Monitoring geological gas storage sites with ambient noise interferometric methods: integration of seismic velocity changes and waveform coherence variations into 2D visualization tools.

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Abstract

Recording the ambient seismic signal over an array of multiple sensors and applying ambient noise seismic interferometric (ANSI) methods can give access to the characterisation of coherent wavefields which can be analysed to infer the seismic properties of the investigated medium and/or to monitor these properties over time. One advantage of those passive seismic methods - in addition to their relatively low cost of implementation - is that they do not require any active seismic source, which allows for their use even in areas where active source deployment is complicated (e.g. inhabited areas, dense industrial infrastructures), and can therefore be relevant to monitor natural gas or CO\textsubscript{2} geological storage sites.

In this paper, we analyse the temporal evolution of a coherent wavefield obtained with ANSI methods to monitor the structural and fluid saturation changes occurring within a natural gas geological storage site where fluid movements induced by gas injection/production operations are expected to take place. Our strategy consists of monitoring two distinct attributes of the reconstructed seismic waves: the relative velocity changes and the waveform coherence. Tracking relative velocity changes gives access to the evolution of the elastic properties of the studied medium, yielding information about the evolution of structural and fluid saturation parameters. The waveform coherence is another wave attribute complementary to the velocity changes related to the attenuation properties of the medium and their temporal evolution.

Seismic noise recordings have been acquired over a period of 6 months, using an array of 48 sensors displayed along a 208 km\textsuperscript{2} circular network centred on the underlying gas geological storage formation. The ambient noise records were cross correlated for each pair of sensors after band-pass filtering in the frequency range chosen to scan the depth of the reservoir, accordingly to the computation of the Rayleigh wave sensitivity kernels. The results of those interferometric processes are the emergence of a coherent wave-field in which multiple components (surface waves, body waves) can be identified and monitored in time.

A specific focus was given to raw data processing, analysis, and data selection operations to increase the signal-to-

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noise ratio of the reconstructed waveforms. A beamforming analysis was also performed, which revealed a significant preferential direction of the ambient seismic signal energy coming from the West and North-West directions, hence likely indicating the oceanic origin of the seismic noise contributing to the surface and body waves reconstruction. Following those results, significant attention has been paid to the non-uniformity of the seismic sources and an analysis and selection of the reconstructed waveforms with respect to the azimuthal distribution of the stations pairs, the inter-station distance value, and the corresponding time of the day was performed to improve as much as possible the global quality and stability of the reconstructed wave-field.

From there, relative seismic velocity changes along the network are computed through measurement of the reconstructed seismic ballistic wave arrival times, using the stretching technique. In parallel, the coherence of the reconstructed surface waves is also monitored in time through cross-correlations of the reconstructed wave signals at different time steps with respect with an averaged reference waveform.

The relative velocity and coherence information are then integrated separately into 2D spatial visualisation tools of different type for subsequent comparison. 1) An averaging process is proposed where the coherence values are uniformly distributed along the geometric path linking each station pair and averaged over a regular rectangular spatial grid. 2) A linear inversion process based on least-square optimization is applied following the principles of the straight ray tomography approach, and 3) a stochastic approach is implemented using Markov chain Monte Carlo algorithms (MCMC). All three methods yield a 2D spatial representation of coherence or velocity change values. The resolution and uncertainty resulting from each process is investigated, and the visualisation results are confronted with available information about gas volumes injection and extraction time-series to evaluate the ability of the presented framework to monitor the dynamic of natural gas geological storage sites.

*Keywords*: Ambient noise, interferometry, relative velocity change, waveform coherence, inversion