Optimized seismic acquisition geometries for CO2 injection monitoring

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Summary

Seismic baseline surveys over CO2 storage reservoirs need to be sampled well enough for a proper characterization of the storage complex including potential leakage pathways over an area at least as large as the anticipated CO2 plume size at the end of injection. These requirements render these surveys expensive to repeat for regular monitoring purposes. We describe a method for designing cost-effective monitoring geometries using sparse nodes and short streamers, taking advantage of the uniform source line coverage provided by modern wide-tow, multi-source streamer geometries. An integrated approach to survey design optimizes geometric repeatability between these very different acquisition methodologies for time-lapse applications. The methodology is illustrated using data that has been modelled with finite-difference wavefield propagation in a realistic model of a storage site, including the storage complex and overburden, after different injection periods.

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Introduction

Seismic baseline surveys over CO_2 storage reservoirs need to be sampled well enough for a proper characterization of the storage complex including potential leakage pathways over an area at least as large as the anticipated CO_2 plume size at the end of injection. These requirements render these surveys expensive to repeat for regular monitoring purposes. We describe a method for designing cost-effective monitoring geometries using sparse nodes and short streamers, taking advantage of the uniform source line coverage provided by modern wide-tow, multi-source streamer geometries. An integrated approach to survey design optimizes geometric repeatability between these very different acquisition methodologies for time-lapse applications. The methodology is illustrated using data that has been modelled with finite-difference wavefield propagation in a realistic model of a storage site, including the storage complex and overburden, after different injection periods.

Method and data examples

We illustrate the concepts described in this paper using synthetic data generated by visco-acoustic finite-difference modelling. The earth model is described in detail in Klüver et. al. (2024). It comprises a saline aquifer CO_2 storage complex that is loosely based on the Sleipner site in the North Sea, including a sufficiently large overburden for modelling 3D surveys of a realistic size. Earth models at different injection states are generated by flow simulation in the reservoir model. This allows the simulation of data acquisition, (time-lapse) processing and imaging for different acquisition geometries at different injection states.

Geologic carbon storage operations will be under substantial pressure to keep cost low. This will also apply to seismic monitoring of the developing CO_2 plume. Cost-efficient acquisition solutions need to provide sufficient data for the purpose of verifying that the plume has developed as forecasted. Any deviation could then trigger a more costly acquisition of data that allows characterization of the size and cause of the deviation to initiate appropriate mitigation measures. As the plume grows over time, only small areas need to be monitored. The survey area of subsequent monitor surveys can grow alongside the plume and be predicted from the reservoir model that is used as basis for conformance verification. If everything goes according to plan over the lifetime of the injection project, the most comprehensive seismic survey might be the baseline survey before start of injection. It needs to be large enough to cover at least the anticipated lateral plume extent at the end of injection plus migration aperture. It further needs to provide high enough resolution for proper characterization of the storage unit including identification and characterization of any potential leakage points. These requirements can easily surpass the quality of legacy data used for initial site screening purposes. In that case, as we assume for our synthetic case study below, a dedicated high-resolution seismic baseline survey is required.

The seismic baseline survey in our synthetic case study is simulated with an efficient towed streamer configuration using a wide source tow concept. The configuration is based on the quad-source geometry described by Widmaier et al. (2023). The vessel tows ten multi-sensor streamers with 12.5 m channel spacing at 15 m depth with 50 m streamer separation and a wide-tow quad-source configuration with 62.5 m crossline source separation at zero inline offset and at 5 m depth. This results in a sailline separation of 250 m and uniform source line coverage over the entire survey area. One source is triggered every 6.25 m, i.e., each individual source is triggered with a 25 m interval along its respective source line. Data has been simulated at 4 ms temporal sampling. The nominal inline and crossline bin size of the simulated data is 6.25 m x 6.25 m.

If the injection well is equipped with down-hole seismic receivers, for instance a permanently installed fiber-optic cable for distributed acoustic sensing (DAS), vertical seismic profiling (VSP) provides sufficient illumination to monitor the initial few years of injection. Beyond that, the plume extension is likely to exceed the coverage provided by DAS VSP geometries. This is illustrated in Figure 1 using

DAS VSP data simulated as part of our case study. While the plume extent after three years of injection is still within the boundaries of the data coverage, it clearly exceeds these boundaries after 10 years of injection. DAS VSP data acquired during seismic monitoring after those initial years of injection are nevertheless valuable for near-well monitoring. They complement other data, but they are not sufficient on their own for conformance and containment verification at later stages of injection.

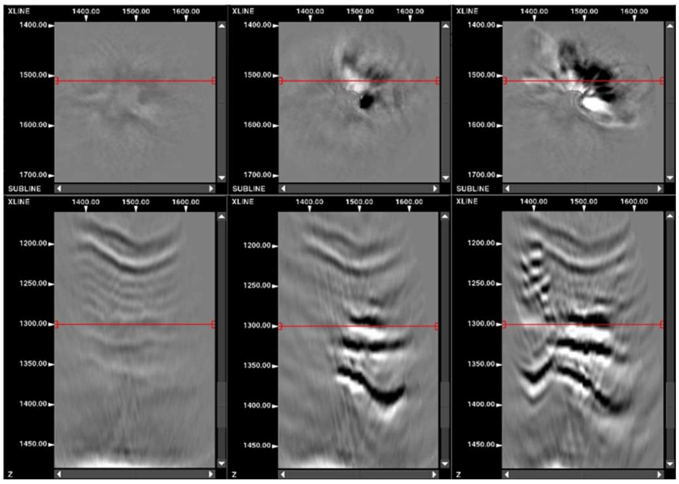

Figure 1 *Depth migrated images generated from simulated DAS VSP data (up-going wavefield) before start of injection (left), after three years of injection (center), and after ten years of injection (right). The top row shows a depth slice through the storage unit, the bottom row shows an inline section covering the storage unit. The position of the corresponding slices is indicated by red lines.*

Restricting coverage to the limited size of the plume early in the project lifetime for cost efficiency likely renders repeating the towed streamer baseline geometry uneconomic since more time would be spent in line turns and streamer deployment than in acquisition of seismic coverage. Acquisition using dense short streamer spreads as proposed by Deghan-Niri (2022) and/or sparse ocean-bottom nodes (OBN) provide cost-effective alternatives that scale favourably in those early years of monitoring since overhead (line turns, node deployment, etc.) can be limited.

Quality considerations and processing difficulties due to shot and receiver sparsity aside, an upper limit on the distance between nodes can be estimated from the depth of the storage reservoir: at least a single trace needs to stay un-muted at reservoir two-way time in a CMP centred between two nodes. Since containment monitoring requires potential leakage detection into the overburden, the actual limit compliant with regulatory requirements needs to be smaller than the extreme single-fold limit. Sparse distribution of (free-fall) nodes over the area covered by the plume combined with, e.g., spiral shooting around the lateral center of the plume or radial source lines allows acquisition of a sparse node monitor survey after, for example, ten years of injection in our synthetic case study with a small node inventory (< 50) and a single shooting vessel within 1-2 vessel days.

With a modest increase in effort and cost, time-lapse compatibility with the towed streamer baseline geometry can be maintained. The approach is based on repeating the source lines acquired in the baseline geometry. The node spacing in the crossline direction cannot exceed the sailline separation of the baseline geometry since no matching trace-pairs in 4D binning could be found otherwise. Node sparsity in crossline direction is therefore limited to at least one node per sailline of the baseline survey. Node sparsity in the inline direction follows the considerations made in the previous paragraph. Figure 2 illustrates the matching of CMP lines in the crossline direction between these two very different acquisition methodologies. It displays the signed crossline offset versus the crossline CMP position for 5 adjacent saillines of the baseline geometry with '+' signs. Individual sailline contributions have been color-coded alternating between red and blue. The signed crossline offset and CMP combinations generated by the node geometry, using repeated source lines and nodes placed at sailline boundaries (250 m apart), are illustrated with 'o' symbols. A continuous subset of equidistant CMP lines with a spacing of 31.25 m is common between both geometries which allows for close matching of trace pairs in terms of offset and azimuth between the two geometries, taking reciprocal coordinates into account where necessary. Note that the dense crossline CMP spacing of 31.25 m is enabled by the wide-tow quad source geometry of the baseline survey (62.5 m source line separation). A narrow tow source geometry (sources between the two innermost streamers) generates only two bundles of densely spaced CMP lines spaced 125 m apart in this case. Classical narrow tow source geometries therefore require denser crossline node spacing for sufficient crossline CMP coverage in the 4D trace matching, increasing node placement related overhead cost.

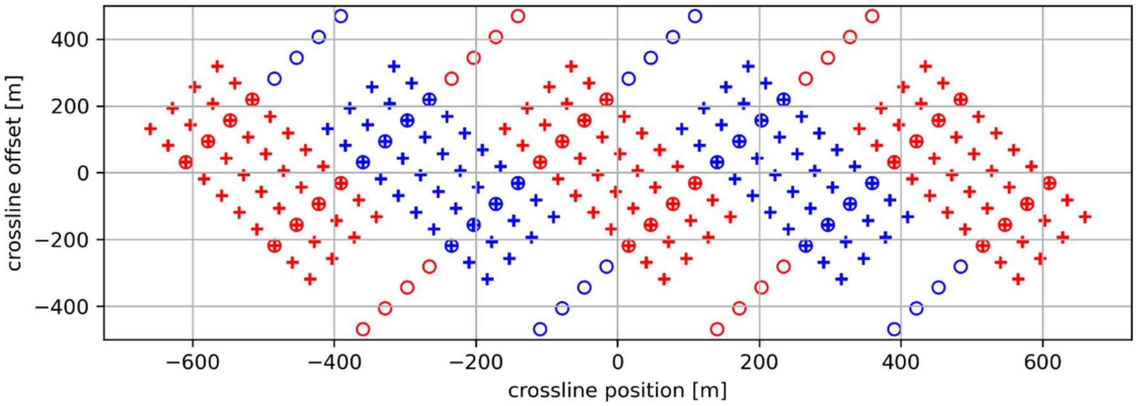

Figure 2 *Signed crossline offset versus crossline CMP position for a wide-tow quad source towed streamer baseline geometry and a sparse node monitor geometry. See main text for details.*

Figure 3 shows the images and the 4D difference that are obtained from matched trace pairs from the towed streamer baseline data and sparse node data, using 500 m inline node spacing. Geometric trace pairing has been performed neglecting the datum difference between the streamers close to the sea-surface and the nodes at the water-bottom. This datum difference leads to potentially significant differences in reflection point locations which partially explains the substantial 4D noise observed in the difference image. Furthermore, traces from the baseline data have been processed through surface related multiple attenuation whereas the node data is taken directly after trace-by trace P-Z summation without any additional processing. These processing differences further add to the 4D noise. Despite these differences, the plume outline and small-scale features within it clearly stand out in the 4D difference image.

The source lines of the node survey can be efficiently acquired with a multi-source shooting vessel, limiting the distance travelled by the source vessel. For better sampled common receiver gathers in the node survey, one source line of the towed streamer baseline survey at a time could be acquired with, for example, a triple source shooting vessel. In the case study described, this would sample common receiver gathers with a shot point grid of 25 m (inline) times 20.83 m (crossline). If the vessel tows a spread of short streamers, a high-resolution survey would be acquired simultaneously which is geometrically matched for time-lapse processing against the near offsets of the towed streamer baseline data.

Conclusions

Efficient acquisition of towed streamer baseline data for carbon storage projects in saline aquifers using wide tow source geometries with high source and streamer count can be cost-effectively combined with sparse node and high-resolution short streamer surveys for conformance and containment monitoring. The uniform dense source line coverage achievable with modern wide-tow multi-source geometries enables geometric repeatability for traditional time-lapse processing with cost-effective sparse node monitoring geometries that would be difficult to achieve in an efficient way with traditional narrow source tow geometries. Furthermore, high-resolution near offset towed streamer seismic can be geometrically matched to tie with the source lines of the towed streamer baseline data. An integrated approach to seismic survey design for monitoring CO_2 injection sites allows cost effective seismic monitoring strategies that satisfy repeatability requirements for the combination of very different acquisition geometries in a time-lapse setting.

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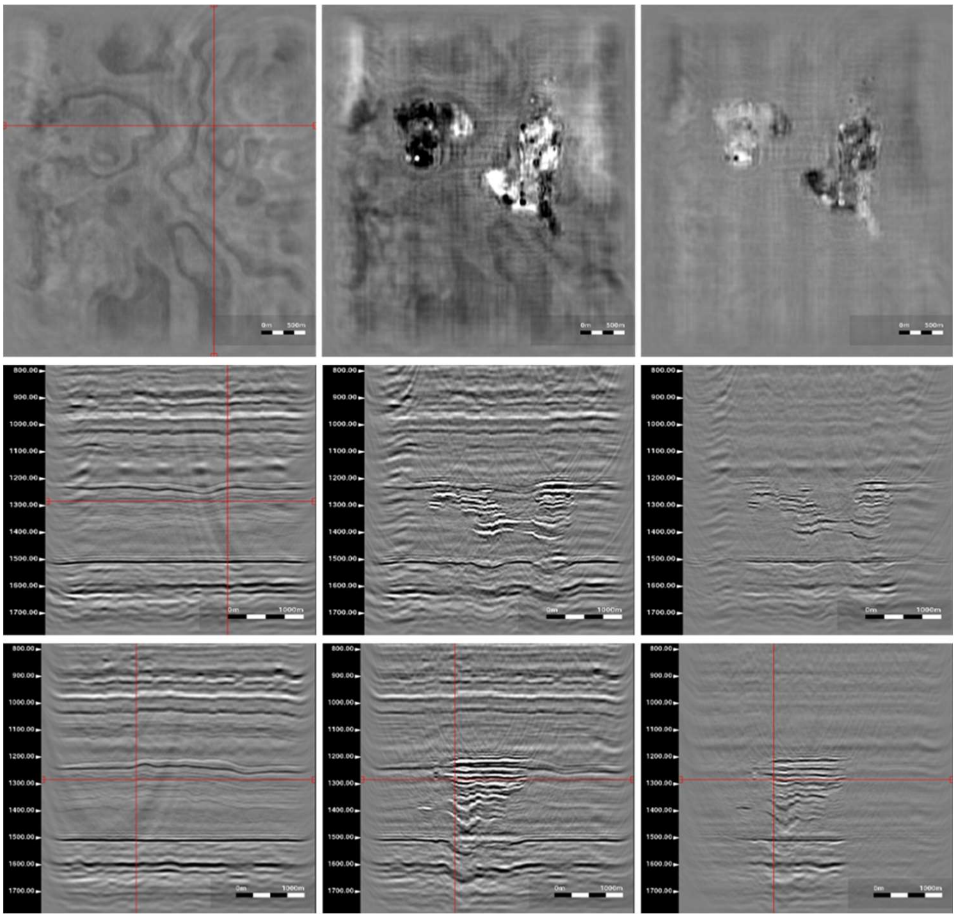

Figure 3 *Imaging results (Kirchhoff time migration) of matched trace pairs of the towed streamer baseline and sparse node monitor surveys. From left to right: baseline data, monitor data, and their difference. From top to bottom: Time-slices, inline sections, and crossline sections. Time slices are displayed with a 1:1 aspect ratio. The axis on vertical sections denotes two-way time.*

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