Annex 5: Template for the final report

1. Identification of the project and report

Project title	**SENSE-Assuring Integrity of CO_2 Storage sites through ground surface monitoring**
Project ID	**299664**
Coordinator	**Norwegian Geotechnical Institute (NGI)**
Project website	https://sense-act.eu/
Reporting period	Q3 2019 - Q4 2022 (**Final Report**)

Participants

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2. Short description of activities and final results

Description of the individual work package activities and the results are described in the following sections. In addition, the overall project summary and deviations from the original work plan are presented. Deviations from work plan and mitigation actions are presented in Section 2.5. A table and plot containing the financial results is presented at the end of the report.

2.1 WP1: Quantification of ground movement

In WP1 we developed and tested novel technologies that enable to acquire high-accuracy and cost-efficient surface deformation data resulting from fluid injection or extraction. The WP1 outcomes are then to provide realistic geomechanical boundary conditions as inputs for WP2, WP3, and WP4. First, we started screening, deciding and planning test sites and reviewing available relevant data in close collaboration between the industry and research partners. As a result, SENSE team successfully initiated all the case studies onshore and offshore. The case studies are:

- In Salah Algeria; new InSAR data
- Hontomín site, Spain
- Hatfield Moors, UK
- Bay of Mechlenburg (Boknis Eck), offshore Germany
- Gulf of Mexico, USA
- Troll gas field, offshore Norway

For the onshore case studies, we collected data on surface uplift or subsidence due to fluid injection into (or extraction from) the subsurface on two sites of the UK Hatfield Moors and Hontomín Technology Development Plant, Spain. In addition, we utilized the existing InSAR datasets for the In Salah case, from previous studies and recently acquired public-domain data. Accessing relevant data is one of the key success elements in SENSE, which was done well thanks to the kind contribution from the industry partners.

In Salah (Algeria):

We accessed the InSAR data for In Salah from freely available as well as Equinor-owned sources for the period of post-injection, processed and made results available to the SENSE team. We analysed the surface uplift and subsidence both along selected cross-section and volumetrically around each injector. Results shows the ground surface started to subside after injection halt which was expected. The subsidence is a because of the post-injection pressure dissipation over time and the rate of subsidence provides important information on reservoir hydro-mechanical behaviours.

Hatfield Moors (UK site):

Hatfield Moors is a natural gas storage where the gas is injected into a porous sandstone formation 450 m deep underground during summer and is extracetd during winter, and repeated annually. Injection and extraction of gas cause pressurization and de-pressurization of the reservoir, respectively, and thus may lead to consequent ground uplift and subsidence cycles. The injection phase of natural gas storage is a good proxy to CO_2 storage. Our hypothesis is that monitoring ground deformation above Hatfield Moors gas storage will help understanding behaviour of the sudsurface formations and the geomechanical performance of reservoir.

We used satellite InSAR data to monitor ground deformation. First, the InSAR data processing from the Hatfield Moors site without the Corner Reflectors (CRs) in place was carried out to examine signal quality. As expected, the CRs are needed to compensate the impact of the peat near the surface. Three passive CRs have been successfully installed at Hatfield Moors. One mounted to the Peat on top of the reservoir and the other two mounted to the Peat outside of the reservoir. InSAR time series data for the past 5 years were analysed and show jumps in displacement that are most likely related to seasonal loading of the peat overlying the gas reservoir.

Key learnings from this study show that flow and geomechanical modelling, including near surface, have a key role to quantify fluid (gas/CO_2) storage site behaviour and demonstrate the value of history matching in predicting site behaviour. These modelling results and the automatized workflow developed for the InSAR data processing could be used to consider how much ground movement would be expected at any particular site. Practical learnings on collecting baseline data and installing additional equipment on the site ahead of fluid injection to aid in detection of small ground movement using InSAR data were also appreciated well during this study.

Hontomín site (Spain):

We focused on processing micro-seismicity data detected by the surface network deployed at the Hontomín CO_2 geological storage test site (**Figure 1**), during the hydraulic characterization of the reservoir. To do this, previous work done on the network performance was thoroughly reviewed together with the timeline of injection activities and with software tools available for micro-seismicity data processing and analysis. This helped define a period of interest, involving July and September 2014, and a workflow (including robust open-access computer programs). Using the designed workflow, 149 events were detected during injection tests performed in the study period. Most of these either correlate with noise due to anthropogenic activities (e.g., explosions at a local explosives' factory) or regional events unrelated to the injections carried out at the Hontomín test site. Only 16 events were located within the Hontomín network and at shallow depths (0 - 2.5 km), showing spatial correlation with the injection well. All the local events had micro-seismic magnitudes, ranging between -1 and 0.4 ML. Three events occurred during July 2014 and the other 13 events occurred tightly clustered in space and time in relation with the largest injection test performed in 2014, that took place in September.

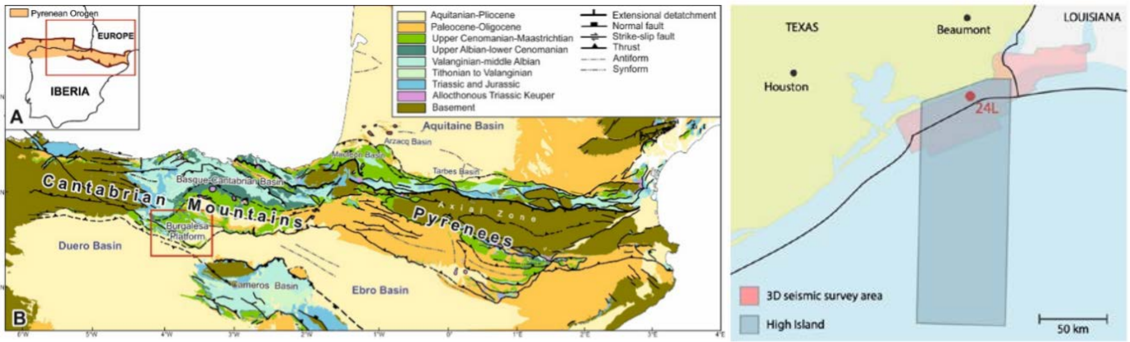


Figure 1. Location of Hontomín site in Spain (left) and High Iland, Gulf of Mexico (right) case studies.

***Bay of Mecklenburg and Boknis Eck (offshore Germany)*:**

The offshore site selected for demonstration of technical tools including distributed strain sensing fiber optics (DSS) and pressure sensors was initially the Bay of Mecklenburg, offshore Germany. We conducted characterization both in lab and field scaled and performed numerical modellig for this site to learn what to expect from the field injection campaign. Thus, the Boknis Eck case was selected as a replacement.

***Boknis Eck**:*

As a replacement for Bay of Mecklenburg, another case in offshore Germany was selected: Boknis Eck, to test seabed ground deformation monitoring equipment developed in SENSE. Activities included instrumentation of seafloor, data acquisition and interpretation. The main results from Boknis Eck:

- Successful design and installation of distributed strain sensing (DSS) fiber optics cables and pressure sensors in a noisy nearshore environment (**Figure 2**)
- Reactivation and uplifting sea floor artificially and measuring vertical displacement
- Data acquisition and processing
- The conclusion from experiments that displacement of about micro-strain can be detected by the Distributed Strain Sensing (DSS) fiber optic cables in offshore environment and SENSE team has developed competence to carry out such monitoring operations where needed.

Figure 2 Design, installation, data acquisition and interpretation of seabed displacement with Distributed Strain Sensing fibre optic cables in offshore Germany.

Gulf of Mexico:

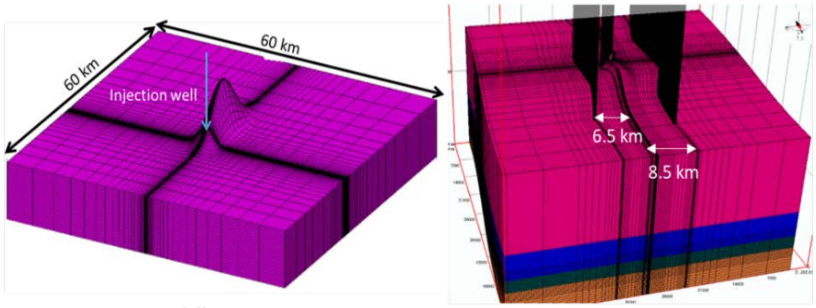
The High Island geologic structure has been mapped by correlating 3D seismic data with spontaneous potential and sonic well logs (DeAngelo et al. 2019, Olariu et al. 2019, Ruiz 2019). Ruiz and colleagues provided a detailed stratigraphy of the HI24L block. The geological model of this work (**Figure 1**) is based on the studies previously mentioned and includes 32 faults that cross the domain. To be more specific, the limits between the geological layers (also called horizons) have been generated using an implicit method first introduced by Mallet (1988). The horizons are represented as isovalues of a scalar field that is constrained to the data (well logs, seismic picks) and interpolated in between. The faults remain explicitly meshed. Analyses and results will be presented in WP2.

Processing and quality control of the acquired data from the different case studies and lab tests were carried out and the data have been used in WP2 and WP3.

2.2 WP2: Understanding the mechanism of surface movement through conceptual and coupled flow geomechanics models

The objective of this work package is to develop conceptual/theoretical models based on the newly acquired and available (e.g. Troll, In Salah) data in the project and synthetic cases to carry out advanced coupled flow geomechanics simulations of the candidate sites (e.g. Gulf of Mexico) in order to finally study the geomechanical behaviour of these sites in response to pressure changes in the reservoir.

The synthetic cases were simulated for evaluating the observability of surface displacements and for optimizing monitoring plan to tell when, where and for which conditions, surface displacement monitoring can be useful. Three synthetic cases (Carbonate, Sandstone I and Sandstone II cases) were considered that contain different geological features; with and without faults (**Figure 3**). In this study, the injection site is considered as onshore. Thus, surface information is directly available and only monitoring tools for onshore context are studied. The main hypotheses regarding the CO_2 injection modelling and subsequent surface displacements are found in Bouquet et al., 2022. We assume the following conditions: open flow; two phase flow; sequential hydromechanical coupling; Drucker-Prager failure criterion for risk analysis; a max overpressure of 50 bar and a max injection rate of 1 Mt/yr. Nine parameters are considered as critical and uncertain as defined in **Table 1**.



Anticline trap

Anticline trap with sealing or draining faults

Figure 3. Anticline conceptual models. Left: anticline trap without fault; right: anticline trap with two major faults and a sub-seismic fault.

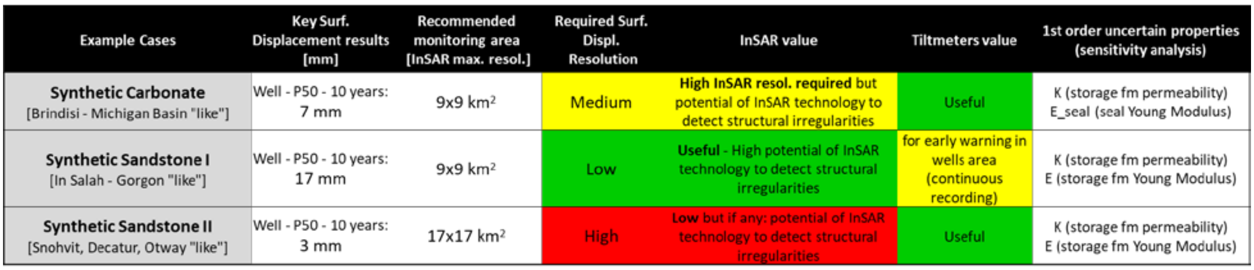
Table 1. Uncertain parameters and related ranges of values for the three scenarios.

VARIABLES – UNCERTAIN PARAMETERS	**Carbonates** min-max	**Sandstone I** min-max	**Sandstone II** min-max
Storage Fm Porosity [-]	0.15 – 0.25	0.1 – 0.3	0.1 – 0.2
Storage Fm Permeability [mD]	**15 – 150**	**5 – 50**	**100 - 1000**
Storage Fm Young Modulus [GPa]	**25 – 45**	**2 – 15**	**5 – 20**
Storage Fm Poisson coefficient [-]	0.15 – 0.25	0.2 – 0.3	0.15 – 0.25
Overburden Porosity [-]	0.05 – 0.4	0.05 – 0.15	0.05 – 0.15
Overburden Permeability [mD]	2e-3 – 6e-2	1e-3 – 1e-1	1e-4 – 1e-2
Overburden Entry Capillary Pressure [bar]	5 – 60	10 – 50	5 - 50
Overburden Young Modulus [GPa]	**6 – 55**	**1 – 20**	**30 – 40**
Overburden Poisson coefficient [-]	0.15 – 0.35	0.2 – 0.35	0.2 – 0.3

Table 2 summarizes key results obtained from the developed workflow to help designing the surface displacement monitoring plan:

- Definition of where/when surface displacements are measurable
- Location of measurements to better constrain the sensitive parameters
- Definition of additional locations with a risk analysis based on a failure criterion
- Early warning of unexpected behavior if the monitored surface deformation does not correspond to the expected one (estimated by simulations) and quickly define the actions of remediation
- Recommendations to acquire critical data from the sensitivity and risk analysis.

Table 2. Summary of key results and recommendations from synthetic cases.



Example Cases	Key Surf. Displacement results [mm]	Recommended monitoring area [InSAR max. resol.]	Required Surf. Displ. Resolution	InSAR value	Tiltmeters value	1st order uncertain properties (sensitivity analysis)
Synthetic Carbonate [Brindisi - Michigan Basin "like"]	Well - P50 - 10 years: 7 mm	9x9 km^2	Medium	**High InSAR resol. required** but potential of InSAR technology to detect structural irregularities	Useful	K (storage fm permeability) E_seal (seal Young Modulus)
Synthetic Sandstone I [In Salah - Gorgon "like"]	Well - P50 - 10 years: 17 mm	9x9 km^2	Low	**Useful** - High potential of InSAR technology to detect structural irregularities	for early warning in wells area (continuous recording)	K (storage fm permeability) E (storage fm Young Modulus)
Synthetic Sandstone II [Snohvit, Decatur, Otway "like"]	Well - P50 - 10 years: 3 mm	17x17 km^2	High	**Low but if any:** potential of InSAR technology to detect structural irregularities	Useful	K (storage fm permeability) E (storage fm Young Modulus)

Finally, compared to data measured locally at the wells, surface data give 2D information of the subsurface behavior with InSAR or continuous records with tiltmeters in informative or risky areas while 2D/3D seismic give the same advantages but at a lower time frequency due to higher costs. The use of the surface deformation as monitoring data help to improve the knowledge on pressure propagation and to monitor CO_2 storage behavior with additional constraints on subsurface properties. In addition, the analysis of the surface deformation shape brings information on the subsurface structure/objects if detectable with a high potential of InSAR data to detect strong heterogeneity and structural irregularity.

A numerical simulation of In Salah was conducted to investigate the impact of reservoir topography on the distribution of initial gas and the plume of injected CO_2. A new static model was developed to represent the reservoir topography accurately and was subsequently rotated by 30 degrees clockwise to align the principal stress direction with its boundary (**Figure 4**). A dual grid system consisting of separate grids for the reservoir flow and geomechanics calculations was implemented using the compositional reservoir simulator, GEM software of the Computer Modeling Group. The exchange of information between the reservoir and geomechanics simulators was accomplished in an iteratively coupled way, resulting in a significant reduction in computational time compared to a single grid coupled simulation. The results showed that the presence of initial gas in the vicinity of the injection wells brought lower wellhead pressure and less ground uplift compared to the scenario where gas was absent. This effect was particularly pronounced when the injection well was adjacent to the gas reservoir, with only half of the deformation observed in the closest well KB502 compared to the simulation result assuming gas absence. The high compressibility of natural gas in the reservoir above the aquifer may have played a role in mitigating the pressure increase. In Scenario 2, where initial gas was considered, lower permeability and Young's modulus were required to match the same level of uplift as observed in the aquifer-only case. In order to describe the double-lobe shape heave occurring around the KB502 injection well, the F12 fault, which intersects the well, was considered. Among several hypotheses, the assumption of a tensile opening of the vertical fault could make the double-lobe shape, achieved by pressure-dependent permeability and much lower horizontal Young's modulus compared to the surrounding formation. Additionally, natural gas production was considered in the simulation, which resulted in ground subsidence near the production wells and reduced uplift around the CO_2 injection wells. However, no data were available for gas production, so the effect of natural gas production could not be examined quantitatively. The study highlights the importance of considering reservoir topography and gas production in geomechanical modeling as they significantly impact reservoir pressure and ground deformation.

Synthetic tilt vectors from finite element simulations performed by CSMP coupled geomechanics and hydraulic fracturing simulator (Salimzadeh et al., 2018; Paluszny et al., 2018; Paluszny et al., 2020; Deb et al., 2021, Salimzadeh et al. 2022) have been used to infer the shape and direction of the CO_2 plume. A set of 10 tiltmeters presumably installed on top of the fault near KB502 show that the ground surface deformation initially corresponds to the inflation of the horizontal layer around KB502. Then quickly the ground surface deformation changes to the one corresponding to a vertical plume (pressurization of the vertical fault). The obvious change in tilt vectors occurs when the surface displacement is sub-millimeters, impossible to detect by InSAR technology.

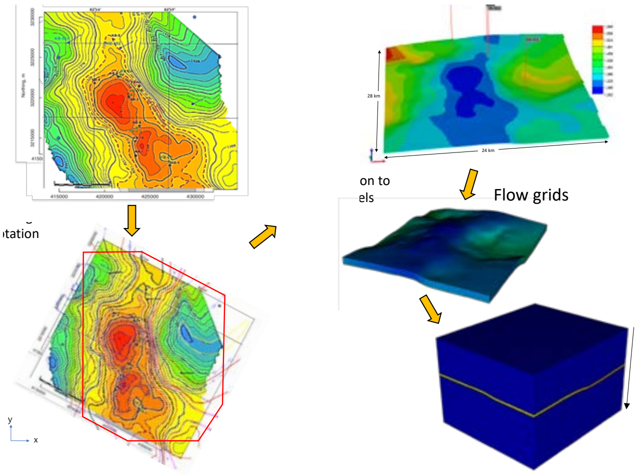


Figure 4. A new static model considering the reservoir topography for flow and geomechanics coupled simulation for In Salah.

Simulation results of High Island, Gulf of Mexico (Figure 5), suggest that ocean bottom pressure recorders have enough sensitivity to detect displacement changes for the whole study area. For strain measurements, fiber optic cables could be deployed to monitor vertical strains along an observation well. The vertical strains magnitudes are above the detection threshold for fiber optic sensors along the reservoir, but not for the overburden. **Table 3** summarizes the detection threshold for this site and the maximum value for displacements at the seabed and for the axial strain measured in the vertical well and along the horizontal line.

The results have also shown how fault sealing assumptions substantially change the fluid flow and consequently the deformation pattern. Sealing leads to a concentration of excess pore pressure and vertical displacement in the vicinity of the injector well, as well as a noticeable asymmetry in the seabed uplift pattern. As a result, it has been shown that monitoring horizontal strains along the seabed may provide us information about faults location in the subsurface. This preliminary assessment has provided an initial understanding of the reservoir and seal units' behavior. However, many topics may be further explored to increase the reliability of the predictions. In particular, future work will focus on better geostatistical constraints on permeability and porosity, an active area of research for unstructured grids. Additionally, future work should address more detailed analysis of well log data to have a better estimate of anisotropic elastic properties, and more detailed fault seal analysis.

Table 3. Precision of displacements and deformation measurement

Technology	Threshold	Max simulation value
Ocean bottom pressure recorders	1mm for 10 m water depth	11 mm
Fiber optic cables	7.5 µm/m	18 µm/m

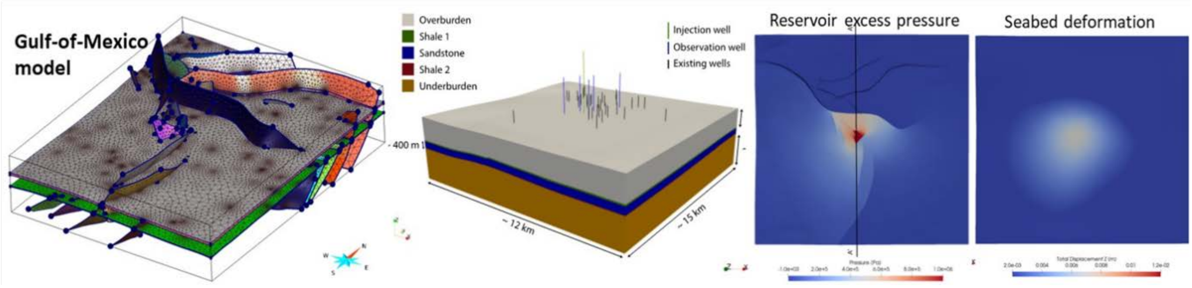


Figure 5. High Island domain. The different geological units were interpreted by correlating 3D seismic data and the well logs.

2.3 WP3: History matching inversion by coupled flow and geomechanics

In WP3, we made important advances that are critical to improve the capability of quantifying subsurface geomechanical behaviours based on ground deformation data during CO_2 injection. First, we developed a generalized Geertsma solution that can analyze for the VTI multi-layered subsurface (Park et al., 2021). Since it is an analytical solution, the computational cost is cheap yet providing more realistic modelling opportunities than the original Geertsma solution. The anisotropy herein refers to a particular case of vertically-transverse isotropic (VTI) stiffness, as shown in **Figure 6**. The analytical solution is derived for a constant pressure change within a reservoir layer, and the pressure change is of cylinder shape i.e., axis-symmetric problem. The reservoir thickness can be any value, not only infinitesimally small as in Geertsma et al. (1973). In addition, any number of VTI or isotropic layers can be modelled. For calculation, we solve analytically the following axis-symmetric governing equation in cylindrical coordinate (r, z) and Hankel transforms with k being the transform parameter (or wavenumber).

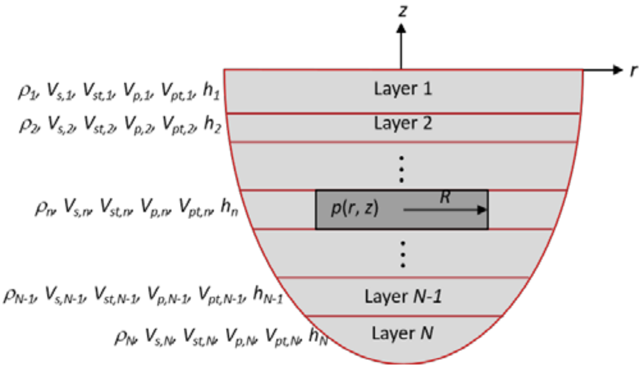


Figure 6. VTI anisotropic subsurface model consisting of N layers and subjected to fluid-induced constant pore pressure p(r, z) (darker-shaded) of radius R in an n-th layer. Note ρ, Vs, Vst, Vp, Vpt, and h are mass density, radial/horizontal and vertical S-wave velocities, radial/horizontal and vertical P-wave velocities, and layer thickness, respectively. Axis-symmetric coordinates (r, z) are used and z-positive is upwards.

Next in WP3, we explored the possibility of recovering the pressure distribution in the reservoir from the surface deformation data using a machine learning (ML) approach. We chose to use a convolutional neural network (CNN) with an encoder-decoder architecture as it has proven to be very efficient in the task of pattern recognition. We evaluated our ML approach on a synthetic dataset replicating the measurements from the In Salah CO_2 injection site in the south of Algeria (Bjørnarå et al., 2018). We demonstrated that a ML approach can be an effective tool to recover the pressure distribution in a reservoir from the surface deformation analysis.

Figure 7 displays the synthetic model tested – the base model for our inversion procedure. On the right (input), the synthetic pressure distribution, considered homogeneous over the reservoir height and on the left (output) its corresponding surface displacement computed from finite element (Bjørnarå et al., 2018). In ML terms, this means translating one image to another image. Those topics are best handled using CNN with an encoder-decoder architecture. The ML network is displayed in **Figure 7**. Input data are the surface displacement maps. The encoder is a series of 3 convolutional layers, decreasing the size of the input, but increasing its dimensionality and the decoder is a series of 3 transpose convolutional layers, reducing the dimensionality but increasing the size (the inverse operation). The output is the pressure distribution map. The activation functions through the network are ReLU functions and the network weights updates are made with a classical Adam optimization. The loss function to evaluate the prediction is a mean square error (MSE), to ensure that our trained model has no outlier predictions with big errors.

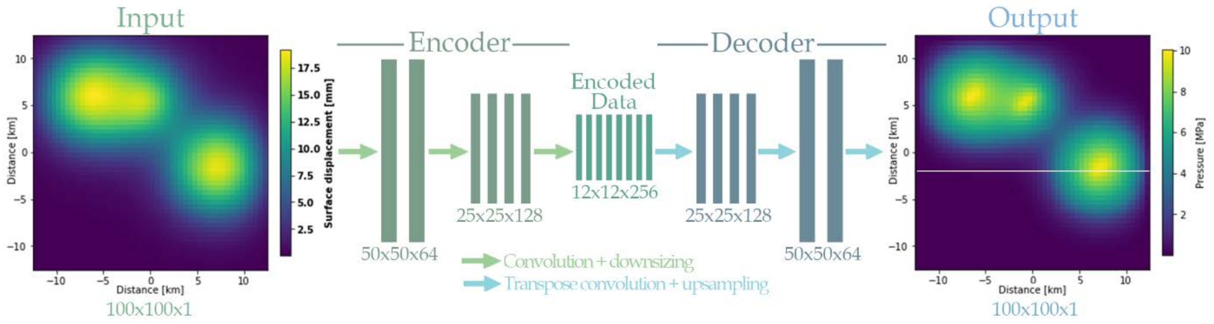


Figure 7. Input and output: synthetic data. Output: Pressure distribution in the reservoir. Input: corresponding surface displacement. Middle: ML network composed of and encoder and a decoder. The encoder is composed of three convolutional layers to extract patterns from the input data while reducing the size of the input. The decoder interprets the encoded version by using transpose convolutional layers and up-scaling the data back to its original format.

Further effort should be spent to add more complexity into the training set. In the context of a real-data application, the data preparation can be extensive. Yet, once a ML is trained, it could be used to invert the data without further modification during an injection process, in a time lapse monitoring for example.

Finally, we present a methodology 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 consists of the three sequential stages (or modules) as shown in **Figure 8**.

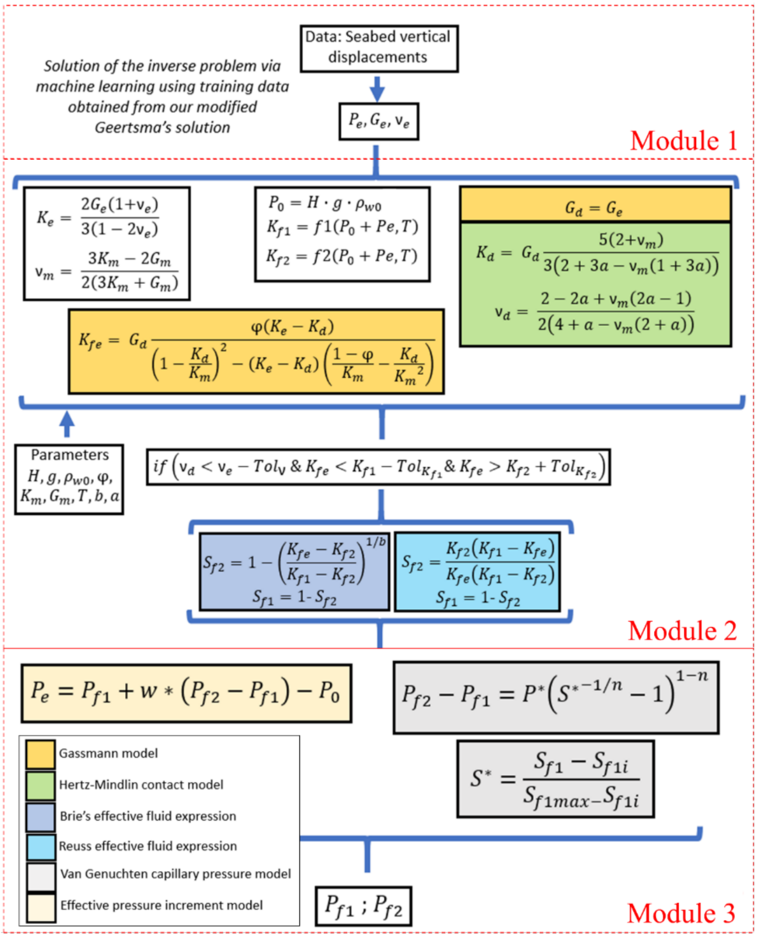


Figure 8. Illustration of three-stage inversion workflow.

We test the methodology using seafloor deformation data from a 2D multiphase hydro-mechanical study of geological CO_2 injection, which are introduced into our ML approach. **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 explain the input seafloor deformations.

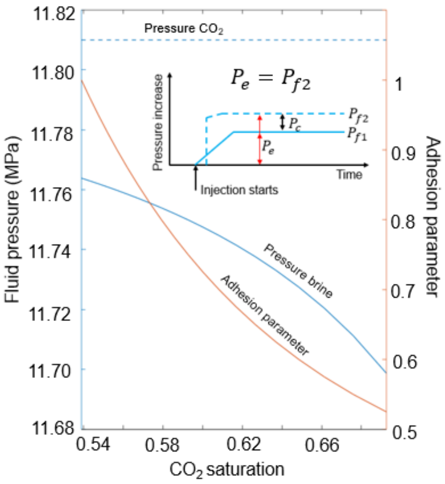


Figure 9. Examples of maximum and minimum fluid pressures and saturations explaining seafloor deformation data.

The results in **Figure 9** consider a model in which the pressure increased obtained with ML is assumed to correspond to the non-wetting phase (in this case CO_2; inset in Figure 7). We observe CO_2 saturations ranging between 0.54 to 0.69 depending on 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) (Mavko, 2009). 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. The methodology is applicable for any fluid injection problem where surface deformation data is acquired.

2.4 WP4: Integration of project results and conclusion

We tested Distributed fiber optics Strain Sensing (DSS) in various settings and environments to find out its resolution and effectivity in measuring small-scale deformations perpendicular to cable axis. Large-scale lab tests, onshore and offshore experiments showed that DSS cables can detect deformations as small as 10 micro-strain, even though in noisy offshore environments and when deformation gradient is high. 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, about 500 mm cover. 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 report 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. Deployment of DSS cables in trenches (offshore and onshore) and at locations that has deformation potential (faults or barriers) will provide continuous data over the target area and will show if the storage conforms as expected or exhibit anomalies that can trigger other monitoring measures or start an alarm.

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 successfully.

Geomechanical simulation of synthetic and real-life cases with focus on ground deformation showed that the magnitude and gradient of the observed deformations at e.g. In Salah are well above the threshold for tiltmeter detection limit, while is about the limit of detection for DSS cables. While more expensive than InSAR data, tiltmeter has a higher resolution and will provide good calibration points. Modelling hypothetical cases like offshore Gulf-of-Mexico revealed that with injection of about one million tons CO_2 per year a seafloor uplift of about 50 mm may be observed and it may have a pattern around faults. This level of uplift can be both detected by pressure sensors and DSS cables. Conclusion from the synthetic cases is that the ground deformation caused by injecting 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 or after decommissioning.

Determination of pressure distribution and plume migration based on the measured ground uplift was also studied. We have developed and verified a semi-analytical solution and an inversion routine that can determine pressure anomaly in the subsurface using ground surface heave as input data. Fast analytical solution of surface heave versus pore pressure change in geological CO_2 storage is a useful screening tool for surface heave monitoring feasibility.

In conclusion, ground deformation can be a useful monitoring parameter. There is a suite of techniques for measuring it onshore (InSAR, Tiltmeter, DSS fiber optics) and offshore (pressure sensors, DSS fiber optics). Deformation observed in our models is in a range that may lead to mechanical failure and induce microseismic events. Monitoring ground deformation combined with microseismic monitoring may provide comprehensive data to understand response of reservoir and cap rock to CO_2 injection. In Short:

- We suggest first-order estimation of ground uplift using the Generalized Geertsma solution (that accounts for reservoir geometry, thickness, anisotropy) (Figure 10). If considerable uplift is expected, then a more advanced 3D geomechanical study is suggested to evaluate integrity and safety of the storage.

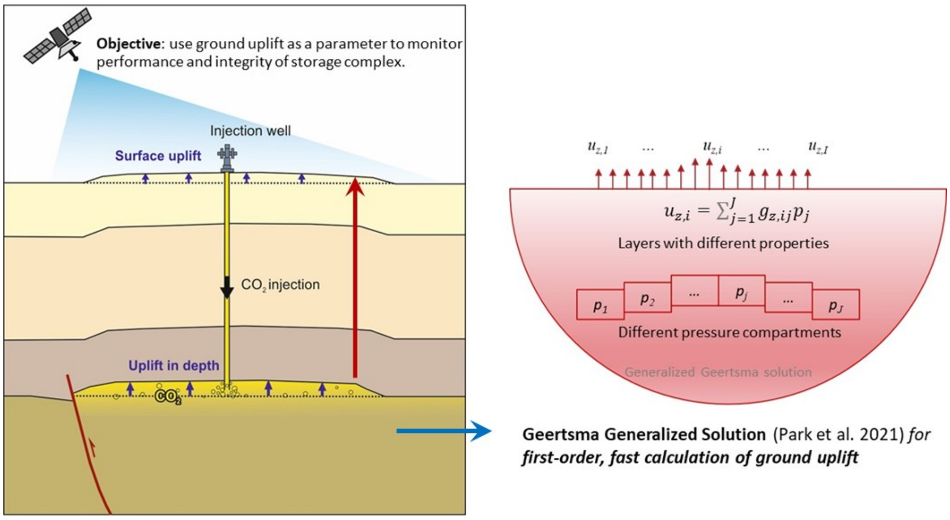


Figure 10 Schematics of SENSE project and the first-order estimation of ground deformation due to CO2 injection using Generalized Geertsma solution.

- Geomechanical modelling of real-life and synthetic cases shows the shape of deformation reveals sealing & draining behaviour of faults in reservoir/caprock. This is complementary to the bullet point above, meaning that in case of measurable ground deformation, such measurements can provide data on the actual response of faults and fractures. In case a fault is draining or leaking, pressure build-up on both sides will be similar and no anomaly may be observed. In contrary, if a fault is sealed, reservoir pressure will be different on both sides and the side with maximum pressure will show ground uplift and thus an anomaly (Figure 11).

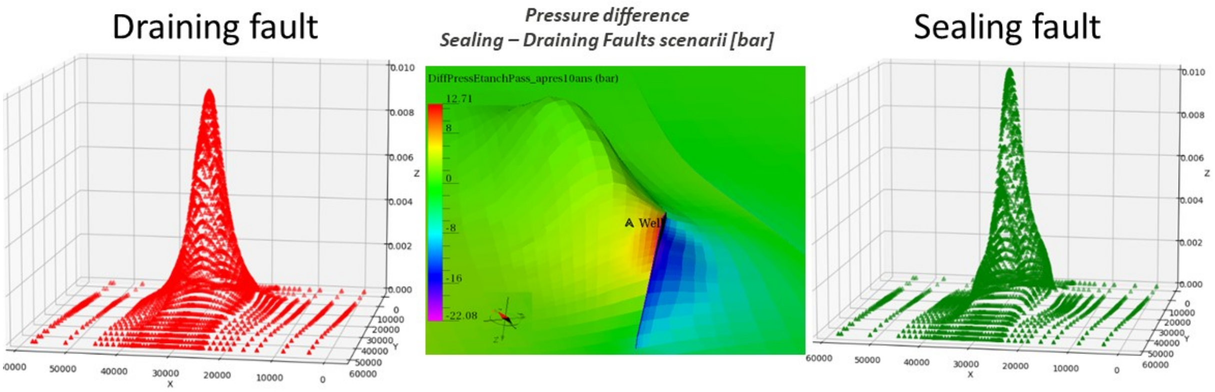


Figure 11 Impact of fault permeability of ground uplift *Anticline trap with sealing or draining faults.*

- Experiments shows Distributed Strain Sensing (DSS) fiber optic cables:

- Provide good coupling with soil when embedded about 40 cm underground-no anchors,
- Can detect deformations of ca. 1 µ strain across cables,
- Can work well for monitoring deformation hotspots (Figure 12).

Large scale lab tests Field scale Offshore tests

Figure 12 Testing different types and layouts of Distributed Strain Sensing (DSS) fiber optics for measuring micro-strain measurements associated with injection of CO_2.

2.5 WP5: Coordination and dissemination

Coordination activities were led by NGI in the initial phases of the project but more and more divided between al project partners when the project progressed, and cases studies were developed. Coordination of the project and collaboration between partners has worked excellent, given the dynamic state of the project and many changes and adaptations that occurred in the course of the project based on mainly COVID-19 restriction. More details are given in Section 5. Some of the activities of WP5 were the management and coordination of the deviations from the original plan.

The deviations were as follows:

1. Cancellation of injection operation at Hontomin, Spain. Injection operation at Hontomin was planned in the course of another project. Due to the budget cut by the Spanish

funding program, the injection was cancelled. SENSE activities were dependent on that operation.
Mitigation: we revised the activities for Spanish partners CIUDEN and IGME such that they will focus on the data available from earlier injection operations. For other activities that were based on satellite data for ground monitoring, we replaced the Hontomin InSAR with the new data from In Salah, Algeria.

2. Cancellation of injection operation at Bay of Mecklenburg, offshore Germany. SENSE project planned for injecting gas and measuring seabed deformation due to pressure build-up. For that operation we needed a cruise ship from GEOMAR. After doing site characterization (geophysical studies, geomechanical testing, and receiving time for cruise ship, the operation has to be cancelled because of COVID-19 restrictions.
Mitigation: we bay of Mecklenburg case with the Boknis Eck, where we used uplifting devices and other instrumentations to simulate seabed uplift and test our measuring instruments and approaches.
3. Change of partners: Geogreen (France) and EPFL (Switzerland) who initially were research partners left SENSE consortium in 2020 due to the negative response from their respective funding agencies.
Mitigation: We communicated with other potential partners and replaced Geogreen with KIGAM (South Korea) and distributed the activities of EPFL between other research partners.

Other results of WP5 in terms of reaching out to scientific community, university students, the public, and industry are presented in Section 6.

3. Project impact

3.1 Contribution to the facilitation of the emergence of CCUS

SENSE project has focused on the geomechanical aspects of CO_2 storage sites and the deformation induced in surrounding formations and observed at surface. Geomechanics controls the integrity of storage sites. Through the experimental and numerical studies in SENSE project, we have learned and showed that ground deformation monitoring will reveal geomechanical changes, that reveal changes in reservoir and overburden, can easily be measured. And the good news is that ground deformations can be calculated beforehand using a mathematical solution that we developed in SENSE project (Geertsma Generalized solution-see WP3). This solution is available for calculating ground deformation (and stress) around and above storage reservoir. This implies that operators do not need to do a costly, full geomechanical modelling in the planning phase of the project but a quick and inexpensive first-order estimation that is reliable. The other good news is that ground deformation, which we propose as a monitoring parameter, is not a stand-alone study but can use the same model as used for analysing faults, fractures, etc. We propose a monitoring workflow that includes ground deformation as illustrated in Figure 13.

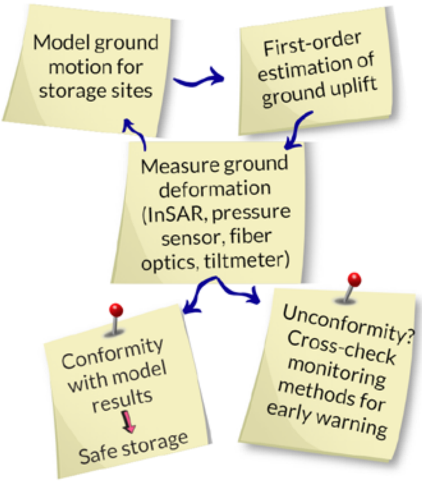


Figure 13 Monitoring workflow for CO2 storage sites considering ground deformation.

3.2 Strengthen the competitiveness and growth of European companies

A major development that we have witnessed through SENSE project is the professional development of our team that have been working on different aspects of the project. This competence development has given excellent ability to the research and industry partners (Equinor and Quad Geometrics) to work more confident with CCS projects and know where to search for a solution/partner if any issues arise related to geomechanics and site integrity and that what technical solutions are available. More specifically:

- QuadGeometrics has applied the Generalized Geertsma solution in its workflow for ground uplift and subsidence that may provide the company a unique position in the market compared with the competitors,
- Equinor is discussing to consider fiber optics cables for monitoring CO_2 storage sites among them, Northern Lights and has asked SENSE and Digimon project for a joint workshop to provide more technical details. The workshop is being planned for March 2023.
- In addition, research organizations involved in the project now feel very confident for doing geomechanical analyses of CO_2 storage sites including fracture /fault reactivation, microseismicty, detection of these events at surface and instrumentation of sites. The confidence gained is a result of the team work through knowing the state-of-the-art solutions both on instrumentation side and on software available and used by others.
- In addition to European Companies, SENSE had the fortune to work with LLNL (USA), RITE (Japan), KIGAM (South Korea) and CSIRO (Australia). SENSE activities and the group work has also strengthened ability of all these partners in doing studies and being able to provide services to CCS projects around the world-which is perhaps the main objective of ACT program.

3.3 Other environmental or socially important impacts, such as public acceptance

SENSE project has completed many field studies (as detailed in WP1) without any harm to the environment. The lab and field work conducted in Norway, Germany, UK and Japan involved about 55 researchers and supporting staff. These works were completed successfully under the pandemic with no personal injuries or issues thanks to the safety measures implemented effectively by all partners.

There were no issues in conflict with the public interest during SENSE field studies.

3.4 Chances for commercializing the technology further

- The type and layout of the Distributed Strain Sensing (DSS) fiber optics developed and used in SENSE is unique. NGI and RITE are working with sensor developers to improve these further not only for CCS projects but also for other applications such as structure health monitoring. NGI and RITE also discussing this with Equinor to explore further potential of these systems.
- GEOMAR has developed a type of ocean bottom lander that was tested and will work further to develop this type of landers in order to provide technology solutions that will be cheaper that the standard, relatively expensive instruments that are available in the market today.

3.5 Gender issues

- None to report.

4. Implementation

The SET Plan Implementation Action 9 states "In order to realise its potential, CCS needs to become a cost-competitive technology and gain public acceptance (mainly regarding storage safety), so that it could start to be commercially deployed and thus contribute to the low-carbon transition of the European economy" 1. SENSE project assists companies to evaluate geomechanical integrity of storage sites and hence assure "storage safety" through providing the first-order deformation assessment, technologies and workflows for satellite data processing, fiber optics systems for measurements, possible microseismic associated with injection and advanced geomechanical modelling if required. Equinor and Quad Geometrics have been active in giving comments and defing the roadmap for SENSE project since the start of the project. Ola Eiken (Quad Geometrics) had the role of Leader of the Steering Committee and Philip Ringrose and Zoya Zarifi (both Equinor) have been actively taking part in SENSE Steering Committee meetings and consortium meeting as well as in the discussions and meeting at WP level and provided lots of useful input and value to the project.

5. Collaboration and coordination within the Consortium

Coordination:

Collaboration of SENSE partners started with making SENSE proposal and later on with the consortium agreement. Despite some initial issues with contracting, we succeeded in reaching an agreement within 5 months from the nominal project start. Despite the different time zones that SENSE partners are spread, participation in online meetings was very successful thanks to the willingness and positive attitude of partners from KIGAM, RITE and CSIRO to participate in the meetings during night local time while US partners had to woke up very early in the morning. Contribution of all partners in the workshops, consortium meetings and traffic light reports worked very well. Communication with ACT Coordinator and funding agencies throughout the project period has also worked very well.

Collaboration on case studies:

SENSE projects had several case studies. Therefore, partners teamed up to work on specific cases. NGI, RITE and GEOMAR worked on the development of instruments (Pressure sensors, tiltmeters and

DSS fiber optics) for measuring small ground deformations which were implemented in Oslo large scale lab tests, Chiba field tests in Japan and offshore Germany. After testing different layouts of instruments in lab and on shore a team from NGI, RITE and GEOMAR attended in a field campaign outside Kiel in Germany. The campaign was very well organized by GEOMAR (with assistance from a diver team from University of Kiel). The planning, preparation and collaboration worked very well and the team performed the offshore experiments successfully. In Salah case study was used for verifying modeling approaches. IFPEN, LLNL, KIGAM, CSIRO and NGI worked collectively on this case. Troll field data were also obtained from Troll License and was shared with partners where UiO, NGI and Quad worked on the data.

The main added value of transnational collaboration is the common understanding about safety of storage sites, confidence about assessment of site integrity assessment and a more important aspect is that partners feel confidence about assessing safety of CO2 storage sites. A major learning is that we can assess sites in advance and can monitor them effectively to manage safe CO_2 storage. In case of any anomaly observed, we know how to detect and propose mitigation methods.

Data sharing portal:

We used a Teams channel for data sharing between project partners. And all research and industry partners got access to the channel. Newly acquired Data for In Salah New data were obtained from In Salah JV and were shared with partners through the Teams Channel and worked well.

In addition to SENSE channel, SENSE website was also used as a portal for sharing published material, information about webinars and news about the project. We do not have statistics on how many visited the website. NGI is now transferring SENSE website to another domain that will be active in at least 10 years from 2023 and will contain information and documents that are open access and are publicly available.

Management structure:

Management structure worked well and was effective. The structure of SENSE consisted of:

- Steering Committee (one representative from each partner organization and one representative from the Research Council of Norway),
- Advisory Board (Vit Hladik-Geological Survey of Czechia, Giovanni Bertotti-University of Delft university of Technology, the Netherlands, Lyess Laloui- EPFL Switzerland)
- WP-leader Team (WP1: Christian Berndt-Geomar, WP2: Sarah Bouquet-IFPEN, Joonsang Park-NGI, White Joshua-LLNL, WP5: Bahman Bohloli)
- Coordinator of SENSE: Bahman Bohloli-NGI

SENSE project had several changes in the course of the project. The changes were discussed in the Steering Committee and were agreed upon. Project Coordinator took the decision up in the WP-leader meetings and were defined as actions and were implemented.

6. Dissemination activities (including list of publications)

SENSE have had a series of webinars information of which are available on SENSE website. The webinars can be watched on the website. Other dissemination activities and list of publications are also available through the website, and also presented in the following sections.

SENSE has contributed to further research ideas and has resulted in two spin-off projects (See Section 6.1 #1 a research initiative at University of Nazarbayev in Kazakhstan which was initiated after a presentation from SENSE to the university faculties, and #2 a project in Norway that QuadGeometrics started to improve accuracy of ground deformation measured in offshore Norway) and three associated projects (see Section 6.1 #3- #5).

We have presented results of SENSE for the industry, policy makers, scientific communities, university students, high school teachers, and the public in 9 countries where SENSE partners belongs to. These activities count 67 and are listed in sections 6.2-6.5. The main follow up and uptake by the industry are the points mentioned under sections 3.2 and 3.4 above. SENSE partners are following up these activities mainly with Equinor but also with other energy companies.

A final technical report has also be prepared (attached) that will be published on SENSE websites soon. This report is the base for an overview paper that is also under preparation for submission to a scientific journal for publication.

6.1 Spin-off and associated projects:

1. Quad Geometrics (PI: Ola Eiken)
   Title: SHAPE - Seafloor Height from Aqua PressurE for offshore CO_2 storage monitoring
   Funding agency: Gassnova

2. Nazarbayev University-Kazakhstan (PI: Prof. Ali Mortazavi, Deputy: Dr Bahman Bohloli-NGI)
   Project title: A Geomechanical Investigation of Mechanisms Involved in CO_2 Storage and Caprock System Integrity
   Funding agency: Nazabayev University, School of Mining and Geosciences

3. RITE-Japan (PI: Ziqiu Xue)
   Project title: Research and development of CO_2 storage technology for safe CCS implementation
   Funding agency: New Energy and Industrial Technology Development Organization (NEDO) and the Ministry of Economy, Trade and Industry (METI) of Japan (JPNP18006)

4. KIGAM-South Korea (PI: Dr. Yong-Chan Park):
   Title: Development of geomechanical modeling technology using test beds in Europe for CO_2 geological storage.
   Funding agency: National Research Foundation of Korea (2020K1A3A1A78114761)

5. CSIRO-Australia (PI: Vincent Mow):
   Project title: CO_2 storage monitoring-Project OD-214816
   Funding agency: Commonwealth Scientific and Industrial Research Organisation (CSIRO).

6.2 Journal and Conference Papers:

1. Ramos, A., García-Senz, J., Pedrera, A., Ayala, C., Rubio, F., Peropadre, C., Mediato, J., 2022. Salt control on the kinematic evolution of the Southern Basque-Cantabrian Basin and its underground storage systems (Northern Spain). Tectonophysics 822, 229178. https://doi.org/10.1016/j.tecto.2021.229178.

2. Salimzadeh, S., Kasperczyk, D., Chen, Z., Movassagh, A., Arjomand, E., Shen (Vincent) Mow, W., & Kear, J., 2022. Ground Surface Monitoring for CO_2 Injection and Storage. *The APPEA Journal* **62**, S492-S496. https://doi.org/10.1071/AJ21105.

3. Bjørnarå T.I., Park J., Bohloli B., 2022. Validation of an upscaled poroelasticity formulation for high-aspect ratio geological structures such as fractures and faults. Submitted to International Journal of Geomechanics.

4. Bohloli, B., Bateson, L., Berndt, C., Bjørnarå, T.I., Eiken, O., Estublier, A., Frauenfelder, R., Karstens, J., Orio, R.M., Meckel, T., & Mondol, N.H., 2021. Assuring integrity of CO_2 storage sites through ground surface monitoring (SENSE). Proceedings of the 15th Greenhouse Gas Control Technologies Conference 15-18 March 2021, http://dx.doi.org/10.2139/ssrn.3818971.

5. Hussain E., Novellino A., Jordan C., Bateson L., 2021 Offline-Online change detection for Sentinel-1 InSAR time series. Remote Sens. 2021, 13, 1656, DOI: 10.3390/rs13091656.

6. Park, J., Bjørnarå, T.I., & Bohloli, B., 2021. An Analytical Solution for Pressure-Induced Deformation of Anisotropic Multilayered Subsurface. Geosciences 11(4):180, https://doi.org/10.3390/geosciences11040180.

7. Ramos, A., Mediato, J.F., Pérez-López, R., & Rodríguez-Pascua M. A., 2021. Miocene to present-day tectonic control on the relief of the Duero and Ebro basins confluence (North Iberia), Journal of Maps, 17:2, 290-300, DOI: 10.1080/17445647.2020.1869111.

8. Salimzadeh, S., Kasperczyk, D., Chen, Z., Movassagh, A., Arjomand, E., Mow, W. S., and J. Kear. "Early Detection of Fault Activation Using Surface Tilt Monitoring During a CO_2 Injection Project." Paper presented at the 56th U.S. Rock Mechanics/Geomechanics Symposium, Santa Fe, New Mexico, USA, June 2022. https://doi.org/10.56952/ARMA-2022-0301.

9. Bohloli, B., Berndt, C., Bjørnarå, T.I., Bouquet, S., Dujardin, J., Eiken, O., Estublier, A., Fourno, A., Frauenfelder, R., Frey, J., Karstens, J., Lee, Y., Marin-Moreno, H., Meland, H., Mondol, N.H., Park, J., Park, Y. Sparrevik, P.M., Vincent, C. Vöge, M., White, J.A., & Xue, Z., 2022. Monitoring CO_2 Storage Sites Onshore and Offshore using InSAR Data and Strain Sensing Fibre Optics Cables (November 25, 2022). Proceedings of the GHGT-16 conference available at SSRN: https://ssrn.com/abstract=4286039.

10. Bohloli, B., Smith, H., Sauvin, G., & Cerasi, P.R., 2021. Frictional properties of natural and induced fractures in two types of shales. European Rock Mechanics Symposium (EUROCK) 2021, 21-24 September, Torino, Italy. 10.1088/1755-1315/833/1/012040.

11. Bohloli, B., Park, J., Bjørnarå, T.I., Sparrevik, P., Frauenfelder, R., Vöge, M., Ritter, S., Mondol, N.H., Berndt, C., & Karstens, K., 2021. Monitoring ground surface and seafloor deformation caused by subsurface fluid injection. 1st Int. Conference on Sustainability in Geotechnical Engineering, Lisbon, Portugal.

12. Bouquet, S., Frey, J., Malinouskay, I., Estublier, A., & Fourno, A., 2022. Evaluation of surface movement observability and optimization of the monitoring plan through conceptual and coupled flow-geomechanics models. Proceedings of the GHGT-16 conference.

13. Bouquet, S., Frey, J., Malinouskaya, I., Soulat, A., Estublier, A., & Fourno, A., 2021. Analysis of Surface Movement through Conceptual and Coupled Flow-Geomechanics Models an Example of Surface Monitoring Assessment for CCS Project. In TCCS–11. CO_2 Capture, Transport and Storage. Trondheim 22nd–23rd June 2021 Short Papers from the 11th International Trondheim CCS Conference. SINTEF Academic Press. https://hdl.handle.net/11250/2780153.

14. Camargo, J.T., Hamon, F., Mazuyer, A., Meckel, T.A., Castelletto, N., & White, J.A., 2022. Deformation monitoring feasibility for offshore carbon storage in the Gulf-of-Mexico. Proceedings of the GHGT-16 conference.

15. Dombrovski, E., Mondol, N.H., Bohloli, B., Gaina, C., and Torabi, A., 2021. Applying machine learning on InSAR data for carbon sequestration site monitoring. NGF Winter Conference, 6-8 January, Trondheim, Norway.

16. Lee, Y., Park, Y., Song, I. & Lee, H., 2022. August. Geomechanical Modeling of Surface Deformation Induced by CO_2 Injection at the in Salah Site. In EAGE Asia Pacific Workshop on CO_2 Geological Storage (Vol. 2022, No. 1, pp. 1-4). European Association of Geoscientists & Engineers. https://doi.org/10.3997/2214-4609.202275004.

17. Marín-Moreno, H., Dujardin, J.R., & Park, J., 2022. Discrimination of fluid pressure and saturation changes during geological CO_2 storage based on surface deformation data. 6th International Workshop on Rock Physics, 13-17 June 2022 A Coruña, Spain. Oral presentation.

18. Movassagh, A., 2022. Concurrent 21. Presentation for: Ground surface monitoring for CO_2 injection and storage. The APPEA Journal **62**. https://doi.org/10.1071/AJ21373.

19. Muela, A.S., Ramos, A., Vidal, J.A.M., Pérez-López, R., Mediato, J.F., and Rodriguez-Pascua M.A., 2022. New insights into fault systems of the Burgalesa Platform revealed by seismic monitoring at the Hontomín Technology Development Plant (Burgos, Spain). IV Reunión Ibérica sobre fallas activas y Paleosismología, Teruel 6-10 Sep. IBERFAULT 7-10 September 2022. Oral presentation (https://iberfault.org).

20. Park, J., Eiken, O., Bohloli, B., & Bjørnarå, T.I., 2022. Insights into injection-induced surface displacement via Geertsma-type models. (November 25, 2022).

21. Park, J., Eiken, O., Bjørnarå, T.I., & Bohloli, B., 2021. Generalized Geertsma solution for isotropic layered medium. In TCCS–11. CO_2 Capture, Transport and Storage. Trondheim 22nd–23rd June 2021 Short Papers from the 11th International Trondheim CCS Conference. SINTEF Academic Press. https://hdl.handle.net/11250/2780656

22. Pratikna, K., Rahman, M.J., & Mondol, N.H., 2022. Porosity Log Prediction of the Utsira Formation in Sleipner CO_2 Storage Site by Implementing Machine Learning Techniques (November 25, 2022). Available at SSRN: https://ssrn.com/abstract=4286107.

23. Pratikna, K., Rahman, M.J., Bohloli, B., Torabi, A., & Mondol, N.H., 2022. Machine learning application for compressional wave velocity log prediction in Sleipner CO_2 storage, offshore Norway. Accepted for oral presentation, EAGE Annual, 7-9 June 2022, Madrid, Spain. https://doi.org/10.3997/2214-4609.202210408.

24. Pratikna, K., Rahman, M.J., & Mondol, N.H., 2022. Characterization of Utsira Formation around the Sleipner CO_2 storage site, central North Sea. Submitted to SEG Annual Meeting, 28 August-1 September 2022, Houston, USA. https://doi.org/10.1190/image2022-3750949.1

25. Ramos, A., García-Senz, J., Pedrera, A., Ayala, C., Rubio, F., Peropadre, C., & Mediato, J., 2021. Salt pillows and salt-cored anticlines driven by progradational loading as key structures for underground geological storage. Applications to the Hontomín pilot plant (Northern Spain), AAPG Europe Evaporite Processes and systems: Integrating Perspectives, October 2021.

26. Ramos, A., Mediato, J.F., Pérez-López, R., & Rodríguez-Pascua, M.A., 2021. Tectonic control on the drainage system of the Bureba sub-basin (North Iberia). X Congreso Geológico de España, 5-7 july 2021, Vitoria-Gasteiz, Spain.

27. Sparrevik, P., Meland, H.J.. Park, J., & Bohloli, B., 2022. Distributed Fibre Optic Strain Sensing of Ground Deformations for CO_2 Storage Monitoring. Conference Proceedings, EAGE GeoTech 2022 Third EAGE Workshop on Distributed Fibre Optic Sensing, Apr 2022, Volume 2022, p.1 – 5. https://doi.org/10.3997/2214-4609.20224026

28. Sparrevik, P., Meland, H.J., & Park, J., 2022. Distributed fibre optic ground deformation sensing. 11th International Symposium on Field Monitoring in Geomechanics, London 4-7 Sep., ISFMG 2022. Oral presentation.

29. Sparrevik, P., & Meland, H., 2022. High resolution ground deformation monitoring by distributed fiber optic strain sensing cables, 11th International Symposium on Field Monitoring in Geomechanics, ISFMG 2022, London.

6.3 Popular science articles

30. Bohloli, B., Sparrevik, P.M., and Skurtveit, E., 2022. Fiberoptisk teknologi sikrer lagring av klimagasser under Nordsjøen. https://geoforskning.no/%ef%bf%bcfiberoptisk-teknologi-sikrer-lagring-av-klimagasser-under-nordsjoen/

31. Bouquet, S., & Estaublier, A., 2021. Review on CCS and SENSE project. Publication in Centrale Marseille, October 2021.

32. Outreach to teachers teaching Earth Sciences in Spanish secondary schools in Spain. CCS and results of SENSE project by IGME-CSIC and CIUDEN. 2021 article in Journal for teachers.

6.4 Reports

33. Bohloli, B., Sparrevik, P.M., Vöge, M., Frauenfelder, R., Park, J., Berndt, C., Bateson, L., Karstens, J., Hussain, E., & Novellino, A., 2020. Quantification of ground movement – State-of-the-art (Deliverable D1.1). SENSE report, 66 p.

34. Bouquet, S., Estublier, A., Fourno A., Frey J., & Malinouskaya I., 2021. Assuring integrity of CO_2 storage sites through ground surface monitoring (SENSE) – WP2.1: Presentation of conceptual models (Delivrable D2.1). SENSE report, Report D2.1, 19 p.

35. Bouquet, S., Estublier, A., Fourno A., Frey J., & Malinouskaya I.,2021. Assuring integrity of CO_2 storage sites through ground surface monitoring (SENSE) - WP2.2: Understanding the mechanism of surface movement (Deliverable D2.2). SENSE report, Report D2.2, 89 p.

36. Camargoa, J.T., & White, J.A., 2020. Deformation monitoring feasibility at an offshore carbon storage site, Interim progress report LLNL, December 2020.

37. Frauenfelder, R., & Moldestad, D.A., 2020. CO_2 storage site monitoring with InSAR. SENSE report, JOP.02.20.2, 10 p.

38. Kizatbay, A., Shahid, A.A., & Mondol N.H. 2020. Grain size analysis of sediment cores from Bay of Mecklenburg, offshore Germany, Lab report, Department of Geosciences, University of Oslo.

39. Rogstad, A., Bohloli, B., & Quinteros, S., 2020. SENSE Case Study: Geotechnical testing of clay and sand, Bay of Mecklenburg, offshore Germany. NGI report 20190570-02-R, 58 p.

6.5 Presentations

40. Agnete Rogstad, 2020. Geotechnical testing of core samples from Bay of Mecklenburg offshore Germany. Lunch & Learn at NGI, Oslo, Norway, 21 July 2020.
41. Almudena Sanchez de la Muela & Bahman Bohloli, 2022. Seismicity monitoring at onshore CO_2 geological storage sites. SENSE Webinar 3 (Virtual), 18 February 2022.
42. Bahman Bohloli, 2022. Brief presentation of SENSE achievements. US-Norway bilateral collaboration event, Bergen, Norway, 29 June 2022.
43. Bahman Bohloli, 2022. Assuring integrity of CO_2 storage sites through ground surface monitoring (SENSE): Results and highlights. CCUS event & ACT Knowledge Sharing Workshop, Rotterdam, The Netherlands, 9-10 June 2022
44. Bahman Bohloli & Nazmul Haque Mondol, 2022. Assessing integrity of CO_2 storage sites based on ground deformation. 83rd EAGE Conference and Exhibition- workshop on CCS monitoring. Workshop WS08- 83rd EAGE Annual, 6 June 2022, Madrid, Spain.
45. Bahman Bohloli, 2022. CCS projects in Norway and CCS research activities at NGI. NGI-BI seminar. Hybrid (BI-Oslo & Online), 8 February 2022.
46. Bahman Bohloli and Elin Skurtveit, 2022. Development of CCS projects in Norway. NGI-Tallinn University Seminar (Virtual), 12 January 2022.
47. Bahman Bohloli & Elin Skurtveit, 2021. Carbon Capture and Storage in Norway- a geomechanics perspective. EAGE* local Chapter Germany, EAGE Local Chapter Czech Republic (Virtual), 14 October 2021.
48. Bahman Bohloli, 2021. Ground surface deformation detection combined with geomechanical models may provide information on pressure distribution and hydraulic behavior of the storage sites. CLIMIT Digit 2021 - Climit CCS Seminar. 10 Feb. 2021. Virtual.
49. Bahman, Bohloli, 2020. Ground surface monitoring techniques to ensure storage integrity. 5th ACT Knowledge Sharing Workshop (Virtual), 16-17 November 2020.
50. Bahman Bohloli & Nazmul Haque Mondol, 2019. Assuring integrity of CO_2 storage sites using ground surface deformation. UiO-NGI research workshop, Oslo, Norway, 10 December 2019.
51. Bahman Bohloli, 2019. Integrity of CO_2 storage sites using ground deformation. OSEG-UiO joint seminar, Oslo, Norway, 19 November 2019.
52. Bahman Bohloli, 2019. Assuring integrity of CO_2 storage sites using ground surface deformation. 4th ACT Knowledge Sharing Workshop, Athens, Greece, 6-7 November 2019.

53. Eiliv Skomedal and Bahman Bohloli, 2021. Geomechanics for CO_2 storage sites. Geomechanics workshop by Norwegian Geomechanics Network, 22 September 2021.
54. Eiliv Skomedal, 2021. CO_2 storage is taking off. SPE (Society of Petroleum Engineers) Technical Sections- Geomechanics. SPE Connect website with focus on Petroleum Engineering professionals (Virtual).
55. Joonsang Park & Bahman Bohloli, 2022. Presentation of SENSE project on ground deformation. CICERO Seminar, 11 January 2022 (Virtual).
56. Joonsang Park and Bahman Bohloli, 2022. Ground deformation for CO_2 storage site monitoring. Norwegian Petroleum Directorate (NPD) seminar (Virtual), 10 January 2022.
57. Joonsang Park, 2021. Geertsma generalized analytical solution for ground deformation. SENSE Webinar 1 (Virtual), 9 November 2021. https://youtu.be/P1w5UZ2Rp1A.
58. Joshua White & Bahman Bohloli, 2021. SENSE project update. SPE virtual workshop - Offshore CCUS. 6-13 April 2021.
59. Malte Vöge & Luke Bateson, 2021. InSAR monitoring at In Salah (Algeria) and Hatfield Moors (UK). SENSE Webinar 1 (Virtual), 9 November 2021. https://youtu.be/P1w5UZ2Rp1A.
60. Per Sparrevik, Jens Karstens & Bahman Bohloli, 2022. Ground deformation monitoring onshore and offshore. SENSE Webinar 2 (Virtual), 25 January 2022.
61. Per Sparrevik, Ziqiu Xue & Bahman Bohloli, 2022. Ground deformation monitoring using fiber optics. SENSE Webinar 2 (Virtual), 25 January 2022.
62. Per Sparrevik and Bahman Bohloli, 2021. Presentation of SENSE project for ground deformation. Presentation of SENSE project for ground deformation seminar (Virtual), 18 November 2021.
63. Sarah Bouquet & Bahman Bohloli, 2022. Hydro-mechanical simulation of ground deformation due to fluid injection-synthetic cases. SENSE Webinar 3 (Virtual), 18 February 2022.
64. Sarah Boquet & Audrey Estaublier, 2021. Presentation of SENSE project and ground deformation monitoring in Geodays, June 2021.
65. Yeon-Kyeong Lee, Oct. 2021. Presentation of a fully coupled simulation for CO_2 storage at In Salah, of KSMER fall Conference, CCUS session, Seoul, South Korea.
66. Sarah Bouquet, September 2022. Poster of SENSE project, surface monitoring for CO_2 geological storage at « Ressources et usages du sous-sol dans la transition énergétique » symposium, 27 & 28 September 2022, Paris, France.
67. Bahman Bohloli. Keynote speech: Underground storage of CO_2 and hydrogen. 25th Conference of the Geological Society of Iran. 25 January 2023, Shahrood University of Technology, Shahrood, Iran.

7. Budget status

Table 4. Financial status of SENSE project at the end of December 2022.

Partner	WP1	WP2	WP3	WP4	WP5	Total at Month 40 (€)	% of total project budget
NGI (€)	316,161	72,023	408,732	259,087	187,170	1,243,173	100%
QUAD GEO (€)	32,000	18,000	30,000		20,000	100,000	100%
GEOMAR (€)	756,500					756,500	100%
BGS (€)	152,200	75,900		35,440	60,100	323,640	100%
IFPEN (€)		674,866	318,753			674,866	100%
UiO (€)	76,978	15,000		15,000		106,978	178% [1]
IGME (€)	72,176			42,324		114,500	99.5 % [2]
CIUDEN (€)	50,372			52,130		102,502	97 % [3]
LLNL ($)	200,000			241,744		441,744	94 % [4]
UT Austin ($)	18,000					18,000	100%
RITE (€)	500,000					500,000	100%
KIGAM (€)		100,000				100,000	100%
TOTAL	2,174,387	955,789	438,732	645,725	267,270	4,481,903	99%

[1] University of Oslo has contributed with in-kind for PhD student. [2-3] IGME and CIUDEN has their project extended until the end of February 2023 and thus will spend the rest of budget. [4] LLNL has US $ 28,710 unspent but assume to spend it on the final report and overview paper.

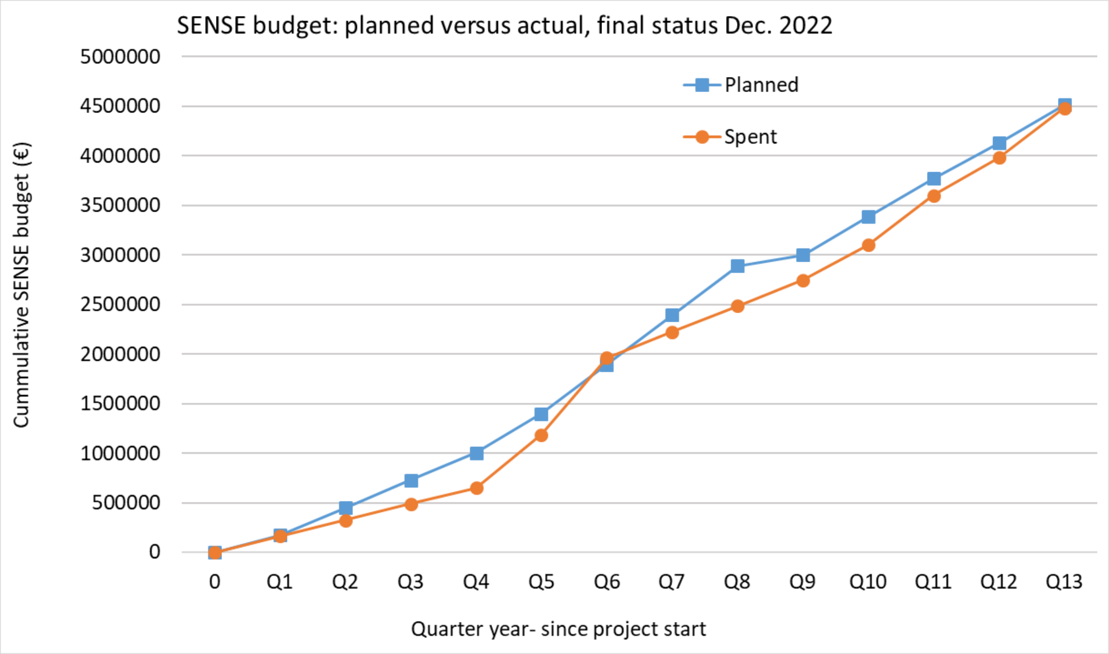


Figure 14. Financial results of SENSE project in December 2022.