Introduction

Ensuring safe and effective storage of CO_2 in deep geological formations, such as saline aquifers or depleted oil and gas fields, requires robust monitoring techniques to track the movement and behavior of the injected gas. Various authors have demonstrated that time-lapse gravity is an effective tool for monitoring, as it can detect subsurface mass changes caused by CO_2 injection (Furrea et al. 2017).

When CO_2 is injected into a reservoir, it alters the in-situ fluid, and consequently bulk density distribution within the formation. These density changes, in turn, produce measurable gravity anomalies that can be detected and analyzed. The primary advantage of time-lapse (4D) gravity monitoring is that it is a cost-effective and noninvasive technique. Gravity offers a comparatively straightforward approach to detecting CO_2 plume dynamics, as it has a direct relationship with mass in the subsurface, making this complementary to other geophysical methods.

Time-lapse gravity analysis can play an important role in the measurement, monitoring, and verification (MMV) process for carbon capture and storage (CCS) projects. It helps detect CO_2 plume migration, identify potential leakage pathways, and validate reservoir models, to enable optimization of injection strategies and enhance safety, and therefore it could be included in multisensor, multigeophysical MMV plans.

In this paper we introduce a new workflow integrating reservoir simulation with high-resolution gravity modeling, aimed at assisting CO_2 storage planning. The workflow is applied to a model based on an offshore aquifer storage site.

Integration of reservoir simulation and gravity modeling

We designed a workflow that integrates reservoir simulation with gravity modeling at the CO_2 storage planning stage. This process converts fluid and rock reservoir properties (porosity, permeability, pressure, saturation) into bulk density, to calculate the corresponding time-lapse gravity anomalies related to CO_2 mass changes in the reservoir. For this purpose, we studied a hypothetical yet realistic model, which is a North Sea CCS storage site analogue, following the work of Harrington et al. (2024). In this study we focused on a shallow saline aquifer at a depth of ~1.2 km and an average thickness of 160 m. The 3D static model (1.4 million grid cells) comprised lithology (three classes), porosity (mean of 20%) and permeabilities (around 400 mD). The CO_2 storage strategy involved 10 years of injection at supercritical conditions with one downdip well starting in 2023. At 2033 injection stops, but the reservoir simulation continues for another 40 years until 2073 to model density change over the post-injection period. Simulated gravity monitoring, with seabed instruments, covers the whole period, enabling a comprehensive investigation of CO_2 plume migration and the reservoir's post-closure evolution (tested till 2323).

To represent dynamic behavior, we opted for isothermal compositional simulation (Hurter et al. 2007) using Soave-Redlich-Kwong equation of state, representative component solubility tables and Ezrokhi equations (Zaytsev and Aseyev, 1993) to model the effects of pressure, temperature, and presence of multiple dissolved components on the brine density (Figure 1).

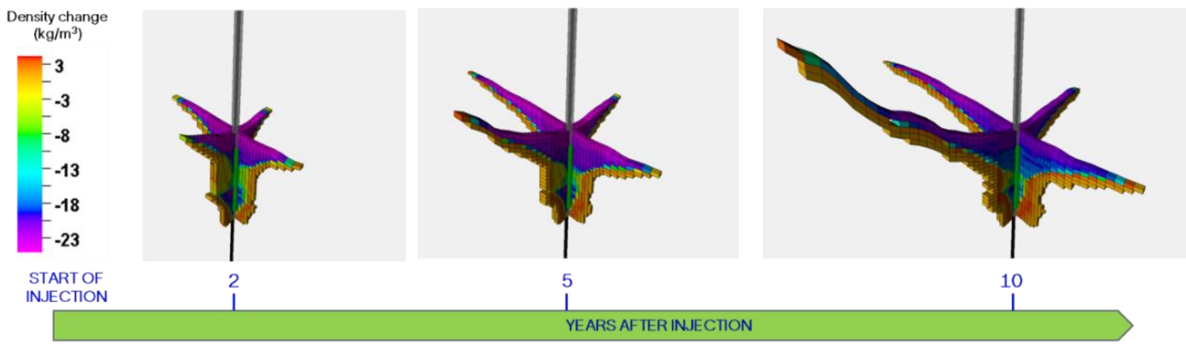

Figure 1 *Change in density over time modeled in 3D, highlighting the CO_2 plume development for base case scenario 2, 5, and 10 years after injection starts in 2023.*

This integrated simulation to gravity modeling workflow made it possible to automate the process of generating the gravity response for various conditions of a reservoir model, with defined injection and property parameters. It also enables us to perform sensitivity and optimization analyses of time-lapse gravity monitoring, assessing the impact of varying reservoir and injection parameters on detectability and operational viability of MMV plans. The ultimate objective is to develop a strategy to ensure the accuracy and reliability of gravity-based monitoring systems in various reservoir conditions.

Time-lapse gravity results

Using a 3D gravity forward algorithm, we calculated the gravity response for the 3D density of the simulated reservoir models throughout the entire monitoring period, with the instrumentation positioned on the sea bottom, and station spacing of 100 m. This generated a time-lapse gravity response, enabling us to track the CO_2 plume and monitor reservoir conditions during and after injection. Each time-lapse gravity response is subtracted from the one reproducing the initial baseline conditions before injection, to obtain the gravity anomaly associated with the corresponding temporal modifications of the CO_2 plume. To monitor the changes in the CO_2 plume, a detectability threshold with an absolute value of 1 μGal (10^{-8} m/s^2) is used, which aligns with the expected accuracy for state-of-the-art gravity measurements and acquisition practices in this environment (Solbu et al., 2023).

Figure 2 shows the time-lapse gravity anomalies overlaid on the average density change against the baseline, highlighting the specific area where the CO_2 plume is detected. This ensemble is relative to the base case with injection rate of 5x10^6 sm^3/d. We observe negative gravity anomalies because CO_2, which is less dense than in-situ fluids, displaces brine in the pore fluids. The anomaly magnitude increases over time during injection, reaching a value of 8 μGal 10 years after injection.

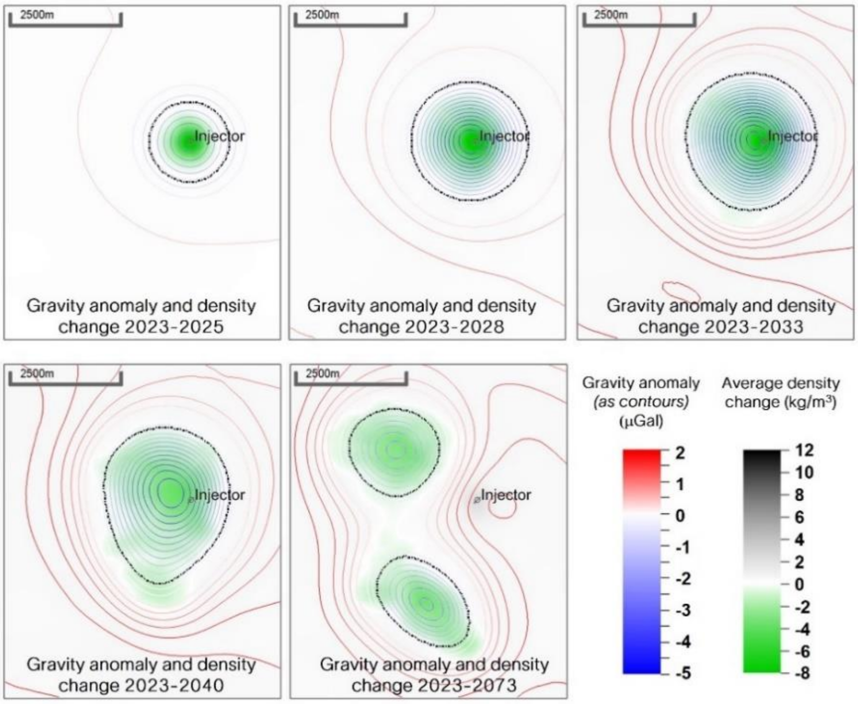

Figure 2 *Time-lapse gravity anomaly maps (contours) overlaid on the average density change (solid colors) for the base case with injection rate 5x10^6 sm^3/d. The black dashed line is the -1 μGal threshold for CO_2 plume detectability.*

The symmetrical shape of the anomaly around the injector point, visible in the first 10 years of monitoring, correlates with the density change induced by the CO_2 accumulation and plume spreading. After 2033 (when injection stops) the anomalies start to develop into two distinct regions, and in 2073 (40 years after injection stops), the gravity signal highlights that the reservoir is evolving towards a different physical state.

Once we established the base case, integrating static modeling, dynamic simulation and gravity modeling, we perturbed both operational (e.g., injection rate) and uncertain reservoir (e.g., porosity) parameters and investigated their influence on timing, shape, and size of detectable gravity anomalies. Figure 3 provides an example for one of the parameters, that is, the CO_2 injection rate, and the corresponding total volume of CO_2 injected.

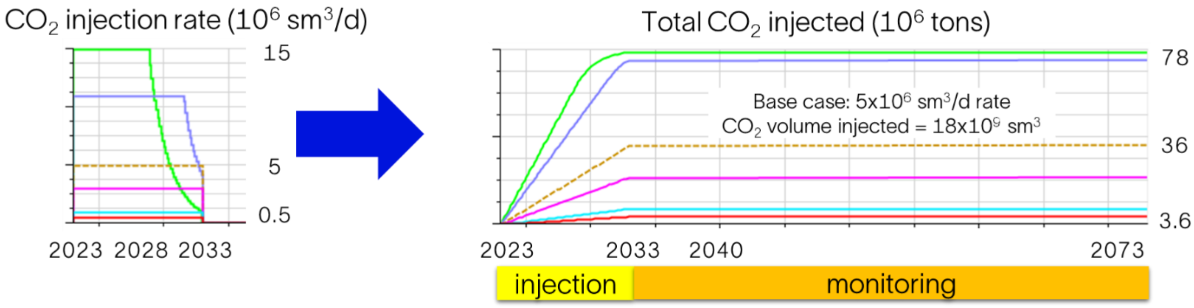

***Figure 3** An ensemble of reservoir simulation cases with varying CO_2 injection rates and corresponding plot of total injected CO_2 volume with the base case scenario at 5x10^6 sm^3/d highlighted (dotted line).*

Figure 4 illustrates the variation in gravity anomalies and bulk density changes resulting from the perturbation of the injection rate, observed at two specific monitoring intervals (10 and 17 years after injection starts). The gravity anomalies are sensitive to these variations and their amplitude and shape reflect three main physical processes, that simultaneously occur in the reservoir:

1. initial brine displacement with supercritical CO_2 decreases fluid density
2. growth of reservoir pressure due to injected volume increases fluid density
3. CO_2 dissolution in brine increases its density.

The impact is combined, but the magnitude of each process above depends on the distance to injector and the timing of observation. Gravity response, in turn, is quite complex to interpret, which makes this integrated reservoir simulation to gravity modelling strategic to derisk CCS operations.

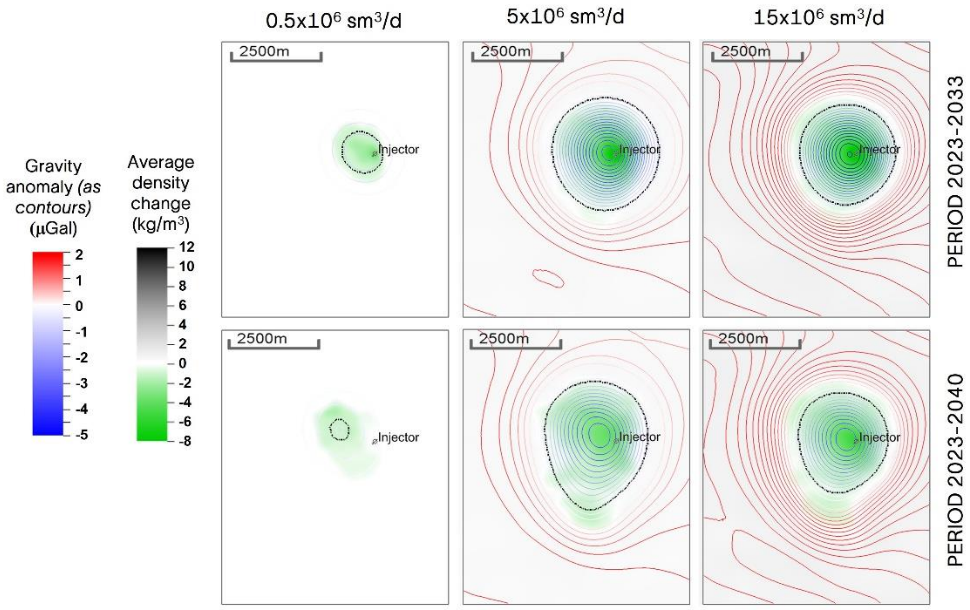

***Figure 4** Gravity anomaly maps (contours) overlaid on the average density change (solid colors) at 10 (top) and 17 (bottom) years after injection starts. First, second and third columns are relative to 0.5x10^6 sm^3/d, 5x10^6 sm^3/d and 15x10^6 sm^3/d injection rates, respectively. The black dashed line is the -1 μGal threshold for CO_2 plume detectability.*

This phase of the study is crucial for decision-making regarding carbon storage site planning and MMV design, as it offers a comprehensive summary of the monitoring capabilities and limitations of the method under the specific characteristics of the storage site.

Conclusions and future work

The results of this study confirm that time-lapse gravity anomalies are highly effective in detecting the presence and in tracking the migration of CO_2 plumes into saline aquifer reservoirs.
The workflow presented for integrated reservoir simulation and gravity modeling facilitated the investigation of the impact of various injection strategies and inherent reservoir uncertainties on the gravity anomaly that tracks the CO_2 plume.
Subsequent steps of this analysis will focus on the optimization of the survey layout and on the definition of an appropriate monitoring frequency. Additionally, we will investigate potential leakage scenarios and apply gravity inversion technique to detect non-conformance cases and derisk CCS operations Another important step will involve studying the application of gravity monitoring for carbon storage in depleted gas reservoirs scenarios, to investigate the benefits over established approaches.
In this context, although we have demonstrated the potential value of time-lapse gravity as a monitoring tool, it is crucial to conduct a comprehensive analysis when approaching real-life cases. As shown above, this analysis should evaluate the feasibility of gravity monitoring based on reservoir depth, in-situ properties with associated uncertainties, and injection strategy. Ultimately, this approach can aid in developing a robust multiphysics monitoring plan, while providing insights into containment, conformance, and contingency monitoring for CCS.

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