Ambient noise seismic interferometry for creating Green's functions as input to shear wave velocity inversion

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Keywords

Reservoir Monitoring; Interferometry; Green's Function; Micro-seismicity

Summary

We have created a workflow for industry-scale processing of data to obtain average cross-correlations for huge data obtained using continuous-reservoir monitoring arrays. We present results of seismic interferometry in mapping shear-wave velocity structures in the near subsurface, which could develop into a method for true continuous reservoir monitoring. We employed dense surface arrays, utilizing ambient noise seismic interferometry to model the shallow subsurface, by extracting Green's functions (at the very least the kinematics) from ambient noise. In this paper, we present virtual-shot gathers computed from industry-scaled data acquired from the Africa and discuss their implications.

Introduction

Induced seismicity is of huge interest to the oil and gas industry given the serious environmental and social impacts of production-related tremors. Repetitive occurrence of strong tremors induced by production-related activities have been challenged by local residents and has led to negative public opinion. This resulted into claims to contain and repair damages to civil structures and has made it critical to understand the causes of these phenomena to create a risk management strategy, while engaging all stake holders in a reasoned and informative debate.

Serious efforts are ongoing to understand the tremor-triggering mechanisms, identify major active faults, and predict ground motions. The overall effort is aiming to mitigate risks by trying to reduce the severity of tremors, as well as addressing concerns about necessary building reinforcement, repair, or compensation. Precisely locating the hypocenter of tremors and accurately predicting their moment magnitudes enable us to understand the faulting mechanism through moment-tensor inversion. This is expected to ultimately lead to a combined - geomechanical/seismic model which predicts the induced ground motion, to assess risks more reliably than currently possible.

For reliable tremor-hypocenter localization and ground-motion studies accurate knowledge of the subsurface is critical. This is especially true of the shallow subsurface properties which play an important role in the propagation of shear waves, and in the amplification of seismic waves, resulting from (micro-) tremors (i.e. the observed ground motions). A major complication is the strong spatial variability of the shallow subsurface; especially the layers between about 200 and 800 m are not well measured by any other industry-standard data set. Standard active-seismic surveys or well-bore measurements are not designed to sample the shallow subsurface wave field well (in fact most are designed to suppress it), and therefore give little information about the shallow subsurface properties.

A novel way to derive shallow subsurface velocities is from a relatively-recent method called Ambient Noise Seismic Interferometry (ANSI, see Wapenaar et al., 2010a). We employ this method on data from dense surface arrays recorded over a long-time duration. Since different frequencies are sensitive to properties at different depths, studying surface-wave dispersion allows us to infer the distribution of seismic waves as a function of the depth (Brenguier et al., 2007). We can use tomography, the technique of inversion of velocities of surface waves of different periods, measured along multiple paths in a given geographical region, to build 3-D velocity models of the shallow subsurface

In this contribution, we detail our data and method, and present virtual-shot records derived from interferometry. We compare our results with earlier work and discuss its implications.

Theory and/or Method

Fully diffuse wave fields contain waves with random amplitudes and phases but propagating in all possible directions. Hence, they contain information about all possible paths that can be extracted from cross-correlations (Shapiro & Michel, 2004). ANSI method shows that the cross-correlation of ambient seismic noise records from two seismic receivers may be used to compute the empirical Green's function between the two (Wapenaar, et al., 2010a; Wapenaar et al., 2010b). Using ambient seismic noise induced by ocean waves, human activity and wind, for example, we can estimate the kinematics of surface wave propagation between (passive) receiver stations.

There are various benefits to using passive recording. At several locations, it may be logistically impossible to conduct active-seismic measurements, such as residential zones, or it may be expensive to use active sources at all locations, such as in rough mountain terrain. Passive recording has very little foot-print in residential areas and/or large industrial facilities. In these situations, we can use arrays of passive recorders placed above the area of interest to record during active shots fired at remote locations or record ambient noise. We can map the subsurface using ANSI on both these types of data (D. Draganov et al., 2013).

To put mathematically, the Green's function for waves traveling from receiver A to receiver B can be derived from the cross-correlation coefficients averaged over a long duration (weeks and months)

Equation 1

$$\{G(xB;\ xA;\ t) + G(xB;\ xA; -t)\} * S_s(t) = \sum_i u_i(x_B; t) * u_i(x_A; -t)$$

While deriving a model of the subsurface from the cross-correlation output, the following conditions need to be met: (a) the medium parameters around the noise-source boundary are smoothly varying, (b) if the receivers are surrounded by many distant sources with a minimum spacing of half the wavelength of the wave (Ruigrok et al., 2010) [Appendix A] that are homogeneously distributed over the whole volume of the Earth. If these are not met we will get amplitude and phase errors in the derived Green's function (Wapenaar & Fokkema, 2006; Snieder et al., 2006). The main contributions for such cross-correlation computation come from sources in the Fresnel zones; for a pair of a virtual source and receiver created using two passive receivers, Fresnel zone lies around the line joining those two passive receivers.

Data

We outline our test data sets used to check and build this work flow. The most critical data for this purpose was acquired in North Africa. In September 2007, Shell recorded ambient seismic noise over approximately 11 h during a night of 3-D seismic-exploration campaign, see Figure 1 (Draganov et al., 2013).

This area is not considered an active seismic area although several large earthquakes have occurred in the past. Not much is known about the specific characteristics of the ambient seismic noise in this area, since only few seismometers have been deployed in the past. Proximity to the Mediterranean Sea suggests that noise induced by storms on the Mediterranean may have contributed to the ambient seismic-noise environment as well.

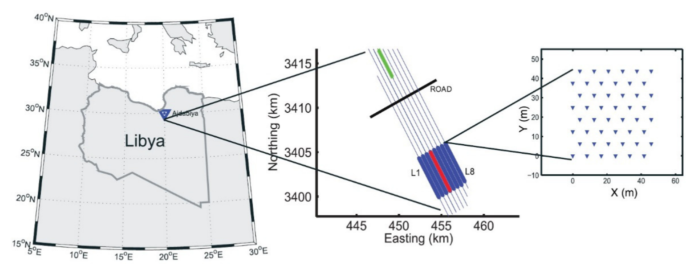

Figure 1: Receiver geometry for test data used by our workflow.

The receiver spread consists of eight parallel lines with 500-m lateral spacing. Each line consists of approximately 400 receiver stations, the number varies per line, with spacing of 50 m. Sensors used in this survey are standard 10 Hz vertical-component geophones that measure particle velocity. Data were acquired continuously on a Sercel 428 recorder and written in 47-s records with a 4-ms sampling interval.

Processing and Cross-correlations

Bensen et al. (2007) provide an excellent summary of the state of data processing procedures that underlie the application of ambient noise tomography to obtain surface wave dispersion measurements. The procedure described in Figure 2 of the paper shows steps involved in preparing receiver data (raw amplitudes from multiple stations) prior to cross-correlation.

The entire workflow was implemented in Shell's production processing software platform. Replicating the cited work, we applied the following steps:

- Geophone correction: We obtain the spectral response function of recorders (standard 10-Hz geophone) to a flat-spectrum input wave-front, and deconvolve this response from the recorded noise. We only correct for phase response; amplitude correction was done in a separate step.
- Normalization of wave-front amplitudes: We carry out `water-level normalization' using multiple steps, using time-variable gain correction and panel-wide gain correction to remove large inter-receiver amplitude and RMS variation.
- Spectral normalization: After correcting for the receiver response we normalize the frequency spectrum of the trace amplitudes.

After preparing data in the above manner we compute cross-correlations (see Equation 1) for individual traces of each receiver pairs, and average them over sections of data (typically an hour) separately. Later we can choose to integrate the products over the entire duration. The main source of noise in our data is the sound of traffic passing by on the road perpendicular to the array. This meant that, for individual receiver lines (or RECLINs), the source was in the Fresnel zone. Hence, the cross-correlation can be interpreted as the band-limited Green's function.

Results

We integrated the cross-correlations from different receiver pairs over 11 hours. Virtual shot gathers (collections of Green's functions of all receiver pairs) were obtained as the average cross-correlation output; four such gathers are shown in Figure 2. We also compute f-k spectrum from one of those shot gathers and display it in Figure 3.

Overall our results from interferometry match very well with those reported in the literature. The difference now is, we have a production-level workflow that can be applied to large data sets obtained from passive-reservoir monitoring arrays. The data can be processed reliably in a short time using standard preprocessing and cross-correlation steps and the output can be used in tomographic imaging using any other industry tools.

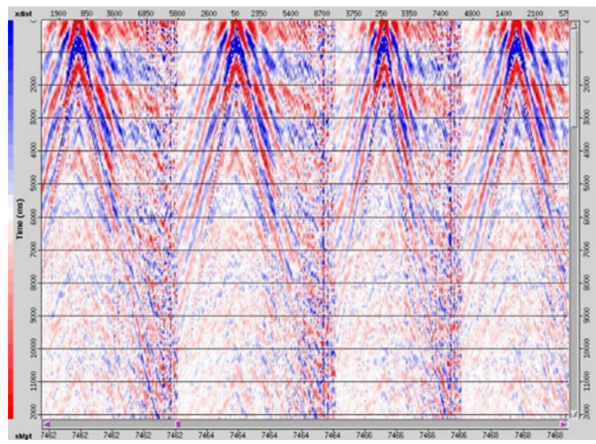

Figure 2: Virtual shot gathers from the output of cross-correlation workflow are shown on the left, where virtual shot numbers are at the bottom, and distance between the virtual sources and receivers in meters on the top.

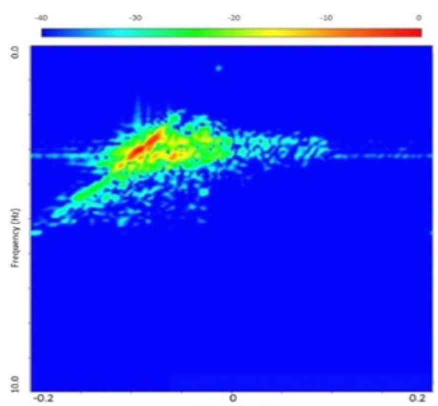

Figure 3: The f-k spectrum extracted from one of the virtual shot panel in Figure 2 is shown. These compare well with results in the literature (Draganov et al., 2013).

Conclusions

We used data from dense, surface arrays to extract Green's functions using the technique of ambient-noise seismic interferometry. In this paper, we presented virtual-shot gathers computed from industry-scaled data acquired from North Africa. The results using our work-flow created using Shell's production processing software platform, agree very well with previous results reported in the literature. These results can be used to produce subsurface tomographic maps using tomographic techniques. Passive-reservoir monitoring is going to be a norm in oil and gas industry, and our results are the first steps towards extracting real-time information about the subsurface velocity structures from such data.

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Acknowledgments

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