

Research Internship Report

presented by

"Emma Willaume"

Internship from 01/07/2025 until 22/08/2025 in :

Laboratory of Soil Mechanics, EPFL

Subject :

Analysis of hydro-mechanical response under deep geological conditions

Director of the laboratory : **"Professor Lyesse Laloui"**

Supervisor: **"Angelica Tuttolomondo"**

In the scope of : **"Laidlaw Research and Leadership Programme"**

Contents

Contents	3
1 Abstract	5
2 Background	7
1 CO_2 sequestration	7
2 H_2 sequestration	7
3 Nuclear Waste disposal	8
3 Literature Review	9
1 CO_2 sequestration	9
2 H_2 sequestration	10
3 Nuclear waste disposal	10
4 Motivations	13
5 Analytical Formulation	15
1 Introduction	15
2 Definition of the input data	15
3 System of equations	16
6 Results	17
7 Discussion	19
8 Conclusion and Next Steps	21
Glossary	23
Bibliography	25

Abstract

Underground storage of CO₂, H₂, and nuclear waste requires accurate assessment of hydro-mechanical processes induced by gas injection. Existing approaches rely mostly on numerical simulations and site-specific studies, but few analytical tools are available to predict coupled variations of pore pressures, saturation, and stress. This work presents an analytical framework for elastic isotropic porous media that defines pore-pressure coefficients linking changes in gas pressure to variations in water pressure, water saturation, and external stress. The formulation incorporates porosity, bulk modulus, Biot coefficient, and fluid compressibility, while assuming linear retention behavior. Simulations show that pore gas and pore water pressures vary almost equivalently, that changes in saturation are negligible, and that stress transmission is strongly influenced by water saturation and gas compressibility. Compared with existing numerical approaches, the proposed framework requires fewer constitutive parameters and provides direct analytical relations, making it a computationally efficient tool for preliminary site assessments. This simplified model forms a basis for future refinement through experimental validation and non-linear retention curve integration.

Background

In this section, an overview about CO₂ and H₂ sequestration and nuclear waste storage will be given. It will cover the current state of the on field projects and the norms that regulates the pressure of the gas (CO₂ and H₂) during the injection and then during the storage inside the reservoir.

1 CO₂ sequestration

Carbon capture and storage (CCS) is an essential technology aimed at reducing greenhouse gas emissions by capturing carbon dioxide (CO₂) from industrial sources or the atmosphere. The captured CO₂ is then injected and stored in geological formations to prevent its release into the atmosphere.

The maximum allowable injection pressure for geological CO₂ storage is generally not fixed by a universal threshold but rather determined on a site-specific basis, depending on geomechanical constraints, formation properties, and the need to avoid fracturing the reservoir or caprock.

For example, in the Netherlands, the Porthos project provides one of the clearest examples of a quantified national standard. There, the injection pressure at reservoir depth is limited to 351 bar, which corresponds to approximately 20 bar below the hydrostatic pressure [14]. The reference values were derived from reservoir modeling and stress analysis, taking into account the original reservoir conditions and the properties of the depleted gas field.

2 H₂ sequestration

Hydrogen production and underground storage are emerging as key components of a low-carbon energy system. Hydrogen can be produced through various methods, including electrolysis, stored in geological formations, and then pumped back when needed.

Hydrogen underground storage projects exhibit a wide range of injection and reservoir pressures, reflecting the diversity of geological settings, operational strategies, and regulatory frameworks across countries. The HyUnder dataset [8] illustrates this diversity by providing detailed information on projects in Austria, Germany, France, Spain and others.

An interesting example of regulation is France, the BRGM (Geological and mining research office) states: "The overpressure at the top of the reservoir must remain below the capillary entry pressure of the caprock. Furthermore, to preserve the mechanical integrity of the caprock, the operational program must be designed and implemented in such a way

that pressure variations within the reservoir do not generate stress changes in the caprock that could approach its failure criterion, maintaining satisfactory safety margins. For the same reason, the operator should avoid situations where the initial pressure is significantly higher than the hydrostatic pressure. Consequently, the maximum pressure in the reservoir formation must be determined based on site-specific studies, particularly taking into account the thickness and the hydraulic and mechanical properties of the caprock, and examining potential tensile or shear failure modes." [1].

In conclusion, hydrogen storage pressures across Europe vary by reservoir type, depth, and national regulatory culture. National guidelines often defer to site-specific geomechanical evidence rather than imposing rigid numerical thresholds, highlighting a shared emphasis on safety, adaptability, and geological compatibility in underground hydrogen storage development.

3 Nuclear Waste disposal

The safe and long-term management of radioactive waste is a fundamental challenge for all countries with nuclear power programs. Radioactive waste is typically categorized based on its level of radioactivity and half-life into three main types: low-level waste (LLW), intermediate-level waste (ILW), and high-level waste (HLW). LLW contains relatively low concentrations of radioactivity and is generally disposed of in near-surface facilities. In contrast, HLW, mainly composed of spent nuclear fuel or vitrified waste from reprocessing, is highly radioactive and heat-generating, necessitating deep geological disposal over timescales of hundreds of thousands of years.

Geological disposal is widely recognized by the scientific community and regulatory authorities as the safest and most sustainable method for the long-term isolation of HLW and long-lived ILW from the biosphere [5].

Several countries have launched major projects aimed at implementing such solutions but one of the most significant concerns is the generation and accumulation of gases such as hydrogen (H_2), methane (CH_4), and carbon dioxide (CO_2). It may build up over time and exert pressure on repository barriers, potentially compromising their integrity.

Literature Review

The topic of interest in this study is the increase of pressure due to gas injection inside a reservoir or a repository. A quick literature review will be carried out in order to assess the state of the art in all three fields.

1 CO₂ sequestration

Geological storage, a central component of Carbon Capture and Storage, involves injecting CO₂ into deep formations (> 800 m), where it exists in a supercritical state, enabling higher density and storage efficiency. Retention relies on structural and stratigraphic trapping, followed by residual, solubility, and mineral trapping. However, high-pressure injection alters the subsurface stress regime and may compromise caprock integrity, reactivate faults, or induce seismicity, making geomechanical modeling essential prior to field operations [7].

During injection, pore pressure increases propagate beyond the injection zone, potentially over several kilometers, influencing effective stress and mechanical stability. Modeling approaches range from uncoupled, where horizontal stresses are constant, to fully coupled hydro-mechanical simulations that account for stress–pressure interactions.

Orlic et al. [11] demonstrates that CO₂ storage in depleted Dutch gas reservoirs produces geomechanical effects that are more localised and predictable than in saline aquifers. Depletion-induced pore pressure drops of 22–32 MPa cause stress changes within reservoirs of 20–40 MPa, but effects in surrounding rock are an order of magnitude smaller and limited to 1–3 km. In contrast, aquifer storage generates lower pore pressure increases (≤ 6.8 MPa at injectors) but affects areas tens of kilometers wide, with induced seal stresses ≤ 0.3 MPa and potential shear reactivation at 3 MPa overpressure.

Khan et al. [6] conducted a fully coupled geomechanical simulation of CO₂ injection into the Biyadh sandstone reservoir, focusing on pore pressure evolution and its implications for stability. Over a 10-year injection period at depths of approximately 1,350 m, the injection pressure was varied between 22 MPa and 26 MPa. The results showed that pore pressure increases were highest near the injection well, with the maximum rise occurring at 26 MPa, approaching the critical reactivation threshold of 25.05 MPa and remaining below the tensile failure limit of 31.10 MPa. These variations were directly linked to volumetric expansion of the reservoir and induced ground uplift, highlighting the importance of maintaining injection parameters within the safe operational envelope to avoid geomechanical failure.

2 H₂ sequestration

Hydrogen can be produced through multiple technological pathways with varying efficiencies, costs, and carbon intensities.

For large-scale, inter-seasonal storage, underground hydrogen storage (UHS) offers capacities far beyond those of surface facilities. The most mature option is storage in solution-mined salt caverns. Other promising geological formations include depleted hydrocarbon reservoirs and deep saline aquifers, which provide terawatt-hour-scale capacities but require careful site-specific evaluation of geomechanical stability, caprock integrity, and microbial or geochemical reactivity. In all cases, cyclic injection and withdrawal can induce pressure and stress variations, necessitating rigorous monitoring, well integrity management, and operational optimization to ensure safe and efficient hydrogen storage. [10]

Injection pressure is a critical operational parameter in underground hydrogen storage, directly influencing both containment security and recovery efficiency. In the Suliszewo structure, Luboń and Tarkowski [9] demonstrated that injection rates must be limited by the reservoir rock's minimum fracturing pressure and the capillary entry pressure of the sealing formation. Their optimal scenario involved an initial month of injection at $0.34 \text{ kg}\cdot\text{s}^{-1}$, followed by $0.51 \text{ kg}\cdot\text{s}^{-1}$, enabling 40 months of continuous injection before reaching the 0.1 MPa capillary entry limit at the reservoir top. Under these conditions, near-well pressures approached but did not exceed 20 MPa, remaining just below the estimated fracturing threshold.

3 Nuclear waste disposal

As explained previously, there are three modes of gas generation, however radiolysis of water generates a negligible amount of gas compared to both other processes [15] so most studies do not take it into account. Microbial degradation produces less gas [15] than corrosion of canisters and it requires viable microorganisms to be present and to survive for a significant fraction of the storage period.

Anaerobic corrosion of carbon steel is the most significant source of H₂. Under anoxic conditions, the reaction $\text{Fe} + 2\text{H}_2\text{O} \rightarrow \text{Fe}(\text{OH})_2 + \text{H}_2(g)$ dominates. Before the system becomes anaerobic, an initial aerobic phase depletes the residual oxygen in pore spaces and backfill materials, typically within 1 to 50 years [13]. After this period, hydrogen generation persists over timescales up to 100,000 years. Corrosion rates vary between 0.1 and $20 \mu\text{m}/\text{year}$, with a reference value of $1 \mu\text{m}/\text{year}$ often selected for modelling [13].

At repository scale, Xu et al. [16] found that under lower corrosion rates ($2.0 \times 10^{-12} \text{ mol}/\text{m}^2/\text{s}$), pressure may gradually increase to 81 bar (8.1 MPa) over 5,000 years and return to baseline after 200,000 years. For higher corrosion rates ($2.0 \times 10^{-11} \text{ mol}/\text{m}^2/\text{s}$), peak pressure of 100 bar (10 MPa) can be reached within 1,000 years, declining as the iron is consumed after 23,000 years.

Overall, uncontrolled gas pressure buildup may compromise engineered barriers, fracture host rocks, and alter groundwater flow. These phenomena highlight the importance of ac-

curately quantifying gas generation rates and understanding their coupled hydro-mechanical effects on repository evolution and safety [16], [4].

Motivations

Recent geopolitical and environmental challenges have intensified the need for CO₂ and H₂ sequestration in soils. The 2015 Paris Agreement set ambitious climate goals, including carbon neutrality by 2050, while the REPowerEU Plan targets 10 Mt/year each of domestic renewable hydrogen production and imports by 2030. In parallel, the EU's Radioactive Waste and Spent Fuel Management [2] requires comprehensive national strategies for nuclear waste disposal, where gas generation and pressure build-up pose significant safety concerns. This study proposes a unified modelling approach applicable to both gas sequestration and gas management in nuclear waste repositories.

The background section demonstrated that legislation generally requires each project to evaluate its own limits of pressure through the implementation of site-specific studies and models. The subsequent review of the literature demonstrated that a considerable number of numerical models had previously demonstrated various dependencies between injection pressure and pore-pressure buildup, in addition to numerous other parameters. However, there is a paucity of tools for engineers to predict their own parameters and threshold pressure with ease. Consequently, the present study proposes an analytical model to facilitate the prediction of the variation of water saturation, water pore pressure, and stress in the rock, given the variation of gas pore pressure and certain parameters of the reservoir rock.

Analytical Formulation

1 Introduction

Three equations will be defined, they provide the variation of the pressure of water, Δu_w , the variation of the saturation of water ΔS_r , and the variation of external pressure $\Delta\sigma$, given the variation of the pressure of gas Δu_g and certain parameters of the reservoir rock.

The pore-pressure coefficients are defined as:

- $A = \frac{\Delta S_r}{\Delta u_g}$
- $B = \frac{\Delta\sigma}{\Delta u_g}$
- $C = \frac{\Delta u_w}{\Delta u_g}$

The model lies on the following assumptions:

- The rock is linear, elastic, homogeneous and isotropic.
- Gas injection or release occurs sufficiently fast so that the process is undrained with respect to pore water.
- Isothermal conditions are assumed throughout the process.

The following equations are used to build our model: the constitutive equations of the gas, of the water and of the solid matrix.

2 Definition of the input data

- K : Bulk modulus of the rock (Pa)
- α : Biot coefficient (dimensionless)
- C_g : Coefficient of compressibility of gas (Pa^{-1})¹
- C_w : Coefficient of compressibility of water (Pa^{-1})
- ζ : $\Delta S_r = \zeta(\Delta u_w - \Delta u_g)$ (Pa^{-1})²

¹ $C_g = \frac{1}{V}(\frac{\partial V}{\partial P})_T$, the reciprocal of this quantity is the bulk modulus.

²We are assuming that the water retention curve is linear as a first approximation.

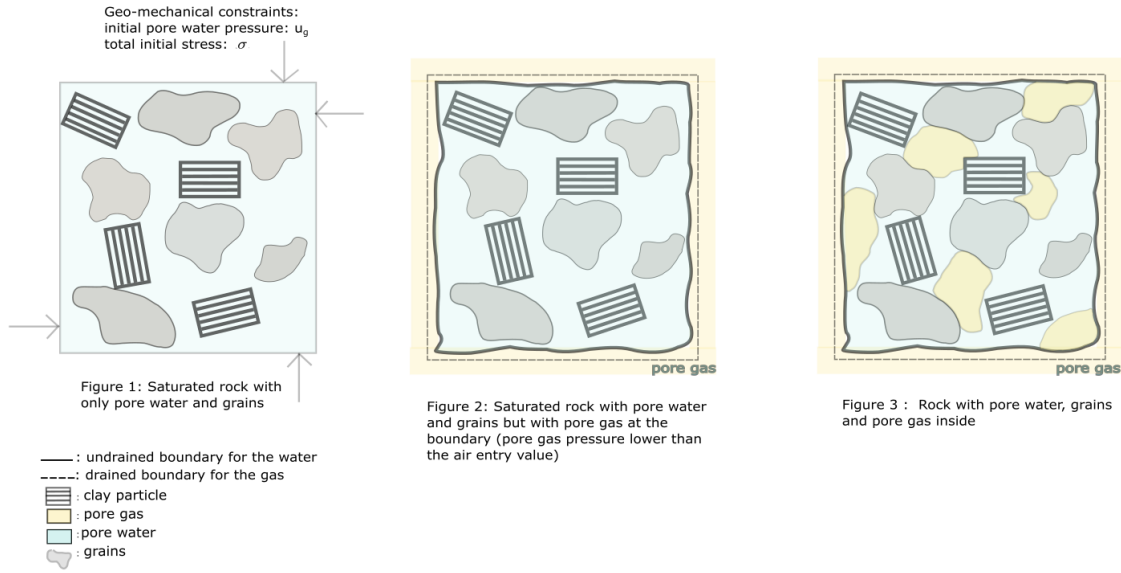


Fig. 5.1 Different states to which the rock will be subjected on site

- n : initial porosity of the soil (dimensionless)
- $u_g - u_w$: the initial difference between gas pressure and water pressure (Pa)
- S_r : Degree of saturation of the water (dimensionless)

3 System of equations

Let us skip the formulation of the equations and go directly to them.

The system is:

$$\begin{cases} \frac{\Delta\sigma}{\Delta u_g} - (\alpha S_r + n S_r C_w K) \frac{\Delta u_w}{\Delta u_g} + \alpha(u_g - u_w) \frac{\Delta S_r}{\Delta u_g} = -n(1 - S_r) C_g K - \alpha(S_r - 1) \\ \frac{\Delta S_r}{\Delta u_g} = \zeta \left(\frac{\Delta u_w}{\Delta u_g} - 1 \right) \\ \frac{\Delta S_r}{\Delta u_g} = -S_r C_w \frac{\Delta u_w}{\Delta u_g} - \frac{S_r}{nK} \left[\frac{\Delta\sigma}{\Delta u_g} - \alpha S_r \frac{\Delta u_w}{\Delta u_g} + \alpha(u_g - u_w) \frac{\Delta S_r}{\Delta u_g} + \alpha(S_r - 1) \right] \end{cases} \quad (5.1)$$

Let us replace the unknown by: $A = \frac{\Delta S_r}{\Delta u_g}$, $B = \frac{\Delta\sigma}{\Delta u_g}$, $C = \frac{\Delta u_w}{\Delta u_g}$.

Which leads to the following system:

$$\begin{cases} B - (\alpha S_r + n S_r C_w K) C + \alpha(u_g - u_w) A = -n(1 - S_r) C_g K - \alpha(S_r - 1) \\ A = \zeta(C - 1) \\ A = -S_r C_w C - \frac{S_r}{nK} [B - \alpha S_r C + \alpha(u_g - u_w) A + \alpha(S_r - 1)] \end{cases} \quad (5.2)$$

Results

The parameters chosen for this simulation are:

$$u_g - u_w = 1Pa$$

$$\alpha = 1Pa$$

$$C_g = 5.10^{-7} Pa^{-1} :$$

isothermal compressibility of the gas at T= 313 K and P= 10 MPa [12]

$$C_w = 5.10^{-10} Pa^{-1} :$$

isothermal compressibility of the water at T= 313 K and P= 10 MPa [3]

$$K=5 \text{ GPa}$$

$$\zeta = 1Pa^{-1}$$

$$n=0.1$$

$$Sr=0.5$$

The coefficients obtained with the programming language Python:

$$A=1,246.10^{-7} Pa^{-1}$$

$$B=0.875$$

$$C=1.000$$

Discussion

Coefficients are defined as: $A = \frac{\Delta S_r}{\Delta u_g}$, $B = \frac{\Delta \sigma}{\Delta u_g}$, $C = \frac{\Delta u_w}{\Delta u_g}$.

- As C is almost equal to one, Δu_g is almost equal to Δu_w in every simulation. It means that if engineers know the variation of pressure of pore gas then it is easy to predict the variation of pressure of the pore water.
- A being close to zero means that the variation of the degree of saturation is negligible compared to Δu_g so only a small volume of water is displaced by gas.
- When S_r increases, the amount of water in pores increase (which means also that less gas is present initially in pores), the total stress σ increases (because B increases). Indeed, as gas is more compressible than water, it will take up a smaller volume and act like a buffer to "absorb" the stress of the rock. As a consequence, the total stress σ applied on the particles of rock will be lower. Cf Fig. 7.2
- Similarly, when B decreases when the isothermal compressibility increases. It makes sense because if the gas is more compressible it can act even more as a buffer. Cf Fig. 7.1

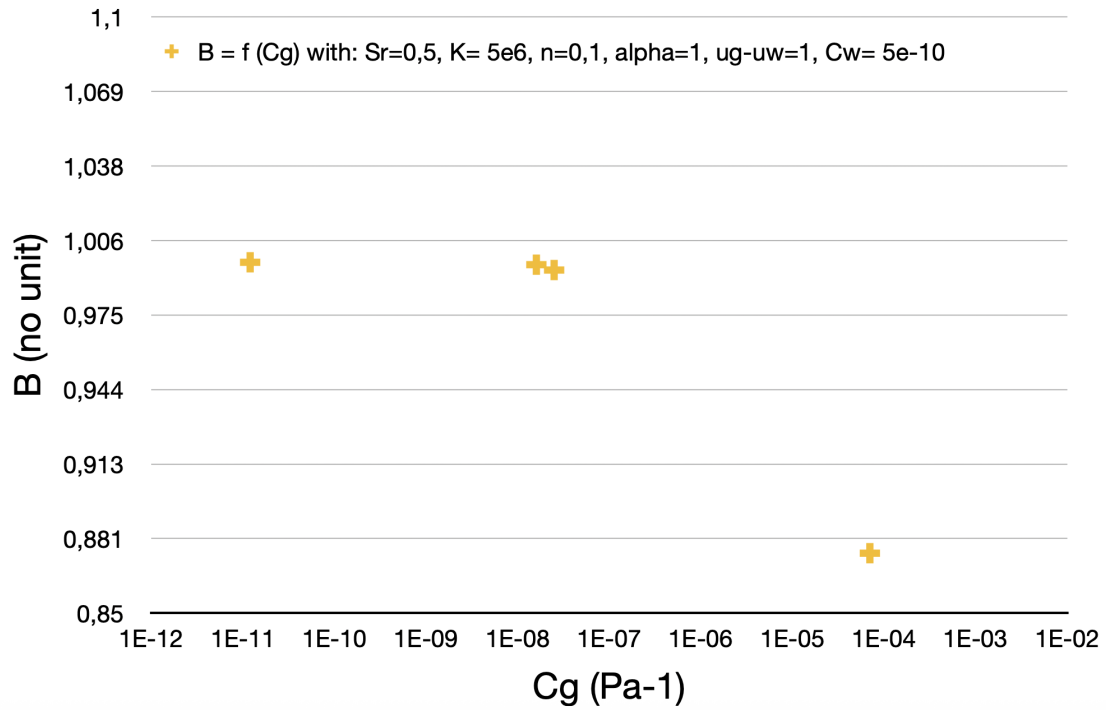


Fig. 7.1 Simulation of the value of B with different values of the compressibility of gas

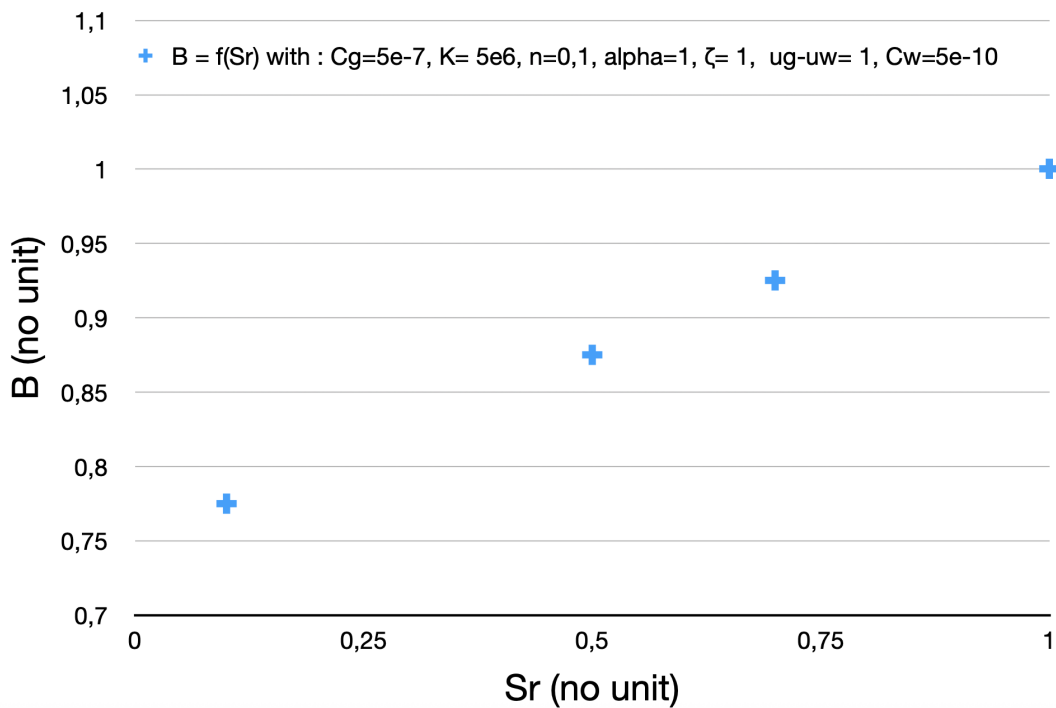


Fig. 7.2 Simulation of the value of B with different values of the degree of saturation of the porous rock

Conclusion and Next Steps

This research internship developed and applied an analytical framework to predict the coupled variations of water saturation, pore pressures, and stresses in geological media during undrained gas injection scenarios relevant to CO₂ and H₂ storage, as well as nuclear waste repositories.

The proposed model integrates key hydro-mechanical parameters, such as porosity, bulk modulus, water retention curve slope, and isothermal compressibility, within a linear elastic, isotropic formulation, enabling the calculation of pore-pressure coefficients with minimal computational cost.

Simulation results confirmed that the degree of saturation and the coefficient of compressibility of the mixture injected strongly influence model outputs. Indeed, it showed that an unsaturated porous rock and a higher compressibility of the gas will lead to lower risks of fracturing.

To go further, it is important to verify with experiments the relevancy of values and trends presented in previous sections as this work is only based on numerical simulations.

Another following step could be to approach more closely the water retention curve to have a more precise idea of the values of the coefficients proposed in this study.

Overall, this work contributes a simplified but robust analytical tool for preliminary site assessments, providing a foundation for more advanced, non-linear retention curve modeling in future studies.

Glossary

capillary entry pressure is the maximum pressure difference that may exist across the interface that separate two immiscible fluids before the non wetting fluid penetrates the pore space. 7

caprock is a layer of hard impervious rock overlying and often sealing in a deposit of oil, gas, or coal. 7

carbon intensities is a measure of how clean our electricity is. It refers to how many grams of carbon dioxide (CO₂) are released to produce a kilowatt hour (kWh) of electricity. 10

depleted gas field is a subsurface geological reservoir that previously produced natural gas but is no longer economically viable for extraction, often because the remaining gas pressure is too low. 7

homogeneous composed of uniform structure or composition throughout. 15

hydrostatic pressure is defined as the weight of a column of fluid per unit area that supports the weight above it. 7, 8

injection pressure is the pressure of the gas at the moment it is injected inside the rock. 7

isotropic having a physical property which has the same value when measured in different directions. 5, 15

porous (of a rock) having minute spaces or holes through which liquid or air may pass. 5, 20, 21

reservoir refers to the underground geological formation into which gas is deliberately injected. 7

stress (on a rock) force applied by unit of surface. 5, 7, 8

undrained without the fluid having been removed or allowed to flow away. 21

unsaturated (of a soil) only a part of the voids are full of water. 21

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