WS6-A03

Probing Near Surface Shear Velocity Structure from Ambient Noise and Surface Wave Array Tomography

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SUMMARY

Ambient noise tomography has provided essential constraints on crustal and uppermost mantle (isotropic and anisotropic) shear velocity structure in global seismology. Recent studies demonstrate that high frequency (e.g., ~ 1 Hz) surface waves between receivers at short distances can be successfully retrieved from ambient noise cross-correlation and then be used for tomography of near surface shear velocity structures. This approach provides important information for strong ground motion prediction in urban area and near surface structure characterization in oil and gas fields. Here we first give a brief overview about the methodology of ambient noise tomography in global seismology. Then we focus on some recent developments on recovering near surface shear velocity structure using ambient noise tomography. We propose a new one-step iterative surface wave tomography approach that directly inverts all path-dependent dispersion data for 3-D shear wave speeds, in which we perform surface-wave ray tracing at each period using the fast marching method and update ray paths for the next step tomographic inversion. The proposed approach is more efficient than the traditional two-step surface wave tomography and provides a consistent framework for future joint surface wave and body wave travel time tomography.

Introduction

Recovery of short and intermediate period (e.g., 5 – 40 s) surface wave Green's functions between pairs of receivers from cross-correlation of ambient seismic noise has been extensively exploited in the past 10 years in global seismology after Shapiro and Campillo (2004). The corresponding ambient noise tomography has provided essential constraints on crustal and uppermost mantle (isotropic and anisotropic) shear velocity structure in regions with seismic arrays (e.g., Shapiro et al., 2005; Yao et al., 2006; Yao et al., 2010). In recent years it has also been demonstrated that high frequency (e.g., ~ 1 Hz or even higher) surface waves between pairs of receivers (seismometers or geophones) at short distances can be successfully retrieved from noise cross-correlation and then be used for tomography of shear velocity structures in top several kilometres or even a few hundred meters underground (e.g., Huang et al., 2010; Lin et al., 2013). This can provide important information for assessing regional seismic hazards by predicting strong ground motions and for characterizing near surface structures in oil and gas fields.

Here we first give a brief overview about the methodology of ambient noise tomography in global seismology and show some examples for investigating crustal structures using regional seismic arrays. Then we focus on some recent developments on recovering near surface shear velocity structure using ambient noise and surface wave tomography. We also propose a new one-step iterative surface wave tomography approach that directly inverts all path-dependent dispersion data for 3-D shear wave speeds.

Method

Cross-correlation of continuous ambient noise data between pairs of receivers typically yields surface wave Green's functions between receiver pairs. For 3-component receivers, cross-correlation of vertical-vertical or radial-radial component data gives Rayleigh waves, while cross-correlation of transverse-transverse component data results in Love waves. Usually phase or group velocity dispersion data between receiver pairs are used to construct phase or group velocity maps via tomographic inversion. In regions with very dense receiver deployment, phase velocity maps can be constructed by directly solving the eikonal equation using inter-receiver travel times of surface waves. This is a forward problem without tomographic inversion, which is called eikonal tomography after Lin et al. (2009). This eikonal tomography approach can also be successfully applied for active-source surface wave data in exploration seismology (Gouédard et al., 2012). The regional period-dependent phase and or group velocity maps are then utilized to invert for 3-D shear wave velocity structure via a point-wise dispersion inversion approach. This is a typical two-step inversion approach from dispersion data to shear wave velocity structure. From surface wave inversion, we may also constrain depth-dependent azimuthal and radial anisotropy of shear wave speed, thus giving important information on deformation patterns of underground media.

For most surface wave tomography that constructs phase or group velocity maps we assume surface waves are propagating along the great-circle path between source and receiver. This is generally valid in global seismology when the regional variation of surface wave speeds is small, for instance, only a few per cent. However, near surface structure typically has very large velocity variations and the effect of ray bending (i.e., off-great-circle propagation) for high-frequency surface waves is sometimes significant in tomographic inversion. For regions with dense receivers, the approach of eikonal tomography is ideal since it automatically accounts for ray bending. However, in regions only with relatively sparse receivers, we need to perform iterative tomographic inversion with ray paths updated at each iteration, for instance, using the fast marching method (Rawlinson and Sambridge, 2004).

We have developed a new one-step iterative surface wave tomography approach that directly inverts all path-dependent dispersion data, e.g., from the ambient noise cross-correlation method, for 3-D shear wave speeds beneath the receiver array. At each iteration step, we compute phase velocity maps from the obtained 3-D velocity model and perform surface-wave ray tracing at each period using the fast marching method. Then we update ray paths and the travel time sensitivity matrix to 3-D shear wave speeds for the next step tomographic inversion. The proposed approach is more efficient than the traditional two-step surface wave tomography and provides a consistent framework for future joint surface wave and body wave travel time tomography.

Examples

We use about 1 year continuous array data in southwest China to illustrate ambient noise and surface wave tomography for investigating the isotropic and anisotropic crustal shear velocity structure. In particular we examine the effect of off-great-circle propagation of short period surface waves on phase velocity tomography in complex media (Fig.1a).

We show several other examples that ambient noise tomography can be successfully used to probe 3-D near surface shear wave velocity structures in the urban area (Fig. 1b) and gas exploration field. In these cases we demonstrate that about half month continuous ambient data are sufficient to produce reliable surface waves (at about 1 Hz frequency or higher) propagating between pairs of receivers at distances ranging from less than a kilometre to about several tens of kilometres. These retrieved high frequency surface waves from ambient noise cross-correlation are essential for characterizing shear wave velocity structure in the top several kilometres to a few hundred meters, which are important for strong motion prediction in earthquake seismology and relatively large scale and low cost structural survey in exploration geophysics.

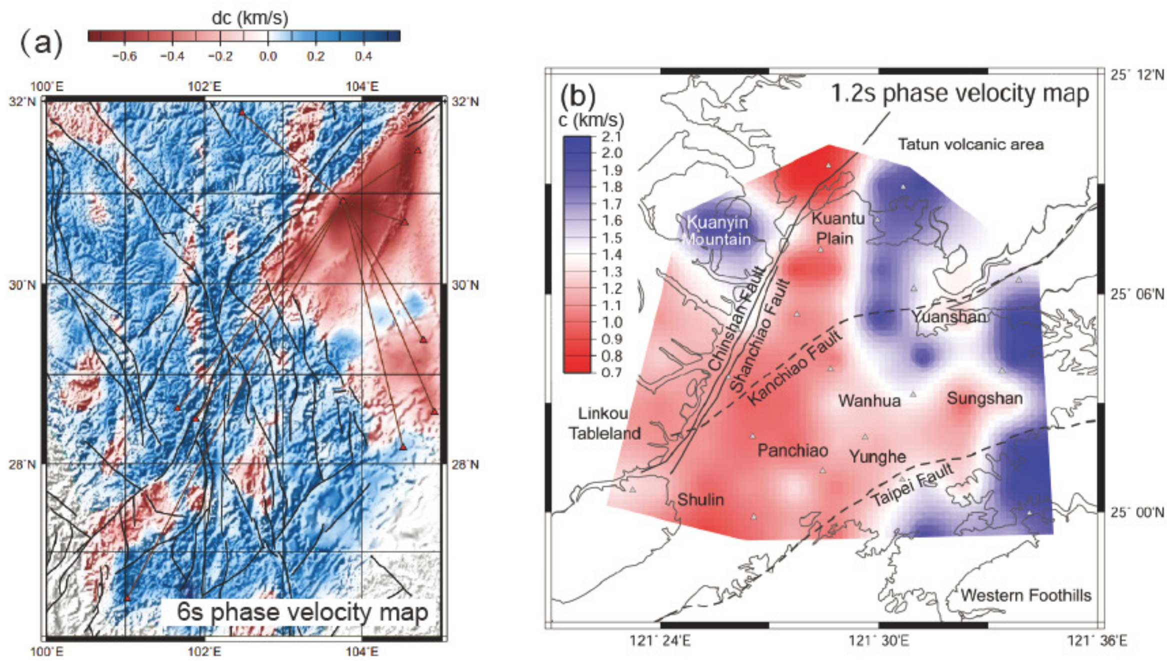

Figure 1 *Examples of phase velocity maps at 6 s and 1.2 s from ambient noise tomography in two different scales: (a) southwest China with a horizontal scale of about a few hundred kilometres; (b) Taipei Basin in Taiwan with a horizontal scale of about 10 kilometres (Huang et al., 2010).*

Conclusions

We demonstrate that ambient noise tomography can be very useful to obtain not only crustal shear velocity structure in regional scale (about a few hundred kilometers) but also near surface shear velocity structure in small scale (about several to several tens of kilometers). The latter provides important information for strong ground motion prediction in urban area and near surface structure characterization in oil and gas fields.

Acknowledgements

This work is funded by National Natural Science Foundation of China (No. 41222028).

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