Introduction

The In Salah gas field in Algeria is the CO_2 storage site where geomechanical monitoring has been performed. Ground displacement was measured using satellites during and after injection while 3.8 Mt of CO_2 was injected through three injection wells (KB501, KB502, and KB503) from 2004 to 2011 (Ringrose *et al.*, 2020). As a result of analysing the change in surface displacement from the interferometric satellite airborne radar (InSAR) data, it was confirmed that surface uplift of 14 to 21 mm occurred near the injection wells in 2010. Bohloli *et al.* (2018) presented surface movement (uplift and subsidence) analysis around three CO_2 injection wells, correlating the surface deformation patterns to the CO_2 injection history. Bjørnarå *et al.* (2018) proposed and validated a correlation between the pore pressure and the permeability of the reservoir with a focus on wells KB501 and KB503. Park *et al.* (2021) analysed pressure-induced deformation in the In Salah CO_2 storage site by applying their novel analytical solution. Previous studies have focused on the deformation during CO_2 injection, but this study includes the deformation change observed after the injection. Through multiphase fluid flow and geomechanics coupled simulation, history matching was conducted on the surface deformation data for three injection wells measured at the In Salah CO_2 storage site. In the matching process, factors to consider when modelling the surface deformation due to CO_2 injection were investigated. The effects of reservoir topography, gas initially in place, and anisotropy of flow and geomechanical properties on the changes in reservoir pressure and surface displacement were analysed as factors that can influence the CO_2 plume change.

SENSE Project

SENSE (Assuring Integrity of CO_2 Storage Sites through Ground Surface Monitoring) is a research project funded by the ERA-NET ACT programme. Its primary objective is to demonstrate reliable, continuous, and cost-efficient CO_2 storage monitoring based on ground surface deformation detection combined with geomechanical modelling and inversion to provide information on pressure distribution and hydraulic behaviour of the storage site. The main findings will offer storage site operators a cost-effective monitoring option that can form part of an effective site assurance/monitoring program and feed into workflows to set up an early alert system for unexpected changes in the subsurface. The project is organised in five Work Packages (WP), as shown in Figure 1.

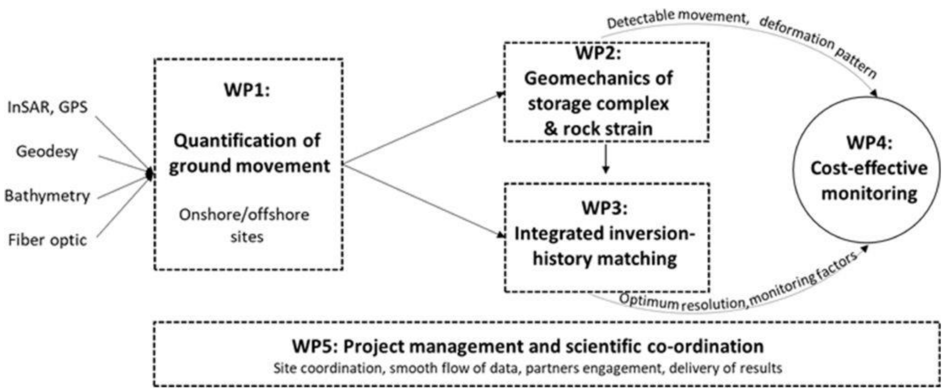

Figure 1 *Work Packages for the SENSE project.*

Fluid Flow and Geomechanics Coupled Modelling of the In Salah CO_2 Storage Site

In this study, a numerical model for the In Salah site was constructed using the GEM software of CMG (Computer Modelling Group Ltd.). GEM is a compositional equation-of-state simulator capable of flow and geomechanical modelling. The two-way coupling method was selected to couple the flow and geomechanics modules. This method first calculates the pressure using the fluid flow and then calculates the stress, strain, and displacement using the geomechanics module from the pressure. These geomechanical properties are used to correct the porosity for each grid, and the corrected porosity updates the pressure for the next time step.

The In Salah site consists of six formations commonly classified in the literature: overburden, caprock, lower caprock, tight sandstone, reservoir, and underburden. The information on each layer's flow and geomechanical properties was from Morris *et al*. (2011) and Shi *et al*. (2013). The reservoir is located at a depth of 1,800 m with a thickness of 20 m. Its temperature and pressure are 96℃ and 18 MPa, respectively. The reservoir formation is the Carboniferous sandstone with permeability ranging from 0.1 md to 300 md, the porosity from 0.13 to 0.2, Young's modulus from 3 GPa to 18 GPa, and Poisson's ratio from 0.1 to 0.7, indicating its heterogeneity. In-situ stress is characterised as the strike-slip fault regime where the vertical stress is intermediate between two horizontal stresses. The direction of maximum principal stress is NW-SE, which is consistent with the trend of the fractures in the reservoir. This indicates the stress anisotropy, and it was reported that permeability also showed the anisotropy. All production and injection wells are horizontal wells in the direction of minimum principal stress. The production wells are located on the up-dip of the anticline structure where the natural gas exists. On the aquifer of the structure down-dip, three injection wells (KB501, KB502, and KB503) are located.

Reservoir Topography, Gas Initially In Place, and Anisotropy

In the In Salah field, CO_2 was removed from the produced gas and then injected into the aquifer. The injected CO_2 was migrated along with the anticline structure, and CO_2 breakthrough was observed at the monitoring well KB5 and production well KB14 in 2007 and 2012, respectively. The CO_2 plume is closely related to reservoir topography, affecting the pore pressure change and geomechanical behaviour. Therefore, it is necessary to construct a static model by reflecting the reservoir topography. Flow grid and geogrid were built for 25 km x 28 km (Figure 2). To numerically stabilise the simulation, the total thickness of geogrid was determined as 9,000 m, including the 20 m thickness of the reservoir.

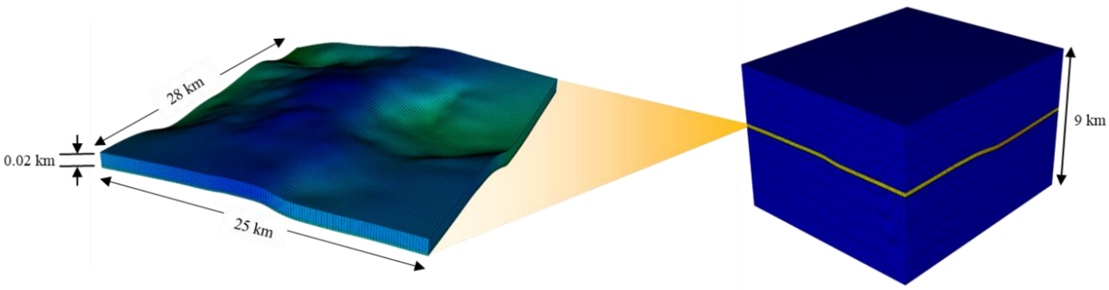

Figure 2 *Static model of In Salah CO_2 storage site reflecting reservoir topography (left) and geogrid for geomechanical modelling where reservoir grid embodied (right)*

Injecting large amounts of CO_2 into the saline aquifer can lead to a sharp increase in pore pressure. However, when the gas zone is present above the aquifer, such as at the In Salah site, it might play a role in alleviating the pressure increase in the aquifer as the gas compressibility is very high. From the simulation results, an increase in pore pressure due to CO_2 injection occurred less in the presence of the gas zone, inducing minor surface deformation. This effect was more prominent in KB502 and KB503 as they were adjacent to the gas zone, while KB501 was relatively farther from the gas zone. In addition, it was more significant in the post-injection period than during the injection.

The InSAR data obtained from the storage site show an elongated surface uplift pattern in the maximum principal stress (NW-SE) direction. This indicates that flow and geomechanical properties such as permeability, stress, and Young's modulus are anisotropy. Among the properties, anisotropy of permeability was analysed in this study. As a result of the anisotropy degree, there was no significant difference in pressure and deformation changes above the horizontal well. It only affected the shape of the pressure distribution and deformation pattern.

Conclusions

In this study, fluid flow and geomechanics coupled simulations were performed for the In Salah CO_2 storage site in Algeria as a part of the SENSE project. The primary goal of the project is to provide information on pressure distribution through surface deformation monitoring. This work conducted history matching the deformation data for the post-injection period, including the injection period. When modelling the surface deformation due to the CO2 injection, factors that need to be considered were investigated. As a result, it was confirmed that reservoir topography, gas initially in place, and anisotropy affected the CO_2 plume, leading to pressure and deformation behaviour changes. For more realistic modelling, further research such as the effects of caprock and fracture/fault zone will be conducted.

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References

Ringrose, P. (2020). How to store CO_2 underground: Insights from early-mover CCS project. Berlin/Heidelberg, Germany: Springer.

Bohloli, B., Bjørnarå, T.I., Park, J., Rucci, A. (2018). Can we use surface uplift data for reservoir performance monitoring? A case study from In Salah, Algeria. *International Journal of Greenhouse Gas Control* 76, 200-207. https://doi.org/10.1016/j.ijggc.2018.06.024.

Bjørnarå, T.I., Bohloli, B., Park, J. (2018). Field-data analysis and hydromechanical modeling of CO_2 storage at In Salah, Algeria. *International Journal of Greenhouse Gas Control* 79, 61-72. https://doi.org/10.1016/j.ijggc.2018.10.001.

Park, J., Bjørnarå, T.I., Bohloli, B. (2021). An analytical solution for pressure-induced deformation of anisotropic multilayered subsurface. *Geosciences* 11, 180. https://doi.org/10.3390/geosciences11040180.

Morris, J.P., Hao, Y., Foxall, W., McNab, W. (2011). A study of injection-induced mechanical deformation at the In Salah CO_2 storage project. *International Journal of Greenhouse Gas Control* 5, 270-280. https://doi.org/10.1016/j.ijggc.2010.10.004.

Shi, J.-Q., Smith, J., Durucan, S., Korre, A. (2013). A coupled reservoir simulation-geomechanical modelling study of the CO_2 injection-induced ground surface uplift observed at Krechba, In Salah. *Energy Procedia* 37, 3719-3726. https://doi.org/10.1016/j.egypro.2013.06.266.