Assessment of the permanent seismic sources for borehole seismic monitoring applications: CO2CRC Otway Project

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SUMMARY
In the CO2CRC Otway Project, seismic monitoring has evolved from traditional campaign-based seismic acquisition using a large array of seismic receivers and mobile sources, towards the techniques using continuous borehole seismic acquisition based on permanently deployed sources and various receiver and DAS arrays deployed in the wells. Permanent borehole-based reservoir monitoring can minimize the cost and the environmental impact of geophysical surveillance. To this end, Surface Orbital Vibrators were deployed as permanent sources in late 2015 to two locations for real time and on-demand plume imaging. The sources include one large and one small motor. After optimisation of the SOV design in 2016, the existing buried geophone array was used to record continuously over several months. First, surface geophone array feasibility was performed and promising seismic repeatability was obtained that validates the borehole applicability of these vibrators. We then ran a series of VSP trials to test performance of DAS in combination of SOV sources. The objective was to test different fibre types and different sweep parameters. The results of the field trials show that the DAS/SOV combination presents good quality VSP datasets and, when using a more powerful motor with sweeps from 0 to 80 Hz, imaging beyond the injection interval. These results provided confidence in progressing further stages of the Otway Project which will focus on permanent borehole seismic monitoring.

Key words: surface orbital vibrators, distributed acoustic sensing, reservoir monitoring, vertical seismic profile.

INTRODUCTION
Time-lapse (TL) seismic monitoring of injected CO2 has been a major research area in CO2CRC Otway Project. Reservoir monitoring is commonly conducted with a combination of various seismic acquisitions utilising a large array of seismic receivers and mobile sources to image the evolution of plume. The Stage 2C of Otway Project, a similar approach was successfully utilised. Although the small scale of injections was successfully imaged (Pevzner et al., 2017), significant labour and costs, prolonged survey times due to the deployment and minimal disturbance to the land owners were noticed. Hence, the complexity of such surveys makes the conventional approach costly and, at times, unviable for carbon geosequestration applications. Additionally, the repeatability of both source and receiver location has a big impact on the effectiveness of the approach. During Stage 2C of the Otway Project, to optimise the receiver side of the surveys, a buried geophone array was deployed to monitor the injected CO2 into the saline aquifer in ~5kT intervals at a depth of 1500 m. Additionally, for the appraisal of an alternative source, two Surface Orbital Vibrators (SOVs) close to the CRC-2 and Naylor-1 wells source were permanently deployed at the Otway site, which would provide the following benefits: reduced environmental footprint and cost savings. Also, improved ground coupling of the source would further increase the repeatability of the TL seismic signal. Furthermore, permanently installed distributed acoustic sensing (DAS) in the wells allowed us to evaluate their long-term applicability with surface and borehole field trials for the next stages of the project (Stage 3), which aims to build a multi-well monitoring approach. In this study, we first present the data processing and analysis of SOV data set acquired with the buried surface array. Following this, we discuss the results of two borehole SOV surveys acquired in the CRC-3 well coupled up with DAS.

FIELD EXPERIMENT SETUP
In seismic monitoring surveys, SOV sources can reduce costs and land impact compared to vibroseis sources. The wells instrumented with DAS and permanent sources can offer even more cost-effective, more environmentally friendly and real time monitoring sufficient to image the CO2 plume and assure reservoir integrity.

DAS detects the acoustic signal by simply using standard fibre-optic cables by sending a series of light pulses through a fibre-optic cable to a surface-based interrogator. Analysing the changes of the backscattered light, the changes of strain along the fibre length could be measured (Parker et al., 2014). For permanent monitoring applications, due to the inherent robustness of the fibre-optic cable and affordability, DAS provides a significantly more economical alternative than the conventional seismic sensors. VSP data acquired with DAS on CRC-3 well present high signal to noise ratio with a potential to image the injection interval (Correa et al., 2017).
In this study, point-vibrating SOV sources that distribute source energy over an extended time through the rotation of two eccentric weights using common AC induction motors were deployed. While SOV1 was located at approximately 630 m from the well, SOV2 was located approximately 380 m from the well (Figure 1). The continuous acquisition of seismic data started in 2015 and carried on for several months to generate a seismic signal to be recorded with the existing buried geophone array. The deployment tests, the initial appraisal of the signal content and the repeatability of the SOV data were demonstrated in Dou et al., 2016, 2017 and Frezfeld 2016. The surface array-SOV data acquisition continued for 107 days with breaks to allow for the conventional monitor surveys. Due to its location and offset coverage, we focus on SOV2. For the field experiment, continuous weather data was also recorded. A sweep analysis followed by the SOV data processing and repeatability analysis were performed.

In January 2017, the CRC-3 well was drilled on site as part of the CO2CRC Otway Stage 3 program. A set of standard straight single-mode and enhanced sensitivity fibres were deployed and cemented behind the well casing. We present the analysis of a series of seismic acquisitions performed at the CRC-3 well using DAS receivers and SOV sources. In this experiment, we acquire DAS VSP using both the standard fibre-optic cable and backscatter enhanced fibre. We also tested different sweep designs on the SOVs and compare the performances on both SOVs coupled up with different fibre types in combination.

DATA PROCESSING AND REPEATABILITY ANALYSIS OF THE SOV DATA ACQUIRED WITH SURFACE GEOPHONE ARRAY

The surface SOV data processing started with generating daily stacks with the data recorded over two hours. Continuous weather data acquisition was recorded and analysed to complement the surface SOV data analysis, specifically to account the near surface conditions. An initial repeatability assessment was performed on these daily stacks with respect to variations in temperature, rainfall and wind both on shot and receiver domains. Previously in the project, TL surface seismic processing accurately imaged the TL signal of the plume in both boreholes, but to improve the signal to noise ratio, a special effort is made on testing various removal techniques and cross-equalisation of the day stacks before producing the difference seismograms. We then generated a baseline (shot/day gather) by stacking the first few days of data acquired from mid-February 2016. The phase and amplitude differences, and the time shifts between the baseline and the day stacks are cross-equalised for all traces in a 600 ms time window above the reservoir level. A zero-phase spiking deconvolution, amplitude compensation, a bandpass filter and radon filter were subsequently applied. Figure 2 displays the SOV2 baseline and one week long data stack acquired on last week of March 2016. While the major known reflections were clearly recovered, seismic signal from the plume could not be retrieved (Figure 3).

A repeatability analysis is conducted on the daily stacks with respect to near-surface conditions showed the gradual decrease in the signal-to-noise ratio. Normalised Root-Mean-Square (NRMS) variations of the strong reflections below the first breaks for two known strong geologic interfaces and the first breaks showed relatively low (up to 0.2) NRMS values for the majority of the traces (Figure 3). To assess the general repeatability trend, a NRMS section generated for the SOV2 baseline and one week long data stack acquired on last week of March 2016 is displayed in Figure 3 as well.

ANALYSIS OF THE BOREHOLE SOV DATA ACQUIRED WITH DAS

To assess the SOVs for the borehole seismic monitoring, two field trials were conducted in May and November 2017. In the first trial, CRC-3 well was utilised for a series of VSP datasets acquisition using a standard straight fibre-optic cable (referred as DASv2 in this paper) and an enhanced sensitivity cable (referred as DASv3). The trial was performed with both SOV sources with sweeps from 0 to 80 Hz as displayed in Table 1. In the second field trial, a standard single-mode fibre was coupled up with both SOVs to test several SOV source configurations. The sweep force of SOV sources is proportional to the frequency squared which results in much lower force in lower frequencies than higher frequencies. To address this, the SOV sources were tested using a larger motor (10 T·m), which would consequently increase the force. However, on large motors, the SOVs were set to sweep up to 80 Hz, as this is close
to the limiting speed of the motor bearings. The higher frequencies were compensated with the small motors (2.5 T-f), varying frequencies to up to 160 Hz (Table 1).

For a comparable data analysis of the first trial, a band pass filter of 5-10-80-140 Hz was applied to all shots for both DAS systems. Figure 4 displays vertical stacks of 14 repeated shots. The VSP data acquired with the enhanced cable (Figure 4a and c) presents less random noise when compared to the standard single-mode fibre (Figure 4b and d), because of the stronger signal. The enhanced fibre presents a set of traces covering 70 m in length, at depth of approximately 1390 m that did not exhibit enhanced sensitivity due to a manufacturing issue. Clear P-wave reflections along the entire length of the standard fibre is also detected. Figure 4 (c and d) shows the data acquired with SOV2 with the standard fibre shows stronger random noise. At both shot positions, P-wave reflections as well as the PS-waves and S-waves are observed.

For the second field trial, a number of repeated sweeps were also stacked to increase the signal-to-noise ratio. While the data acquired with the large motors were stacked with 10 repeated sweeps, the data acquired with the small motors were stacked for 16 repeated sweeps for the 120 Hz maximum frequency and 5 repeated sweeps for the 160 Hz maximum frequency. Wavefield separation was then applied to all datasets. The upgoing P-wave reflections were then NMO corrected using a one-dimensional velocity model, through the VSP to CDP transform.

Figure 5 shows the second field trial VSP-CDP transform results. The 2D lines produced for all sources are displayed side by side for the well location where both lines meet (well path is displayed in red). Various reflections were recorded in all datasets for at least down to 1000 m depth. The large motors sweeping from 0 to 80 Hz present by far the best performance, given it presents higher signal to noise ratio. Hence, it images deeper reflectors down to 2 km depth. It should be noted that the reflections on the 2D line for SOV1 match well with the reflections for the 2D line for SOV2 (Figure 5a). Data acquired with sweeps from 0 to 160 Hz presents higher resolution at shallow depths. However, it was unable to image deep reflectors (Figure 5c).

Table 1. Acquisition parameters of SOV – VSP Surveys.

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<tr>
<th>May 2017 Field Trial</th>
<th>November 2017 Field Trial</th>
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<tr>
<td><strong>SOV 1</strong></td>
<td><strong>SOV 2</strong></td>
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<td>Large motors, 0 – 80Hz</td>
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<td>Small motors, 0 – 120 Hz; 50% peak force</td>
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<td>Small motors, 0 – 160 Hz; 50% peak force</td>
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CONCLUSIONS

SOVs coupled with surface geophone array were proven to be a reliable seismic source providing enough energy to image the target horizons. Sweep analysis of SOVs showed that CW-CCW rotations generates asymmetric signal which needs to be considered during the processing. While the body waves observed on SOV images are stable, surface waves change with near surface conditions. To image the CO2 injected in CO2CRC Otway Stage 2C, we would need to position SOVs such that the ground roll would not contaminate the part of the record carrying TL signal. It should be noted that downhole measurements will prevent seismic record from being contaminated with the ground roll. VSP DAS data acquired with the cemented cable and SOVs provided high quality images which had sufficient signal to image the injected gas plume. While the first borehole trial assessed the performance of DAS/SOV using a standard fibre-optic cable and an “enhanced” sensitivity cable, the second trial aimed to test for optimal performance of the source by acquiring a range of sweeps with large and smaller motors, from maximum frequency of 80 to 160 Hz. In both wells, DAS was able to acquire P-wave up-going reflections, presenting lower levels of random noise on enhanced fibre compare to the standard fibre. Nevertheless, the standard fibre was able to record the same P-wave reflections (while using larger motors). The large motors provided higher signal levels due to the higher source power than the small motors. Because of the higher frequency content, small motors provide better resolution. Both sweeps from up to 80 Hz and up to 120 Hz were able to record reflections from the target depth at 1500 m at the nearest offset (SOV2). We conclude that DAS combined with SOVs is a cost-effective option for permanent reservoir monitoring. Hence, DAS/SOV combination is one of the key strategies to be
pursued in the subsequent part of this project, CO2CRC Otway Stage 3.

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REFERENCES


Figure 2. Day stacked shot gather of SOV 2.
Figure 3. SOV 2 a) Baseline shot section b) stacked shot section (one week data) from the end of the March 2016 and NRMS section c) is generated from a) and b).

Figure 5. Results of VSP to CDP transform for test with sweeps from 0 to 80 Hz, large motors (a), from 0 to 120 Hz, small motors (b), and from 0 to 160 Hz, small motors (c). The 2D line correspondent to SOV1 and SOV2 are displayed side by side. Well path is displayed in red.