Regional Estimates of Pressure-Constrained Potential for Geological Carbon Storage under Uncertainty

Introduction

Geological CO_2 storage is a key component of climate mitigation strategies, yet its large-scale deployment is hampered by the risks of rock failure and fault reactivation, which may compromise storage integrity. Mitigating these risks requires robust assessment of injection-induced pressure buildup and associated geomechanical risks, particularly in heterogeneous reservoirs and under uncertain geological and operational conditions. Furthermore, scaling up this technology to the gigatonne scale requires multiple injection sites sharing regional aquifers. To assess the risk in such a large-scale context, the use of highly accurate models is often unfeasible. Instead, less detailed regional models are needed to enable preliminary techno-economic analyses and identify potential bottlenecks. One important challenge in this context is improving the accuracy and realism of such screening-level approaches while maintaining their computational efficiency.

In this study, we propose a fast software tool to estimate the amount of CO_2 that can be safely stored without jeopardizing fault stability using physics-based analytical pressure solutions coupled with geomechanical failure criteria. Although constrained by certain assumptions, it can provide reliable estimates of pressure-constrained storage capacity while explicitly accounting for geological uncertainties. The tool is intended to support early-stage evaluation of storage potential by enabling rapid comparison of alternative injection strategies and design assumptions.

Background

We build upon the open-source tool CO2BLOCK, which enables fast, screening-level estimation of pressure-constrained CO_2 storage capacity in saline aquifers using analytical pressure solutions, but relies largely on deterministic geological and mechanical assumptions(De Simone & Krevor, 2021). CO2BLOCKSEISM extended this framework by incorporating probabilistic geomechanical analysis to assess fault slip potential under uncertainty at the basin scale (Kivi et al., n.d.). While effective for seismic risk screening, CO2BLOCKSEISM does not focus on the direct estimation of maximum pressure-constrained storage capacity. The present work integrates the strengths of both approaches to retain computational efficiency while improving storage capacity estimation and explicitly accounting for fault stability and geological uncertainty in regional-scale CO_2 storage assessments.

Method and/or Theory

By combining the approach of CO2BLOCK with the uncertainty quantification from CO2BLOCKSEISM, we developed a new improved version of CO2BLOCK, named CO2BLOCK.2. We keep the focus on the estimation of the pressure-constrained storage capacity, but we incorporate a number of improvements on the pressure estimation and the uncertainty about faults and geological conditions.

Storage potential is evaluated for a range of injection scenarios and well configurations using analytical solutions that capture the magnitude and spatial extent of pressure buildup, along with geomechanical analyses to define pressure limits. This approach makes it possible to examine how changes in injection strategy and reservoir characteristics influence regional storage capacity, while maintaining computational efficiency suitable for large scenario ensembles. The software is organized in a modular structure, enabling stand-alone use of single modules. The whole workflow is performed in the framework of an uncertainty analysis.

The workflow allows pressure-limited storage to be evaluated from different reference perspectives, depending on the assessment objective. Critical conditions may be defined at the location where the overpressure is maximum (typically coinciding with the inner most well), user-defined location of interest, as well as user-defined or stochastically-generated fault systems. Pressure build-up is estimated at these locations of interest and then compared against pressure limits, which are estimated based on fault reactivation risks through a geomechanical analysis.

Faults and fractures can be incorporated as user-defined or stochastically generated. In the latter case, a discrete fracture network (DFN) approach is adopted, in which structural features are treated explicitly as individual geometric entities. This framework enables simplified but realistic representation of structural heterogeneity and provides a basis for evaluating how fault characteristics influence pressure response and mechanical behavior, without requiring detailed site-specific characterization. Size, location and orientation of the population of fractures are based on probabilistic distribution in agreement with experimental observations from the literature (Davy et al., 2010a; Scholz et al., 1993).

The module dedicated to overpressure estimation makes use of analytical solutions (Nordbotten et al., 2005) coupled with a superposition scheme to take into account multiple injectors. A correction is applied to tackle the non-linearity of multiphase flow. Additional corrections are incorporated to improve the accuracy of pressure estimation in closed reservoirs, ensuring that boundary effects are appropriately reflected in the analytical pressure response.

The geomechanical module addresses fault reactivation potential using Mohr-Coulomb failure criteria, leading to the definition of critical pressure thresholds. Fault reactivation is estimated on user-defined or stochastically-generated faults, or on optimally-oriented faults assuming a most conservative scenario.

For each injection scenario, pressure buildup computed at a reference injection rate in the pressure module is compared with the fault stability thresholds estimated in the geomechanical module. The maximum allowable injection rate is then obtained by scaling the reference injection rate according to the identified critical pressure. If the critical conditions where the comparison is performed coincide with user-defined or stochastically-generated faults, we refer to this case as fault-controlled estimate; if the conditions coincide with the most pressurized point where optimally-oriented faults are assumed, we refer to this case as pressure-controlled.

The entire workflow can be integrated into an uncertainty framework, where probabilistic distributions are assigned to stress state, fault orientation, and mechanical properties, and a Monte Carlo approach is used to obtain distributions of critical pressure thresholds for individual faults. These distributions allow alternative interpretations reflecting different risk tolerances: conservative (pessimistic) and optimistic bounds define lower and upper limits of tolerance, while percentile-based criteria derived from cumulative distribution functions provide a probabilistic interpretation. Thresholds corresponding to low exceedance probability (P90) represent conservative cases, median values (P50) represent average conditions, and high exceedance probability cases (P10) reflect less restrictive assumptions.

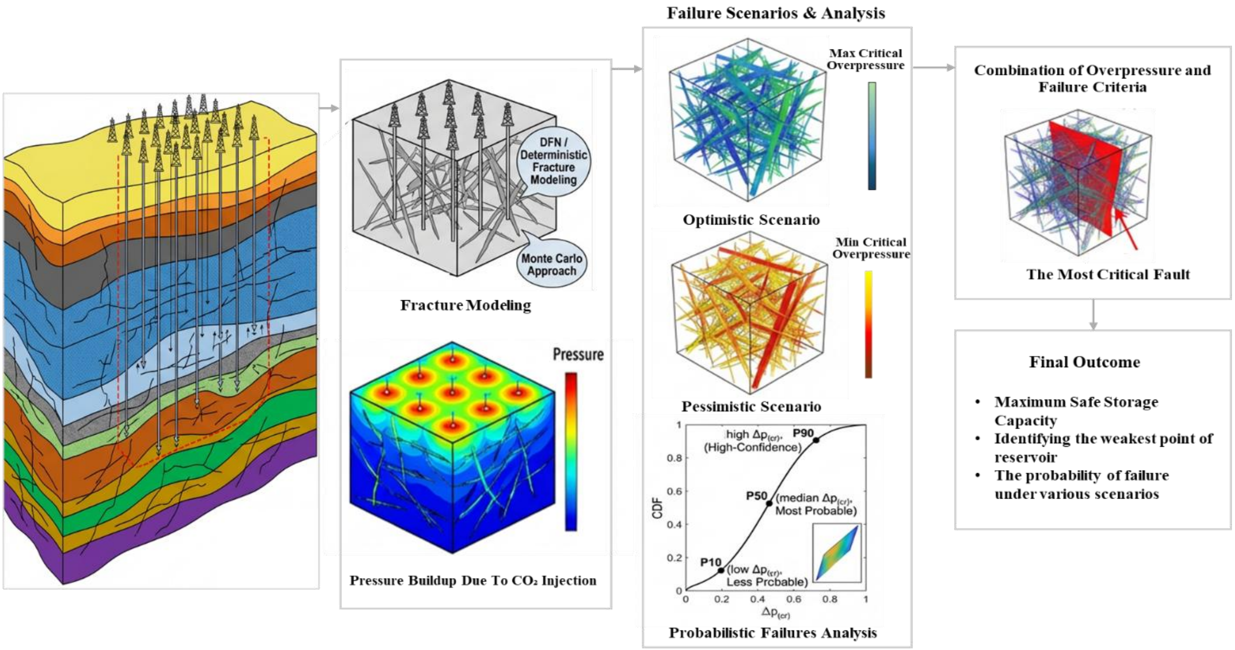

Figure 1 *Schematic of CO2BLOCK.2 workflow.*

Conclusions

The results show that pressure-constrained CO_2 storage capacity is strongly influenced by injection strategy, reference point selection, and the chosen interpretation of fault stability.

Probabilistic analysis highlights substantial variability in fault stability thresholds, emphasizing the importance of accounting for subsurface uncertainty rather than relying on single deterministic values. Percentile-based interpretations provide a clear and consistent way to compare optimistic, average, and conservative outcomes across scenarios and to link capacity limitations to underlying geomechanical controls. This probabilistic perspective supports risk-informed evaluation of storage integrity and highlights parameters that most strongly control fault reactivation potential.

Because pressure is evaluated using analytical solutions, the framework enables efficient assessment of multiple injection scenarios and uncertainty realizations. The proposed tool therefore provides practical support for regional-scale screening, early-stage site selection, and injection strategy design, helping to reduce geomechanical risk as CO_2 storage projects move toward deployment.

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