Coupled inverse modelling of tight CO\textsubscript{2} reservoirs using gravity and ground deformation data

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SUMMARY
Injection of CO\textsubscript{2} into tight reservoirs produces both gravity change and ground deformation, which provide great opportunities for more accurate coupled inverse modelling. In this study, we incorporate signals generated from several synthetic models to estimate the CO\textsubscript{2} distribution in the reservoir. A relationship is found that connects density variations to volumetric changes associated with injected CO\textsubscript{2}, taking advantage of a common set of model parameters for both gravitational and geo-mechanical inverse modelling. This is achieved by assuming that the injected CO\textsubscript{2} increases pressure in the reservoir, which in turn generates extra porosity that is then filled in by the CO\textsubscript{2} mass. Tikhonov regularization, supported by the Generalized Cross Validation (GCV) technique for finding the optimized model, is used to solve the ill-posed inverse problems. The results indicate that the uncertainty and ambiguity in gravimetric modelling due to high levels of noise is mitigated by implementing highly accurate ground deformation measurements, which normally have a higher signal to noise ratio.

Key words: Geomechanics; Gravity anomalies and Earth structure; Inverse theory; Joint inversion.

INTRODUCTION

Human activities such as hydrocarbon production, and fluid injection, induce subsurface pressure and volumetric changes that can subsequently be transmitted to the surface and deform the ground surface, causing heavy damage to infrastructure. The ambient or intrusive fluids can also be redistributed by leaking into shallow formations, aquifers or even the atmosphere. The corresponding hazards are avoidable using surface monitoring systems that can predict the destructive consequences in advance (Kabirzadeh 2016).

Recently, thanks to advancements in instrumentation, data processing and modelling methodologies, geological storages creating very small gravity anomalies, such as geological CO\textsubscript{2} storages, have been the subject of gravimetric studies (Kao et al. 2014; Kim et al. 2015). Nonetheless, field applications of geological CO\textsubscript{2} storage monitoring are still rare in gravimetric studies. Sleipner is a commercial CO\textsubscript{2} sequestration site in which excessive CO\textsubscript{2} extracted from a natural gas field is injected into a saline aquifer (Nooner et al. 2007). Three Scintrex CG5 relative gravimeters combined in an assembly detected a negative gravity signal with 12 μGal maximum magnitude, and \sim5 μGal uncertainty in the measurements (Alnes et al. 2011). The results confirmed the applicability of gravity sensors in detecting injected CO\textsubscript{2}, although for leakage or migration detection purposes, more accurate measurements are required. In another study, Sugihara et al. (2013) researched the feasibility of CO\textsubscript{2} monitoring by means of hybrid gravimetry as the result of the combination of spring, absolute, and superconducting gravimeters (SGs). They extended their research to field measurements at the Farnsworth CO\textsubscript{2}-EOR field, Northern Texas, USA (Sugihara et al. 2014). They concluded that two SGs are required to make parallel measurements in order to detect the subtle gravity signal attributed to CO\textsubscript{2} injection. At another CO\textsubscript{2} injection test site, Southeast Partnership (SECARB), located at Cranfield, Mississippi, temporal gravity data collected in two boreholes demonstrated displacement of CO\textsubscript{2} within a thin reservoir (Dodds et al. 2013).

In addition to the engineering and field developments, investigations in forward and inverse modelling are equally important for surveillance of geological CO\textsubscript{2} storages. Wilkinson et al. (2017) evaluated the gravity effect of CO\textsubscript{2} storage with different characteristics and the possible leakage. In other studies, simulated gravity signals at the surface and in boreholes were inverted to evaluate the injection of CO\textsubscript{2} into aquifers (Krahenbuhl et al. 2011, 2015; Jacob et al. 2016).

Equally as important as gravity surveys are geodetic techniques which locate the CO\textsubscript{2} distribution in a reservoir by measuring the resulting ground deformation. These techniques have been the subject of many studies associated with induced surface deformation...