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Monitoring CO_2 storage sites onshore and offshore using InSAR data and strain sensing fibre optics cables

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Abstract

A key requirement for geological CO_2 storage is site integrity management and monitoring during operation through to the post-decommissioning period. This paper focuses on monitoring deformation of the ground surface and seabed as a proxy for overall deformation in the reservoir and surrounding layers. The objective is to inform, based on deformation data, on how the reservoir is responding to CO_2 injection and to ensure any issues with regard to storage integrity are rapidly detected. The magnitude and pattern of deformation at the surface reveals geomechanical/hydromechanical processes that occur in reservoir due to CO_2 injection. We acquired deformation data from the In Salah CO_2 injection site and from four additional study cases during the course of this study; one in the onshore UK, the other a combined campaign onshore Norway and offshore Germany, and the third in onshore Japan. Significant developments in measurement techniques, processing tools and interpretation algorithms were developed through this project. Models were then developed to simulate the observed data and to couple surface deformation to displacement in the subsurface. The results show millimeter-scale deformations in the subsurface have a signature at the surface that can be captured by the tools and workflows developed in this project. These deformations, particularly the patterns, are important factors to consider when monitoring a CO_2 storage site.

Keywords: CO_2 storage monitoring; Fibre optics; Geomechanics; Injection; Offshore monitoring; Pressure; Seafloor deformation; SESE-ACT

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1. Introduction

Demonstrating secure storage through measurement, monitoring and verification (MMV) is one of the main requirements for geological CO_2 storage sites. There are various monitoring methods that target different aspects of a site, such as pressure gauges that give information about near-well areas, microseismic monitoring that provides information about possible formation failures, etc. However, monitoring methods that can provide continuous data over long time periods at feasible costs while also monitoring large volumes, are rather limited. There are developing techniques which can be used to monitor ground movement with reduced cost and increased efficiency compared with current resource-intensive survey techniques. Thus, the SENSE (assuring the integrity of CO_2 storage sites through ground surface monitoring) project focuses on the development of techniques for detecting ground movement. The project investigates ground deformation measured at the surface caused by the pressure distribution in the reservoir (and geomechanical properties of the storage complex) to draw conclusions on storage integrity. Ground deformation, measurable from space (e.g. InSAR data) or directly on the surface without interfering with operations, gives information about the pressure build-up in the whole reservoir, possible pressure barriers, hydraulic networks, and geological features which otherwise may not be detectable. Easy and quick access to such data will assist site operators in recognizing pressure propagation in the subsurface and provide early warning if anomalies are detected in the pressure distribution.

The SENSE project demonstrates continuous, cost-effective, and reliable storage monitoring using ground surface deformation, combined with geomechanical modelling and inversion to provide information on pressure distribution and hydraulic behaviour of storage site units. To achieve the project goals, the SENSE project is structured into four interlinked scientific work packages (WPs). In WP1, SENSE increases the certainty of surface deformation measurements, both onshore and offshore, through further development and improvement of acquisition and data processing systems and techniques (including ground reflector installation, high-precision processing of seabed uplift data, automated InSAR data processing, fibre optic/Distributed Strain Sensing (DSS), tiltmeter, innovative seabed lander). In WP2, SENSE improves understanding of surface deformation data and its relation to subsurface behaviour (e.g., pressure, stress, permeability, topography, fault, etc.) through thermo-hydromechanical coupled numerical simulation of both real and synthetic geological models. In WP3, SENSE improves the history-matching capability of surface deformation data to reservoir response to enable rapid prediction of pressure evolution in the subsurface. WP4 demonstrates how the surface deformation monitoring can be effectively integrated into the site monitoring with other techniques (seismic, micro-seismic, bottom-hole pressure) and how this may be used to reduce the cost of monitoring (for example, through Direct Anomaly Indicator-DAI) while increasing confidence in data and analysis for subsurface integrity. Ground deformation measurements at laboratory and field scale, numerical simulation and the development of algorithms for translating deformation in the subsurface to uplift at the surface were used in this study, and are described in the following subsections.

2. Model and field experiments

2.1. Distributed fibre optic Strain Sensing (DSS) for small-scale deformation measurements

Injection of fluids in the subsurface will cause reservoir expansion which will show up at the surface in the form of ground uplift. The signature of uplift at the surface is often very small and the induced gradient is very low. To detect such deformation, there is a need to further advance innovative measuring tools and techniques. Distributed fibre optic Strain Sensing (DSS) cables have very high sensitivity to deformations occurring along the cable by directly measuring the axial strain. Optic fibre cable sensitivity to deformations occurring perpendicular to the cable axis depends on many factors and is more difficult to assess; therefore, a series of experiments were performed to simulate such conditions, with cables installed along the seabed or surface of the ground with a shallow embedment and deformations induced by injection. Comprehensive series of tests were carried out in a large sand box, 10.5 m long and 0.7 m wide, to simulate shallow cable embedment in a trench (Fig. 1). The uplift was simulated using air bags at three locations at the bottom of the sand box and below the sand layer. Three types of DSS cables were deployed to monitor the uplift. The cables were covered with an additional 20 cm of sand. The air bags incrementally lifted the sand layer with 2 m long, thin, flexible steel plates on top, providing a smooth uplift profile (Fig.1).

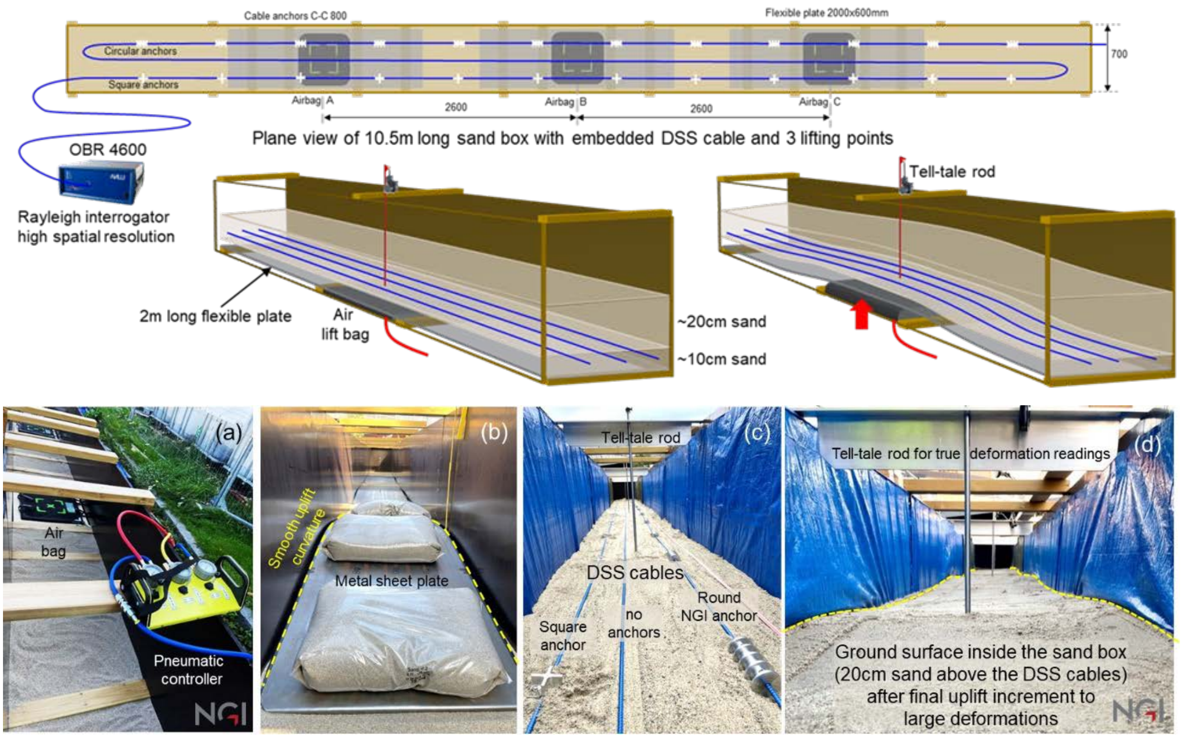

Fig. 1. (Upper) Arrangement of the fibre optic DSS experiments in the sandbox; (lower) (a) The airbags and pneumatic controller (b) Flexible steel plates above the airbags (c) Different configurations of DSS cables, with and without soil anchors, installed on the lower sand layer (d) The surface of the additional 20 cm sand covering the cables showing the surface of sandbox after inflation of the airbags.

The results (Fig. 2) showed that very small smooth uplift deformations (0.1 mm over 1 m length or 0.01% slope gradients) could be detected by the DSS cable and that only 20 cm of sand cover was required to obtain sufficient coupling between the cable and sand cover. Furthermore, the records from the DSS cable section without any soil anchors were shown to be as equally sensitive as the cable section with anchors. This is a very positive result as it suggests that soil anchors, which make the cable more expensive and installation more complex, are not required for a cable embedded in the seabed provided the cable is buried at a depth greater than 20 cm. In practice, cable deployment over very large areas will be expensive, and the DSS interrogator must be located topside. However, deployment integrated with the control umbilical to the injector well and across hot spots where deformation could be expected (geological faults, possible hydraulic barriers, etc.) may be a realistic approach.

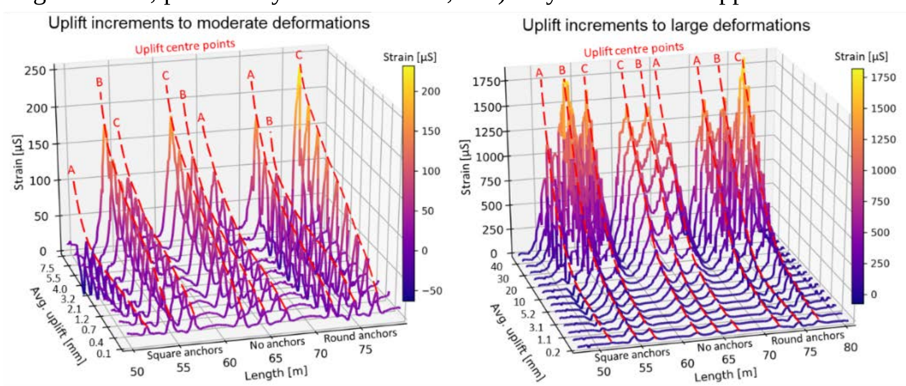

Fig. 2. Examples of recorded strain response during tests with incremental uplift sequences to moderate (left) and large deformations (right).

2.2. Field tests at Boknis Eck, near-shore Kiel (Germany) using DSS fibre optics and pressure sensors

A set of offshore experiments were designed where a sand layer at the seafloor could artificially be lifted using actuators. The fibre optic test cables were 600 m long run from an onshore cabin with interrogators out to the subsea test area located 300 m from the beach. At the 7 m long test section, the cables were laid out on top of a set of plates that could be lifted by airbags and then covered with sand (Fig. 3.). In addition, pressure/inclination recorders were installed on top of the buried DSS cables to provide spot readings of seabed movements. The results showed that although these experiments were less controlled than the sandbox tests, a similar sensitivity for detection of ground deformations was possible with the DSS cables in a nearshore environment that is subject to wave noise. By means of stacking several readings, the signal-to-noise ratio could be significantly improved. Results from the pressure/tilt recorders are ongoing at the time of preparing this paper.

Fig. 3. (a) Three different configurations of DSS cables installed before covering with sand; (b) seafloor uplift actuators at the bottom, sand layer and pressure/inclination recording units placed on top during near-shore experiments outside Kiel

2.3. Field-scale ground deformation measurements using DSS cables, Chiba Prefecture, Japan

We carried out the DSS field experiments at the Chiba Prefecture (near Tokyo, Japan) to study the interaction (attachment) of DSS cable to the ground and DSS response to ground deformation. First, the cable was buried in a shallow trench and covered with soil and then the experiment was repeated with the DSS cable covered with cement (Fig. 4). Deformation was induced by placing steel plates on top of the buried cables with an incremental increase of weight while recording strain response of the cable to loading. Results of the experiments showed that the cable buried with soil would give a stronger variation in deformation response than the cable buried with cement. This result suggests it is better to cover the cable with cement to assure strain data quality [1]. The experiments also confirmed that covering the cable with cement is advantageous for long-term deformation monitoring since this effectively reduces potential perturbations from rainfall and air temperature variations.

Fig. 4. (left) Distributed fibre optic Strain Sensing (DSS) cable installed in a trench; (right) DSS cable covered with cement [1].

2.4. Improving acquisition and processing of satellite InSAR data- onshore UK

Fig. 5. One of the corner reflectors placed at the Hatfield Moors natural gas storage site

Hatfield Moors natural gas storage site uses a sandstone reservoir for seasonal storage. During the SENSE project, this field site was used as an analogue for a geological CO_2 storage site. The Hatfield Moors geological storage reservoir is shallower than typically used for CO_2 storage (top reservoir is around 440 m compared with the 800 m typically sought for CO_2 storage). However, this site offered an onshore case study site where the use of satellite data based techniques to detect ground movement could be advanced. The site has shallow peat coverage, is vegetated, and has small lakes resulting from historical peat mining, thus the InSAR signature related to storage of natural gas is difficult to detect. Vegetated areas are generally more challenging in terms of detecting mm-scale ground movement with InSAR data. In addition, peat has a seasonal signature; swelling during the winter months when rainfall is higher.

Early in the SENSE project, Corner Reflectors (Fig. 5.) were anchored at the Hatfield Moors site to improve InSAR data quality. Through the SENSE project, a range of techniques to detect ground movement were tested on various InSAR data products. The Persistent Scatterer Technique (PS) [2, 3] and the Small BAseline Subset technique (SBAS) [4] were applied to SENTINEL-1 data. The PS method relies on having persistent reflectors that present a stable signal from one acquisition to another. The SBAS technique relies on stacking data to reduce noise and identify ground movement. The Corner Reflectors placed onsite clearly improved data coherence, however, it was not possible to isolate ground motion resulting from seasonal natural gas storage as the signal from the peat shrinking and swelling is relatively large (mm-scale). An additional data product was purchased from SatSense Ltd. This product uses a proprietary frequency-based method (RapidSAR technique) that can extract signals from noisy radar data, which works better in vegetated areas. The data shows cyclical ground motion that aligns with the expected motion that would be caused by seasonal peat movement owing to a higher water table in the winter months. The European Ground Motions Service (EGMS) has launched the new Copernicus Land service, these data showed a pattern consistent with the SatSENSE data. Work to isolate the signal resulting from the seasonal gas storage at the Hatfield Moors site is ongoing at the time of writing.

Two automated detection techniques were advanced during the SENSE project. The first ‘detector’ relied on finding changes in the data that could indicate an unexpected change in ground motion. The second ‘classifier’ technique examines clusters of data for changes in time series, again seeking to identify unexpected changes in the SAR data. The ‘detector’ relies on the regular data acquisition of SAR data, a statistical approach for detecting offsets and gradient changes in InSAR time series has been developed. This approach was tested using SENTINEL-1 data for the Hatfield gas storage site using five years’ worth of data. The gradient change detector identifies statistically significant movements in the second derivative series. This technique exploits the high spatial resolution of Sentinel-1 data and the spatial continuity of geophysical deformation signals to filter out false positive detections that arise due to signal noise. When combined with near-real time processing of InSAR data these detectors, particularly the gradient change, could be used to detect incipient ground deformation associated. The results of this work were published in [5].

3. Numerical simulations of ground deformation due to CO_2 injection

The portfolio of medium- to large-scale CCS projects (>0.5 Mton/year) in the world is increasing with many different characteristics: Onshore and offshore, shallow to deep, faulted and compartmentalised to large saline aquifers, and high to low-permeability reservoirs. For all CCS operations, monitoring of performance as well as safety is important. It is important to know if, and when, a monitoring method can provide useful information in capturing the behavior of the storage and sealing complex. For surface heave monitoring, this entails knowing what magnitudes to expect. Analytical solutions are good tools to provide fast calculations that allow for statistical analysis, e.g., Monte-Carlo simulations when there are large uncertainties in the geological description, to consider expected magnitudes.

In this study a semi-analytical tool provides a first-order estimate of expected surface heave magnitude and patterns for a selection of geological settings for CCS operations. To calculate the pore pressure build-up, the analytical solution for two-phase immiscible fluid flow pore pressure build-up resulting from constant rate injection by Mathias et al. [6] was used, and to calculate the resulting geomechanical response, the analytical Generalised Geertsma solution developed during SENSE [7] was used. For each site, a hydro-mechanical profile was defined, a constant injection rate was specified, and then thousands of model realisations (various combinations of material properties, in various layers, here Young's modulus and Poisson's ratio) were solved to obtain a distribution of resulting surface deformation patterns and pore pressure build-up. In Fig. 6 the results from applying this approach to the In Salah site is presented (hydro-mechanical profile and horizons are given in Bjørnarå et al. [8]. Here the results are presented as a probability distribution of maximum expected surface deformation magnitude (left), maximum expected surface deformation gradient (centre), and maximum expected surface deformation per pore pressure increase (right). The result shows that the geomechanical response and surface heave have good sensitivity to pore pressure increase over time, but little sensitivity to surface heave gradient over time.

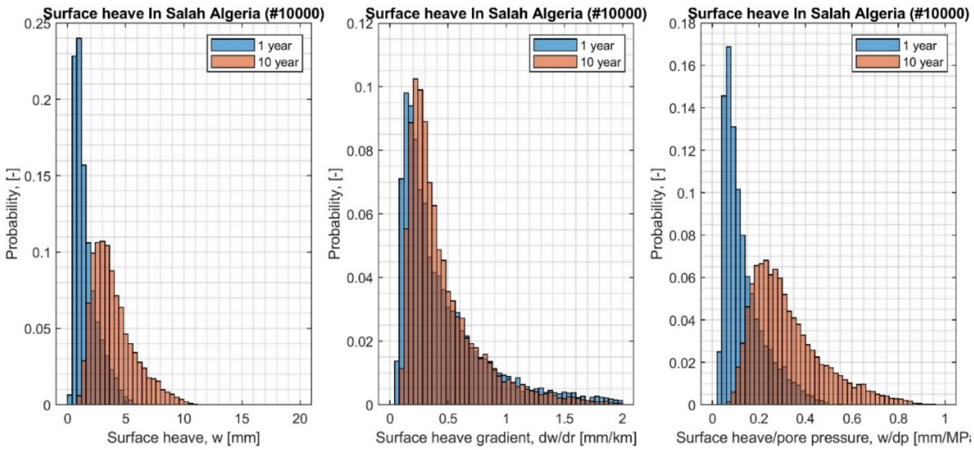

Fig. 6. Surface heave versus pore pressure change in geological CO_2 storage, result of 10000 Monte Carlo model realisations for the In Salah case study. Left: Calculated surface heave; w [m]. Centre: Surface heave gradient in radial direction; dw/dr, [mm/km]. Right: Surface heave per unit of pore pressure increase; w/dp [mm/MPa]. The figure is shown after 1 and 10 years of continuous injection.

A numerical simulation of In Salah considering reservoir topography was conducted, as the distribution of the initial gas and the plume of injected CO_2 are closely related to reservoir topography. The results showed that where it was assumed that initial gas was present, wellhead pressure increased less than in the case where there was an absence of gas near the well, yielding less ground uplift. This phenomenon was significant when simulations were run with the injection well adjacent to the gas reservoir, e.g., only half of the deformation occurred in the closest well KB502 compared to simulations assuming gas absence. Since natural gas compressibility is very high, the gas reservoir above the aquifer might play a role in alleviating the pressure increase in the aquifer. In considering initial gas, lower permeability and Young's modulus were required to match the same uplift compared to the aquifer-only case.

Additionally, a simulation was performed considering natural gas production from the initial gas in place while injecting CO_2 into the aquifer. The amount of gas production was assumed to be ten times the amount of CO_2 in volume since no data were available for gas production. The result of this simulation was that the ground subsided near the production wells. In addition, the increased gas production rate accelerated ground subsidence and reduced uplift around the CO_2 injection wells. The results also show that reservoir topography and gas production should be considered in geomechanical modeling as factors affecting the changes in reservoir pressure and ground deformation.

We have also developed analogue models representing a potential storage target in the Gulf-of-Mexico. The geologic framework model is based on well logs and 3D seismic available for High Island 24L leasing block (Fig. 7). An unstructured mesh was constructed to smoothly conform to the complex faults at the site. A compositional poromechanics simulator (GEOSX) was then used to simulate CO_2 injection into the formation brine coupled with the poromechanical response. Results suggest that downhole fiber optic cables and ocean bottom pressure sensors would likely be able to detect deformation at the expected magnitudes. Trenched sea-bottom fibers may struggle to detect a signal for this particular site given the low-pressure buildup, but such a system could be useful at other sites or under other injection conditions.

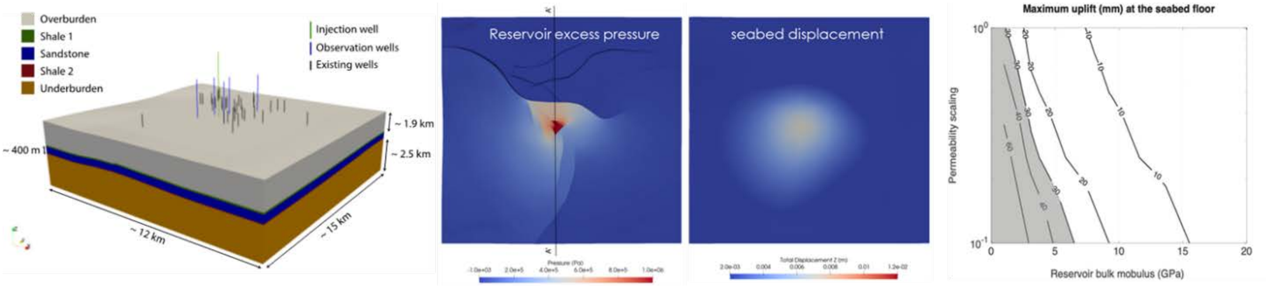

Fig. 7. (a) Simplified geologic framework model for the Gulf-of-Mexico site; (b) Reservoir excess pressure computed after three years of CO_2 injection; (c) Seabed displacement computed after three years of injection; (d) Sensitivity plot showing maximum seabed uplift as a function of the uncertain permeability and reservoir bulk modulus.

4. Efficient history matching or inversion for joint flow and geomechanics

Fluid pressure and saturation vary temporarily and spatially, when CO_2 is injected into the reservoir (depending on e.g. injection rate, reservoir permeability, presence of pressure barriers) and this can create uplift of the materials above the reservoir, as discussed in the previous sections. Therefore, monitoring surface deformation during CO_2 geological sequestration is considered useful to track the evolution of the CO_2 plume and to manage unexpected events that could potentially affect storage efficiency and integrity. Once all relevant data are acquired, such as surface heave, reservoir pressure and temperature, seismic surveys, etc., then we may perform history matching or inversion of such data in order to better understand and even predict the behaviour of the subsurface during CO_2 injection. Such history matching or inversion can be performed by applying fully coupled flow-geomechanics [9], which approaches are well established and applied in the oil and gas industry. However, the fully-coupled inversion approach may be not only computationally expensive but also too poorly-constrained to perform satisfactory inversion studies. Marin-Moreno et al. [10] present an efficient inversion framework to discriminate fluid pressure and saturation changes from surface uplift data by combining an analytical solution for pressure-induced deformation of a multilayered subsurface, machine learning (ML), analytical rock physics modelling, and a capillary pressure model. The methodology follows three sequential stages:

i) Creation of a synthetic training dataset of seabed deformations from 1000 three-layer (overburden, reservoir, underburden) models with different elastic properties and pressure perturbations using the generalised Geertsma's solution [7]. The dependency of fluid saturation on seabed deformation is provided by defining the bulk modulus according to an effective media model such as Gassmann [11]. This bulk modulus is changed randomly for different combinations of CO_2 and brine saturations, assuming a sandstone reservoir with constant mineral grain bulk and shear moduli, constant brine bulk modulus and, pressure and temperature dependent CO_2 bulk modulus. It is assumed that the bulk modulus of the material does not depend on effective stress.

ii) A convolutional neural network (CNN) with an encoder-decoder architecture (Fig. 8) is trained with the inputs (synthetic pressure perturbation) and outputs (corresponding surface deformation) from step (i) [12]. The encoder comprises a series of three convolutional layers, decreasing in input size but increasing in its dimensionality, and the decoder is a series of three transposed convolutional layers, reducing the dimensionality but increasing in size (the inverse operation). The activation functions through the network are Rectified Linear Units (ReLU) functions and the network weights are updated based on a classical Adam optimization. The loss function to evaluate the prediction is a mean square error (MSE), to ensure that the trained model has no outlier predictions with large errors.

iii) Upper and lower bounds of the CO_2 and brine pressures and saturations are defined that can explain surface deformation data by combining several rock physics models (Gassmann, Hertz-Mindlin contact model, Reus effective fluid model; [10] and a capillary pressure model.

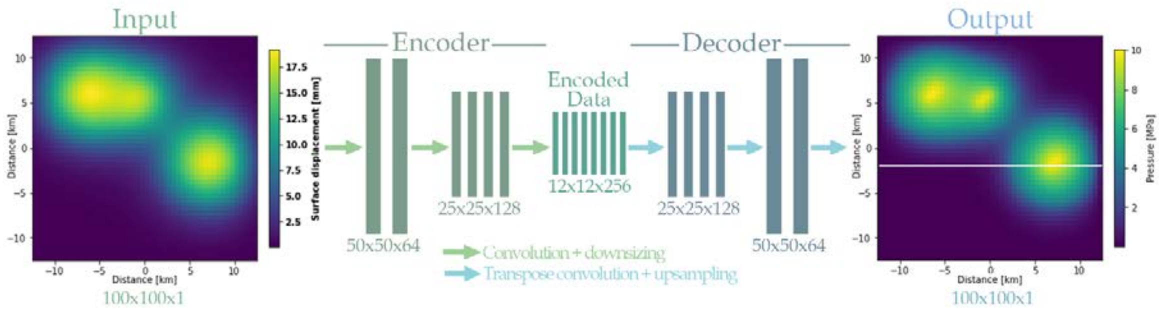

Fig. 8. Synthetic example showing the input surface deformation (left), the ML architecture (middle) and the output pressure field (right) [12].

The methodology described above was tested using seafloor deformation data from a 2D multiphase hydro-mechanical study of geological CO_2 injection. Figure 9 shows an example of the brine and CO_2 pressures and saturations estimated from ML results of 2 MPa pressure increase in a sandstone reservoir with an effective bulk and shear moduli of 1.6 GP and 1 GPa, respectively, that resulted in the inputted seafloor deformations.

The results in Figure 9 consider a model in which the pressure increase obtained with ML is assumed to correspond to the non-wetting phase (in this case CO_2; see inset in Fig. 9). CO_2 saturations ranging between 0.54 to 0.69 are observed, depending on the adhesion parameter. The adhesion parameter is a free parameter in the Hertz-Mindlin model ranging between 0 (no friction between grains) and 1 (perfect adhesion) [11]. The CO_2 pressure remains constant and the capillary pressure increases with the increase of saturation of CO_2, as expected, based on the capillary pressure model.

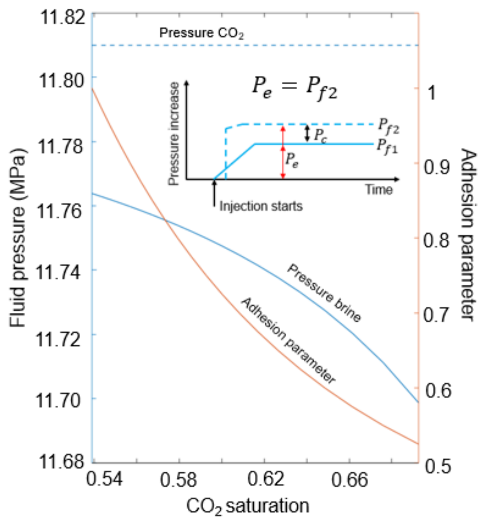

Fig. 9. Examples of maximum and minimum fluid pressures and saturations explaining seafloor deformation data.

The methodology is applicable for any fluid injection problem where surface deformation data is acquired. It is also important to note that the methodology can (or even should) be considered as a precursory step before moving onto the fully-coupled flow-geomechanics based inversion study so that the latter can be well constrained and can be carried out more efficiently based on the outcome from the former.

5. Conclusions

SENSE has advanced a range of techniques for MMV of ground movement to demonstrate CO_2 storage site behaviour, and to link the expression of the pressure increase at surface to the response of the reservoir at depth. Distributed fibre optics Strain Sensing (DSS) cables were tested in various configurations and environments to investigate the sensitivity for measuring small-scale ground deformations perpendicular to the cables. Large-scale laboratory tests, and onshore and offshore experiments showed that embedded DSS cables could detect vertical slope gradients as small as 0.01%, including in offshore environments affected by wave noise. The sensitive DSS cable must have as little slippage relative to the ground as possible and must therefore be trenched into the seabed. Deployment of embedded DSS cables (offshore and onshore) along long baselines across parts of the target area that where uplift might be expected (e.g. faults or pressure barriers), can provide continuous monitoring for verification that the storage site is conforming to expectations, or to detect anomalies that can trigger additional monitoring measures or alerts to adjust the rate of injection.

InSAR data are readily available over large parts of the world; however, the use of these data for ground monitoring requires heavy processing in order to be used for ground deformation monitoring. We have developed automatic data processing algorithms that can facilitate access to processed data and thus reduce costs for using InSAR data. The processing has been applied to Hatfield Moors natural gas storage site in the UK, demonstrating the feasibility of applying automated procedures to identify ground motion and to confirm that the motion is within expected limits.

Geomechanical simulation of synthetic and real-life cases with a focus on ground deformation showed that the magnitude and gradient of observed deformations, are well above the threshold for tiltmeter detection limit, but at about the limit of detection for DSS cables for some reservoirs. Tiltmeters can be a useful deformation monitoring technique. While more expensive than InSAR data, the tiltmeter has a higher resolution and will provide good calibration points that can be used to confirm InSAR data interpretations. Modelling hypothetical cases such as the offshore Gulf-of-Mexico revealed that with an injection of about one million tonnes of CO_2 per year, a seafloor uplift of about 50 mm might be observed, and it may have a pattern around faults. This level of uplift can be detected by pressure sensors and DSS cables. The conclusion from the synthetic cases is that the ground deformation caused by injection CO_2 is usually in a range that can be detected by InSAR and that deformation around features like faults exhibit patterns that may be used to gain more knowledge about sealing or leaking behavior of these features during operation.

In conclusion, ground deformation can be a useful monitoring parameter. There is a suite of techniques for measuring ground deformation onshore (InSAR, Tiltmeter, DSS fibre optics) and offshore (pressure sensors, DSS fibre optics). Fast analytical solution of surface heave versus pore pressure change in CO_2 storage complex is a useful screening tool for surface heave monitoring feasibility.

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