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Cost-optimal design of pressure-based monitoring networks for carbon sequestration projects, with consideration of geological uncertainty

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ABSTRACT

Leakage from geologic faults and abandoned wells represents one of the major risks to industrial-scale carbon capture and storage (CCS) projects. Current CCS regulations and best practice guidance suggest that operators emplace risk-informed monitoring, verification, and accounting (MVA) plans to protect public safety and reduce property and environmental damage. Deep subsurface pressure monitoring is regarded as one of the most cost-effective technologies for early leakage detection in CCS projects. In practice, however, the number of deep pressure monitoring wells that an operator can deploy often remains limited because of the high costs associated with drilling, instrumenting, and operating these wells. Thus, optimal design of the pressure monitoring network is essential to minimizing monitoring and liability costs and gaining public support. In this work, we present a general, binary integer programming approach to solve an optimal monitoring well network design problem under multiple constraints. Specifically, our approach helps a CCS operator to design a cost-optimal monitoring network that covers all potentially leaky locations (in a worst-case-scenario sense) while satisfying a prescribed carbon dioxide (CO_2) storage performance criterion and considering geological uncertainty. Instead of using cost surrogates as has been done in many other studies, our formulation allows the user to directly assess total costs in terms of monitoring costs and potential economic losses associated with brine and CO_2 leakage. Our numerical examples demonstrate that a cost-optimal monitoring network may save millions of dollars in total costs, including well construction and leakage costs. Factors exerting the most impact on the cost-optimal monitoring network design are unit leakage damage costs, pressure threshold for leakage detection, and geological uncertainty.

1. Introduction

The key to success of geological carbon storage (GCS) is an understanding of how much, how safely, and how long the injected CO_2 can be stored in host geological formations, such as saline aquifers or depleted oil and gas reservoirs. Potential migration of injected and in situ fluids from the injection formation poses one of the greatest risks to long-term safe storage (Benson and Cole, 2008).

In the most commonly evaluated risk scenarios, CO_2, leaking through either abandoned wells or geologic faults, may ultimately migrate to the above-zone aquifers, causing water quality degradation of the underground sources of drinking water (USDW) and posing direct threat to the public safety (Carroll et al., 2009; Class et al., 2009; Navarre-Sitchler et al., 2013; Nordbotten et al., 2005; Sun et al., 2017; Trainor-Guitton et al., 2016). In other scenarios, the injected CO_2 may migrate out of the project lease boundary or pore space, causing unplanned interruptions to nearby oil and gas production. Various liability costs may be incurred as a result of these leakage-related incidents, for example, environmental remediation, injection interruption, well cost, legal cost, and business disruption (Bielicki et al., 2014). These potential costs may become too high for carbon-capture and storage (CCS) operators to bear.

Nowadays a wide array of GCS monitoring, mitigation, and verification (MMV) techniques are available for detecting and monitoring leakage (Jenkins et al., 2015). In particular, pressure monitoring has been established as an MMV technique for early leakage detection (Birkholzer et al., 2015; Hovorka et al., 2013; Sun and Nicot, 2012). In recent years, pressure-based sensing has been used to detect leakage from CO_2 injection zones by monitoring pressure anomalies in an otherwise quiescent interval or the so-called above-zone monitoring interval (AZMI) (Hovorka et al., 2013). Some recent works also demonstrate the merits of increasing the signal-to-noise ratio of pressure

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Nomenclature

C_{well}	Cost of constructing and operating monitoring wells [$]
$C_{leakage}$	Expected leakage cost of brine and CO_2 [$]
S	A set of scenarios such as different geological models
I	A set of candidate locations of monitoring wells
J	A set of potential leakage locations
v_{ijs}	Accumulative amount of leakage at detection time at monitoring location i for a leakage event at leakage location j in scenario s [ton]
Superscript b	Brine
Superscript c	CO_2
c_j^b	Unit leakage cost of brine at leakage location j [$/ton]
c_j^c	Unit leakage cost of CO_2 at leakage location j [$/ton]
c_j^{in}	Intervention cost to fix leakage at leakage location j [$/well]
c_i^w	Construction cost for monitoring well i [$/well]
c_i^o	Operation cost for monitoring well i [$/well/day]
T_p	Total period of CO_2 storage project [days]
v_{js,T_p}^c	Accumulative amount of CO_2 leakage at leakage location j in scenario s during T_p [ton]
N	Maximum number of budgeted monitoring wells [wells]
T_{ijs}^d	Detection time at monitoring location i for a leakage event at leakage location j in scenario s [sec]
$q_{l,js}^b$	Leakage rate of brine at leakage location j in scenario s [m^3/sec]
$q_{l,js}^c$	Leakage rate of CO_2 at leakage location j in scenario s [m^3/sec]
V_{max}^c	Permissible CO_2 leakage amount

signals by conducting oscillatory pumping tests in the storage reservoir and checking for potential pressure signal deviations in the frequency domain (Sun et al., 2016, 2015). Adopting a pressure-based, continuous monitoring network for intercepting anomalies is thus appealing for CCS operational monitoring.

However, pressure monitoring wells have limited spatial coverage for leakage detection because pressure anomaly signals diminish quickly away from a leaky location, as explained by the hydraulic diffusivity equation (Nordbotten et al., 2005). Also, construction ($O(\$10^6)$) and operation ($O(\$10^5)$ annually) costs of deep monitoring wells are high (U.S. Environmental Protection Agency, 2008). Given limited spatial coverage, high costs of monitoring wells, and limited monitoring budget, the number and placement of pressure monitoring wells need to be optimized to detect potential leakage. Previously, Cameron and Durlofsky (2012) optimized well placement and controls of CO_2 injection and brine cycling to maximize CO_2 storage security. In this study, we find an optimal well placement of pressure monitoring wells to minimize the well costs and liability costs associated with potential leakage risk.

Sun et al. (2013) suggested an approach for designing optimal pressure-based monitoring networks to minimize brine leakage for homogeneous and two-dimensional heterogeneous rock models. They assumed single-phase flow, which is appropriate when leakage is detected before the CO_2 plume arrives at a leak location. However, CO_2 plume migrations should be three-dimensionally described because CO_2 plume migrations are governed by strong buoyancy forces and three-dimensional heterogeneity (Jeong and Srinivasan, 2017, 2016). In situ brine naturally has high concentrations of heavy metals (Kharaka et al., 1987) and may get even more polluted after CO_2 injection (Islam et al., 2016). On the other hand, CO_2 is a weak acid and may trigger dissolution reactions to release heavy metals and other toxic chemicals (e.g., arsenic) after rising to the above zone aquifers (Carroll et al., 2009).

In this work we have developed an extended design approach that relaxes some of the assumptions in the original work of Sun et al. (2013) and that is applicable to three-dimensionally heterogeneous formations and multiphase flows. Note that instead of using cost surrogates, our new optimal design approach directly minimizes total

1	2	3
4	5	6
7	8	9

(a) Cell index

		L1
	INJ	
L2		

(b) Well names and locations

4	3	1
4	3	2
-	5	3

(c) Detection time for L1, days

5	8	-
3	7	-
2	5	6

(d) Detection time for L2, days

0.4	0.3	0.1
0.4	0.3	0.2
1.2	0.5	0.3

(e) Leakage amount at detection time for L1, Mt

0.5	0.8	1.2
0.3	0.7	1.2
0.2	0.5	0.6

(f) Leakage amount at detection time for L2, Mt

5.5	6.5	7.5
4.5	6	8
8	6	5.5

(g) Total cost ($M) for c_W = $1 M/well, c_L = $5/t

Fig. 1. Example of optimization of a single monitoring well location. Cell indices are shown in (a). In (b), INJ, L1, and L2 represent the injection well, the 1st abandoned well, and the 2nd abandoned well, respectively. In (c) and (d), "–" means leakage is not detected. In (e) through (g), M denotes 10^6. In (g), c_W and c_L represent unit well and leakage costs, respectively.