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Time-lapse VSP with permanent seismic sources and distributed acoustic sensors: CO2CRC Stage 3 equipment trials

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Abstract

Effective monitoring of the carbon dioxide storage is essential to ensure safe containment of the CO_2 plume in the reservoir. Currently geophysical monitoring usually involves a combination of various seismic surveys acquired using a large array of seismic receivers and moveable sources to image the emplaced gas plume. Deployment of equipment for such surveys usually takes a long time which becomes expensive. At the CO2CRC Otway Research Facility we are exploring the use of distributed acoustic sensing (DAS) combined with permanent surface orbital vibrators (SOVs) in order to build a permanent seismic monitoring array that is able to image the development of the plume in real time. In this study, we acquire 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 DAS/SOV configuration present good quality VSP datasets, imaging beyond the injection interval when using a more powerful motor with sweeps from 0 to 80 Hz.

Keywords: fibre-optics sensing; distributed acoustic sensing; reservoir monitoring; vertical seismic profile.

1. Introduction

In carbon geosequestration projects there is an essential need for effective monitoring of the carbon dioxide storage over decades to ensure safe containment of the CO_2 plume in the reservoir. Geophysical monitoring of the reservoir usually involves a combination of various seismic surveys acquired using a large array of seismic receivers and moveable sources to image the emplaced gas plume. Deployment of equipment for such surveys usually takes a long time. The standard geophysical approach is to temporarily deploy seismic receivers, such as geophones; the inherent effort requires significant labour and results in significant equipment maintenance costs. Also, conventional onshore seismic surveys depend on accessing large swathes of terrain with heavy hydraulically operated vibroseis trucks or auger rigs (for dynamite surveys). The complexity of such surveys makes the conventional approach costly and, at times, unviable for carbon geosequestration applications. Furthermore, errors in repeatability of source and receiver locations can limit the effectiveness of the approach. Permanent reservoir monitoring seeks to overcome the limitations

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of the conventional approach by fixing either the seismic receivers, sources or both. At the CO2CRC Otway Research Facility, we developed a permanent monitoring array consisting of permanently installed distributed acoustic sensing (DAS) in wells, combined with surface orbital vibrators (SOVs) also installed permanently, to create a continuous seismic monitoring array and track the injected CO_2 plume.

DAS senses the seismic signal by simply using standard fibre-optic cables. A surface-based interrogator unit sends a series of light pulses through a fibre-optic cable. By analyzing the differences of the backscattered light, DAS can measure the changes of strain along the fibre length [1]. For permanent monitoring applications, DAS is becoming significantly more economically viable compared to conventional seismic sensors due to the inherent robustness of the fibre-optic cable and affordability.

SOV sources can be used in monitoring surveys to reduce the cost and land impact compared to vibroseis sources. The seismic signal is generated by rotating eccentric weights. The SOV sources produce both a vertical and horizontal shear force [2]. The combination of observation wells instrumented with DAS and permanent sources can offer the cost-effective real time monitoring sufficient to image the CO_2 plume and assure reservoir integrity. The surface trenched fibre-optics DAS and the SOV sources were also evaluated at Otway, showing that they could potentially be used as an economical configuration in time-lapse surveys [3].

The CO2CRC Otway Research Facility is Australia's first demonstration of deep geological storage of carbon dioxide. The next stage of the project (Stage 3) aims to build a multi-well monitoring approach [4]. Several wells will be drilled on site and will be instrumented with fibre-optic cables along their length. In January 2017, a new well (CRC-3 well) was drilled on site as part of the Stage 3 program. A set of standard straight single-mode fibres and enhanced sensitivity fibres (engineered to increase light backscatter) were installed cemented behind the well casing. Field trials show that VSP data acquired with DAS on CRC-3 well present high signal to noise ratio and has the potential to image the injection interval [5].

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. The VSP survey is acquired with two SOV sources installed at offsets of approximately 380 and 630 meters. We also tested different sweep designs on the SOVs and compare their performances.

2. Data acquisition

Two field trials were conducted at the Otway Project site. The first field trial was conducted in May 2017. We acquired a series of VSP datasets in CRC-3 well, 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 two SOV sources. SOV1 was located at approximately 630 m from the well, and SOV2 was located approximately 380 m from the well. The aim of this trial was to test the performance of different fibre types in combination with the SOV sources. In this trial, we used sweeps from 0 to 80 Hz (Table 1).

The second field trial was conducted in November 2017. A standard single-mode fibre was used to acquire DAS data. In this field trial, different SOV source configurations and sweeps were tested. The force of the sweep on SOV sources is proportional to the frequency squared. This means that the force on the low frequencies of the sweep is much lower than the force on the high frequencies. To overcome this issue, the SOV sources were tested using a larger motor (10 T-f), which will consequently increase the force. However, on large motors, the SOV sweeps should only go up to approximately 80 Hz, as this is close to the limiting speed of the motor bearings. To overcome the lack of high frequencies in the data, we tested sweeps using small motors (2.5 T-f), varying frequencies to up to 160 Hz (Table 2).

Table 1: Acquisition parameters for May 2017 field trial.

May Test	
SOV 1	*SOV 2*
Large motors, 0 – 80Hz	Large motors, 0 – 80Hz

Table 2: Acquisition parameters for November 2017 field trial.

November Test	
SOV 1	*SOV 2*
Large motors, 0 – 80Hz	Large motors, 0 – 80Hz
Small motors, 0 – 120 Hz ; 50% peak force	Small motors, 0 – 120 Hz; 50% peak force
	Small motors, 0 – 160 Hz; 50% peak force

3. Data analysis

We analyse the data quality of the VSP acquired by DAS with both SOV sources from the first field trial (May test). To compare both DAS systems, a band pass filter was applied on all shots to select frequencies from 5 to 140 Hz (filter had 5 to 10 Hz taper, and 80 to 140Hz taper). Each display shows vertical stacks of 14 repeated shots. Figure 1 (a and b) shows the VSP data acquired for SOV1, at 630 m distance from the well. The VSP data acquired with the enhanced cable (a and c) presents less random noise when compared to the standard single-mode fibre (b and d), probably due to the stronger signal amplitude in relation to noise. The enhanced fibre presents a set of traces covering 70 m in length, at depth of approximately 1390 m that did not exhibit enhanced Rayleigh scattering due to a manufacturing error. The standard fibre presents higher level of random noise compared to the enhanced fibre. It also detects clear P-wave reflections along the entire length of the fibre. Figure 1 (c and d) shows the data acquired with SOV2, at 320 m distance from the well. Both fibres present clear reflections, with the standard fibre showing stronger random noise. At both shot positions, DAS acquired not only P-wave reflections, but also PS-waves and S-waves.

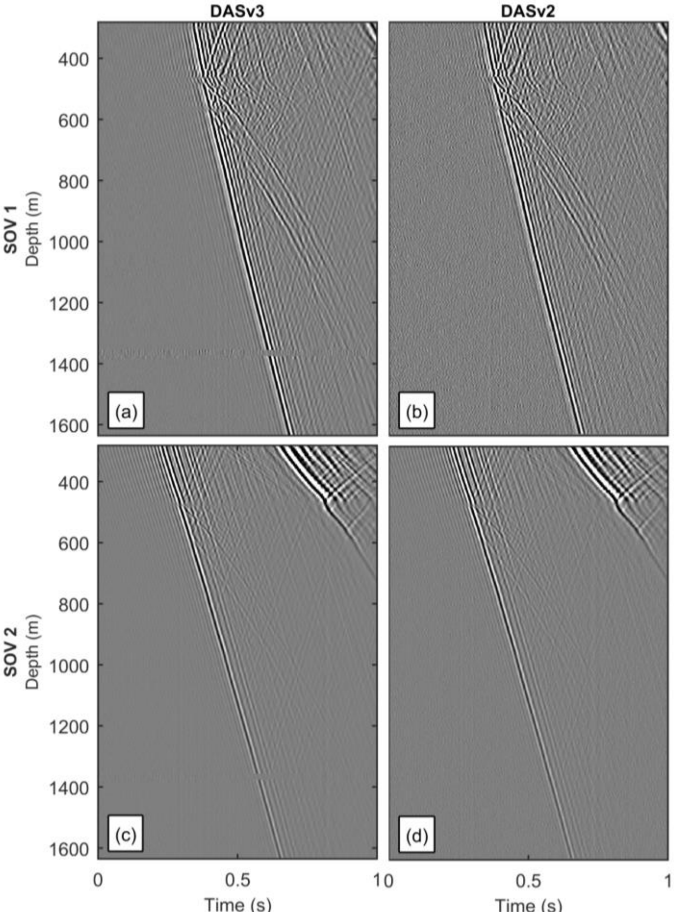

Figure 1: VSP records acquired for SOV 1 (a – b), and SOV 2 (c – d), stack of 14 sweeps.

For the second field trial (November test), we also stack a number of repeated sweeps to increase the signal-to-noise ratio. DAS datasets with large motors were stacked with 10 repeated sweeps, with small motors of maximum sweep frequency of 120 Hz - 16 repeated sweeps were stacked, and for small motors of maximum sweep frequency of 160 Hz - 5 repeated sweeps were stacked. Wavefield separation was applied to each dataset to obtain the upgoing P-wave reflection, where they were then NMO corrected using a one-dimensional velocity model, through the VSP to CDP transform. Figure 2 shows the results from the second field trial after VSP-CDP transform. The 2D line produced for each source is displayed side by side; the well location is where both lines meet (well path is displayed in red). The data acquired in all tests were able to record reflections, at least until 1000 m depth. The large motors using sweeps from 0 to 80 Hz present by far the best performance, given it presents higher signal to noise ratio [6] and it images deeper reflectors. The data with the large motors was able to acquire reflection from beyond 2 km depth. Note that the reflections on the 2D line for SOV1 match well with the reflections for the 2D line for SOV2 (Figure 2a). Data acquired with sweeps from 0 to 160 Hz presents higher resolution at shallow depths, however, it was unable to image deep reflectors (Figure 2c).

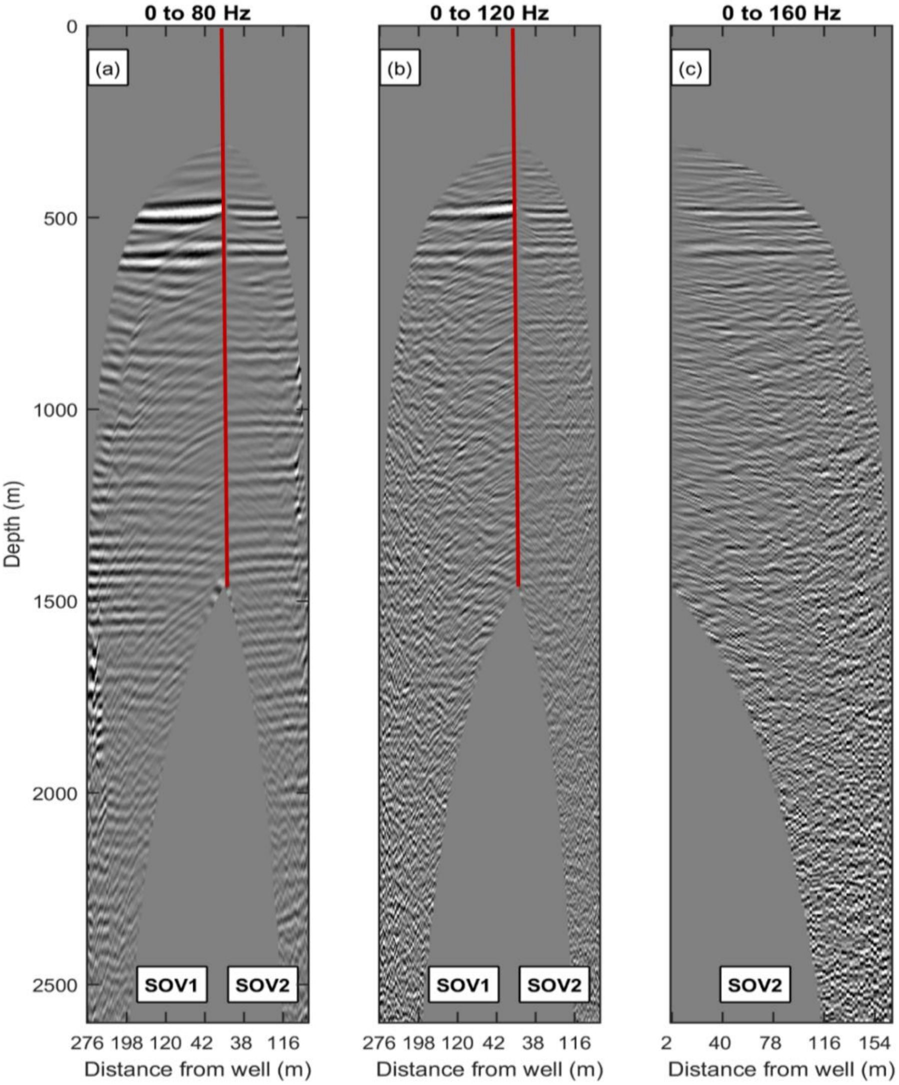

Figure 2: Results of VSP to CDP transform for test with sweeps from 0 to 80 Hz, large motors (a), from 0 to 120 Hz, small motors (b), and from 0 to 160 Hz, small motors (c). The 2D line correspondent to SOV1 and SOV2 are displayed side by side. Well path is displayed in red.

4. Conclusions

The results show that a VSP DAS acquired with a cemented cable and SOVs yields high quality datasets, sufficient to image the injected gas plume. We conclude that DAS combined with SOVs is a cost-effective option for permanent reservoir monitoring.

The first field trial assessed the performance of DAS/SOV using a standard fibre-optic cable and an "enhanced" sensitivity cable. The second field 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.

At both locations DAS was able to acquire P-wave up-going reflections. DAS acquired with the enhanced fibre shows lower levels of random noise 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 provide higher signal levels due to the higher source power than the small motors. Due to 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).

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