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Early detection of brine and CO_2 leakage through abandoned wells using pressure and surface-deformation monitoring data: Concept and demonstration

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ABSTRACT

In this paper, we develop a methodology for early detection of potential CO_2 leakage from geological storage formations using pressure and surface-deformation anomalies. The basic idea is based on the fact that leakage-induced pressure signals travel much faster than the migrating CO_2; thus such anomalies may be detected early enough for risk management measures taking effect in avoiding substantial CO_2 leaks. The early detection methodology involves automatic inversion of anomalous brine leakage signals with efficient forward pressure and surface-deformation modeling tools to estimate the location and permeability of leaky features in the caprock. We conduct a global sensitivity analysis to better understand under which conditions pressure anomalies can be clearly identified as leakage signals, and evaluate signal detectability for a broad parameter range considering different detection limits and levels of data noise. The inverse methodology is then applied to two synthetic examples of idealized two-aquifer-and-one aquitard storage systems, with an injection well and a leaky well, for different monitoring scenarios. In Example 1, only pressure data at the monitoring and injection wells are used for leakage detection. Our results show that the accuracy of leakage detection greatly depends on the level of pressure data noise. In Example 2, joint inversion of pressure and surface-deformation measurements significantly improves the speed of convergence toward the true solution of the leakage parameters and enables early leakage detection. In both examples, successful detection is achieved when two monitoring wells are appropriately placed within up to 4 km from the leaky well.

1. Introduction

The ability to detect CO_2 leakage is a key component of risk assessment and management associated with geologic carbon storage (GCS) [1,2]. Injected CO_2 may escape from the deep storage formation to shallower groundwater aquifers, ultimately to the atmosphere, through abandoned wells that are not properly plugged [3,4], through permeable or semi-permeable faults that are pre-existing or injection-induced [5,6], or through caprock fractures. Current techniques for CO_2 leakage detection are based on the physical, geophysical, or/and geochemical signatures that are induced by migrating CO_2 and that can be observed in the deep and shallow subsurface, at the land surface, and in the atmosphere [7–10]. For example, seismic reflection surveys may detect secondary accumulations of leaked CO_2 in overlying formations, groundwater sampling and soil gas surveys can be successful in the shallow subsurface [11], and Eddy Covariance towers or airborne monitoring techniques can find CO_2 escaping from the subsurface into the atmosphere [12–14].

One of the great challenges in CO_2 leakage detection is that many of these techniques have relatively low spatial resolution and coverage, in comparison to the footprint of CO_2 plumes that is on the order of tens to hundreds of square kilometers for an industrial-scale GCS project [15,16], and may not be effective in locating and identifying unknown leakage pathways that are not identified by near-field site characterization. The other great challenge is that all these techniques can only detect anomalous CO_2 signals long after CO_2 leakage has first occurred, thus lacking the ability to provide an early indication of potential CO_2 leakage before happening. For successful risk management of large-scale GCS, it is important to develop or devise a monitoring method capable of early detection of unknown leaky pathways.

Pressure-based detection techniques for CO_2 and brine leakage have recently been proposed in the community of GCS [17–22]. The original idea of using pressure signals can be dated back to 1980s when Javandel et al. [23] proposed hydrologic detection of abandoned wells for hazardous waste disposal. To date, researchers have mainly focused on evaluating signal detectability via

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pressure monitoring in the aquifer overlying the storage formation, separated by a caprock. For instance, Benson et al. [17] focused on pressure anomalies induced by brine leakage through a leaky abandoned well and a leaky fault, and concluded that the pressure-based detection method could be useful for providing early warning of large leaks within one year after the start of fluid injection. Chabora and Benson [18] investigated the detectability of pressure signals at a monitoring well in the overlying aquifer, caused by brine leakage through the monitoring well or CO_2 leakage through the injection well. Nogues et al. [19] investigated the spatial probability of being able to detect a leakage event using one monitoring well in an overlying aquifer, and determined the average time needed for successful detection. Zeidouni et al. [20] formulated an inverse problem for leakage detection and evaluated the 95% confidence intervals of the location and transmissivity of leaky well using up to five monitoring wells in the overlying aquifer. Sun and Nicot [21] and Sun et al. [22] applied different optimization methods for leakage detection using the pressure signals in the overlying aquifer.

All studies mentioned above used analytical forward models [23–25], assuming that the caprock was impervious and any pressure changes observed in the overlying aquifer were caused by well (or fault) leakage. However, intact caprock is usually of low, but not zero, permeability [26,27], and slow "diffuse" migration of brine through the caprock (referred to hereafter as diffuse leakage) may induce signals in the overlying aquifer that can be hard to discern from those related to focused leakage through leaky wells or faults [15,16,28–30]. In other words, the pressure-anomaly signals of focused well (or fault) leakage in the overlying aquifer may be "contaminated" by diffuse leakage through the caprock or aquitard, in particular when the monitoring sensors in the overlying aquifer are not in the vicinity of the leakage location. Therefore, the effects of diffuse leakage through the caprock should be considered when evaluating early detection methods for focused leakage through leaky pathways [31,32].

Another concern about pressure monitoring for leakage detection is that it can be conducted at high temporal frequency but is often limited to a few spatial locations (available only at a very small number of wells and gauges). Surface deformation measured by Interferometric Synthetic Aperture Radar (InSAR) may be considered as a complementary monitoring tool for detecting large leaks. The InSAR technology provides dense spatial information on the scale of kilometers, and has been successfully used to assess ground surface deformation induced by earthquakes [33,34], groundwater pumping and recharge [35–43], oil and gas production [44,45], geothermal energy exploitation [46], and CO_2 injection and storage [47–49]. At least for large leakage events, we may expect that the surface deformations induced by fluid leakage would show recognizable anomalies that can support early leakage detection methods, even at vegetated or urban sites [36,38,41].

We therefore propose a monitoring and inverse modeling method utilizing complementary data sources for detecting large leaks: (1) transient pressure monitoring in both the storage formation and the overlying aquifer, which takes into account the effects of both focused and diffuse leakage through the caprock, and (2) InSAR surface-deformation monitoring, which has large spatial coverage and high spatial resolution. In this paper, we conduct a comprehensive inverse modeling investigation to test the feasibility of early leakage detection via pressure and surface-deformation monitoring data. Section 2 discusses the concept of early leakage detection as part of a broader framework for real-time operation and risk management of CO_2 storage projects. Section 3 then introduces the inverse modeling methodology for locating leaky pathways and estimating their properties, based on a discussion of parameter sensitivity. We apply the inverse detection methodology to synthetic and somewhat idealized examples, the first using only pressure monitoring data with varying degrees of noise (in Section 4), and the second using both pressure and surface-deformation data to improve leakage detection (in Section 5). In both examples, we demonstrate improved accuracy of the leakage detection (i.e. the estimated leaky-well location and permeability) with incremental increase of monitoring time.

2. Framework for early leakage detection

Fig. 1 shows schematically a typical storage system with CO_2 injection through an injection well into a deep saline formation

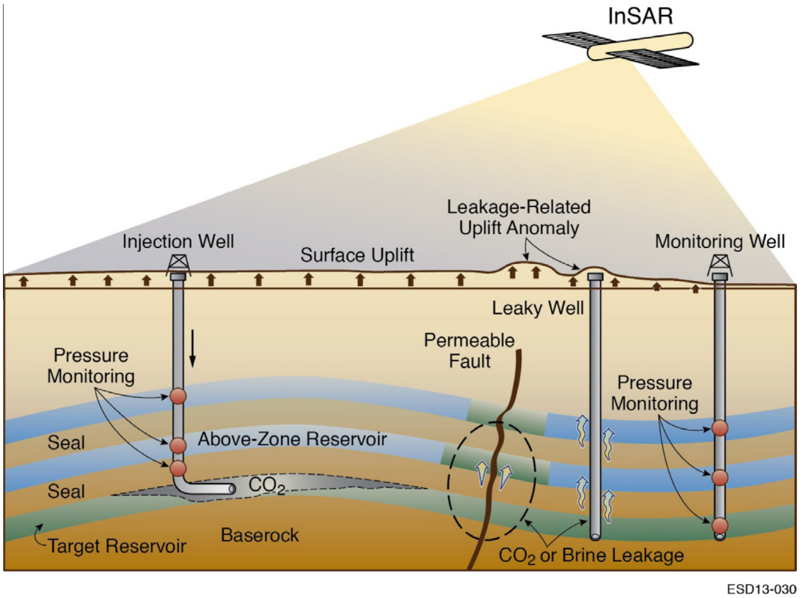

Fig. 1. Schematic of a typical storage system with CO_2 injection through an injection well into a deep storage formation, pressure monitoring at gauges and sensors (orange symbols) in the storage formation and overlying permeable aquifers, and InSAR monitoring of ground-surface deformation, and with a permeable leaky fault and a leaky-well that may act as leaky pathways of resident brine or injected CO_2.