Introduction

Long-term seismic monitoring of carbon capture and storage projects (CCS) is needed to verify that the injected gas is safely stored in the subsurface until permanence can be assured. Conventional surface seismic monitoring techniques are usually expensive, require highly invasive surface operations, and need significant time investments on the part of personnel for both the field effort and processing the acquired data. For these reasons, permanent reservoir monitoring (PRM) technologies are preferred, as they can offer a cost-effective solution for long-term monitoring. In this context, we have developed and trialed the use of distributed acoustic sensing (DAS) coupled to permanent rotary sources, called surface orbital vibrators (SOV), with the objective to build a continuous monitoring array for CCS projects.

Fibre-optic based DAS technology is capable of acquiring continuous on-demand seismic data with fine spatial sampling; because of this, it has become a popular technology in recent years for time-lapse vertical seismic profiling (VSP) (Mateeva et al., 2017). SOV sources are rotary seismic sources that generate horizontally and vertically polarized signals by rotating eccentric weights (Daley & Cox, 2001). DAS sensors coupled with SOV sources have been tested in a variety of field experiments (Ajo-Franklin et al., 2017; Cheng et al., 2019; Freifeld et al., 2016), with successful applications using offset VSP geometry (Correa et al., 2018).

As part of the monitoring program of the Archer Daniels Midland's (ADM) large-scale injection of CO_2 in Decatur, Illinois, USA, a continuous seismic monitoring array was installed using a combination of SOV sources and fibre-optic cables for DAS acquisition. The ADM company has a biofuel processing plant on the site, where CO_2 is captured as a by-product of ethanol production, and stored subsurface in the Mt. Simon Formation. The ADM's biofuel production complex houses two distinct CCS projects: the Illinois Basin-Decatur Project (IBDP) and the Illinois Industrial Carbon Capture and Storage Project (ICCS).

The objective of the ICCS project is to store 5 million tons of CO_2, while demonstrating the integration of the CO_2 capture facility into the ethanol production plant. The permanent seismic monitoring component of the project aims to integrate the existing monitoring infrastructure on-site, comprised of a combination of multi-level geophone arrays, pressure gauges, fibre-optic acoustic and temperature sensors, and surface seismic stations (Kaven et al., 2014; Williams-Stroud et al., 2019). DAS/SOV was added to the monitoring program as a potential method to improve the temporal resolution of the infrequent surface seismic acquisitions. Here, we focus on the lessons learnt from the preliminary operation of the DAS/SOV array. With this, we hope to broaden acceptance of the DAS/SOV method as well as provide suggestions to improve future deployments.

Permanent seismic monitoring at the ADM ICCS project

The ADM ICCS project is located within the Illinois basin, in Decatur, Illinois, USA, approximately 120 miles northeast of St. Louis, MO. The installation of the DAS/SOV permanent monitoring system was completed during the fourth quarter of 2017, as part of the ADM ICCS project (Figure 1a). Five 10-ton force SOV motors were installed (Figure 1b), along with approximately 10,000 ft of permanent DAS cables. The DAS cables consist of a combination of standard single-mode fibres as well as engineered high sensitivity optical fibre that increases the light backscatter (Constellation fibre, Silixa Ltd., Elstree, UK). Since the DAS cable was deployed near the ground surface, the chosen cable contained helically wound fibres to increase the angular sensitivity of DAS to reflected P-waves (Kuvshinov, 2016) (Figure 1c). The DAS cable was installed at a depth of 25 ft using horizontal directional drilling, forming two lines from the injection well CCS#2, which we call the NW line (the northwestern portion of the cable) and the NE line (the northeastern portion of the cable). A shallow monitoring well GM#2 is located close to the injection well, while a deep monitoring well, VW#2, is located 2,600 ft from the injection well. A fibre-optic cable was deployed in VW#2 monitoring well using blown in optical fibres for distributed temperature sensing (DTS) acquisition. However, the blown in fibre does not provide enough signal-to-noise ratio for DAS acquisition due to its poor coupling.

After commissioning of the permanent monitoring system, a Silixa iDASv2 interrogator unit was connected to the standard single-mode fibre. Continuous DAS/SOV data was acquired for approximately two years. Each SOV source generated 30 180 second sweeps a day, 15 clockwise (CW) and 15 counterclockwise (CCW), with sweeps from 0 to 80 Hz.

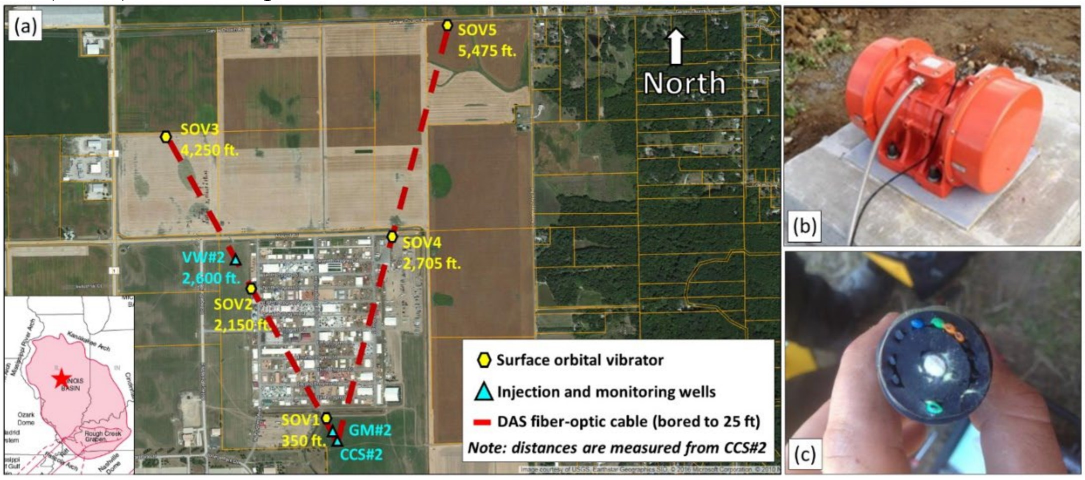

Figure 1 *Areal image of fibre-optic cable deployment and surface orbital vibrators (a). Surface orbital vibrator deployed on-site (b). Helically wound fibre-optic cable deployed on-site.*

Optimization of source signature

The sweep generated by the SOV motor is recorded by a near-field geophone, which provides the source signature used for the deconvolution process. During the commissioning of the system, a 3-component geophone was installed for each SOV location at a depth of 60 ft. This depth was chosen as it was expected it would decrease the effects of the near-surface on the sweep signature while decreasing ambient noise. After analysis of the 60 ft deep geophone (Figure 2a), the signature for each component was noted to contain a series of notches. In 2018, a shallow geophone was installed at 10 ft depth for each SOV location, in an attempt to improve the source signal. Figure 2b shows a comparison of the frequency spectrum of the geophone signature at 60 ft depth (orange) and at 10 ft depth (green). A clear notch at approximately 50 Hz is seen on the 60 ft geophone. The notch seen in the frequency spectrum is probably a "ghost" reflection (Figure 2c), which generates destructive interference at 50 Hz. When the geophone was installed at 10ft depth, the notch was not seen on the data.

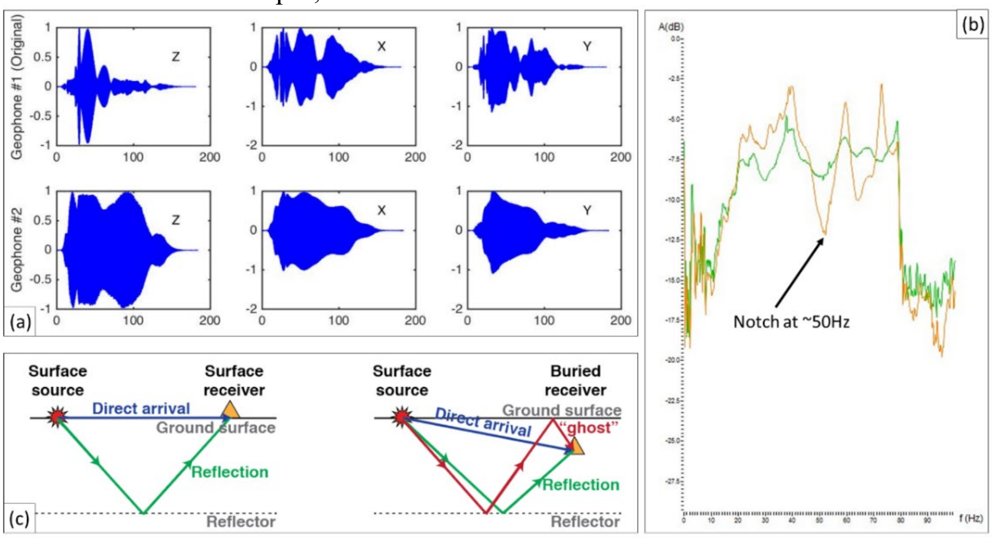

Figure 2 *Time series of the recorded SOV sweep with a geophone installed at 60 ft depth (top) and at 10 ft depth (bottom) (a). Frequency spectrum comparison showing notch at 50 Hz on the 60 ft geophone (orange) (b). Diagram of "ghost" reflection (c).*

DAS/SOV data acquisition with standard single-mode fibre

Due to the rotary characteristic of the SOV source, the force of the sweep signal increases as the angular frequency of the motor squared. For this reason, deconvolution of the sweep signal with the recorded DAS is applied to the data in order to flatten the frequency spectrum. To improve the signal-to-noise ratio, each day's sweeps are stacked for each direction of the rotation (15 sweeps CW, 15 sweeps CCW).

A noise attenuation flow was applied to the data targeting random noise and ground roll. Ground roll is a type of coherent noise generated by a surface wave, typically a low-velocity, low-frequency, high-amplitude Rayleigh wave. Ground-roll noise was found to significantly affect the quality of the data on-site, especially for the SOV sources located close to the DAS line (i.e. SOV#1, SOV#2, and SOV#3 are near the NW line). Because ground roll noise is generated by slow moving surface waves, they arrive at a similar time as the SOV generated P-wave reflections moving through the target area (injection zone - Mt Simon Sandstone). Regarding the more distant SOV sources, the surface waves arrive after the reflected P-waves and have little effect on data quality.

A band pass filter was applied from 5 to 85 Hz (taper from 5-10 and from 75 – 85) to the data. To attenuate ground roll noise, a "ground roll" model was developed to predict (simulate) the noise (surface waves) experienced at our site. To develop the ground roll model, first a band pass filter is applied from 5 to 30 Hz, which approximates the ground roll frequency band. Next, an FK filter is applied to separate the velocities up to 1800 m/s. Finally, the ground roll (noise) simulated by the model is subtracted from the dataset. The final step of the noise attenuation data processing flow is the application of a 2D spatial filter followed by a FX Predictive Filter. Figure 3 shows the SOV#2 data acquired on NW DAS line before noise attenuation (Figure 3a), and the ground roll model (Figure 3b). SOV#4 on NW line is not affected by ground roll, therefore, the data was processed and migrated. Figure 3c shows the migrated SOV#4/NW line acquired with engineered DAS fibre. Between 750 to 800 ms, the migrated line shows strong reflections, though, the reflections are not continuous, possibly due to coupling issues along the fibre cable. When comparing the migrated line to a synthetic seismogram generated using well log information (Figure 3d), the strong reflections largely correlate.

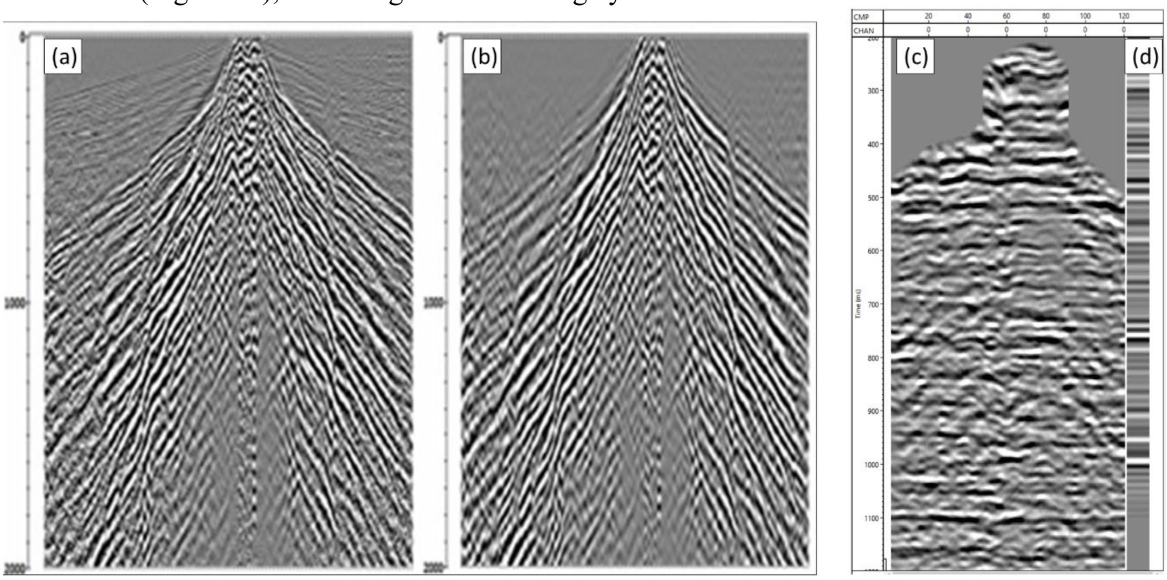

Figure 3 *DAS/SOV#2 data acquired on NW line using single-mode fibre (a) and the ground roll noise model after noise attenuation (b). Migrated section of DAS/SOV#4 on NW line acquired with engineered fibre (c). Synthetic seismogram (d).*

Discussion and lessons learned

CO_2 geosequestration projects require robust long-term monitoring to verify the permanence of emplaced CO_2 and ensure no risk of leakage. The use of DAS coupled with permanent orbital vibrators offers a cost effective approach for permanent reservoir monitoring. We have built an autonomous seismic monitoring system with DAS and SOV sources at the ADM ICCS project as part of the monitoring of a large-scale CO_2 injection. The system was successfully acquiring data in semi-autonomous fashion for approximately 2 years, with minimum intervention. While the acquisition of the continuous DAS/SOV data was successful, a series of data quality limitations hindered the integration of the DAS/SOV into the monitoring program. Nonetheless, the challenges allowed us to understand the limitations of the system and develop workarounds for some of the issues.

One of the most significant limiting factors on the data quality was the strong angular sensitivity of the DAS method to broadside waves. Although the helically wound cable improved the angular sensitivity, in practice the improvement was not sufficient to detect P-wave reflection from the target interval using a standard single-mode fibre. Additionally, the presence of strong ground roll noise limited the usability of the near-offset sources as the ground-roll was masking any possible reflections. Another aspect that degraded the signal quality was the presence of ghosts in the reference geophone signature. The quality of the source signature improved after installation of the shallower geophone. A last challenge was managing the substantial data flow from the site (6-12 TB/wk); while an on-site processing server with a RAID array was deployed to manage edge analysis needs (e.g. deconvolution & stacking), internet bandwidth at the site was quite limited, resulting in bottlenecks in both quality control and processing parameter testing. While data transfer of raw records on HD via USPS was sufficient for off-line analysis, a more comprehensive solution would be required for deployment of such a system in a commercial monitoring context.

For future deployments of DAS/SOV for seismic reflection monitoring using surface cables, we would make the following recommendations: (1) investigate and model ground roll as part of the process of selecting SOV source locations, (2) install the source recording geophone directly under the SOV at depths shallow enough to avoid ghosting, and (3) use engineered fibre to improve signal sensitivity (Correa et al., 2017). There are other changes that can lead to DAS/SOV improvements that we have noted from work conducted at other field sites. These include developing optimal SOV sweeps, such as a quadratic ramp up in velocity, that flattens the recorded DAS spectrum, as well as options for running larger and multiple motors from a single SOV location. Given the operational success of the ADM DAS/SOV network, the method holds promise for providing cost-effective high-resolution time-lapse seismic data.

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