Introduction

Carbon Capture and Storage (CCS) is one of the key measures for mitigating climate change. Better understanding of the geomechanical behaviour of CO_2 storage complexes is important to verify the subsurface integrity and maximize the real storage capacity and injectivity for successful CCS projects. To address this challenge, the international research project https://sense-act.eu/, focuses on the monitoring of static ground deformation that occurs as a response to pressure build-up in the subsurface. The motivation for using ground deformation as a monitoring parameter is that it can provide direct feedback of the geomechanical behaviour over time and may be less costly than other methods. The SENSE project has used various case studies as proxy for CO_2 storage sites and tested different monitoring technologies. For onshore monitoring of ground deformation over large storage areas InSAR satellite monitoring is cost efficient and can provide sufficient sensitivity for long term monitoring. For offshore ground deformations, the present state of the art to monitor subsidence by means of hydrostatic depth and/or seabed tilt measurement can also be used to monitor seabed uplift above CO_2 storage sites. However, these methods only provide point measurements and data harvesting from self-contained nodes or periodic benchmark surveys are costly. As an alternative approach, monitoring seabed deformations along long baselines by fibre optic cables utilising distributed strain sensing (DSS) methodology has been tested and evaluated in the "SENSE_ACT" project.

DSS tests with simulated ground deformation

The axial strain sensitivity along a DSS cable is high (±1.0 µstrain), however quantifying crossline deformations based on axial strain measurements is not trivial and depends on several factors such as cable-soil friction, spatial resolution and the shape of deformations. DSS cables laid out along seabed baselines must have a mechanical coupling to the ground to monitor seabed uplift and possible fault movements, (Figure 1). The cable must not move due to currents and/or scour, thus be embedded (trenched down) into the seabed which also provides a coupling to the ground.

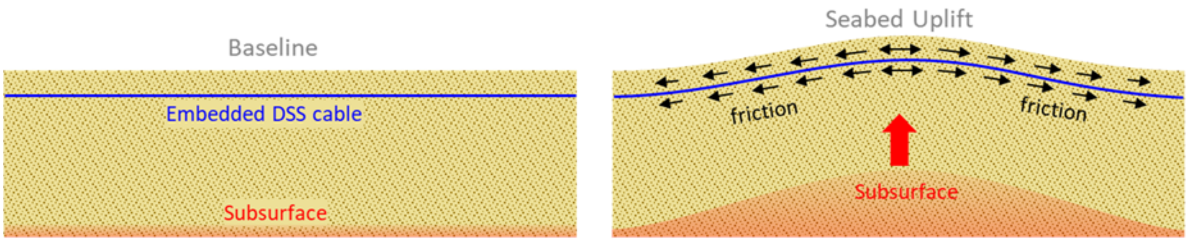

Figure 1 *The principles for monitoring vertical seabed deformations with embedded DSS cable.*

Instead of burying the cable in a trench, the simulated tests were performed in a long "sand box", (Figure 2). The bottom could be raised and lowered at three different sections (denoted A, B, C in the figures) using airbags beneath 2m long flexible metal sheet plates. The smooth slope gradients generated by the plates are anticipated as representative for simulation of uplift above CO_2 storage sites and more difficult to detect by DSS cables than sharp deformations such as faulting. The true uplift was measured by tell-tale rods connected to the plates at the maximum uplift point, the DSS cables were laid out on a 10cm sand layer above the plates and finally covered by another 20cm sand layer simulating cable embedment. No effort was done to pre-tension the cables, only minor hold back was applied to lay out the cables straight along the sand bed. Strain readings with high spatial resolution and several cable configurations were tested including different types of micro anchors along the cables. Robust armoured cables suitable for embedment in the ground with corrugated grip surface and a tight buffered single mode fibre protected inside a central metal tube were used for the tests.

The strain readings were made by Optical Frequency Domain Reflectometry based on Rayleigh backscatter enabling high spatial measuring resolution of interrogated cables at a distance up to 2km. Multiple tests were performed, each with several uplift increments. The walls of the box and sand surface was vibrated between each test to reconstitute the sand and soil coupling to the DSS cables. The main test objectives were to check the sensitivity of the DSS cables to vertical deformations and establish a correlation between measured strain and actual uplift.

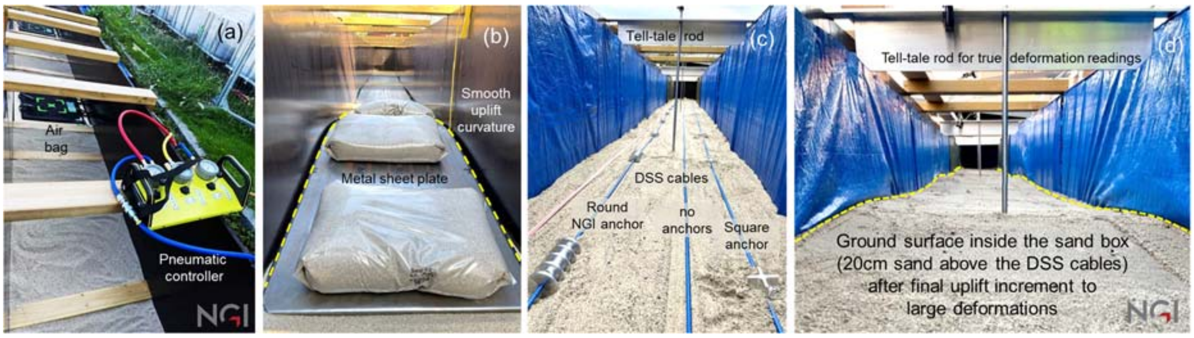

Figure 2 *The sand box erected for simulated uplift tests using airbags (a) beneath flexible steel sheet plates (b) covered with sand where DSS cables with different micro anchor configurations were laid out (c) and the DSS cables finally covered with 20cm sand (d).*

Test results and observations

Fibre optic DSS readings are sensitive to temperature variations, however no compensation was required during the test as the temperature was stable. Each test series started with a baseline reading as only relative strain changes can be recorded by DSS. Typical results from gradually increasing uplift increments are shown in Figure 3. For large uplift the three lifting points (A, B and C) interact and generate increased strain also along the cable sections that remain stationary between the lifting points.

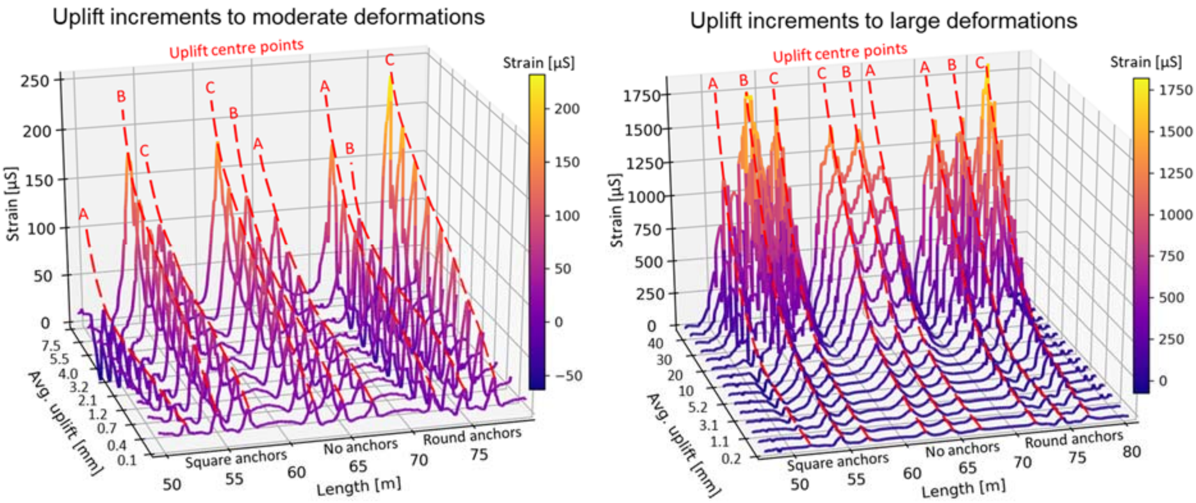

Figure 3 *Examples of recorded strain response during tests with incremental uplift sequences to moderate (left) and large deformations (right).*

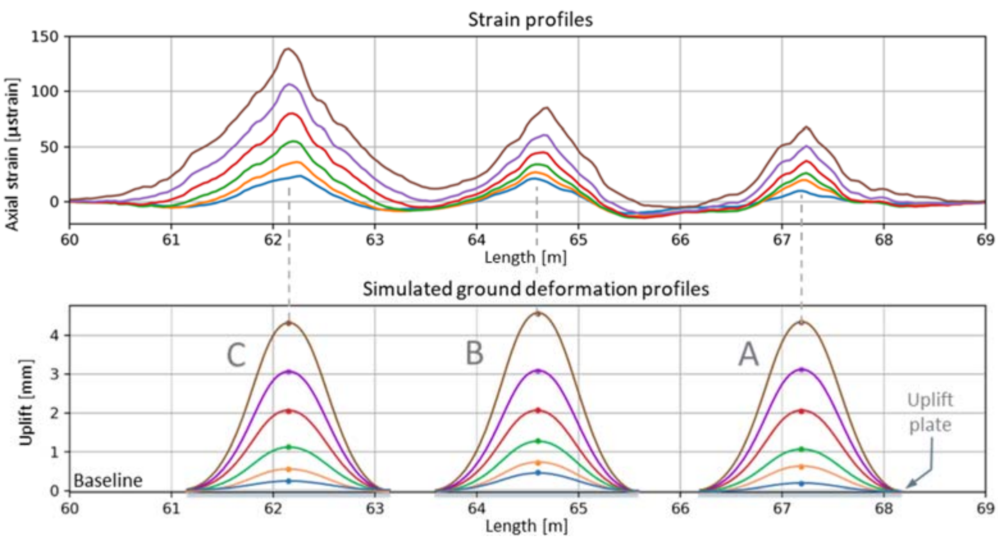

Figure 4 *Example of strain response and uplift profiles for the DSS cable without micro anchors.*

For CCS monitoring, high detection sensitivity for uplift is of key importance. A recorded example of the strain response to small uplift increments for the cable without micro anchors is shown in Figure 4.

The strain recorded at the highest uplift points has been compiled for all performed tests and examples are plotted in Figure 5. As indicated in the plots, high sensitivity is present also for the initial small uplift increments. Uplift of ~0,1mm over 1m length or a slope gradient of 0.01% (minimum applied lift increment) could clearly be observed by the axial strain response in the DSS cable. Cables with micro anchors did not provide significantly higher sensitivity compared to the bare corrugated cable. The round NGI anchor performed better that the square anchors which are sensitive to axial rotation (must be carefully placed in the sand) which can affect the axial strain response (less conformity).

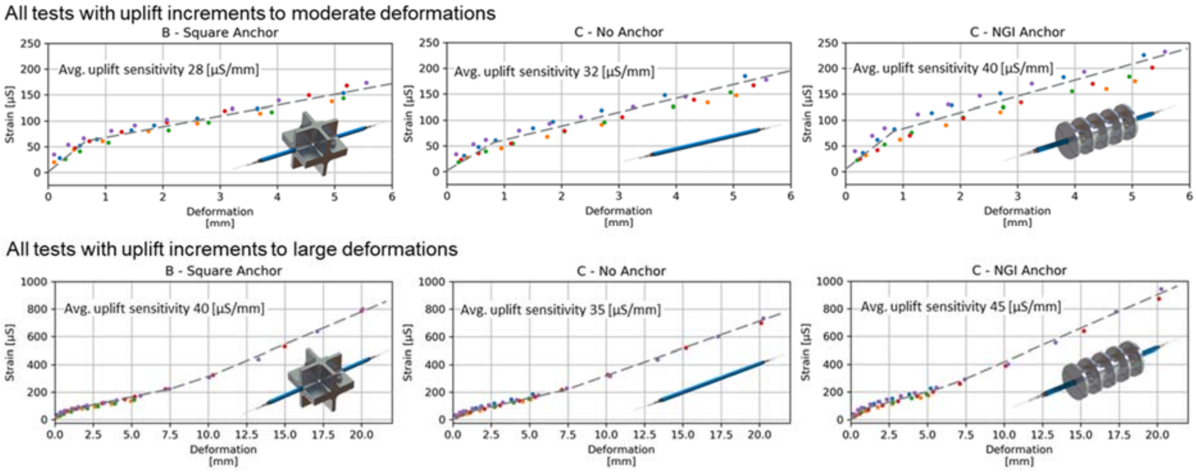

***Figure 5** Maximum strain versus highest uplift plotted for lifting increments to moderate (top) and large simulated deformations (bottom), the average sensitivities are indicated by dashed lines.*

DSS suitability for ground deformation monitoring above CO_2 storage

The simulated tests show that the DSS cable can measure the axial strain response with high sensitivity of micro-strain range. To look briefly at the implication of this high sensitivity in a field application, the vertical displacement and horizontal strain is calculated for a homogenous subsurface (E=5 GPa, ν=0.25) subjected to a 100m thick 1MPa pressure anomaly with 2500m radius. The reservoir depth is varied from 500m to 3000 m and the analytical solution by Park et al. (2021) is implemented. Figure 6 shows the calculated results in terms of vertical displacement in (a) and horizontal strain in (b).

It is clearly illustrated that the behaviour of vertical displacement and horizontal strain in the subsurface are related to each other, and that continuous measurements along baselines with DSS cables can be beneficial for in-direct monitoring of the vertical displacement in the ground. It is also noted that the apparent sensitivity of the DSS cable is within the range for detection of the deformations derived by this simplified subsurface model. The simplified model does not include the seabed-DSS cable interaction which however has been demonstrated to yield high uplift sensitivity in the performed tests.

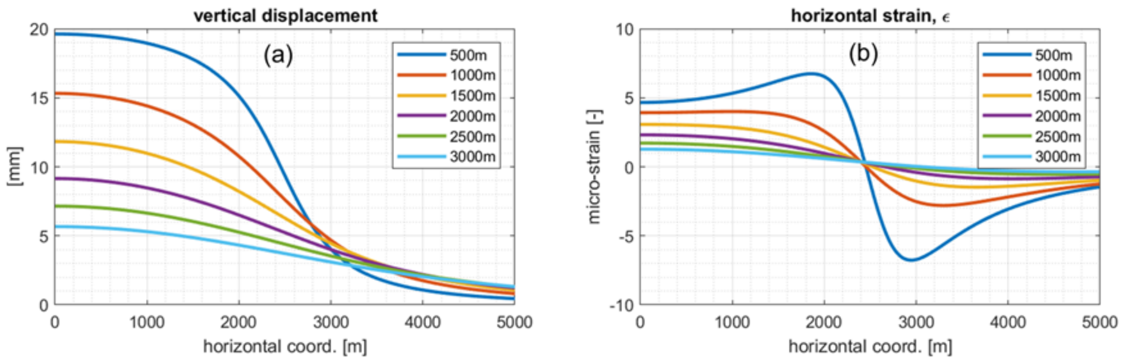

***Figure 6** Comparison of calculated results for different reservoir depths: (a) vertical displacement [mm] and (b) horizontal strain [µS].*

Conclusions

The ability of embedded DSS cables to register vertical ground deformations with sufficient sensitivity for CO_2 storage monitoring has been demonstrated by the simulated tests. To prevent influence from the environment and to provide the required coupling to the ground the cables must be trenched and buried in the seabed. Using a steel armoured cable with corrugated outer sleeve, further anchoring to the ground did not improve the sensitivity significantly and is evaluated as obsolete. Although the scaled tests were performed with strain readings at high spatial resolution (some centimetres), less dense readings can probably be used in the field scale, enabling other interrogation techniques based on Optical Time Domain Analysis of Brillouin and/or Rayleigh backscatter to be used. The long-term stability of the readings depends on temperature variations that can be compensated for, and the interrogator itself can also be calibrated if required. Today the interrogators are not suitable for subsea stand-alone operation. However, as the DSS technique allows for measurements over very long distances (20-30 km) the interrogator hardware can in many cases be located topside or onshore.

A reasonable approach for offshore CO_2 storage deformation monitoring can be to install DSS cables along CO_2 pipelines or the control umbilical to the injector template, including vertical cable routing along the injector well itself. Quantification of vertical deformation by down-hole DSS measurements in the axial direction of the cable has been thoroughly described by Zhang et al. (2020). A monitoring scheme based on DSS can also be combined with seabed benchmarks that can be utilized for hydrostatic depth surveys and reference measurements.

The work presented in this paper confirms the feasibility of the DSS monitoring principles. However, more tests and large-scale applications with reference measurements are necessary for better understanding and quantification of vertical ground deformations based on DSS data acquisition.

Acknowledgements

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