Studying shallow seafloor structure based on correlations of continuous seismic records

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SUMMARY

Ambient-noise surface wave tomography has recently emerged as a very powerful tool in regional-scale seismology and is now widely used to study Earth's crustal structure in areas where dense regional-scale seismic networks are available (e.g. Shapiro et al. (2005)). Here, we investigate the feasibility of this approach using continuous marine noise data to extract the information about shear-wave structure of the superficial seafloor. We use data from the Valhall Field permanent seismic system (e.g., van Gestel J.-P. et al. (2008)) and compute cross-correlations of 6-hour continuous seismic records. Resulting waveforms clearly contain low-frequency dispersive Love waves. An initial analysis of arrival times of these waves indicates that the dominant source of seismic noise is located below the platform. We then select a profile of stations suitably aligned relative to the platform and compute cross-correlations of horizontal geophones between all stations of this profile to construct record sections. We construct group velocity dispersion curves of the Love waves extracted from these sections and invert them to construct a 2D shear-velocity profile down to a 20 m depth. In this paper, we present theory and application of this new approach to estimate S-wave velocity just beneath the seafloor and S-wave statics.

THEORY AND METHOD

Ambient-noise seismic imaging is based on the theory that cross-correlation of a random wavefield recorded at two receivers is equivalent to the Greens function between the locations of these receivers. This theory can be mathematically demonstrated using different approaches (e.g., Weaver and Lobkis (2001); Snieder (2004); Wapenaar (2004)) and has been recently successfully applied to extract surface waves in microseismic band (0.025-0.2 Hz) and to use them to image the Earth's crust (e.g.,Shapiro and Campillo (2004); Sabra et al. (2005); Shapiro et al. (2005)). The applicability of this approach is strongly dependent on the distribution of the seismic noise sources. First, because of the superficial origin of most of these sources, fundamental mode surface waves are most easily extracted from cross-correlations. Second, a spatially homogeneous distribution of sources is ideally required for the method to work perfectly. A minimal requirement is to have enough noise sources well aligned with a particular pair of receivers to illuminate the wave propagation between these receivers (e.g., Snieder (2004)). This implies that prior to measuring and inverting travel times, a study of distribution of noise sources must be performed to determine pairs of stations that can be used to reconstruct surface waves using noise cross-correlations.

Our method includes the following steps: (1) pre-processing continuous records with a spectral whitening and a temporal normalization to equalize the noise distribution in time and frequency domains, (2) computing cross-correlations between pairs of receivers, (3) locating dominating noise sources, (4) selecting appropriate profiles of receivers well aligned relative to determined noise sources, (5) extracting Love waves and measuring their group velocity dispersion curves for all selected pairs of stations using a Frequency-Time Analysis (Levshin et al. (1989)), (6) inverting for horizontal distribution of Love-wave group velocities for a set of frequencies, (7) constructing localized dispersion curves and inverting them for local 1D shear velocity profiles with a Monte-Carlo method (Shapiro et al. (1997)), and (8) computing S-wave statics in the top 20 m for a set of acceptable models found during the Monte-Carlo inversion.

EXAMPLE WITH SEISMIC DATA FROM THE VALHALL FIELD PERMANENT SEISMIC SYSTEM

The Valhall Field Life of Field Seismic (LoFS) system operated by BP is the world's largest permanently installed seismic array (e.g., van Gestel J.-P. et al. (2008)) where the data are recorded continuously by 120 km of cable with more than 2500 4C seismic receivers, which provides a unique opportunity to study the feasibility of noise-based imaging methods in an exploration environment and which gives a different approach from previous work studying shallow velocity structure at the sea bottom (e.g., Muyzert et al. (2002); Hatchell et al. (2009)). BP kindly provided us 6 hours of continuous 4-component records from more than 2500 receivers from a 12 profiles array (Figure 1a), resulting in more than 30 million possible inter-station and inter-component cross-correlations, a tremendous amount of information. In this initial study we concentrate on two aspects. First, we study the distribution of dominant noise sources (see Dellinger and Yu (2009) for a complementary noise sources analysis at Valhall) and, then we use horizontal-component geophone records, which are very close to the transverse component of the profile CD (Figure 1a), to extract and to invert Love waves along a profile of 50 receivers.

To pre-process the data, we whitened original record between 0.2 and 100 Hz and then applied a 1-bit normalization (e.g., Derode et al. (1999)). Example of cross-correlations at 500 m offset demonstrates the presence of low-frequency Love waves (Figure 1b) and also indicates that their arrival times follow a clear pattern depending on the position and the orientation of the considered station pairs. A simple analysis of this pattern for a subset of 1000 randomly selected inter-station cross-correlation shows that most of the low-frequency seismic noise is generated in the vicinity of the platform (yellow spot in Figure 1a).

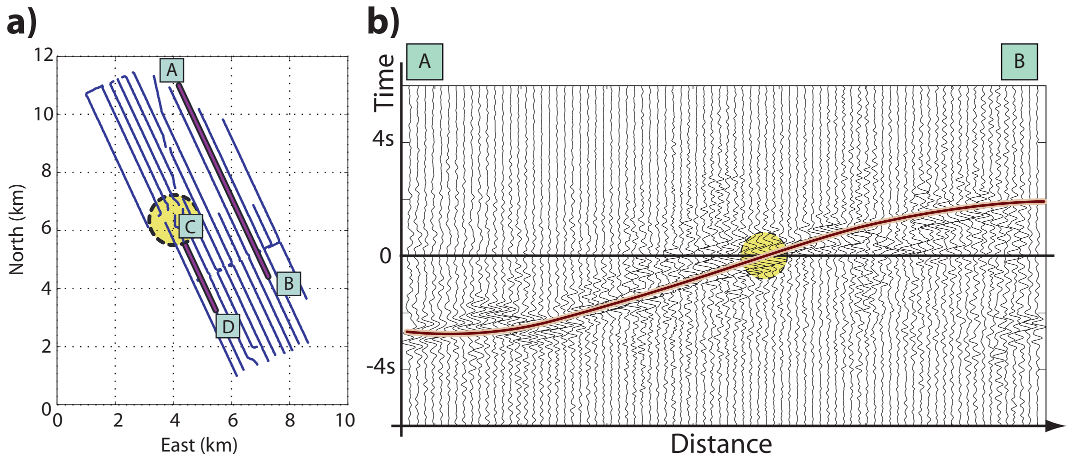

Figure 1: (a) Map showing location of stations of the Valhall permanent seismic system (blue dots). Solid lines show profiles AB and CD illustrated in Figures 1b and 2a, respectively. (b) Cross-correlations for pairs of stations separated by 500 m and located on the profile AB and low-passed at 10 Hz. Red line show a cosine-like variation of travel time indicating that the observed low-frequency waves are generated by a localized source.

With the seismic noise mostly generated near the platform, we decided to analyse a profile that is suitably oriented with respect to this dominating noise source (profile CD). An example of a ”record section” reconstructed from cross-correlations is shown in Figure 2a. Low-frequency dispersive wave train composed of Love waves is clearly observed. A simple visual analysis of waveforms shows that the propagation velocity of these waves along the selected profile varies very strongly (Figure 2b). We therefore decided to measure dispersion curves of the Love waves for all 1225 inter-station pairs of the selected profiles and to invert them for horizontal distribution of frequency-dependent group velocities.

A detailed analysis of waveforms emerging from cross-correlations shows that group velocities can be measured in two frequency bands: between 3 and 12 Hz and between 24 and 29 Hz. The high frequency part of the signal disappears at receivers located more than 1200 m away from the platform (it might be possible to reconstruct them with correlating time series longer than 6 hours). Results of the group velocity analysis are summarized in Figure 3b and confirm strong along-profile variations. We selected the part of the profile that is closest to the platform where group velocity in the whole frequency range could be measured to invert them for the depth-dependent shear-velocity structure. At every location along profile, we reconstruct local group velocity dispersion curve and invert them for a local 1D shear-velocity structure. We use a very simple model parametrization with a single shallow layer overlying a half-space. The layer thickness and shear velocities within the layer and the half space are modified during the inversion. We use a random sampling of model parameter space (Shapiro et al. (1997)) to find a set of models that fit the measured dispersion curves within acceptable level. Examples of inversions for two locations are shown in Figures 3c and 3d. For every acceptable model, we calculate S-wave static in the top 20 m (approximate depth of sensitivity of Love waves at considered periods), which allows us to estimate variations of average S-wave statics and of their standard deviations along the profile. In particular, our results show that in the part of the profile with slowest measured velocities of Love waves, the statics are about 15 ms above the average level (Figure 3e).

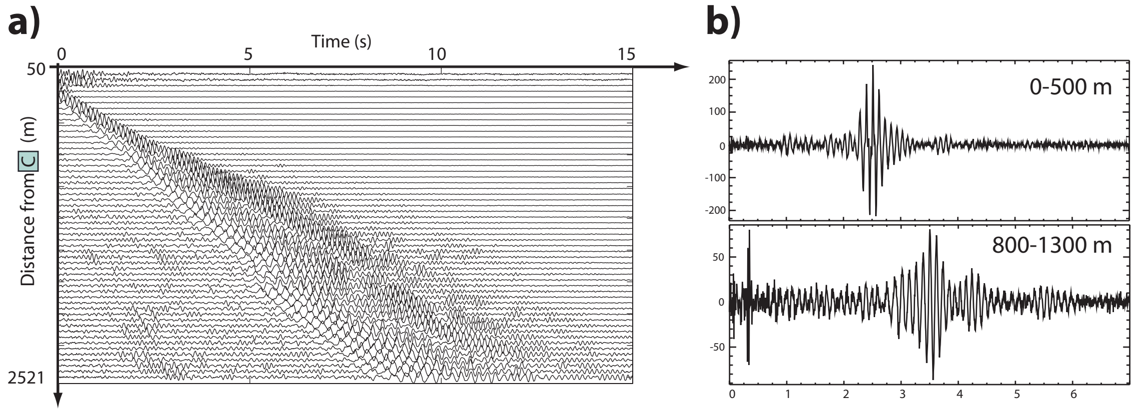

Figure 2: (a) East component cross-correlations between all-stations of the profile CD with the station located in C. (b) Cross-correlations for two pairs of stations separated by 500 m: sites at 0 and 500 m (upper frame) and at 800 and 1300 m (lower frame).

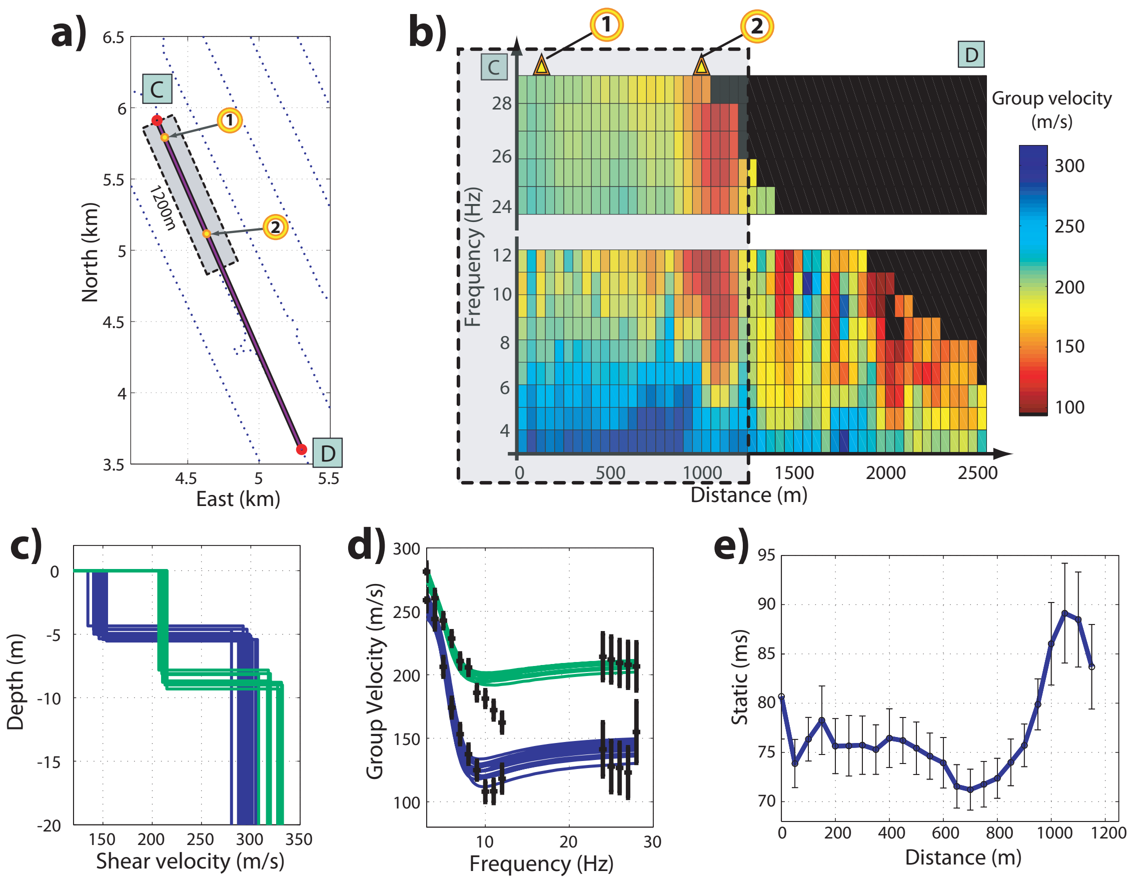

Figure 3: (a) A magnified map of the profile CD showing indicating which part of the profile was used for the depth inversion (grey rectangle). (b) Results of Love-wave group velocity inversion along the profile CD. Black background indicates locations and frequencies where Love waves were not recovered. Dashed rectangle indicates the part of the profile that has been used for the depth inversion and static computation. (c) Acceptable 1D shear velocity models obtained with Monte-Carlo inversions in locations 1 (blue lines) and 2 (green lines) indicated in frames 3a and 3b. (d) Corresponding group velocity dispersion curves of Love waves. Vertical bars show measurement results. (e) S-wave static (average standard deviation) computed in the top 20 m.

CONCLUSIONS

1. We find that seismic noise at frequencies between 3 and 30 Hz is dominantly generated by operation of platforms in the Valhall field.
2. With a known location of main noise sources, we were able to extract Love waves from correlation of seismic noise for suitably oriented pairs and profiles of receivers.
3. Measurement and inversion of the dispersion of these Love waves shows that the top 20 meters of the seafloor are characterized by strong variations of shear velocities that give rise to S-wave statics as large as 15 ms.

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