance significantly at longer periods. The bias for each cross-correlation can be positive or negative based on its direction. At a tomographic node where many paths cross, the varying bias tends to cancel. Therefore, its effect on tomographic results is small even in a region with strong source anisotropy.

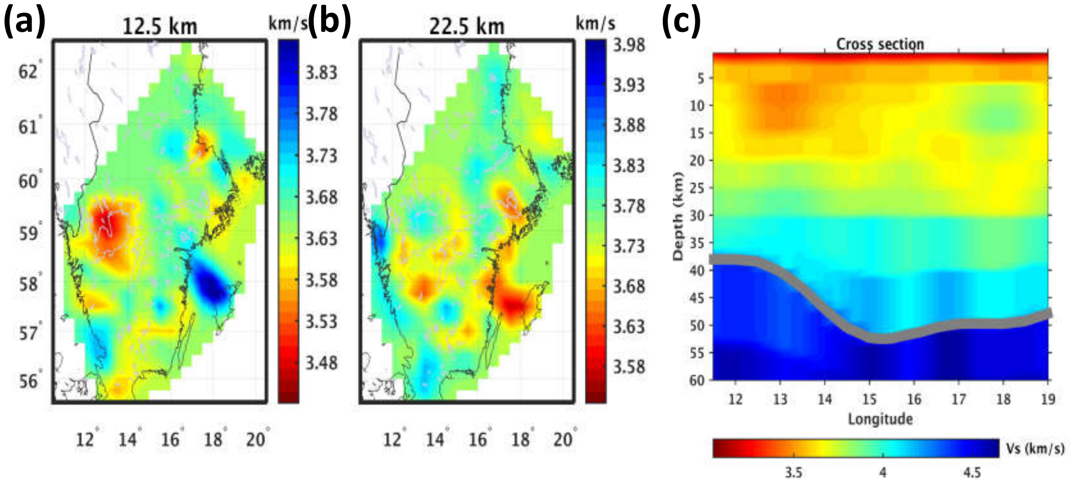

Figure 3. (a) and (b) Depth slices showing shear-wave velocity at indicated depths. (c) shear-wave velocity depth profile at the location indicated in **Figure 1a**. Moho depths at different locations are shown as a gray curve.

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