Sparse seismic monitoring at CMC's Newell County CO_2 storage facility

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ABSTRACT

Active-source seismic monitoring provides crucial Measurement, Monitoring, and Verification (MMV) data for Geological CO_2 Storage (GCS). Conventional 2D and 3D surface seismic monitoring of GCS becomes prohibitively expensive for CO_2 plumes extending over 10s of kilometers, particularly at storage hubs operating on the scale of 100 – 1000 Mt of injection. Sparsely distributed, automated monitoring nodes with permanently installed sources and receivers can provide active monitoring capability over large areas by using sparse seismic reflection points to detect injection-related changes in the subsurface over time. Seismic receivers at each sparse node simultaneously provide passive monitoring capability for injection-related microseismicity and induced seismicity. Source and receiver repeatability is crucial in the case of sparse monitoring. Field tests of seismic sources on a permanent source location were performed at Carbon Management Canada's (CMC) CO_2 storage pilot site in Newell County, Alberta, Canada. The source location is a steel pile screwed through 24.7 m of unconsolidated glacial till, allowing the pile's toe to act as a point source coupled with sedimentary bedrock. Impulsive and vibrational seismic signals were successfully transmitted through the steel pile and recorded on borehole and buried seismic sensors, bypassing the highly attenuative and non-stationary filtering effects of the near-surface. A maximum frequency of 180 Hz was consistently observed in each source test, likely caused by attenuation within the geology between the pile toe and the borehole receivers. With the goal of automating shots and recordings, field tests achieved proof of concept for synchronized source and recording trigger systems, independently controlled by GPS timing. The installation of two additional screw pile permanent source locations at the Newell County Facility is planned for the end of 2023, with the long term objective of automated, daily monitoring of the CO_2 plume starting in 2024.

INTRODUCTION

The Accelerating CCUS Technologies (ACT) program is an international initiative to advance the CO_2 capture, utilization, and storage (CCUS) sector. Within the 4th round of ACT projects, Carbon Management Canada (CMC) and the University of Calgary are participating in the SPARSE project (Sparse Passive-Active Reservoir monitoring using Seismic, Electromagnetics, gravity, and surface deformation), which is funded by Canada (Emissions Reductions Alberta), Germany, India, Norway, and the United States. The goal of SPARSE is to develop and evaluate cost-effective geophysical monitoring of Geological CO_2 Sequestration (GCS) using a sparse multi-physics monitoring node approach. With an ongoing pilot-scale CO_2 injection and monitoring program (Macquet et al., 2022), Carbon

Management Canada's Newell County Facility (formerly known as CaMI.FRS) in southern Alberta, Canada, provides one of the field experiment locations for testing sparse monitoring nodes. Though the SPARSE project involves a multi-physics approach to monitoring, this report focuses specifically on sparse seismic monitoring.

The sparse geophysical monitoring concept is motivated by the desire to cost-effectively monitor the large areal scale of CO_2 plumes as the GCS sector progresses toward gigatonne-per-year storage rates. Figure 1a schematically illustrates the estimated scale of seven 10 Mt CO_2 plumes in the Basal Cambrian Sandstone of the Western Canadian Sedimentary Basin (WCSB), placed over the city of Calgary for scale. Green 10 x 10 km outlines depict the typical size of 3D surveys in the WCSB, which often cover one 6 x 6 mile township of Canada's Dominion Land Survey system, at a cost of millions of dollars per 3D survey. Figure 1b depicts a sparse seismic monitoring array covering the same area, with a sparse distribution of reflection midpoints between multi-physics nodes that include permanent, automated sources and receivers. In practice, the sparse array would require a greater spatial density than depicted in Figure 1b in order to provide meaningful information about the growth of each CO_2 plume. Such a sparse monitoring approach could provide more cost-effective time-lapse seismic monitoring compared to infrequent 2D or 3D surface acquisition, though with much reduced imaging capability and without the benefit of seismic migration and surface-consistent deconvolution. Automation of the sparse sources and receivers, paired with a high degree of time lapse repeatability, would provide frequent, nearly real-time longitudinal monitoring data. These data would act as proof of conformance of the CO_2 plume with reservoir modeling predictions, or alternately would alert operators to a lack of conformance. As a distributed network of receivers with the ability to record continuously, the sparse nodes would also fill the role of passive seismic monitoring for induced seismicity.

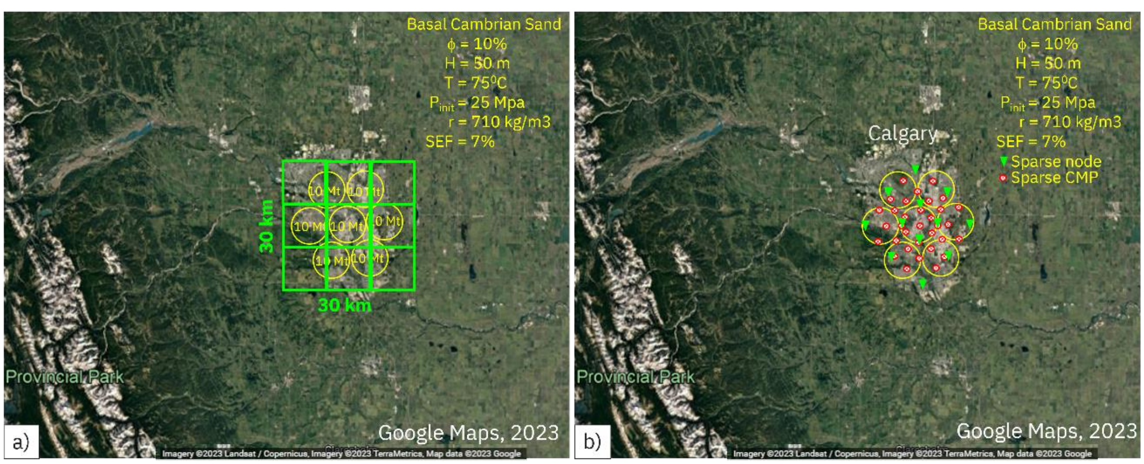

FIG. 1. Sparse node CO_2 monitoring concept. Panel a shows seven 10 megatonne CO_2 plumes in the Basal Cambrian Sandstone relative to nine township-scale 3D survey outlines, overlain over the city of Calgary for additional perspective. Panel b shows a schematic representation of sparse monitoring nodes and corresponding reflection midpoints.

Previous work towards sparse monitoring at the Newell County Facility saw the testing of surface orbital vibrators and the installation and initial testing of a steel screw pile acting as a permanent source location (Lawton et al., 2020; Spackman, 2019). Existing passive seismic monitoring infrastructure recording continuously at the Newell County Facility consists of an array of twenty-eight 3-component geophones buried 1 m deep, five broadband stations, twenty-four 3-component geophones permanently cemented into the annulus of an observation well, and volumetric phased arrays of receivers, for seismic and acoustic detection and ranging (SADAR®), buried 10 – 22 m below surface (Zhang et al., 2023). Of those, the borehole geophones and the SADAR® arrays operated by Geospace Technologies are most isolated from repeatability challenges posed by weather-related seasonal differences near surface, such as water saturation in the soil and weathering layer, snow cover and freezing, and groundwater level. Those dynamic effects on the elastic properties of the surface affect near-surface multiples and attenuation. Negative effects on time-lapse acquisition repeatability can be mitigated to an extent through deterministic deconvolution in Vertical Seismic Profiles (VSP) (Kolkman-Quinn et al., 2022), or by surface-consistent deconvolution of 2D & 3D surface acquisition. However, to achieve high-quality, high-repeatability data for individual source and receiver locations in a sparse network, the non-stationary filtering effects in the near surface must be avoided.

As part of the SPARSE project, new field tests were performed between July and November, 2023 on the steel screw pile source location previously installed in 2020. Alongside more conventional hammer and vibroseis sources from the University of Calgary, a prototype plasma-discharge impulsive source from Hyfold Technologies was also tested with the intention of permanent installation and automation. This electrically-controlled source also provided the opportunity to test new control boxes for independent, GPS-synchronized triggering of shots and recordings, developed for future automation of the sources and receivers. The variety of sources tested on the steel screw pile provided new observations of its elastic behaviour and its viability as a permanent source location.

THEORY

Figure 2 provides a section-view schematic of the sparse node concept, with two permanent seismic nodes of the style being tested at the Newell County Facility offset from a well outfitted with distributed acoustic sensing (DAS) optical fiber for VSP acquisition. Receivers at the sparse node provide passive monitoring for injection-related microseismicity and induced seismicity. Automated sources controlled by GPS timing and mounted on steel screw piles transmit broadband signals to sedimentary bedrock, bypassing the unconsolidated sediment of the weathering layer. The node proximal to the well provides a highly-repeatable, far-offset VSP shot gather providing two dimensional imaging for containment verification near the well. Beyond the practical limit of the borehole receivers, each node produces a seismic reflection trace, or grouping of traces, at the midpoint between it and other nodes. These traces detect the arrival of the CO_2 plume, demonstrating conformance or non-conformance of the plume with model predictions. Reflection points intentionally located at known containment risks such as faults, caprock discontinuities, or legacy wells provide early warning in the event of a loss of containment.

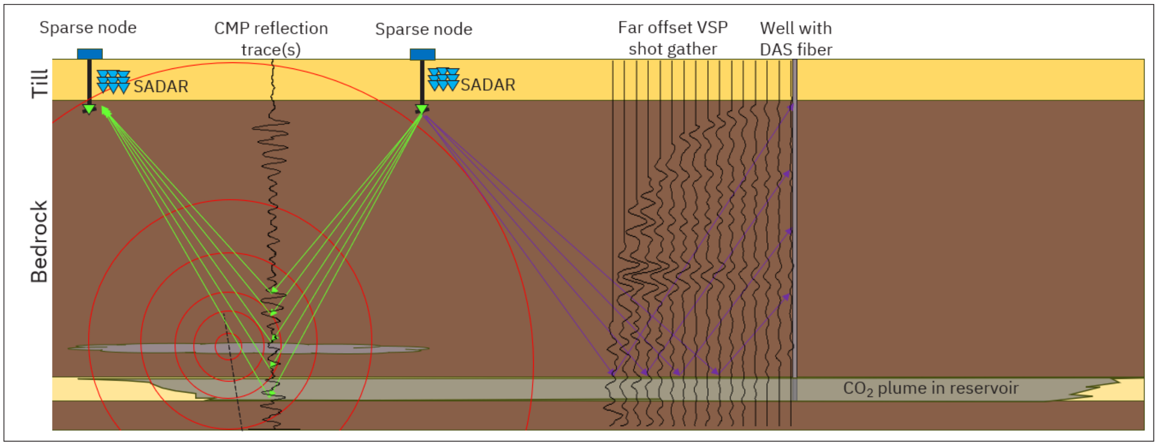

FIG. 2. Section view schematic of the sparse node concept. Continuously recording receivers fulfill passive seismic monitoring requirements for induced seismicity (red wavefronts) while also recording regularly scheduled permanent source signals (green raypaths). Borehole receivers record VSP shot records from nearby permanent source locations (purple raypaths).

The spatial distribution of sparse seismic nodes is constrained by the optimal offset for reflection seismology, as described by Hunter and Pullan (1989). Figure 3a illustrates the optimal offset range between sources and receivers for which seismic reflections arrive after refraction head waves but before the air blast and surface wave noise cone. Shallow reflections have a more limited optimum offset range than deep reflections. Figure 3b shows a common receiver gather from a 2D surface acquisition at the Newell County Facility, with red arrows indicating three reflection interfaces at different depths. Optimum offsets broadly range from 0.3 – 2 x reflector depth.

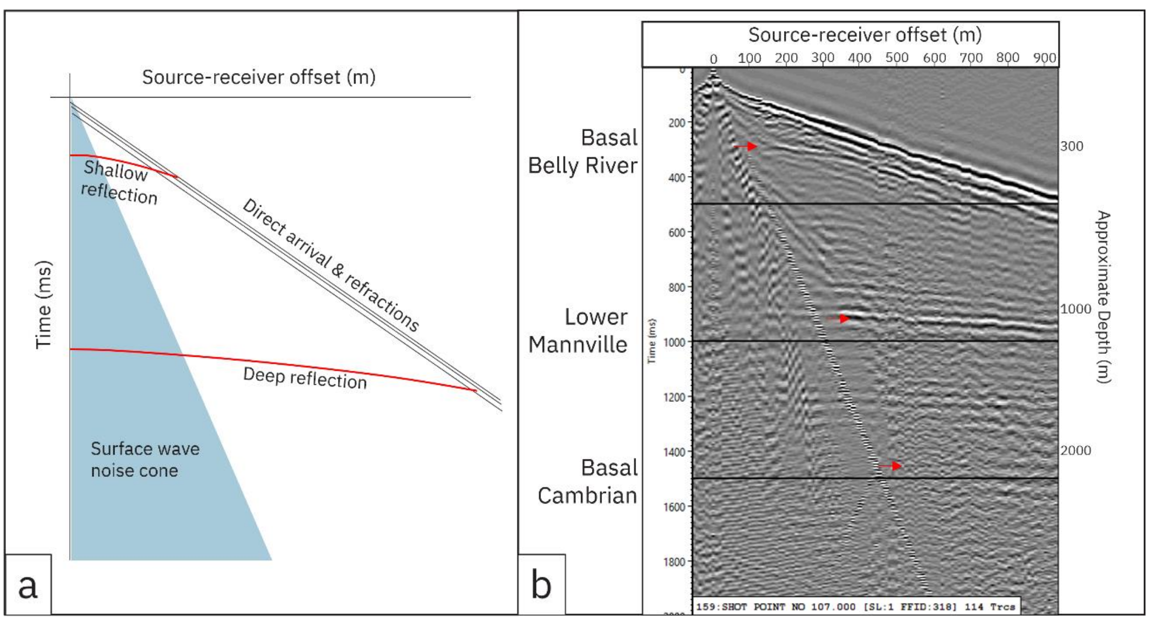

FIG. 3. Optimum offset concept (a) as described by Hunter and Pullan (1989). A 2D surface common receiver gather (b) shows the small optimum offset window of the BBRS reservoir along with deeper reflections. AGC and a bandpass filter were applied to enhance the reflections relative to the noise cone and shear wave.

In structurally simple areas, a minimal amount of prior seismic information such as sonic and density logs from injection wells and legacy wells may suffice to properly interpret the unmigrated, 1D seismic data from sparse node midpoint reflection traces. In more depositionally and structurally complex areas, baseline 2D or 3D surface seismic data may be needed to inform the sparse data interpretation.

For monitoring gigatonne-scale CO_2 storage on 10+ year time scales as illustrated in Figure 1, permanent seismic nodes must satisfy the following conditions: (1) produce a highly repeatable signal with sufficient energy for signal penetration kilometers deep, (2) provide automated shots and recordings with precise GPS controlled timing, (3) be remotely accessible for control, diagnostics, and re-programming, (4) require minimal maintenance, and (5) be physically accessible for maintenance or replacement. To address the first requirement, both the source itself and the source location must have high signal repeatability. Figure 4 shows a prior installation of a steel screw pile at the Newell County Facility (Lawton et al., 2020). The steel pile was screwed through 24.7 m of unconsolidated sediment, down to sedimentary bedrock. At the Newell County Facility this unconsolidated sediment is primarily heterogenous glacial till, but in more general cases it could be sand, muskeg, bog, or other attenuative and dispersive media. By mounting a repeatable seismic source on the steel pedestal shown in Figure 4b, the source signal is transmitted to the screw pile's toe which acts as a point source coupled with the more competent sedimentary bedrock. This direct coupling to bedrock preserves the original source spectrum by avoiding attenuation and near-surface multiples, and most crucially by avoiding or reducing the seasonal and weather driven changes to the elastic properties of the surface and near surface.

FIG. 4. Screw pile installation photos from Lawton et al. (2020). After screwing in the steel pile (a), a steel plate (b) supports small seismic sources. After the photos were taken, the pile was screwed in deeper until the steel plate was approximately 15 cm above the ground and the toe was 24.7 m below surface.

METHODS

The screw pile installed at the Newell County Facility is located in the south-west corner of the barbed-wire fence, as indicated by the green X in Figure 5. A welded steel plate on the top of the screw pile provides a mounting point or pedestal for different seismic sources (Figure 4b). The Basal Belly River Sandstone (BBRS), which is the current CO_2 reservoir at the Newell County Facility, is at a depth of nearly 300 m. Its corresponding optimum offset range is severely constrained at approximately 90 – 270 m, when compared to the larger range of offsets available to supercritical CO_2 storage depths of 800 m and deeper. The SW screw pile is located within optimum offset range of three out of four SADAR locations, with one reflection point near the edge of the CO_2 plume, as interpreted from time-lapse VSP data (Figure 5). A north-east screw pile location is planned opposite the injection well, providing two additional reflection points near the plume for the SADAR arrays, as indicated in red in Figure 5. A third screw pile location is planned in the south-east, coloured blue in Figure 5, contributing additional reflections near the plume as well as additional optimum offset reflection points that should show no change over time. As the CO_2 plume expands and both CO_2 gas saturation and pressure increase outward, time-lapse changes are expected at the sparse reflection points nearest its edges. A source location near the pre-existing north-west SADAR location was considered in order to demonstrate a complete sparse node with source and receivers. However, the reflection point distribution within optimum offset was less ideal than the other locations. As indicated by dashed lines in Figure 5 and illustrated in section view in Figure 2, the source locations will also provide VSP shot gathers for geophone and DAS receivers in the observation wells flanking the injection well.

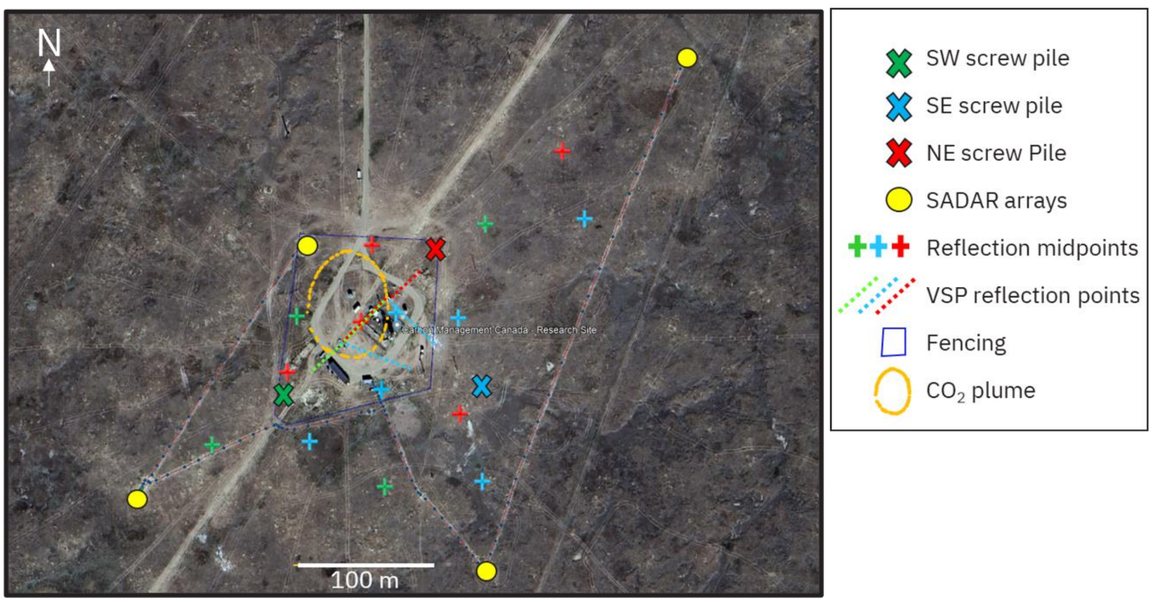

FIG. 5. Map of CMC's Newell County Facility with permanent source locations and corresponding reflection midpoints between them and between source locations and permanent SADAR arrays. Only the SW screw pile (green) is currently installed.

In addition to the reflection points between the screw piles and SADAR arrays, the south-east and north-east screw piles will be installed with a closed toe to allow instrumentation with seismic receivers inside the piles. This will provide reflection points between screw piles. Figure 6 shows the planned installation of a 3-component geophone and cabling lowered to the toe of the pile, then packed with sand or bentonite to provide coupling. The main purpose of the geophone is to measure the source signal at the toe of the pile, in order to observe the transfer function effects of the pile. This could be accomplished with a 1-C geophone, but a 3-C geophone provides the opportunity to also determine if this is a viable installation method for deep, high SNR receivers. The geophone will be fixed within a 7.5 cm diameter PVC pipe to be more smoothly lowered to the toe, and the longer profile of the PVC pipe will minimize tilting away from vertical orientation. Optical fiber for DAS acquisition can be included in the PVC pipe assembly, providing an extended sensor that may provide additional insight into how the source signature is or is not altered between the top and bottom of the screw pile. Installation of a second geophone halfway down the pile will be attempted, provided that the cabling of the first does not interfere with the second. If the coupling is similar for each receiver and no significant receiver scalar effects are at play, multiple sensors should allow for measurement of amplitude loss, attenuation, and resonance within the pile.

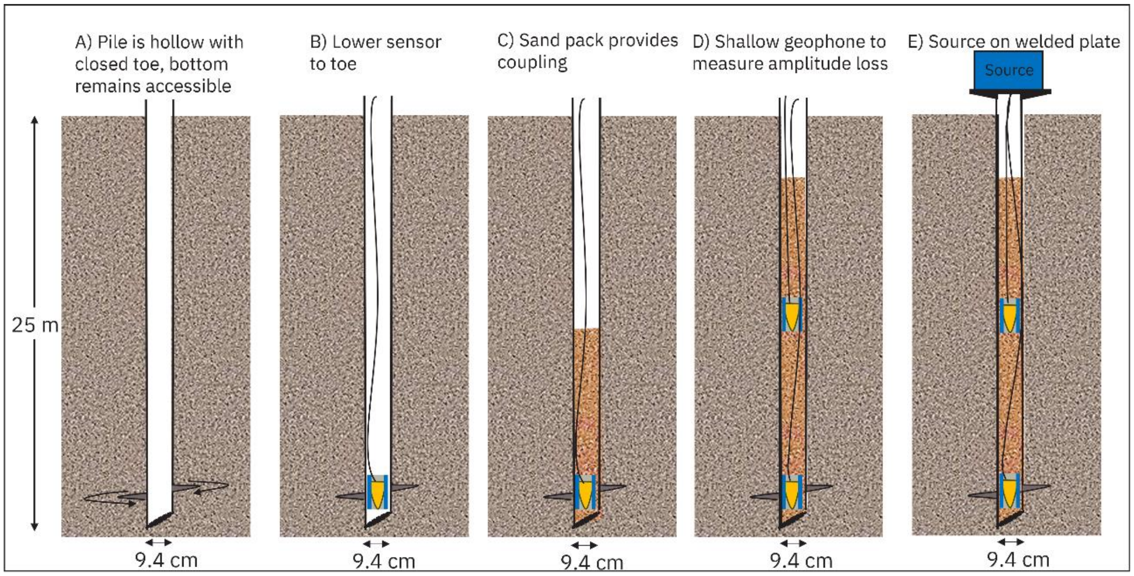

FIG. 6. Schematic showing the design for new screw pile installations at the Newell County Facility.

To achieve precise timing and synchronization of shots and recordings at each sparse node, the leading edge of the pulse-per-second (PPS) signal from the GPS network is used for triggering. Figure 7 shows a 30 second recording on the Z-component from the twenty-four 3-C borehole geophones, including dead traces, in the geophysics observation well. This set of geophones is remotely accessible with a live data feed and small data volumes, therefore the source timing will be matched to the 30 s recordings. The control box for the Hyfold source mounted on the screw pile forces the shots to occur every 30 seconds, for example at 9:00:00, 9:00:30, 9:01:00, etc.. The PPS signal has μs-range precision and the Hyfold source's electronics have +/- 25 μs precision. A second GPS-timed control box independently forces the borehole geophone recordings to trigger at the same time as the source, synchronizing the shots and recordings. The source signal therefore appears consistently at the start of each borehole geophone record, as shown in Figure 7. Precise GPS controlled timing will allow for automated stacking of all shots within an acquisition window, for example 100 shots per day. The high precision of the shot and recording triggers prevent jitter between records, allowing for automated stacking of raw traces during each acquisition window. Simple processes such as cross-correlation and differencing can also be automated to check for changes between each acquisition window's stacked trace. The 30 second shot interval shown in Figure 7 is a pre-existing recording parameter from the passive seismic monitoring program at the Newell County Facility. The automated shot interval could be reduced to as low as 2 seconds as the sparse network evolves and incorporates more networked receivers.

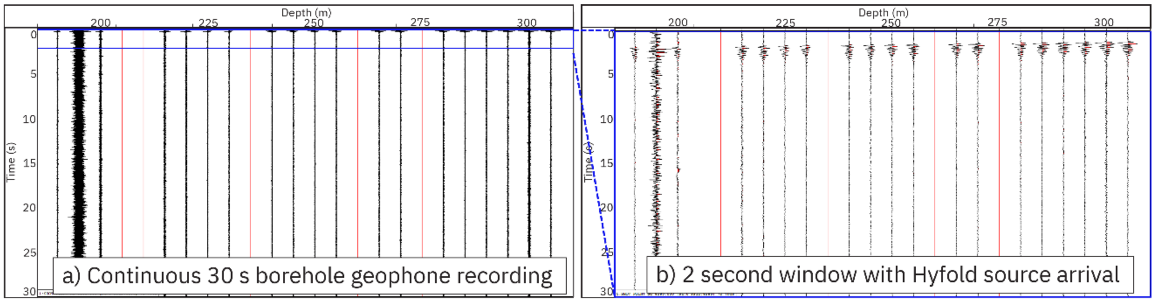

FIG. 7. Source and recording automation. The PPS signal from the GPS network triggers the shots and recordings at 30 second intervals (a) with shots appearing at the start of each record (b).

Three seismic sources were tested at the existing south-west screw pile. One of the intended permanent sources for the SPARSE project, a GPUSA surface orbital vibrator (SOV) previously tested on an earlier steel pile installation (Spackman et al., 2019), is currently inoperable and awaiting maintenance in early 2024. As an ad hoc replacement for a frequency-swept source, the vibrator plate of the University of Calgary's Envirovibe was centered over the pedestal (Figure 8a). The main purpose of that vibe test was to determine a maximum frequency for signal transmission through the pile. Out of caution for the integrity of the pile under the oversized vibe truck, the hydraulic controls for the hold down pressure of the vibe plate were manually reduced to a minimum, putting a crudely estimated force of 2000 lbs on the pedestal. The sweep was set at 20 – 300 Hz over 10 s with 0.2 s cosine tapers, and was run with 10% and 15% power. Low frequencies were omitted to avoid excessive shaking of the pile during the start of the sweep. A flat power spectrum was not achievable at the minimum settings, but the sweep to 300 Hz was performed with no undesired shaking observed from the vibe plate or pedestal.

A second ad hoc source test involved the University of Calgary "thumper" (Figure 8b), a compressed nitrogen powered hammer built as a P-wave and S-wave source (Lawton et al., 2013). While manually triggered and not intended for permanent deployment, this source produced an impulsive seismic signal that was used to both evaluate the steel pile and to compare against other sources. The foot of the thumper has 5 steel teeth, only three of which fit on the pedestal. A piece of wood was placed between the steel teeth and the pedestal to distribute the force from the thumper. Between the available range of 100 psi and 1000 psi, the 400 psi setting on the thumper provided the sharpest impulsive signal.

The third source tested was a prototype impulsive source from Hyfold Technology Corp (Figure 8c). This source is electrically powered and controlled, consisting of a pulse network with associated electronics, a large capacitive storage chamber, and a plasma reactor chamber (T. Hunter, personal communication, 2022). Its deployment follows previous tests of plasma discharge sources at the Newell County Facility (Lawton et al., 2020). When first installed in September, 2023, this source was manually triggered. However, the automated trigger system previously described was successfully tested in the field in November 2023.

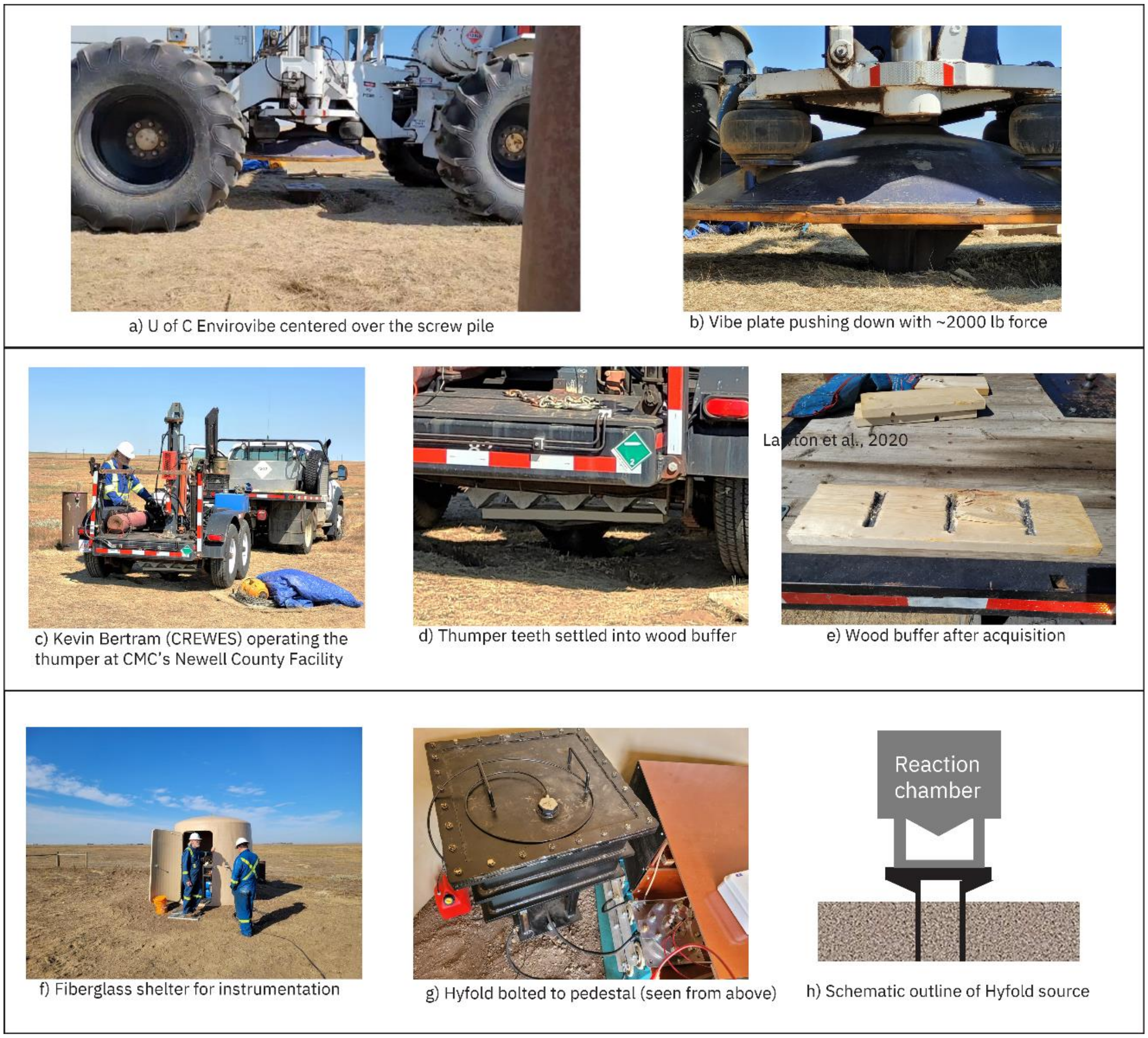

FIG. 8. A variety of sources tested on the steel pile at the Newell County Facility in 2023: (a-b) U of C's IVI Envirovibe, (c-e) U of C thumper, and (f-h) Hyfold plasma source.

RESULTS

The Z-component of the borehole geophones in the geophysics observation well, offset 58 m north-east of the south-west screw pile location, provide the highest SNR data with which to inspect the field test results. The amplitudes of each source were within the same order of magnitude. The number of shots acquired for each source were different, therefore diversity stacks were performed to allow a comparison of stacked data while preserving original amplitude. Figure 9 shows a 64x diversity stack of the thumper on the pedestal, a 24x stack of the thumper on the ground beside the pedestal, an 8x stack of the Envirovibe on the pedestal, and a 25x stack of the Hyfold source on the pedestal. Dead traces have been interpolated on the displays in Figure 8, but otherwise the data are unprocessed and are equally scaled. Figures 9a and 9b show two effects of the steel pile as a source location: The impulsive thumper source signal is sharper on the screw pile, while the dominant frequency is much lower for the thumper shot on the ground. In Figure 9a, the direct arrivals, indicated by arrows, arrive 15 ms earlier due to the shorter travel time through 24.7 m of steel rather than through glacial till (Lawton et al., 2020).

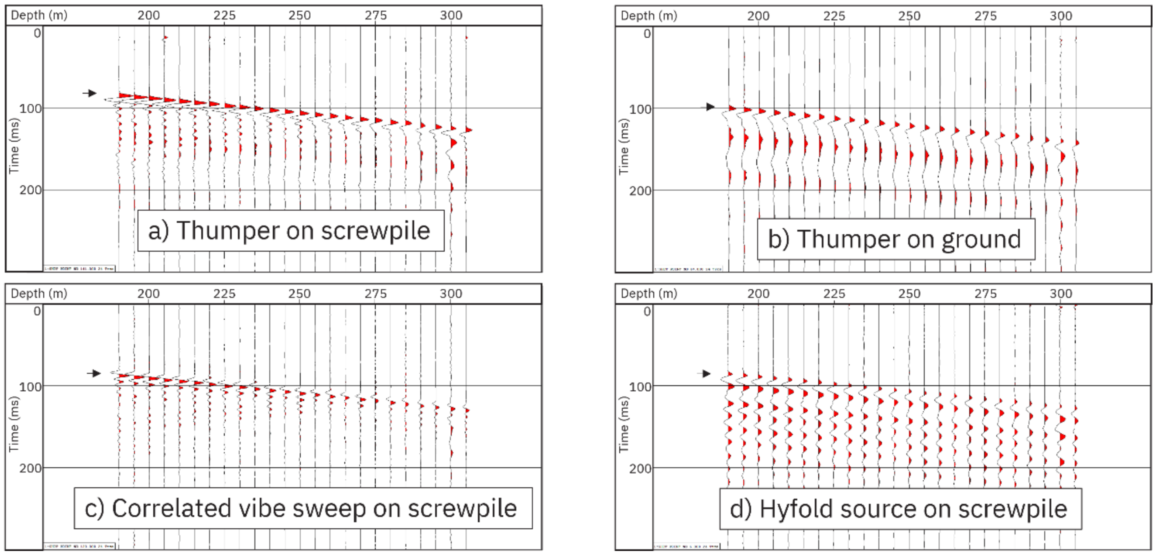

FIG. 9. Borehole geophone shot gathers of sources tested on the SW screw pile location: a) thumper on screw pile, b) thumper on ground adjacent to screw pile, c) Envirovibe on screw pile, and d) Hyfold source on screw pile.

Following cross-correlation with a synthetic sweep, the vibroseis record in Figure 9c shows a higher frequency but less compact direct arrival than the thumper. The Hyfold source was expected to produce a sharp front-loaded impulse similar to the thumper in Figure 9a, but instead produced an extended, ringing direct arrival (Figure 9d). Figure 10a shows the amplitude spectra of the four displays from Figure 9, while Figure 10b more clearly shows the recoverable bandwidth of each source, following deterministic deconvolution of the raw gathers using the downgoing arrivals isolated with a median filter. The sharp compact arrival of the thumper on the pile has a broad spectrum tapering off at 135 Hz to a maximum frequency of 175 Hz, with a recoverable bandwidth of 7-150 Hz recorded on the 10 Hz geophones. The spectrum of the thumper on the ground is skewed toward lower frequencies due to attenuation in the subsurface, losing much of the 100 – 150 Hz band. It is unclear whether the low frequencies have been amplified within the

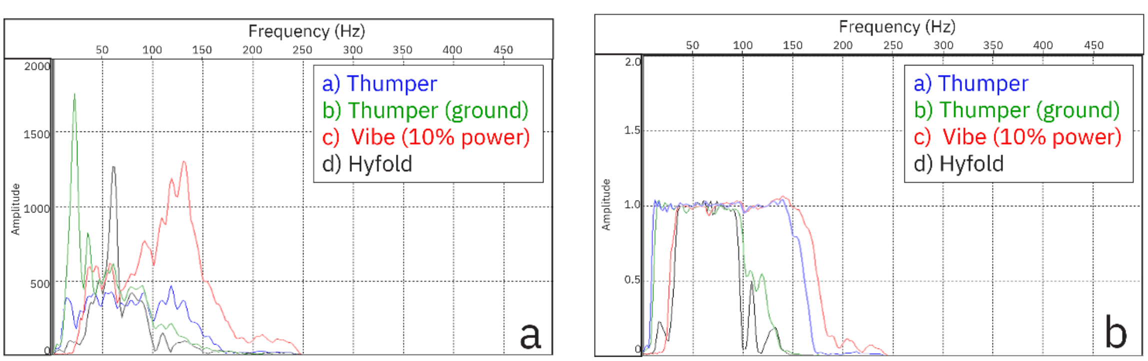

FIG. 10. Amplitude spectra from raw, stacked borehole geophone records (a) before and (b) after deterministic deconvolution. Amplitudes are presented on the same scale.

weathering layer, or if the steel pile is reducing the overall amplitude of the broadband impulse. This is one motivating factor for the placement of seismic sensors within the new steel pile installations (Figure 6). Due to the instability of the source sweep at the extremely low pressure and power settings of the ad hoc test , the vibroseis spectrum, correlated with a synthetic sweep, is not flat. Beyond 180 Hz, the vibroseis spectrum drops below the noise floor, which is relatively high due to being stacked only 8 times rather than 24, 25, or 64 as with the other sources. The plasma source shows a more limited bandwidth of 35 – 90 Hz centered around 58 Hz.

During surface acquisitions, the U of C's Envirovibe consistently generates a low frequency primary shear wave as the vibration plate starts to move, which is more easily seen in the DAS data than geophone data. Figure 11a shows a DAS shot record of the 64x stacked pedestal shots from the thumper compared to a vibroseis shot on the surface, acquired previously with the 10- 150 Hz sweep and normal power and hold-down pressure settings that are used for VSP monitoring surveys. Though there are P-S conversions in Figure 9a, there is no observed primary shear wave generated by the toe of the steel pile.

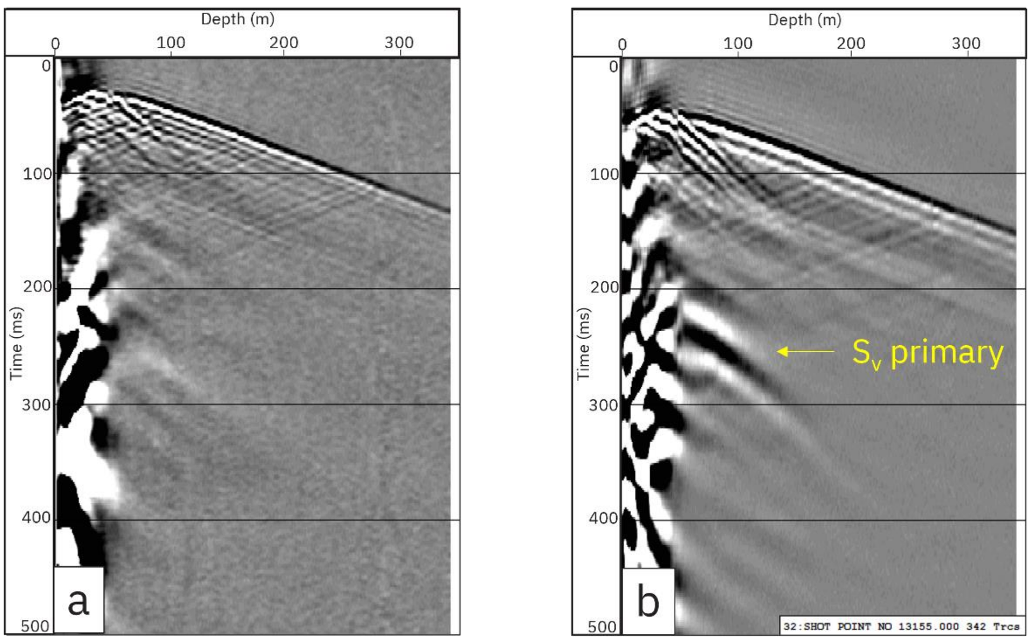

FIG. 11. DAS records of (a) thumper on pedestal and (b) vibroseis on surface. No primary shear wave was observed from the steel pile.

DISCUSSION

Figures 9, 10, and 11 indicate the steel screw pile acts as P-wave point source below surface, bypassing the severe attenuation in the weathering layer without significantly altering the source spectrum during transmission to the pile toe. The steel pile is also expected to avoid the seasonal and weather-related effects of changes in the elastic properties of the surface and near-surface. Once the trigger systems are finalized, longitudinal testing with daily acquisition is expected to produce high-repeatability data for time-lapse analysis. Of the sources tested, the thumper data provided the best example of successful transmission of a broadband signal through the steel pile. The spectrum in

Figure 10a is relatively flat, and the minor notching in the spectrum also appears in the thumper-on-ground spectrum and the vibroseis-on-pedestal spectrum. This consistent notching on and off the steel pile likely occurred in the geology between the pile toe and the borehole receivers, rather than from filtering or resonance within the steel pile. Similarly, the maximum frequency of 175 – 180 Hz observed in both the thumper and vibroseis data may be due to subsurface limitation rather than a limitation of the steel pile. While the skewed spectrum of the thumper-on-ground shot was expected, the higher 20 – 50 Hz amplitudes, compared to the pedestal shot, were not. This may indicate an energy loss within the pile, or an amplification effect in the subsurface. The installation of the north-east and south-east screwpiles indicated on Figure 5, instrumented with geophones and optical fiber, is expected to provide more insight into the transfer function of the screw piles.

The Hyfold plasma discharge source was expected to produce an impulse similar to the thumper, rather than the extended arrival seen in Figure 9. The observed behaviour of the source in the field is not well understood. Lab tests by Hyfold are ongoing to develop a more impulsive plasma discharge source to ultimately replace the existing source installed on the screw pile. Until then, the current source provides the opportunity to test the automated trigger system. Most of the data presented in this report were acquired with manual triggering rather than the automated GPS-controlled timing system described in the Methods section. Successful field tests of the GPS-timed control boxes were performed for the borehole geophones and Hyfold source in November, 2023, providing proof of concept and generating synchronized shots and recordings such as the example in Figure 7.

SUMMARY

Field tests of triggering systems and of three seismic sources on a permanent steel screw pile source location were performed at Carbon Management Canada's Newell County Facility in Q3-Q4 2023. These tests were performed for the international ACT4 SPARSE research project intended to develop sparse geophysical monitoring technologies and methods for measurement, monitoring, and verification of geological CO_2 sequestration. The testing of a permanent seismic source location is a step in the development of sparse nodes that provide both passive and active reservoir monitoring capability. The attenuative effects of the glacial till weathering layer were successfully avoided by the steel pile coupling directly into the sedimentary bedrock 24.7 m below surface. The steel pile transmitted broadband source signals with high fidelity. A trigger system for sources and receivers with precise GPS-controlled timing was built and field tested, providing proof of concept for automation of sparse nodes at the Newell County Facility. Two new permanent source locations are planned for installation at the Newell County Facility in December, 2023, consisting of steel piles which will be instrumented with geophones and fiber optic cables in 2024.

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