Hourly 4-D Subsurface Time-Lapse Monitoring using Seismic Ambient Noise

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SUMMARY

We use seismic ambient noise recorded by the ocean bottom nodes (OBNs) in the Gorgon gas field, Western Australia to compute time-lapse seafloor models. The extracted hourly cross-correlation (CC) functions of 0.1 – 1 Hz contain mainly Scholte waves with very high signal to noise ratio. The conventional time-lapse analysis suggests relative velocity variations (dv/v) up to 1% assuming a spatially homogeneous dv/v, with a likely 24-hour cycling pattern. With high-resolution baseline models from full waveform inversion of Scholte waves, we present a double-difference waveform inversion (DD-WI) method using travel time differences for localizing the time-lapse dv/v in the heterogeneous subsurface in depth. The time-lapse velocity models show velocity increase/decrease patterns in agreement with that from conventional analysis, with more notable changes at the shallower depths. We demonstrate the feasibility of using ambient noise for quantitative monitoring of subsurface property changes in the horizontal and depth domain at an hourly basis.

Key words: Ambient noise; seismic inversion; time-lapse; double-difference

INTRODUCTION

Seismic monitoring using environmental ambient noise (passive seismic data) has been demonstrated as a powerful and cost-effective solution for detecting and quantifying such property changes (Sens-Schönfelder and Wegler, 2006). A simple cross-correlation (CC) of ambient noise wavefield recorded at two receivers reconstructs the virtual interstation Green's function, which can be interpreted as the seismic response that would be measured at one of the receiver locations as if there is a source at the other location (e.g., Shapiro and Campillo, 2004). The ever-present natural ambient sources enable continuous and reliable retrievals of the seismic responses between pairs of stations across times, for example at a daily (de Ridder and Biondi, 2013) or hourly basis (Mao et al., 2019); the waveform changes (e.g., the travel time shifts) from the time-lapse CC functions can be used for deriving the temporal variations of seismic velocity (dv/v). Compared with expensive controlled-source seismic survey for time-lapse monitoring (Hicks et al., 2016), seismic monitoring using ambient noise helps reduce the operational cost significantly and is also environmentally friendly; it is also preferred to monitoring methods using nature-sourced earthquakes because of the lack of repeatability and universal distribution for the latter (Kamei and Lumley, 2017).

The main signals extracted from seismic ambient noise are usually surface waves (e.g. Sens-Schönfelder and Wegler, 2006). Seismic monitoring technique using ambient noise has been successfully applied for many scenarios, including time-lapse studies for groundwater table monitoring, CO_2 injection, volcano and earthquake-related velocity changes, and can be sensitive to minor velocity changes (at the order of 0.1%, Sens-Schönfelder and Wegler, 2006, Brenguier et al., 2020). However, most of the previous studies only estimate the temporal changes without locating the spatial distribution of these changes; a few limited exceptions (Mordret et al., 2014; de Ridder and Biondi, 2013) localize the velocity changes but without determining the depth extent, and without using the state-of-the-art wave-equation based inversion techniques.

Seismic monitoring using ambient noise may be of great potential for industrial applications, especially for real-time monitoring carbon/hydrogen geological storage in subsurface reservoirs. In this study, we obtain cross correlation functions at an hourly basis from an ocean bottom node (OBN, Fig. 1a) seismic survey over the Gorgon gas field in Western Australia prior to its production collected by Chevron Australia in 2015-2016. Time-lapse analysis using the stretching method show a shear wave change (up to 2%) with a cycling pattern. A trace-normalized full waveform inversion (FWI) method is applied to derive a high-resolution baseline model. We then introduce an ambient-noise based double-difference full waveform inversion (FWI) method using differential arrival times, that is able to estimate both the spatial and temporal distributions of subsurface velocity changes.

Data and ambient noise interferometry

Between 2015 and 2016, Chevron Australia and its partners acquired a 3-D OBN seismic survey over the Gorgon gas field for a better description of the Gorgon reservoir sands for carbon capture and storage, with the survey area located in the North West Shelf offshore of Western Australia, approximately 200 km from the mainland (Fig. 1a and 1b). Each seismic node comprised four channels, with two horizontal components (X, Y) and one vertical component (Z) for measuring displacement, and a hydrophone component for recording pressure. The survey used controlled air-gun seismic sources, but there were several quiet time windows without using controlled active sources. The recorded ambient seismic wavefield in the absence of active seismic sources provides the opportunity for passive seismic monitoring using a dense seismic array of industrial scale. We select a time window of Julian Days 1 and 2 of 2016 for the passive seismic monitoring experiment.

We detrend and down-sample the vertical component of the data from 250 Hz to 20 Hz with anti-aliasing filtering. The ambient noise data are then filtered at 0.1 – 1 Hz. We divide the recordings of the selected quiet time window without active source shooting into hour-long segments; each segment is then subdivided into 30 s long records with a 50% overlap. Green's functions are reconstructed by computing CC functions of the 30 s ambient noise window between station pairs. We use weighted phase stacking (Schimmel et al., 2011) for stacking the CC functions within each hour-long segment to improve the signal to noise ratio. Fig. 1c shows the CC functions at Hour 15 Day 1 for Line 3924 (indicated by the black arrow in Fig. 1b), which contain mainly Scholte waves (travelling along the interface between the seawater and seafloor) and provide constraints for the shear-wave velocity of the seafloor. The hourly extracted CC functions have a very high signal to noise ratio. The energy concentrates on the positive side of the CC time lags, suggesting that the ambient noise between 0.1 and 1 Hz propagates from the ocean to the coast.

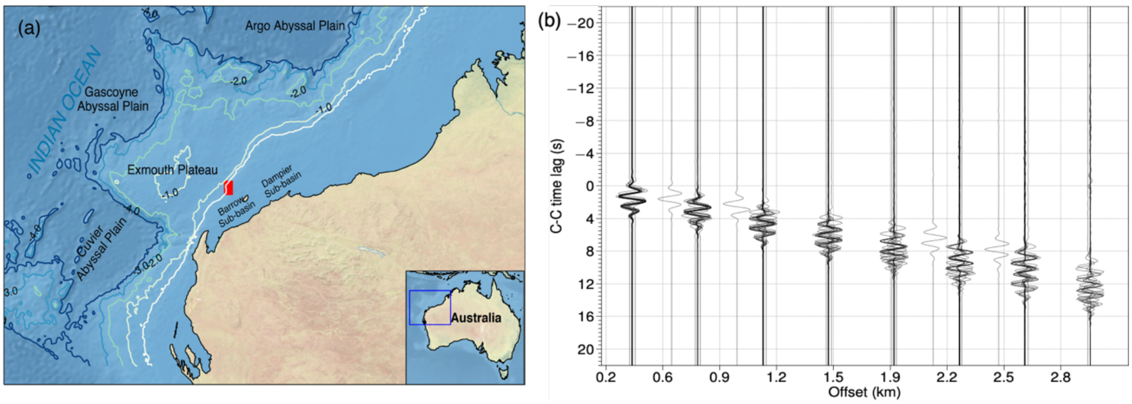

Fig. 1. Map of the ocean bottom seismic survey in Western Australia and cross-correlation (CC) functions from ambient noise interferometry. (a) Ocean Bottom Node (OBN, red rectangle) seismic survey in the Gorgon gas field offshore Western Australia by Chevron Australia and its partners. (c) CC functions (Scholte waves) sorted by offsets (the distance between stations of a station pair) from Hour 15 of Julian Day 1, 2016. We limit the CC functions to 3 km.

The conventional time-lapse analysis for the passive data using the stretching method assumes that the relative velocity variation (dv/v) is uniform in space, therefore we have the relation of dv/v with the relative travel time change (dt/t) as $dv/v=-dt/t$ (Sens-Schönfelder and Wegler, 2006). Fig. 2 shows the measured velocity changes across the two days from each of the CC functions between station pairs. We notice that the seafloor velocity changes up to 1% (Fig. 2a), with a likely sinusoidal pattern of ~ 24-hour cycle. Please note that this measurement does not require knowledge of the subsurface seismic velocity.

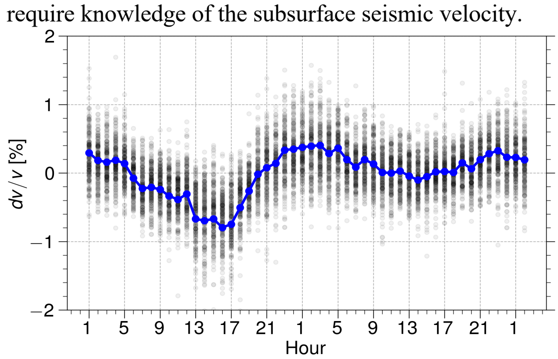

Fig. 2. The relative velocity temporal changes (dv/v) from the stretching method: dv/v of the seafloor at an hourly basis for Julian Day 1 and Day 2 of 2016. The velocity changes were estimated from the ballistic part of the extracted Scholte waves. Each black dot is the dv/v from a station pair measurement. The blue curve is the average dv/v.

We sort the CC functions of all the station pairs into common-station gathers. Each common-station gather can be considered as a seismic common-source gather that the shared common station is the source, and the rest of the stations from the selected survey line are the receivers. Fig. 3 contains common-station gathers of the baseline data and the monitoring data from Hour 15 of Day 1 (Fig. 3a) and Hour 1 of Day 2 (Fig. 3b). We observe that the main difference between the baseline and monitoring data of different hours are the arrival times of the Scholte waves. Scholte waves from Hour 15 of Day 1 arrive later than the baseline data (Fig. 3a, 3c), indicating a velocity decrease than the baseline model, while those from Hour 1 of Day 2 arrive at an earlier time than the baseline data (Fig. 3b, 3d), suggesting a velocity increase; these observations from the common-station gathers are consistent with Fig. 2.

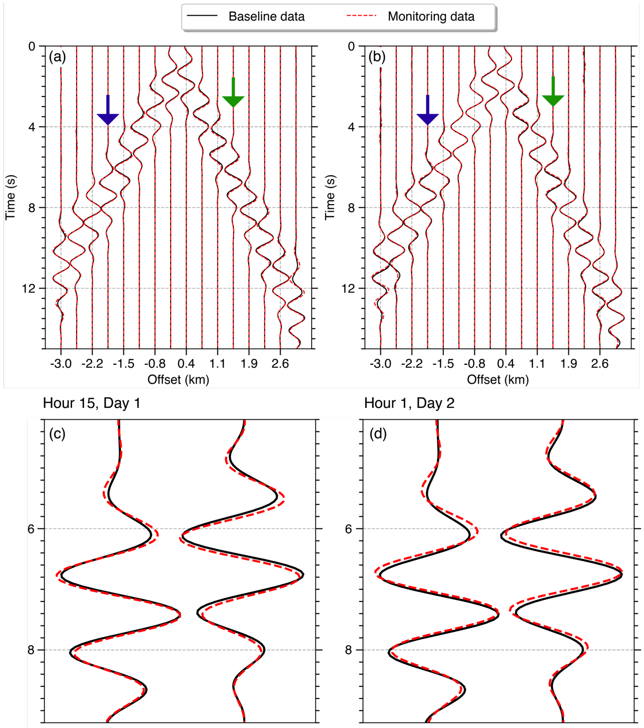

Fig. 3. Common-station gathers sorted from CC functions of station pairs of Line 3924. (a) is the comparison of the baseline data (solid black curve) and the monitoring data (dashed red curve) of Hour 15 Day 1. (b) is the comparison of the baseline data (solid black curve) and the monitoring data (dashed red curve) of Hour 1 Day 2. (c) and (d) are zoom-in of the seismic trace at -1.9 km and 1.5 km offsets (from left to right, indicated by the blue and green arrows, respectively) from (a) and (b).

Baseline model building from full waveform inversion

A baseline data for each station pair can be obtained by stacking the hourly CC functions across all the available hours from the two-day passive recordings. We compare the ballistic part of the Scholte wave arrivals of the baseline data with that of the hourly CC functions (monitoring data) for quantifying the temporal velocity variations. We use the full waveform inversion (FWI) (Tarantola, 1984; Shipp & Singh, 2002; Guo et al., 2022) technique for estimating a high-resolution baseline model using the extracted Scholte waves. We use the baseline data in the form of common-station gathers as the observed data for the baseline FWI. Considering that the phase information in the virtual Scholte waves of the CC functions is more reliable than the amplitude, here we use a trace-normalized FWI method (Shen, 2010) where each seismic trace is normalized by the l-2 norm of the trace itself in the misfit function. The starting model of FWI is built using the wave-equation dispersion inversion (Fig. 4a). The baseline model from FWI is shown in Fig. 4b.

Double-difference wave-equation inversion for localizing time-lapse velocity changes

The most straightforward approach for generalizing seismic inversion to the time-lapse monitoring is to perform two inversions for the baseline and the monitoring data respectively, however the results are sensitive to the baseline model and could be heavily contaminated by the residual data misfit from the baseline inversion (Denli and Huang, 2009). Double-difference waveform inversion (DD-WI) (Denli and Huang, 2009) using differential waveforms has been used for providing more reliable subsurface models of velocity changes with body waves from controlled sources.

The time-lapse difference of the data mainly manifests in the travel times (Fig. 3), which suggests that an objective function of the seismic time-lapse inversion problem using travel time differences (shifts) between the monitoring and baseline data may be the most stable for quantifying the time-lapse velocity models. DD-WI using travel time differences as an objective function has been proposed before, but in the background of seismic adjoint tomography for estimating seismic wave velocity structures, where the differential measurements are constructed between receivers (Yuan et al., 2016). We introduce it for elastic-wave equation based time-lapse inversion where the differential measurements are constructed between baseline and monitoring data.

Here, we propose the DD-WI method using travel time differences for obtaining time-lapse velocity models using the extracted Scholte waves from ambient noise. The misfit function is defined as

$$J = \sum_{i=1}^{Ns} \sum_{j=1}^{Nr} \left\| \Delta t_{i,j}^{d} - \Delta t_{i,j}^{s} \right\|^2$$

where Δti,jd is the travel time difference between the monitoring and the baseline observed data, and Δti,js is the travel time difference between the synthetic data from the monitoring model and the baseline FWI model. i and j are the indexes for the sources and receivers, Ns and Nr are the number of sources and receivers. The time difference (shift) can be estimated by comparing waveform data using cross correlation. The term ‘double-difference’ comes from the two-level differences in equation 3: (1) the difference between baseline and monitoring data, either synthetic or observed, and (2) the difference between the synthetic and observed measurements from (1). The adjoint source for the DD-WI of travel time differences (Yuan et al., 2016), which is used for elastic wave propagation in backward time steps for computing the adjoint wavefields, can be derived as

$$\chi_{i,j} = [\Delta t_{i,j}^{d} - \Delta t_{i,j}^{s}] \partial t \; s_{i,j} \; (t - \Delta t_{i,j}^{s})$$

where $\boldsymbol{s_{i,j}}$ is a seismic waveform trace (1-D time-series vector) from the synthetic data. The only difference with the FWI is the adjoint source. Both the baseline and time-lapse inversion methods honor the seafloor bathymetry which is implicitly included when solving the elastic-wave equation. We apply the DD-WI method to the differential measurements of monitoring and baseline data for localizing the shear-wave velocity changes in the seafloor at an hourly basis.

The derived velocity difference between the model of Hour 15 Day 1 and the baseline model is shown in Fig. 4c, with that of Hour 1 Day 2 shown in Fig. 4d. The changes in Fig. 4c are overall negative suggesting a slower velocity than the baseline model, while the velocity differences in Fig. 4d are mainly positive indicating a faster velocity than the baseline; both are in agreement with Figs. 2 and 3. Therefore we successfully localize where the velocity changes for time-space subsurface monitoring using ambient noise.

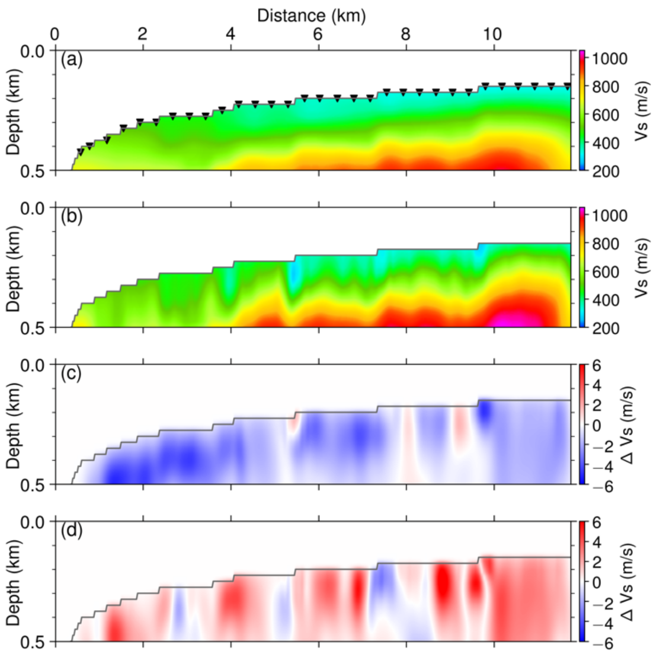

Fig. 4. Baseline velocity model and time-lapse subsurface models of velocity changes in the shallow seafloor. (a) The starting model for FWI from wave-equation dispersion inversion. (b) The high-resolution baseline velocity model from trace-normalized FWI, which is used as the starting model for DD-WI. (c) The time-lapse image of velocity

changes for Hour 15 Day 1. (d) The time-lapse image of velocity changes for Hour 1 Day 2. The black triangles in (a) indicate the locations of the OBNs.

Conclusions

In this study, we demonstrate that the new passive monitoring technique provides a cost-effective and environmentally-friendly solution for real-time 4-D quantitative monitoring of subsurface property changes with high temporal (hourly) and spatial (hundreds of meters) resolution. Using seismic ambient noise data recorded by a dense array of OBNs offshore Western Australia, we detect temporal variations of shear-wave velocity up to 1% in the seafloor, with a likely 24-hour cycling pattern. To localize the velocity changes in the subsurface, we first build a high-resolution baseline seafloor model from FWI of Scholte waves. Then from DD-WI of wave arrival time differences we obtain the quantitative time-lapse seafloor images containing the heterogeneous relative velocity variations in the horizontal and depth domain, where the velocity changes decrease with increasing depths. The elastic-wave equation based workflow from building high-resolution baseline model to time-lapse inversion using surface wave measurements honors the full wave physics, is robust to data noise and errors from the baseline model, and is sensitive to subtle velocity changes, which can be applied to dense passive seismic data from seismic arrays and Distributed Acoustic Sensing (DAS) for real-time monitoring of groundwater level, volcano, subduction zone and CO2 capture storage and hydrogen underground storage, in the aim for an in-depth understanding of the evolving 4-D Earth.

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