Comprehensive review of geomechanics of underground hydrogen storage in depleted reservoirs and salt caverns

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Abstract

Hydrogen is a promising energy carrier for a low-carbon future energy system, as it can be stored on a megaton scale (equivalent to TWh of energy) in subsurface reservoirs. However, safe and efficient underground hydrogen storage requires a thorough understanding of the geomechanics of the host rock under fluid pressure fluctuations. In this context, we summarize the current state of knowledge regarding geomechanics relevant to carbon dioxide and natural gas storage in salt caverns and depleted reservoirs. We further elaborate on how this knowledge can be applied to underground hydrogen storage. The primary focus lies on the mechanical response of rocks under cyclic hydrogen injection and production, fault reactivation, the impact of hydrogen on rock properties, and other associated risks and challenges. In addition, we discuss wellbore integrity from the perspective of underground hydrogen storage. The paper provides insights into the history of energy storage, laboratory scale experiments, and analytical and simulation studies at the field scale. We also emphasize the current knowledge gaps and the necessity to enhance our understanding of the geomechanical aspects of hydrogen storage. This involves developing predictive models coupled with laboratory scale and field-scale testing, along with benchmarking methodologies.

Keywords: Underground gas storage, Cyclic injection and production, Fault reactivation, Caprock and wellbore integrity, Experiments and modelling, Leakage

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1. Introduction

Increasing the contribution in the energy mix of renewable energy sources as alternatives to traditional fossil fuels is the immediate task to be able to reach future net-zero goals [1]. Aside from solar and wind energy, green hydrogen production is expected to play a big role in that transition. The wide range of applications of H_2, such as fuel for transportation, and feedstock for a variety of industrial processes like the production of steel, along with its nearly zero greenhouse gas emissions, make H_2 an attractive solution for the current energy landscape [2, 3, 4, 5]. Current challenges for renewable energies are to be able to balance the seasonality of energy [6], which corresponds to fluctuations of both supply and demand from winter to summer. As such, there is a need for large-scale storage, capable of storing green energy in the range of terawatt-hours (TWh) during the summer and discharging it in the winter. For that large scale, storage in underground reservoirs is being considered. Compressed air energy storage or aquifer thermal energy storage can be used, depending on the storage capacity required and the type of available green energy [7]. But most prominently, green H_2 produced from renewable energy using electrolysis [8, 9] is regarded as the best option for underground energy storage when there is excess electricity produced. Underground Hydrogen Storage (UHS) involves utilizing underground formations like salt caverns, aquifers, and depleted oil and gas fields in a safe, efficient, and reliable manner [10, 11, 12]. Figure 1 shows a schematic illustration of UHS in depleted reservoirs and salt caverns. Recent studies have explored the technical, techno-economical aspects and risks associated with the potential of UHS in different countries such as Romania [13], Netherlands [14], China [15], Canada [16], UK [17, 18], Germany [19, 20], Finland [21] and Austria [22].

Still, UHS is in its nascent stage. H_2 is stored in very few salt caverns, such as Teeside (UK) and Clemens, Moss Bluff, and Spindletop in the US [5, 23, 24]. The International Energy Agency (IEA) released a report outlining the current and upcoming UHS projects across the world [25]. From an economic point of view, it was found that aquifers and depleted reservoirs are slightly more economical compared to salt caverns for the chosen storage sites in the USA [26, 27]. Indeed, depleted porous reservoirs have significantly more storage capacity than salt caverns, on the order of (TWh), which is suitable for a seasonal time scale. There are already a few gas storage sites that store a percentage of H_2 such as in aquifers of Beynes (France), Lobodice (Czech Republic), and in the depleted gas reservoirs of Diadema (Argentina), Sun storage (Austria) [28, 29]. The geomechanical perspective of UHS in aquifers is beyond the scope of this review article, because its technology readiness level is relatively low (i.e., 2 to 3), implying it is still in the conceptual stage [25]. Furthermore, the amount of uncertainties for aquifers is relatively much higher than salt caverns and depleted porous reservoirs.

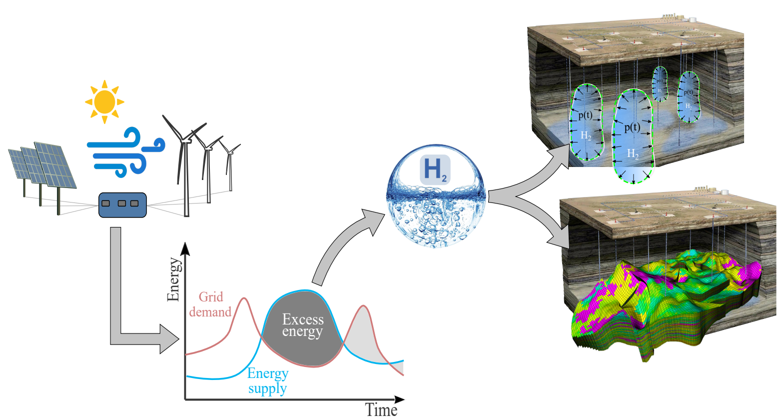

Figure 1: An illustration describing UHS in salt caverns and depleted reservoirs using green H_2 produced from renewable energy.

Many risks associated with UHS overlap evidently with the ones from various storage technologies such as carbon capture underground storage (CCUS), underground natural gas storage (UGS), and disposal of acid gas which have been employed at an industrial scale in the past [30]. Since H_2 storage is still an upcoming area of research, it becomes critical to understand the underlying reservoir mechanisms associated with other storage operations and further clarify how much of this knowledge can be reliably transferred to UHS. Fortunately, gas storage sites and salt caverns have been utilized in various applications such as natural gas storage [31, 32, 33, 34], crude oil [35], compressed air energy storage (CAES) [36, 37, 38] and in recent years, for CCUS operations [39, 40, 30]. Additionally, abandoned salt caverns have been repurposed for alkali waste disposal [41, 42] and for nuclear waste disposal [43, 44]. However, further extensive multidisciplinary research is needed to ensure the safety and longevity of gas storage sites. Table 1 briefly presents the differences in the storage technologies. A detailed review of each of the mechanisms which can impact the storage integrity is presented in subsequent sections.

Table 1: Comparison of natural gas, CO_2 and H_2 storage in the perspective of geomechanics

#	CCUS	Natural gas storage	UHS
Operating conditions [45]	Constant injection of CO_2 in the depleted reservoir and salt caverns. Possibility of using CO_2 as cushion gas for UHS. Once the CO_2 is injected completely, the pressure is kept constant.	Cyclic injection and production of natural gas on longer timescales.	Cyclic injection and production of H_2 with a higher frequency compared to natural gas. H_2 shows higher mobility compared to other stored gases which can bring unknown operating challenges due to lack of practical experience. progressive damage of rocks can occur due to intergranular swelling and shrinkage cycles.
Bio-geo-chemical interactions [45, 46]	Interaction of host rock with supercritical CO_2 can alter properties of rocks and alter ductility and cohesion of rocks.	Depending on the chosen reservoir site, stored methane can react and release different gases such as sulfides which can degrade the rocks.	Bio-chemical reactions of reservoir rocks and H_2 can change the properties of the rocks and further cause degradation. These interactions can also impact the integrity of the seal. In terms of caverns, salt rock is widely known to be inert to H_2.
Leakage risks [45, 47, 25]	Leakage can occur from seal failures and faults opening. CCS with a corrosive environment and low gas-water interfacial tension can alter the porosity and permeability of rocks. The failure of the roof of salt caverns can lead to leakage depending on the operational limits of the caverns and heterogeneities.	High interfacial tension in methane water systems reduces the risk of leakage in the caprock.	Dissolution of minerals which can change the reservoir and caprock properties. Possibility of permanent deformation and a low threshold to fault slip which can lead to fracture propagation/growth. In terms of salt caverns, H_2 percolation, hydraulic fracturing at the cavern roof, and salt creep especially in heterogeneous geological domain can accelerate the fault slip leading to hydrogen leakage.
Potential hazards [30, 25]	Subsidence/uplift, induced seismicity, and fracture propagation can occur in CCUS depending on the operating conditions and the chosen reservoir site.	Subsidence/uplift, induced seismicity, and fracture propagation can occur in natural gas storage sites depending on the operating conditions and the chosen reservoir site.	Fast cyclic loading can accelerate induced seismicity, affect the caprock integrity, and further cause permanent subsidence/uplift on the ground. Inelastic deformation such as creep can accelerate the movement along pre-existing faults.
Well integrity mechanisms [25, 48]	Corrosion, cement carbonation, and elastomer degradation due to the presence of carbonic acid	Relatively low risk in corrosion, cement carbonation, and hydrogen blistering which depends on the chosen reservoir site.	High risk of steel corrosion, hydrogen blistering, sulphidation which can also result in elastomer degradation due to the presence of H_2.

Indeed, assessing the viability of porous reservoir sites is challenging due to their inherent multiscale heterogeneity and uncertainty [49]. Besides economic considerations, several scientific aspects need to be investigated to ensure the safe deployment of UHS, including thermodynamics, hydrogeology, geomechanics, microbial activity, and geochemical interactions [50, 17, 51, 52]. These investigations are needed to model and quantify several important processes linked to UHS, such as the reactive transport of H_2 in the subsurface, leakage potential of H_2 through the caprock, change in the gas mixture due to biochemical reactions, and many more [52, 53, 54]. One crucial area of focus in understanding UHS is the study of geomechanical effects on the reservoir rock, caprock, and surrounding area. The injection and production of energy-rich green fluids into underground reservoirs are influenced by the cyclical nature of demand and supply of renewable energy [55, 56]. Consequently, the reservoir's pore pressure and temperature will cyclically vary, leading to potential hazards during and after operations, such as reduced strength, subsidence, or uplift [57], compromised well integrity [48], chronic H_2 leakage, reduced caprock sealing capability, and induced seismicity from fault reactivation [58, 59]. The use of salt caverns for storage may also result in unintended consequences, including excessive cavern convergence (loss of storage volume) [60], roof collapse [61], fluid leakage [62], and other events [63]. Salt caverns with complex geometry and thick heterogeneous interlayers along with multi-cavern interactions in the same geological region, can pose additional challenges when used for UHS. The common aspect of depleted reservoirs and salt caverns is the use of wells for the injection and production of H_2. Wellbore integrity is highly important to ensure that there are no leakage pathways of H_2 which affect the safety and efficiency of the entire storage technology.

To understand and characterize the geomechanical challenges relevant to UHS, a comprehensive review elaborating on the effects of using the depleted gas fields and salt caverns for H_2 storage is presented in this work. First, an overview of the rock mechanics relevant to gas storage technology is briefly introduced. Next, the experimental and numerical studies relevant to UHS both at the laboratory scale and field scale are reviewed, highlighting the geo-mechanical processes at play. The integrity of the wellbore from the perspective of UHS is discussed, highlighting the leakage pathways and the importance of materials chosen in the wellbore infrastructure. Finally, research recommendations are outlined.

2. Overview of rock mechanics

The subsurface contains several types of rocks and different soil making it highly heterogeneous. Each material point in the subsurface is at equilibrium with the overburden pressure and the horizontal stress, as illustrated in Figure 2 and subject therefore to the stress tensor $\boldsymbol{\sigma}$, expressed in x-y-z plane as

$$\boldsymbol{\sigma} = \begin{bmatrix} \sigma_{xx} & \sigma_{xy} & \sigma_{xz} \\ \sigma_{yx} & \sigma_{yy} & \sigma_{yz} \\ \sigma_{zx} & \sigma_{zy} & \sigma_{zz} \end{bmatrix}. \tag{1}$$

When the stress tensor is transformed in a way that the shear stress components $(\sigma_{12}, \sigma_{13}, \sigma_{21}, \sigma_{23}, \sigma_{31}, \sigma_{32})$ become zero, it yields the principal stresses $(\sigma_1, \sigma_2, \sigma_3)$. Those are commonly used to describe the stress state, along with the Von Mises stress and the hydrostatic stress, two different metrics representing respectively the deviatoric and mean stress.
Rocks are porous materials with interconnected pores saturated with fluid and allowing storage spaces for H_2. The rock is also at equilibrium with the pressure of that fluid called pore pressure (P_p). To account for that natural state, stresses are rather expressed as effective stresses $\boldsymbol{\sigma'}$ defined by Terzaghi's principle [64] as

$$\boldsymbol{\sigma'} = \boldsymbol{\sigma} - \alpha P_p I. \tag{2}$$

Note that α is the Biot coefficient [65] representing the compressibility of pores and given by

$$\alpha = 1 - \frac{K_T}{K_S}, \tag{3}$$

where K_T and K_S are the bulk moduli of the rock and grains respectively. When H_2 is injected, an increase in the pore pressure is observed. The resulting elastic strain $\boldsymbol{\varepsilon_{el}}$ can be derived from the elastic constitutive model expressed as $\boldsymbol{\sigma} = \boldsymbol{C} : \boldsymbol{\varepsilon_{el}}$ in which the elasticity coefficient matrix $\boldsymbol{C}$ is a function of Young's modulus and Poisson's ratio. In the subsequent section, the rocks' plastic regime and the failure criteria, which rely on stress analysis, are discussed.

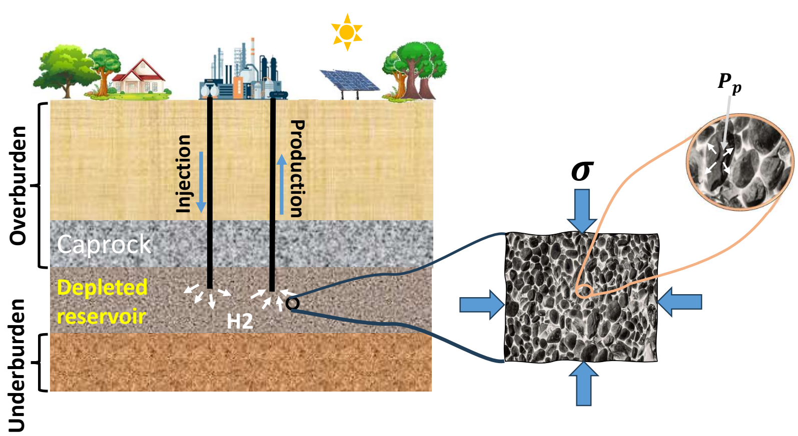

Figure 2: Illustration of rocks undergoing stresses in the depleted reservoir. Here $\boldsymbol{\sigma}$ is the total stress and P_p is the pore pressure in the pores caused by H_2.

3. Depleted gas fields

Depleted oil and gas reservoirs are primarily composed of permeable sandstones or carbonates with an impermeable shale or rock-salt layer acting as a sealing cap (i.e., caprock). When gas (or any other fluid) is injected or produced from these reservoirs, various geomechanical processes are initiated, necessitating careful control. Figure 3 shows the geomechanical processes at play, highlighting potential hazards. While many of these processes have been observed in previous operations, the introduction of H_2 and its interactions with rocks, especially in the presence of microbes, could contribute to the degradation of rock integrity.. To ensure safe and efficient operations, it is vital to identify and comprehend the key geomechanical processes involved (see Figure 3). The investigation of each of these processes begin by reproducing them at a laboratory scale under controlled conditions, closely resembling field conditions. These laboratory experiments aim to reveal the fundamental physical mechanisms underlying specific phenomena. Once these physical mechanisms are adequately understood, mathematical models can be formulated and integrated into reservoir simulators. Finally, the predictions offered by reservoir simulators should be compared with field measurements, a process known as history matching.

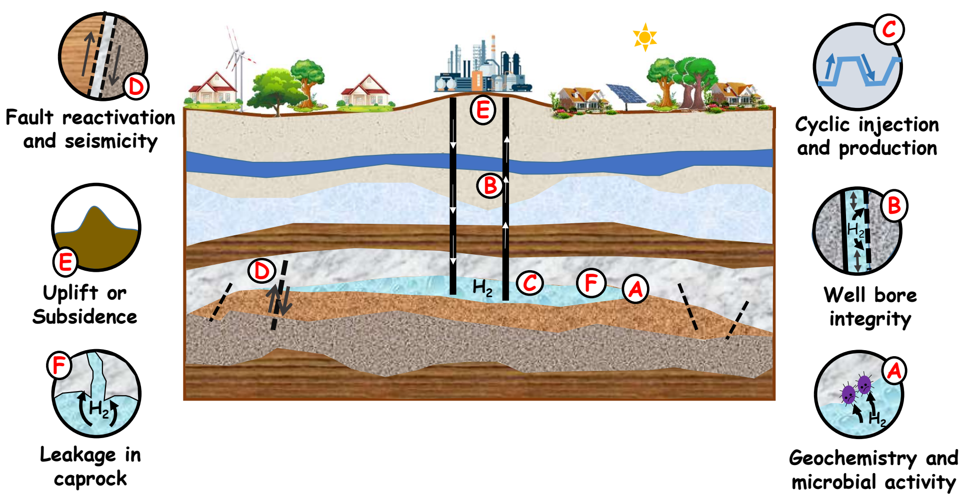

Figure 3: A schematic of UHS in depleted gas fields illustrating the geomechanical processes at play, highlighting potential hazards.

In this context, the subsequent sections initially provide an overview of experimental investigations concerning the geomechanical behaviors of porous rocks. Specifically, the focus is on cyclic loading circumstances, given their relevance to operational conditions anticipated for hydrogen storage. Additionally, the discussion delves into fault reactivation, the impacts of heterogeneity, geochemical responses, and microbial behaviors when exposed to H_2. Moving forward, the content addresses constitutive modeling and explorations conducted at the field scale, culminating in proposed directions for further research.

3.1. Experimental studies

Numerous laboratory scale research studies conducted over past decades have examined the strains and stresses experienced by rocks when subjected to various load types (such as uniaxial and triaxial) as well as their cyclic variations. However, within the context of UHS, there is a notable absence of experimental investigations involving porous rocks with H_2 as the pore fluid at the laboratory scale. Instead, we refer to the work of Cerfontaine et al. [66], who presented a comprehensive review of cyclic loading experiments on porous rocks, categorized according to parameters such as loading frequency, maximum axial stress, confinement stress, degree of saturation, anisotropy, dynamic seismic waveforms, and the size of rock samples. In the context of energy storage, it is crucial to consider these factors under realistic operational stress conditions in the presence of pore fluids. Figure 4 illustrates the typical laboratory scale experiments frequently conducted to study various processes occurring in UHS. Notably, the diagram excludes rock degradation attributed to bio-chemical processes, as analyzing this aspect would necessitate diverse types of apparatus. The forthcoming subsections provide detailed explanations of this set of experiments.

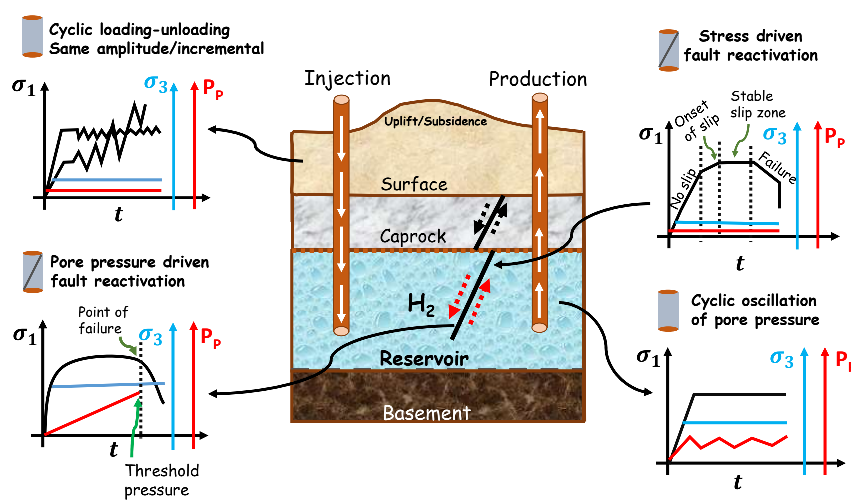

Figure 4: Illustration of the type of experiments being conducted in the laboratory scale relevant to UHS for the variation of different stresses (σ_1, σ_3) and pore pressure (P_p) with time (t).

3.1.1. Cyclic mechanical loading and unloading experiments

Experimentally determining the mechanical properties of reservoirs through the cyclic alteration of horizontal and vertical stress conditions has often been performed to assess storage feasibility. Indeed, several researchers reported subsidence or uplift in sandstone reservoir formations due to injection of CO_2 during enhanced hydrocarbon recovery or due to water injection in enhanced geothermal systems [67, 68, 40]. Pore fluid injection alters the stress conditions and density of the reservoir, and therefore, depending on the tectonic setting, the reservoir can undergo subsequent upliftment or subsidence. A significant decrease in porosity and pore connectivity of sandstones after consecutive cycles of loading due to the closure of microcracks in the reservoir was also reported [69]. Despite changes in porosity, Wang et al. [70] highlighted that cyclic loading-unloading in a tight sandstone within a defined stress range has a minor effect on permanent rock deformation. Although acoustic sensors can pick up crack generation in the first few cycles, the recurrence of such events is limited unless the peak load exceeds the load applied in the previous stage due to the Kaiser effect (to be discussed in Sub-section 3.1.2). This observation has also been confirmed for similar rock types [71]. The accumulation of plastic strain in sandstones that can take place due to repeated low-frequency cyclic loading-unloading in the context of UHS operation has been recently documented [7]. However, the field-scale applicability of the findings needs further investigation. Indeed, failure of rocks sustaining multiple equal value stress cycles is reported to accumulate more plastic strain and show a lesser number of dominant cracks with complex crack networks [7]. Formation or growth of cracks in sandstone are strongly dependent on the maximum deviatoric stress and direction of principal stresses [72]. As long as the direction of the stresses is unchanged and the maximum deviatoric stress magnitude is constant, stress cycling will only increase or decrease the aperture of pre-existing cracks, and the memory effect of the rock will deter the formation of cracks nucleation or growth. However, the plastic deformation accumulating in the process should not be ignored, as it accounts for a significant change in reservoir stability. The caprock overlying the target reservoir, usually low permeable shale or mudrocks, is also experiencing cyclic loading and unloading because of the direct influence of the reservoir. Injection of H_2 into the pore spaces of the reservoir increases the buoyancy-driven force by the pore fluid, which pushes the overburden caprock from the bottom, perturbing the stress conditions of the caprock. Repeated injection or production of H_2 results in frequent fluctuations of buoyancy-driven force, which, in turn, induces cyclic loading-unloading on the caprock. Shales are characterized as ultralow permeable fine-grained sedimentary rocks composed of quartz, clay, and often rich in organic matter. The low permeability of shale makes it an efficient caprock; however, compared to reservoir rocks like carbonates and sandstones, shales are weaker and have a lower Young's modulus. Compared to reservoir rocks, shales have higher plastic deformation under stress, and their mechanical behavior is strongly dependent on their organic composition and fabric anisotropy [73, 74, 75]. The presence of organic matter and clay minerals in shales contributes to their ductility, whereas quartz richness results in a more brittle response to stress change [76]. The contrast and distribution of these constituents lead to heterogeneous stress response and complex crack propagation in shale [77]. Shales are composed of thin successive laminations compared to thick bedding sequences in reservoir rocks, which act as weak planes during deformation. The direction of the principal stress concerning these laminations plays a significant role in the stress response of shale. The presence of organic matter in shales and its finer grain size leads to a narrower crack aperture and less catastrophic failure. Shales behave differently from sandstone under cyclic changes due to bedding plane orientations when maintained under effective stress conditions [78]. Unlike sandstones, shales rarely show memory effects due to the accumulation of irreversible fatigue during cyclic loading. The number of cycles endured before failure also depends on the amplitude and frequency of axial loading. In shales, because the inherent heterogeneity in shale reservoirs is more prominent compared to sandstones, the direction of maximum stress experienced by the caprock samples greatly depends on the direction of laminae or bedding planes in shales [79]. The fatigue damage in shales follows an inverse power law relationship with the maximum stress, and the crack formation zone in the stress-strain profile of shales is more pronounced than in reservoir rocks [80].

When conducting laboratory scale triaxial tests, it is difficult to visualize the crack initiation and propagation sequences. The stress-strain profile can only indicate major events of deformation and limits our understanding of the microscale deformation leading up to failure. Ultrasonic acoustic sensors attached to the samples can capture the sounds generated during the tiny events of grain sliding, crack initiation, and propagation. Incremental cyclic loading parallel to bedding planes in shales initially emits sparse acoustic signals, which could be due to the initial opening and closing of cracks along the bedding planes. However, after crossing a stress threshold, the number of acoustic signals increases with increasing stress [79], indicating frequent events of crack generation or propagation in the plastic deformation zone. The amplitude of the sound waves is also proportional to the energy emitted by the cracks, which increases as the sample approaches failure. An array of multiple acoustic sensors is often used to precisely locate the crack surface through moment tensor inversion [81, 82]. Emission of significant acoustic signals during cyclic deformation at lower stress levels, opposite to the Kaiser effect and popularly known as the Felicity effect [83], can be observed in shales during cyclic loading. Initially, cumulative acoustic emissions decrease in consecutive cycles and increase again during incremental cyclic loading [84]. The stress release mechanism and b-value of the seismicity also depend on the bedding plane orientation, as reported in [85].

Safe operating pressure of a reservoir, i.e., the pressure at which H_2 is injected, strongly depends on the strength of the reservoir and caprock. An injection pressure higher than the tensile strength of the reservoir rock can create new fractures, which can act as conduits for upward H_2 migration, eventually risking the integrity of the caprock under elevated stresses. A good grasp of the in-situ stress magnitudes is imperative to maintaining the pore pressure lower than the stress required to activate pre-existing faults. The repeated cyclic injection can also induce volumetric change and buoyancy-driven deformation in the reservoir and caprock, which might reactivate weak planes or create seismicity due to sliding along those weak planes [86, 87, 88]. In terms of the applicability of shale as a caprock for H_2 reservoirs, an important factor to consider is the yield strength of the shales, which should be above the stress tolerance of reservoir stress cyclicity; otherwise, leakage pathways may generate through the caprock. It is recommended to keep the injection pressure lower than the original pore pressure of the reservoir, to keep the stress perturbation minimal. Besides that, the disposition of the shale bedding plane concerning the principal stress directions plays a critical role in governing the type of fractures generated in the caprock. More importantly, the Kaiser effect is not as pronounced in shales compared to sandstones, which could cause fractures in caprock after prolonged operations.

3.1.2. Cyclic pore fluid injection

In this sub-section, we focus more specifically on the behavior under pore fluid injection which is responsible for the cyclic load during UHS. Since the concept of gas injection in subsurface porous reservoirs is not new, several studies in the laboratory scale have been performed worldwide, particularly for CO_2 storage feasibility assessment. Contrary to UHS, CO_2 is permanently stored in the reservoir, which implies that studies on the cyclic fluctuation of pore pressure are unprecedented. Extensive study of cyclic pore fluid injection and production has been performed for applications ranging from enhanced hydrocarbon recovery to geothermal energy. Although limited studies have been performed using H_2 as pore fluid, related studies with other gases or fluids can help us understand the reservoir behavior and mechanics related to cyclic pore fluid injection. After the first evidence of observed permeability alteration with effective stress [89], several studies have confirmed similar understanding, specifically for tight or low permeability reservoirs. It has been observed that with an increasing number of cyclic effective stress oscillations due to gas storage, the permeability decreases faster initially and gradually slows down [90]. Similar experiments on sandstone rocks reveal a strong correlation between the strain accumulated in each cycle and the resulting change of permeability and after 30 cycles, the permeability change becomes negligible as the strain stabilises [91]. Those irreversible changes in permeability are shown to be more pronounced for reservoirs of low permeability [92, 93, 94, 95, 96].

Low- and high-frequency oscillation-based creep experiments of pore pressure in sandstones concluded that even a significant monotonic increase in pore pressure has a minor effect on the mechanical properties of the rock [97]. However, faster oscillations of pore pressure can increase the dilatancy rate and decrease peak strength, particularly close to failure. To avoid crack generation during UHS in reservoirs, it is suggested to maintain a low-frequency pore pressure oscillation and ensure a significant offset between peak pore pressure and peak strength under in-situ stress conditions [98]. Notably, through numerical simulations the memory effect of rock, known as the Kaiser effect was highlighted which holds a significant relevance in porous reservoirs like sandstone [99]. This effect indicates that reservoir rocks rarely exhibit seismic events under cyclic pore pressure injection until the pore pressure surpasses the previous maximum pore pressure in the reservoir. However, the Kaiser effect remains valid only when the reservoir isn't experiencing inelastic deformation. In reality, due to continuous creep deformation in subsurface reservoirs, it's unlikely to observe the Kaiser effect [100]. Still, to continue raising the debate, field scale injection of natural gas into sandstones has shown more high magnitude seismic events in the first cycle, followed by fewer events in the consecutive cycles [68, 101], further bolstering the dominance of Kaiser effect. Cyclic fluid injection at low frequency can utilize more pore volume, decrease the chance of seismic events, and lead to slower relaxation of pore fluid pressure for the safe operation of subsurface reservoirs. Subsequently, it induces permanent fatigue in the reservoir and results in less energy output from future seismic events, making long-term reservoir operation safer [102]. In summary, recent literature indicates that the deciding factor for cyclic pore-fluid-induced mechanical changes is linked to the validity of the Kaiser effect in real scenarios. Resolving such ambiguity warrants more laboratory scale experiments with field-scale validations in equivalent P-T conditions shortly.

3.1.3. Laboratory studies of injection-induced fault reactivation

Insufficient knowledge about the subsurface reservoir and stress conditions, especially in faulted reservoirs can lead to injection-induced seismicity. In the worst case, scenario of triggering an earthquake [103], which on top of challenging the stability of subsurface resource storage operations, has a societal impact and increases public concerns with regards to those subsurface operations [104, 105]. Injection of fluids at very high pressure leads to loss of frictional strength along the fault plane and a decrease in effective overburden stress conditions in the fluid-pressurized zone. This leads to an increase in driving shear stress and loss of frictional coefficient due to lubrication in sandstones [97, 106, 107]. The induced stress change can also contribute to activating remote faults depending on the difference between the injection rate and diffusion rate of the fluid injected in the reservoir. Typically, laboratory experiments of fluid-induced fault reactivation in different rock types can be studied using triaxial shear, direct shear, double shear, or rotary shear setup [108, 70]. These experiments can be performed with natural faults or saw-cut fault planes in rock matrix with or without the presence of fault gouges. The fault planes made for these studies are usually at an angle of 45-60 ^{o} with the vertical or overburden stress (σ_v), which is the general dip of normal faults according to Anderson's theory [109]. This fault dip angle ensures that the slip will occur along the synthesized fault plane during vertical loading and no new fault planes will be created under stress. Under dry conditions, the effective normal stress (σ_n) and shear stress (τ) can be defined as

$$\sigma_n = \frac{1}{2}[(\sigma_1 + \sigma_3) - (\sigma_1 - \sigma_3)\cos 2\theta] = \sigma_3 + (\sigma_1 - \sigma_3)\sin^2\theta \tag{4a}$$

$$\tau = \frac{1}{2}[(\sigma_1 - \sigma_3)\sin 2\theta] = (\sigma_1 - \sigma_3)\sin\theta\cos\theta \tag{4b}$$

where θ is the slope of the fault plane concerning σ_3. Using the values σ_n and τ, we can construct the failure stress-paths based on the Mohr-Coulomb failure criterion. When fluids are introduced in the fault plane, the effective normal and effective shear stresses decrease, shifting the failure criterion towards the left, resulting in failure even at reduced stress conditions (Figure 5).

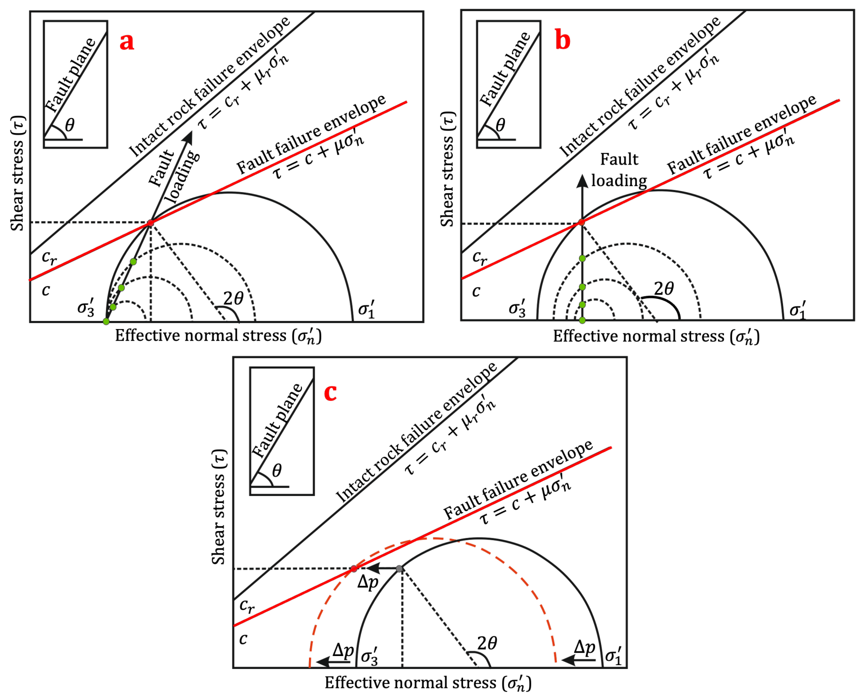

Figure 5: Mohr circle representing different stress changes in a faulted rock mass modified after [108] a. shear test under the triaxial condition at constant confining pressure, b. shear experiment under constant normal stress. The dots on the Mohr circles represent the stress path at different stages c. Triaxial shear test in a permeable faulted rock, assumed fully drained, where the Mohr circle shifts towards the left due to the influence of pore pressure. Here σ_1 and σ_3 represents maximum and minimum effective principal stress. σ_2 and σ_3 are considered to be equal for simplicity. c and c_r are the cohesion for the fault plane and the bulk rock mass respectively, β is the angle of the fault plane concerning the horizontal plane, μ and μ_r are the coefficient of friction for the fault plane and the bulk rock mass respectively, Δp is the pore pressure.

The distribution of injected fluid across a fault plane depends on factors like rock mass permeability, fault surface, fluid injection rate, and fluid viscosity.

Fluid injection can result in either a fully drained condition, where it's evenly spread, or a locally undrained state with pressure buildup near the injection point, due to low fault permeability and fast injection rates. Rocks with different permeability, when subjected to fluid injection to investigate slip, exhibit different responses in terms of change in the effective stress [110]. Depending on the injection rate and fault permeability, slips can be either seismic or aseismic [111, 97]. In the case of subsurface fluid injection in heavily faulted reservoirs, it is always recommended to keep the injection rate low to allow enough time for the fluid to dissipate along the fault plane which also reduces the probability of seismic events due to such operations. Although slip along the fault plane is a direct feedback of fluid injection, there can be a significant temporal lag between the injection and slip to occur, depending on the local stress and operating conditions. It is also assumed that numerous smaller seismic events will precede a larger magnitude earthquake, however, such assumptions do not consider aseismic slips into account [112]. It is thus recommended that strain sensors should be included as standard monitoring strategies to accurately assess the fault plane evolution. Ye et al. [113] conducted triaxial fracture slip experiments in sandstones and concluded that very slow aseismic slip is common both before and after a seismic slip. Dynamic frictional weakening due to stick-slip or creeping friction along the fault plane at higher pore pressure was also observed [114]. Interestingly, Fryer et al. [115] pointed out that high pore pressure in reservoirs within normal faulting stress regimes can help stabilize high-stress paths, however, injection of very low-temperature fluids can destabilize such conditions.

Moreover, an essential property of H_2 to consider is its lower viscosity compared to other gases injected into the reservoir. For context, at 50 ^oC, the dynamic viscosity of H_2 (9.4 μ Pa s) is lower compared to CO_2 (16.1 μPa s) and CH_4 (11.9 μPa s), which contributes to the higher mobility and diffusivity of H_2, making it more prone to flow through narrower apertures. Therefore revisiting the fault leakage experiments with a special focus on H_2 as pore fluid is essential to understand the sensitivity of fault aperture on H_2 mobility. Chemical reactions of H_2 and rock mass near the fault zones may play a major role in governing the stability of fault, which will be discussed in the next section.

3.1.4. Chemical reactivity of pore fluid and host rock

The interaction between injected fluids and reservoir rocks can have long-term implications for reservoir efficiency and safety. The dissolution or precipitation of minerals along fault planes is crucial in determining slip potential and the load-bearing capacity of the faulted surface [17, 116]. Studies on the chemical interaction of the commonly injected supercritical CO_2 with host rocks have shown increased ductility and reduced cohesion in sandstones [117]. While research has been conducted on the CO_2 enriched brine interaction with sandstone and carbonate reservoirs, there is still a need for investigations into the chemical interaction of H_2 with reservoir rocks. Still, there exist a few studies contributing to this area of research. Some researchers have observed minimal changes in reservoir porosity and permeability due to the slow reaction rates between H_2 and Fe-bearing minerals [118, 119, 120]. The reactivity of H_2 with quartz or clay minerals is minimal even over geological timescales. The chemical reactivity of carbonates with H_2 is also negligible, although the extent of calcite dissolution and H_2 loss depends on the brine salinity, pH, and temperature of the reservoir [121, 122, 123]. The interaction of H_2 with formation brine can alter reservoir wettability and contribute to significant trapping of gaseous H_2, thereby reducing the relative permeability of the mobile H_2 phase [124, 125]. However, the implications of this on the mechanical properties of the rocks have yet to be documented. In carbonate reservoirs, the expansion of calcite grains during interaction with H_2 has been identified as a dominant chemical phenomenon, resulting in a reduction of the reservoir's effective porosity by up to 50% [126].

Clay minerals, which are often abundant in certain sandstones and low-permeability claystone, can also serve as hosts for H_2. While there are no significant irreversible chemical reactions between clay minerals and H_2, the swelling of clays due to sorption can lead to stress changes in the reservoir [17], as has been extensively studied for CO_2 injection in sandstone, shale, and coal reservoirs [127, 128, 129]. Volumetric sorption experiments of H_2 on clay-rich Callovo-Oxfordian rocks have shown an uptake of up to 0.1 wt% H_2 within a pressure range of 0-90 bar. However, as water and H_2 compete for adsorption sites in clay minerals, the uptake of H_2 will be significantly lower in brine-saturated reservoirs [130]. Although similar experiments and numerical modeling of H_2 sorption kinetics on natural and synthetic clays have been conducted [131, 132], the effect of sorption on the mechanical properties of clay minerals is yet to be explored. In summary, while irreversible chemical reactions may not be the dominant factor affecting the mechanical properties of rocks in subsurface UHS, further research is needed to investigate grain-scale swelling and sorption dynamics and their impact on reservoir-scale stress configurations.

3.1.5. Effect of heterogeneity

Reservoir heterogeneity originates from variations in grain size distribution, depositional conditions, and reaction kinetics during diagenesis. The spatial extent of heterogeneity, compositional difference, and the grain-scale response of heterogeneous layers under elevated stress conditions govern the efficiency of the reservoir for gas storage operations. Heterogeneities in sedimentary reservoir rocks originate from their depositional condition as well as the diagenesis pathway during consolidation. Disparate distribution of porosity or spatial difference in pore sizes can result in differences in mechanical responses. Similarly, cementation during diagenesis can enhance the mechanical stability of the host rock but causes a drastic reduction in pore spaces [133]. Fluid-inclusion structures and the formation of fault gouges in the reservoir can also result in local heterogeneity.

Numerical simulations also found that the presence of soft heterogeneous particles in sandstone can decrease the crack initiation stress, damage stress, and static modulus values [134]. Grain-scale heterogeneity in sandstones can also govern the stress concentration points of crack initiation and crack propagation

direction. Heterogeneity within rocks, including variations in grain size, mineral composition, bedding structures, and inclusions, critically influences crack initiation, propagation, and plastic strain accumulation. In high-crystalline quartz, stress triggers microcracks at mineral boundaries, deflecting from grain boundaries. Conversely, in low-crystalline quartz, cracks tend to penetrate through grains [135]. Uneven grain size distribution and inclusions further encourage crack formation along host rock and inclusion interfaces [136]. The crack aperture and frequency of secondary crack formation are proportional to the grain size of the rock mass [135]. The cohesion of a heterogeneity (fracture or assemblage of contrasting minerals) also plays a significant role in guiding and opening existing cracks and the formation of new cracks. It has been demonstrated that under tensile stress, compared to a pre-existing fracture, a cohesive heterogeneous surface can lead to the generation of intensive cracks [137].
Sandstones having higher porosity and larger pore sizes are more prone to fail at lower stresses compared to sandstones with lower porosity. Indeed, pores act as local weak zones, which govern the origination of cracks, and it is observed from related research reporting significant enhancement of permeability and porosity due to load cycling in high porosity sandstones [138]. Geometry, distribution, type, and orientation of heterogeneous microstructures also determine the crack propagation path and their development [139, 140]. Crack propagation occurs primarily along the bedding plane, where the mineralogical difference across the bedding plane is pronounced. Fine-grained reservoir rocks are preferred for gas storage operations due to their smaller pore spaces and higher pore volume. They also show higher peak strength due to diffused stress distribution compared to coarse-grained sandstones [141], which leads to the suitability of pore fluid injection at higher pressure. On one hand, heterogeneity of reservoir rocks can lead to complex strength behavior and partial fault reactivation, whereas heterogeneity of caprocks like shale can play an opposite critical role in the successful containment of gas within the reservoir. Hence more experimental and numerical studies on the effect of heterogeneity for both reservoir and caprock need to be performed for potential H_2 reservoirs and special attention should be given on the interaction of pervasive heterogeneities (e.g. bedding planes) and its orientation with the principal stress components.

3.1.6. Effect of microbial interaction on rock mechanical property

The presence of microbial community in subsurface hydrocarbon reservoirs is well understood [142] and its influence on oil and gas recovery is also well studied. However, there is significant diversity of the microbial community in such reservoirs and the community responsive to hydrocarbons is different from the ones that can interact with H_2 [53, 143]. H_2 is one of the oldest and most simple electron donors, which makes it an ideal metabolizing agent among the microbial community [144]. Although the activity of the microbial community in reservoir analog P-T conditions in the presence of H_2 is not well documented yet, laboratory scale batch experiments have proven their metabolic sensitivity to temperature, pressure, and pH conditions [17]. Not only do the microbes consume H_2 to produce contaminant gases like CH_4, H_2S, and other organic acids, they form biofilms, which can alter the wettability of the reservoir and reduce accessible pore spaces after successive cycles of H_2 injection and production [53]. Although there is sufficient evidence on the effect of biofilms creating a barrier to flow in H_2 reservoirs, not many studies have been performed to understand the alteration of the rock mechanical properties. Still, we expect microbial-induced wettability alteration of the reservoir [145, 146, 147] to change the interaction of H_2 and formation brine with the pre-existing fault plane, which can cause mechanical instability. Fe-reducing microbes can replace Fe from minerals in the presence of H_2, which may change the stability of the reservoir depending on the abundance of Fe-bearing minerals [148]. Consumption of H_2 can also reduce the reservoir pressure [148] and cause creeping subsidence of the reservoir due to increasing effective stress. Intuitively, the presence of biofilms can increase reservoir stability, however, scientific evidence supporting or rejecting this hypothesis is lacking. It is worthwhile to mention that for a CO_2 storage operation, the presence of carbonate-producing microbial community in reservoirs can significantly enhance the mechanical properties of the reservoir by reducing permeability and closing pre-existing cracks [149, 150], however, such studies have not been performed specifically for UHS perspective. As discussed already, the geochemical effect of microbes on the reservoir rocks is minimal, however, H_2 consuming bio-organisms produce gases like H_2S, CH_4, and CO_2, which might in turn affect the mechanical properties of sandstone/carbonate reservoirs [148, 143, 151].Considering the attention that has been given to the relationship of biofilms and flow properties of H_2, similar attention should be given to understanding their role in the alteration of reservoir mechanical properties.

3.2. Constitutive modeling and field scale results

The preceding section focused on examining experimental research concerning various aspects, including cyclic external loading, pore fluid injection, injection-induced fault reactivation, bio-chemical interactions, and the impact of heterogeneity. Laboratory experiments allow for a detailed examination of rock behavior, such as deformation, stress, and failure mechanisms. Understanding these rock properties is vital for accurately predicting the response of subsurface reservoirs during hydrogen injection and storage. However, conducting experimental research can be time-consuming making it impractical for studying the long-term behavior of subsurface reservoirs. The scarcity of appropriate sampled materials and the destructive nature of most experimental methods further limit the scope of experiments. Additionally, the constrained range of testing conditions restricts the data that can be collected. To comprehend rock behavior over extended timescales, researchers construct constitutive models based on experimental data and subsequently integrate them into field-scale simulators to extrapolate the reservoir's overall behavior. Laboratory experiments offer valuable initial data for comprehending short-term rock responses and benchmarking geomechanical models, forming a basis for extrapolating and predicting long-term behavior in field-scale simulations. By conducting controlled laboratory experiments, researchers can identify potential risks associated with hydrogen storage, such as subsurface deformations, rock fracturing, or induced seismicity issues. Incorporating this knowledge into field-scale simulations allows for a more comprehensive risk assessment and effective risk management strategies. Field scale simulations also allow for understanding overall reservoir performance by conducting probabilistic sensitivity-based simulations. In the following subsections, constitutive models developed based on experiments conducted at the laboratory scale are elaborated and further relevant field-scale simulations are discussed.

3.2.1. Geomechanical constitutive models

To gain insight into the hydro-mechanical behavior of the subsurface, it is crucial to investigate the mechanisms experienced by rocks under cyclic loading. To facilitate this, constitutive models are developed to forecast the long-term behavior of rocks. These models aid in predicting how rocks will behave under various operational conditions that cannot be replicated at the laboratory scale. Figure 6 provides a general depiction of how strain varies with time when a constant load is applied.

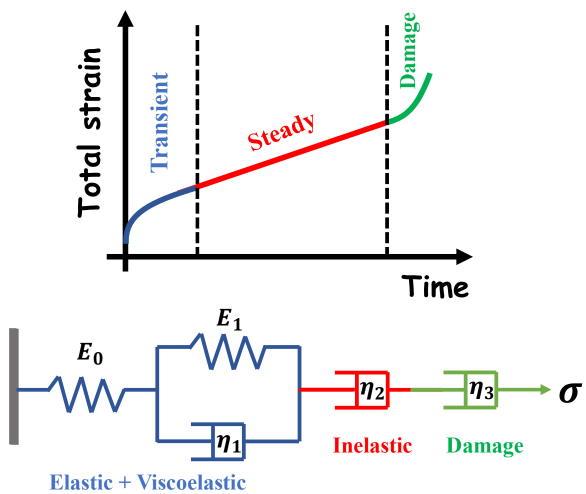

Figure 6: A simplistic general description of rock deformation mechanisms under a constant imposed stress σ. The parameters E_0, E_1 are Young's modulus of elastic and viscoelastic elements and η_1, η_2, η_3 are the viscosity of the elements.

The transient region can be characterized by elastic components and time-dependent elastic strains (viscoelasticity) [152, 153]. The next region is the steady state region which can be further decomposed to time-dependent inelastic strain and time-independent inelastic strain (plasticity). Inelastic strains such as plasticity, viscoplasticity, and creep are commonly observed in underground formations. Plasticity is a permanent deformation that occurs instantaneously (time-independent) when the stress levels reach a certain yield limit (yield surface) [154, 155, 156, 157]. Similarly, viscoplasticity also refers to a permanent deformation when the stress levels touch the yield surface. In this case, however, the rate at which stress is applied also plays an important role [158] which makes the deformation time-dependent [159, 160]. Another type of time-dependent inelastic deformation is known as creep deformation, in which the material constantly deforms under the application of a constant and persistent external load, irrespective of the stress levels [161, 156]. Lastly, damage strain can occur which can initiate microcracks and lead to the failure of rocks [162, 163]. Few rocks also show anisotropic elastic deformation which needs to be accounted for effectively using appropriate constitutive formulations [164, 165, 166]. This particular stage must be avoided to ensure the safety of UHS technology. The subsurface consists of various types of rocks, each exhibiting distinct primary deformation mechanisms governed by different constitutive laws due to variations in grain composition.

Constitutive models relevant for subsurface energy storage in different rocks such as sandstone, shale, and carbonate rocks are presented, whereas rocksalt physics is discussed later in subsection 4.3. Constitutive models are relevant to underground energy storage for understanding the inelastic and frictional behavior that can be used in field scale simulation for sandstone, shale, and carbonate rocks are listed in Table 2.

To quantify the deformation in rocks, models based on different physics including fault slip laws, viscoelasticity, plasticity, and creep, need to be accommodated. Field-scale simulators can employ these models to compute permanent deformation, stresses in the region, and fault slips with careful calibration from lab experiments. To study the potential of fault slippage and induced seismicity in heavily faulted reservoirs, fault slip models derived from laboratory scale experiments can be integrated into field simulators. For detailed information on the physics underlying these models, readers are referred to the respective references.

However, when applying constitutive models obtained from laboratory scale experiments with a timescale of days or weeks to field-scale simulations spanning years or decades, it is important to exercise caution in interpreting the results. Most of these models are developed based on external loading experiments conducted on rock specimens. Therefore, it is crucial to verify the applicability of these constitutive models in scenarios involving cyclic injection and fluid production. The confidence in these constitutive models can be strengthened when they are used to predict the behavior of the reservoir over longer timescales and compared with field-scale observations. The following subsection provides elaboration on field-scale studies relevant to underground hydrocarbon storage (UHS).

Table 2: Constitutive models of different rocks subjected to a load in the context of subsurface energy storage

Physics	Constitutive model	Type of rock	Characteristics
Viscoelasticity [152, 167, 68]	General Kelvin model: $\frac{\varepsilon}{\sigma} = \frac{1}{E_1} + \frac{1}{E_2}\left[1 - \exp\left(-\frac{E_2 t}{\eta_K}\right)\right]$ Fractional maxwell model: $\frac{\varepsilon}{\sigma} = \frac{1}{E_H} + \frac{1}{\eta_A^\alpha}\frac{t^\alpha}{\Gamma(1+\alpha)}$	Sandstone	Time-dependent viscosity-driven elastic behavior was shown by 18 % tight sandstone obtained from Changqing field, China [152]. Field-scale modelling shows the importance of including the viscoelastic behavior of sandstone and shows a better comparison of results with field data.
Plasticity [168, 169, 161, 157, 170]	MCC Yield surface: $\mathcal{F}(\boldsymbol{\sigma}, \varepsilon_v^p) = q^2 + M^2 p'(p' - p_c'(\varepsilon_v^p)) = 0$ Generalized plasticity : $d\sigma = \frac{1}{H_{vp}}(n_{gL/U} \otimes n)$ General cyclic plasticity model : $f^y = (q-(p+p_c)\alpha)^2 - (p+p_c)^2(M^y)^2$	Sandstone	Permanent deformation caused due to triaxial load imposed on the sandstone is modelled using cyclic MCC [167]. Combining hyperelasticity, plastic deformation, and wetting deterioration generalized plastic model was developed [157].
Creep [156, 171]	Power law: $\dot{\varepsilon}_{cr} = Ae^{-\frac{Q}{RT}}\boldsymbol{\sigma}_{\mathrm{vM}}^{n-1}\boldsymbol{s}t^{m-1}$ Linear relationship: $\varepsilon_{cr} = \frac{\sigma-\sigma_{BP}}{\eta}\Delta t$	Sandstone	Based on Norton's law and linear dependency, creep strain is derived from experimental data which is a function of time and stresses in the region.
Viscoplasticity [172, 173, 174]	Yield surface: $\mathcal{F}(\boldsymbol{\sigma}, \varepsilon_v^p) = q^2 + M^2 p'(p' - p_c'(\varepsilon_v^p)) = 0$ $\dot{\boldsymbol{\varepsilon}}^{vp} = \dot{\gamma}\frac{\partial_\sigma \mathcal{F}}{\lvert\partial_\sigma \mathcal{F}\rvert}$ and $\dot{\varepsilon}_v^{vp} = \dot{\gamma}\frac{\partial_{p'}\mathcal{F}}{\lvert\partial_\sigma \mathcal{F}\rvert}$	Shale	Viscoplasticity in shale rocks are solved for using Duvaut Lions viscoplasticity model and Perzyna based model that could also accommodate anisotropy.
Plasticity [170, 175]	General cyclic plasticity model : $f^y = (q-(p+p_c)\alpha)^2 - (p+p_c)^2(M^y)^2$	Carbonate	Plasticity model for carbonate based marble rock when cyclic load is imposed is compared with the experiment [170]. To further accommodate hyperelasticity and damage, the Drucker Prager based model is suggested [175]
Creep [176, 172, 177]	Yield surface: $\mathcal{F}(\boldsymbol{\sigma}, \varepsilon_v^p) = q^2 + M^2 p'(p' - p_c'(\varepsilon_v^p)) = 0$ $\dot{\boldsymbol{\varepsilon}}^{vp} = \dot{\gamma}\frac{\partial_\sigma \mathcal{F}}{\lvert\partial_\sigma \mathcal{F}\rvert}$ and $\dot{\varepsilon}_v^{vp} = \dot{\gamma}\frac{\partial_{p'}\mathcal{F}}{\lvert\partial_\sigma \mathcal{F}\rvert}$ Power law $\frac{\varepsilon}{\sigma} = Bt^n$	Carbonate	Viscoplastic formulation for carbonate rocks was able to be reproduced using Perzyna based formulation.
Fault stability models [178, 179, 180, 181]	Byerlee law: $\tau^{max} = \lvert\mu_c + \mu_f \cdot \sigma_n\rvert$ RSF law: $\tau = \tau^* + a\sigma_n \ln\left(\frac{V}{V^*}\right) + b\sigma_n \ln\left(\frac{V^*\theta}{D_c}\right)$ CNS law: $\tau = \frac{(\tilde{\mu}+\tan\psi)\sigma_n}{1-\tilde{\mu}\tan\psi}$	Fracture models in different rocks like carbonates	These models help in capturing the frictional behavior of faults in the reservoir to compute the fault slip and the stresses around the faults effectively.

3.2.2. Field-scale studies

Field-scale studies are conducted through the monitoring of geophysical data, simulation modeling of the storage site, or a combination of both approaches. A concise overview of field-scale works relevant to subsurface energy storage, based on monitoring data and well logs, is presented in Table 3. To obtain comprehensive real-time field data, a combination of multiple monitoring methods tailored to the specific site is employed. Past studies on CO_2 storage sites like In Salah, Sleipner, and Weyburn have utilized analytical models and field-scale measurements such as Interferometric Synthetic Aperture Radar (InSAR) and seismic surveys [40]. For instance, the In Salah site exhibited a 2 cm uplift accompanied by numerous microseismic events due to an increase in pore pressure resulting from injection into the water leg of the reservoir [40]. Among the potential causes of observed deformations at the In Salah site, hydro-fractures induced by injection pressure were considered the most likely explanation, surpassing other possibilities such as fault leakage or reactivation of pre-existing fractures [67]. To date, no significant seismic events have been reported from any CCUS storage site [30]. The case study conducted at the In Salah site, utilizing monitoring data and field tests, emphasizes the significance of geomechanical studies in understanding the various factors that contribute to ground surface deformation.

Table 3: Geomechanical studies using geodetic, analytical and experimental data

Reference	Objective	Characteristics	Summary
Vidal et al. [182] CO_2 storage site	An analytical study based on the solution of Eshelby is employed to evaluate the geo mechanical risk of fault reactivation in CO_2 storage in Naylor field, Otway Basin (Shale, sandstone)	Depleted natural gas field with a depth of 2025 m at pore pressure of 175 bar	Assuming strike-slip stress regimes, this work highlights the importance of Biot's coefficient and stress paths to find the maximum sustainable pore pressure increase for different inclined faults.
Verdon et al. [40] CO_2 storage site	Three commercial sites have been compared when CO_2 was injected for 1 megatonne/yr based on the geomechanical response monitored using geodetic methods, seismic reflection surveys and microseismic monitoring.	Sleipner (Aquifer), Weyburn (Depleted reservoir), and Salah (Depleted reservoir) in Norway, Central Canada, and Algeria.	Different monitoring methods were useful in different sites which call for site-specific characterization. Salah showed the highest uplift of up to 2 cm compared to the rest of the sites which was caused due to injection into the water leg of the reservoir.
White et al. [67] CO_2 storage site	Geomechanical study is conducted on leakage in Salah CO_2 storage site based on the hypothesis of reservoir only behavior, fault leakage, flow through pre-existing fractures and hydraulic fractures.	Salah reservoir (sandstone) suggested possible CO_2 migration in the lower portion of caprock (Shale, mudstone).	Using InSAR deformations, seismic velocity anomalies, well logs, and core measurements the probability of each of the hypotheses happening in the site is elaborated. This work also highlights the usage of diverse monitoring techniques.

Similar to CCUS, hydro-fractures or changes in pore pressure resulting from H_2 injection can lead to uplift, subsidence, and induced seismicity. The cyclic nature of UHS introduces fluctuations in pore pressure and temperature, potentially causing modifications in the intergranular structure and accelerating crack propagation and rock degradation compared to CCUS. Simulation studies are also valuable in comprehending and identifying potential critical zones within and around the reservoir. Field-scale simulators are instrumental in studying the variations in reservoir deformation and stress over time. There are many field scale simulators used to model geomechanics in gas storage sites, which include FLAC [183], OpenGeoSys[184], CODE-BRIGHT [185], VISAGE [186] and STARS [187]. These simulators can be coupled with fluid flow models to simulate reservoir-scale hydro-mechanics [188, 30, 189]. The choice of specific software depends on factors such as the advantages or limitations of the code, the type of geomechanical problem, and the available information. Table 4 provides an overview of relevant geomechanical simulation studies for subsurface energy storage.

Insights obtained from geomechanical studies are highly valuable for predicting the long-term safety of UHS technology. For instance, researchers have reported that greater subsidence occurs in regions with weak faults compared to strong faults [190], and considering rock heterogeneity in simulations leads to lower subsidence and reduced CO_2 leakage risks [191, 192]. It has also been observed that higher injection rates result in earlier reactivation of highly permeable faults compared to low permeable faults [193]. Simulations also demonstrate that considering the permeability change resulting from deformations obtained from coupled flow-mechanics simulations leads to a 13% rise in the rate of CO_2 leakage [194]. Considering the higher mobility of H_2 when compared with CO_2, this shows the importance of accounting for coupled poromechanics in the context of UHS.

Table 4: Relevant field scale subsurface storage studies to understand the geomechanical impact

Reference	Objective	Characteristics	Summary
Shi et al. [195] Eclipse 300 software	Coupled hydromechanical simulation for CO_2 injection rates. Study potential for shear failure and activation of faults in Puchkirken formation (sandstone, shale, and mudstones)	Depleted gas reservoir (Austria). Initial pressure 160 bar (depth 1.6 km).	Mohr-Coulomb criteria was used assuming the elastic response of the reservoir to simulate from 1963 to 2004. Tensile deformation of up to 2.1 cm was predicted for the pressure of 200 bar.
Vidal et al. [196] IFP Finite volume simulator + Abaqus software	Evaluate deformation, stresses, and the potential effect on faults using one-way coupling in SMB field, France (carbonates, limestone, shale). Mohr coulomb analysis was used to determine fault slip tendency.	Depleted carbonate reservoir (SMB field). Initial pressure 145 bar, temperature 65 C (depth 1.45 km)	Assuming linear elastic response, mechanical effects of injecting CO_2 showed no effect on caprock. A decrease in shear stress was observed during injecting CO_2.
Ouellet et al. [192] Eclipse + VISAGE software	3D MEM model (Mechanical earth model) is built by including geologic, seismic, logging, drilling, and laboratory test data to study the effect of CO_2 injection (one-way coupling) in Ketzin, Germany (claystone, dolomitic mudstones, anhydrites, halite).	Saline reservoir was simulated for 477 days. Pore pressure (61.5 bar)	Zechstein salt formation as caprock had to be included in the model due to its effect on the initial stress field. No effect on faults stability was observed and a minimum subsidence of 5 mm was observed.
Bergermeer field [197, 68] DIANA software	Geomechanical dynamic analysis which includes elastic and viscoelastic models to incorporate seismic slip to assess the safety of the project is conducted by considering seismic log data for calibration.	Production from gas storage site Bergermeer (sandstone, rock-salt). The largest subsidence was observed to be 10.5 cm.	It showed that injection of gas in the Bergermeer reservoir stabilizes the intersecting faults and a time-dependent viscoelastic model was necessary to capture surface heave caused due to cyclic injection and production.
Rinaldi et al. [191] TOUGH-FLAC simulator	Studying the effects of CO_2 leakage to shallow groundwater by considering stress strain-dependent permeability and its effect on leakage rates through major and minor faults.	2D simulations of two scenarios simulated in an aquifer with configurations of undetected fault and long fault.	Poor correlation was observed between the induced seismicity events and the leakage of gas stored. The heterogeneity of rocks in the subsurface showed a decrease in risk of CO_2 leakage within the reservoir.
Teatini et al. [198] GEPS3D simulator	Study the geomechanical effects of sequestering CO_2 (1 Mt/yr) in the compartmentalized offshore northern Adriatic sedimentary basin using 3D FE elasto-plastic simulator.	Aquifer (2km deep) Sandstone and shale rocks.	The effect of geomechanical constraints such as maximum allowable shear failure, initial stress regime, and fault slopes was found to be critical to predict failure. Small variations of cohesion or internal friction angle can change the rate of failure of CO_2 storage site.

Table 4 – Continued from previous page

Reference	Objective	Characteristics	Summary
Konstantinovskaya et al. [193] Tough-FLAC code	Evaluate the potential of shear failure in pre-existing high-angle normal faults and tensile failure in caprock in St. Lawrence Lowlands, Canada using a 2D geological model.	Aquifer with sandstone, shale, limestone rocks and heavily faulted	30 years of injection with no shear or tensile failure was observed with low injection rates and maximum injection pressure. High injection rates showed that high permeable faults are reactivated earlier than low permeable faults.
Zhang et al. [190]FLAC 3D	3D coupled flow and the geomechanical study was developed using seismic, structural, experimental, and structural data to assess the reservoir stability in Southern Perth Basin, Australia (Sandstone, shale, sandy clay).	Aquifer with injection rates of 3 mt/yr, simulated for 20 years at depths 2400 m.	Uplifts were found to be smaller for strong faults and with weak faults the subsidence was less than 1.85 cm for 1-5 mt/yr. No fault reactivation was observed and no upward flow discharge along the faults was observed.
Zhu et al. [188] ToughH_2-FLAC simulator	Coupled fluid flow and geomechanical modeling to study the effect of CO_2 injection in Shenhua, China.	Deep saline aquifer simulated for 10 years with a rate of 1e5 tn/yr with multilayer injection in storage layers.	A maximum uplift of 2.22 mm was induced close to the injection well. The highest uplift was observed in the first year (45 %) which depends on pressure change, injection volume, and elastic properties of the reservoir.
Norg Field [199]	Investigate the potential of fault reactivation and induced seismicity in Norg field, Netherlands using laboratory compression experiments and numerical simulation.	Gas storage site (Sandstone, rocksalt). No seismicity observed for 17 years. at different rates	Pore pressure rise, temperature difference between injected gas and rocks, and, irreversible stress paths involved with cyclic loading are investigated to have caused induced seismicity.
Bakhtiari et al. [200] Petrel + Visage software	Coupled hydromechanical tests were conducted with experimental data on the Sarajeh field, Iran to evaluate caprock integrity and risk of fault reactivation.	Aquifer with a depth of 1775 m and 3860 bar	Maximum subsidence and uplift was found to be 16 cm and 6 cm during injection and production in the vicinity of injection wells with circular displacement fields.
Bai et al. [201]	3D hydro-mechanical simulation was employed to evaluate hydraulic and geomechanical effects during 3 annual injection-production cycles in the Powder River basin, Wyoming.	Saline aquifer with a depth of 2510 to 2555 m with sandstone and shale rocks	A maximum magnitude of 1.6 cm uplift was observed from simulation. Mohr coulomb criteria was used to demonstrate the safety of the storage scenario.
Zeng et al. [202]	Geochemical modelling of UHS using kinetics in Majiagou carbonate formation, China to assess the risks associated with the dissolution of carbonates and loss of H_2.	Carbonate natural gas reservoir with calcite, dolomite, and small amounts of quartz, pyrite, and feldspar	H_2 loss of 6.5 % at 0.5 years, 7.6 % after 5 years and 77.1 % over 3000 years was observed conclude that the site is suitable for short term UHS. Weakening of host rock, caprock, wellbore, and formation of methane was observed from calcite dissolution.

The risks associated with storing CO_2 and methane largely coincide with those of storing H_2, albeit with additional complexities arising from the disparities in physical and chemical properties of the stored fluid, as well as the cyclic operating conditions. Swelling of overburden clay can occur due to the change in pH caused by the H_2 injection, which results in permeability decrease and tighter storage [203]. However, due to higher diffusion, leakage risks into caprock can be higher compared to methane or CO_2 storage sites. The properties of fault friction and fracture propagation rates can vary if there are changes in the rock properties along the fault plane due to chemical reactions. Figure 7 illustrates the fault slip and the surrounding seismic waves caused due to H_2 injection in the subsurface.

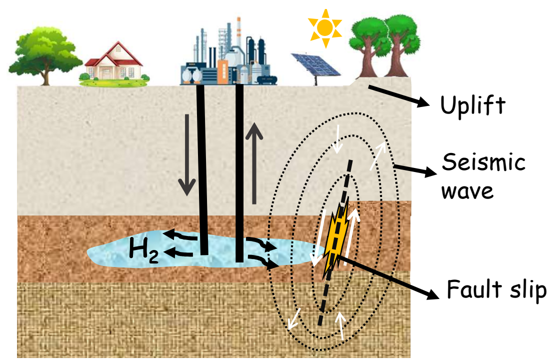

Figure 7: Schematic of H_2 injection-induced fault slip and the surrounding seismic waves in the subsurface. Adapted from [30, 204].

In the case of gas production, the Groningen field in the Netherlands serves as a well-known example of induced seismicity [205]. Since the 1990s, there have been over 1000 recorded events with magnitudes greater than 1 in this field [206], and numerous studies have been conducted on this topic, encompassing numerical, analytical, and field-scale investigations. Numerical finite element simulations have shown the influence of production rate on seismic activity [207], particularly regarding the impact of fault offset in the reservoir, which leads to varied and intensified stresses on the fault caused by depletion [206]. Recent studies have also examined the effects of rupture nucleation and arrest in depleted gas fields [208]. Analytical studies have provided valuable insights into shear stress patterns resulting from injection and production in reservoirs with offset faults [209], as well as proposing advancements in fault modeling within numerical simulators to address convergence issues [210].

Usually, simulations assuming elasticity along with pressure boundary conditions are employed to study the propagation of fractures [30]. In the case of cyclic injection and production of H_2, incorporating inelastic deformations and considering the possibility of tensile and shear damage can become important to model the sealing capacity of the reservoir [211, 212, 213]. Caprocks such as shale are rich in organic substances [17] and microbes. The interaction of H_2 with shale caprock can result in the loss of H_2 and the production of different chemical compounds, further weakening and degrading the rocks. However, these factors are often not adequately considered in reservoir-scale simulation studies.

Although numerical simulations offer valuable output, their effectiveness is tied to the accuracy of the input parameters they rely upon. The coupled models demand numerous input parameters, some of which, like those related to geomechanical-geochemical interactions, may not be easily obtainable from laboratory-scale experiments or the parameters obtained from laboratory scale are not relevant in the fieldscale. In certain cases, simpler analytical models can therefore be privileged, because they still produce reasonable results, relative to the uncertainty surrounding the input parameters. Still, conducting meticulously-planned field research for demonstration-scale projects is crucial. Specifically, direct observations through field site characterization and monitoring campaigns are essential to reduce the uncertainty of the input parameters of the numerical models.

Despite the significant knowledge accumulated over the years, particularly in the context of natural gas and CO_2 storage, there are still several gaps that need to be addressed to fully understand underground hydrogen storage. These gaps and research needs will be discussed further in the following section.

3.3. Mitigation measures

Mitigation strategies for the geomechanical hazards of UHS are crucial to ensure the safe and sustainable operation of storage sites. One of the most suitable prevention measure for any geomechanical hazards is to choose a site with complete geomechanical characterization of the storage reservoir and caprock to understand the rock properties, stress distribution, and potential failure mechanisms. This information is crucial for designing appropriate storage operations and assessing the long-term stability of the reservoir. Characterisation of the lithology also helps in identifying bio-chemical reactions which degrade the stored hydrogen. The microbial alteration of the rock properties needs to be mitigated to ensure the mechanical stability of rocks. A possible strategy is to employ biocides to deter microbial activity to mitigate souring and degradation of the growth of sulphur-reducing prokaryotes [214]. Moreover, the adsorption of biocides onto the reservoir rock surface and their flow through fractures or biomass plug will safeguard against microbial growth in the area. Other methods to inhibit microbial impact include nitrate injection [215] and perchlorate treatment [216, 217]. A detailed review of these methods is presented in the recent literature [218]. Porous reservoirs may experience permanent deformation that results in volume loss. To mitigate that, careful management of injection and withdrawal rates is necessary to avoid excessive pressure changes that would lead to induced seismicity. A detailed mapping of the faults is necessary for the implementation of robust seismic monitoring. In supplement, early warning systems can detect any signs of geomechanical instability or leakage in real time. As a result, operators can implement preventive measures proactively.

These measures may include adjusting injection or production rates, altering pressure management strategies, or even temporarily halting operations if necessary. Regular risk evaluations can help adapt and improve mitigation strategies over time. In addition to the structural integrity of the storage system, ensuring the integrity of wellbores is vital to prevent any leakage. Proper well construction, cementing, and regular monitoring are essential to detect any potential issues and take corrective actions promptly. In conclusion, robust mitigation strategies are of paramount importance to control the geomechanical hazards of UHS. It not only ensures the safe and sustainable operation of hydrogen storage facilities but also contributes to the acceptability of hydrogen as a viable and reliable energy solution.

3.4. Research recommendations

- Effect of pressure and temperature of the injected H_2 on reservoir stability should be analyzed in detail through both laboratory scale and field-scale trials. The area of influence and effect of the pressure and temperature fluctuations closer to the injection wellbore should be constrained and the resultant influence on stress configuration and fault reactivation should be emphasized.

- The effect of biofilm growth and chemical interaction between reservoir rocks and microbes on reservoir mechanical properties needs further investigation. More emphasis should be given to studies conducted at reservoir equivalent temperature, pressure, saturation (H_2 and brine), pH, and salinity conditions.

- Heterogeneity in reservoir rocks and especially heterogeneity in caprocks plays a critical role in governing reservoir efficiency and leakage potential. Detailed analysis of time-dependent deformation in both reservoir rocks and caprocks should be carried out at in-situ P-T conditions for developing a concrete idea on the operating window for the rate and pressure of H_2 injection and production.

- There is still no consensus in terms of the validity of the Kaiser effect in H_2 reservoirs and caprocks, which will, in turn, govern the mechanism of H_2 injection as a pore fluid. More lab experiments and field-scale research should be analyzed to establish a governing relationship between seismicity and H_2 injection strategies.

- Understanding the chemical reactivity of H_2 and brine with reservoir rocks is extremely important. Contaminant gases and organic acids forming in reservoirs due to microbial influence can have higher reactivity towards reservoir rocks compared to H_2 itself. Such clarity should be developed before attempting field-scale operations.

- Usually, all the constitutive models are developed based on data obtained from tests with external loading (triaxial or uniaxial). However, loading caused by cyclic injection and production of H_2 in porous rock will give more insight into the variation of deformation which can also depend on the type of stored liquid, as it reflects better the type of loading experience by the reservoir.

- Performing progressive swelling and shrinkage cycles in a laboratory scale using H_2 as the fluid is imperative to enhance understanding of the behavior of rocks. The sensitivity of swelling in different clay minerals and carbonates should be studied to scope appropriate host rock for H_2. Understanding the competitive sorption of H_2 in the presence of different brine compositions should be given paramount importance.
- Coupled hydro-mechanical modeling of field scale reservoir sites with faults and fractures, solving not only for elasticity but also plasticity, under imposed cyclic injection and production of H_2, would be very important to perform sensitivity analysis of the reservoir by studying the impact of different parameters.
- Reservoir and caprock integrity tests should be performed using risk-based probabilistic methods such as Monte-Carlo simulations which can help in quantifying the effect of different input parameters and in detecting critical regions such as high-stress regions or leakage pathways.
- Effective monitoring methods need to be investigated to allow for the assessment of long-term UHS with the partially unknown characteristics of cyclic loading. The efficacy of advanced monitoring techniques such as time-lapse seismic surveys or fiber-optic sensors should be tested to ensure continuous safe storage.

4. Salt caverns

Salt caverns are a viable option for H_2 storage. They have been used for storage and disposal purposes for many decades, accompanied by great successes. The properties of salt rock that make it such a good storage unit include low permeability, chemical inertness, solubility in water, mechanical stability, and self-healing. Despite its apparent attractiveness, the use of salt caverns for large-scale storage of H_2 should be preceded by careful experimental and numerical analysis. This is because H_2 presents some particularities in terms of fluid properties (e.g. low viscosity, small molecules) and loading conditions during storage (cyclic) that are not exactly encountered in other applications.

Figure 8 illustrates the processes and potential challenges involved with UHS in salt caverns. An important aspect to be considered is the mechanical behavior of salt rock under cyclic loading due to the intermittent production of green H_2. Furthermore, the interaction between adjacent caverns in a multicavern system under fast cyclic loading conditions is also a matter of concern. Other physical processes are related to crack formation and propagation (which can lead to gas leakage), thermal stress effects and influence of interlayers, heterogeneity, and microbial activity. As discussed for the depleted reservoir section, all these processes need to be understood and properly modeled to ensure safe and efficient operations.

In the following subsections, we start from the construction of salt caverns, as this is the beginning of stress disturbances in the salt formation, and proceed with a brief review of the usage of salt caverns for storage and disposal purposes. Next, we present the most important deformation mechanisms involved in salt rock mechanics. The particular aspects related to H_2 storage in salt caverns, as depicted in Figure 8, are discussed in the sequence. Once all phenomenological aspects are covered, we present a review of current constitutive models for rock salt mechanics and numerical models for salt cavern simulations. To close this section, research recommendations are presented based on the above discussion.

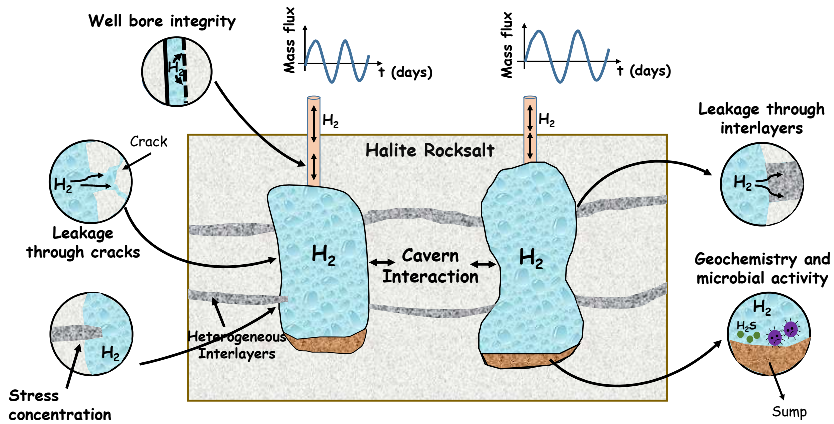

Figure 8: A schematic of UHS in salt caverns highlighting the geomechanical challenges and probable effects.

4.1. Construction aspects

Salt caverns refer not only to naturally formed cavities but can also be man-made in salt deposits. The construction of a salt cavern starts by drilling a well with two annular tubes into a suitable salt formation. Figure 9 shows the leaching process of caverns involving four phases. Fresh water is injected to dissolve the salt rock and create the cavity in a process known as solution mining, or leaching [219, 220]. Additionally, to protect the cavern's roof from excessive leaching, a blanket pad of diesel or nitrogen is employed. During the leaching process, the cavern shape must be carefully designed to promote mechanical stability [221], as this is one of the major concerns for the subsequent energy storage [222, 223, 220]. The shape of the cavern can be controlled with the position of the annular tubes, the blanket pad depth, the flow direction (freshwater injected through the inner tube and brine discharged from the outer tube, or vice-versa), water flow rate and duration of injection [220, 223]. Cavern shape and volume depend on the type of salt formation. Salt domes are tall and narrow cylindrical structures composed of mostly halite and are ideal for creating caverns with large storage volumes. Bedded salt formations, on the other hand, consist of alternating layers of salt and non-salt (anhydrites, shale, carbonates), resulting in shorter, wider caverns with smaller volumes. The presence of non-salt formations causes distorted shapes and can also compromise the permeability of the formation [224]. In this type of salt formation, horizontal caverns [225, 226] built with two wells can also present feasible storage volumes and stability [219].

4.2. Storage and disposal applications

Salt cavern technology has matured over many decades, with the first reported usage for storage in Canada in the 1940s [227]. In the US and EU during the 1950s, salt caverns were used for storing hydrocarbon derivatives [63] and crude oil [35]. Today, natural gas storage is the most common application of salt caverns [34], which started in the 1960s in the US [228] and England [229]. Currently, there are over 500 operational salt caverns around the world, with their usage increasing from 11% to 25% in the US between 1998 and 2008 [230]. A less common use for salt caverns is the mechanical energy storage through compressed air (CAES) [36, 37, 38], located in Germany, US, and Canada. H_2 storage in bedded salt caverns is not new, with the first report dating back to the 1970s in Teesside, UK [224]. Since 1986, H_2 operations in caverns built-in salt domes have been carried out in Clemens Dome, Texas (US). Recently, two more H_2 storage sites (Moss Bluff and Spindeltop) in the US have been commissioned [11]. Technical details of current operational plants are summarized in Table 5.

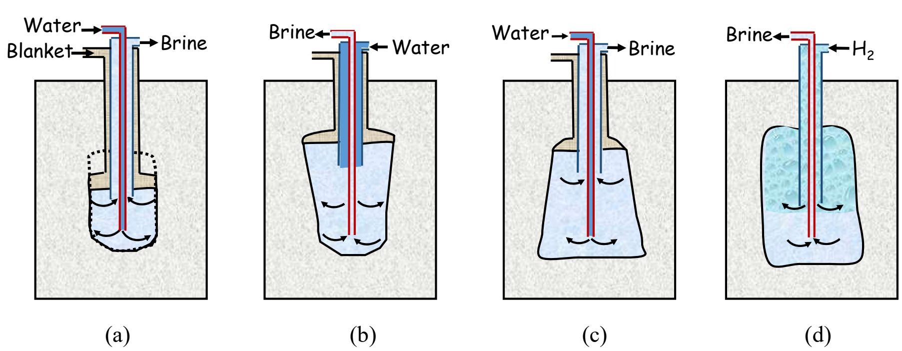

Figure 9: The above figures show the construction process of a salt cavern. Figure (a) shows the leaching phase, (b) shows the water injection from the top favoring the expansion of the upper part, (c) shows the water injection from the bottom favoring the expansion of the lower part, and lastly (d) is the debrining phase where gas is injected from the top.

Table 5: Current Hydrogen Storage Projects in Salt Caverns. Adapted from [231].

	Teeside (UK)	Clemens Dome (Texas, US)	Moss Bluff (Texas, US)	Spindletop (Texas, US)
Salt formation	Bedded salt	Salt dome	Salt dome	Salt dome
Operator	Sabic Petrochem.	Chevron Phillips Chem. Comp.	Praxair	Air Liquide
Commissioned	1972	1986	2007	Information not available
Volume (m^3)	210 000	580 000	566 000	906 000
Mean cavern depth (m)	365	1 000	1 200	1 340
Pressure range (bar)	45	70-135	55-152	68-202
Net energy stored (GWh)	27	81	123	274

Salt caverns have various applications beyond energy storage. They have been explored as an option for CCS to facilitate the mitigation of greenhouse gases [39]. In Brazil, salt caverns are being considered to store CO_2 from petroleum production in pre-salt reserves [232]. Additionally, abandoned salt caverns have been used for the disposal of solid industrial waste like alkali waste from soda industries, which also increases the structural stability of the cavern [41, 42]. The mechanical properties of salt rock also make it an appropriate option for nuclear waste disposal [43, 44].

As with many underground operations, the use of salt caverns for storage purposes is not free from risks, and safety regulations must be strictly followed. Undesired outcomes from salt cavern operations comprise excessive cavern convergence (i.e. loss of storage volume) [233, 234, 235], roof collapse [236, 237], fluid leakage [62], among other events [63]. For this reason, caution must be taken in defining operational limits in salt caverns.

4.3. Mechanics of rock salt

To safely store H_2 in salt caverns, it is crucial to understand the mechanical behavior of salt rock. Halite, the main component of salt rock, is made up of sodium chloride crystals with some impurities in the lattice structure. The lattice structure has micro-sized sub-grains that form larger millimeter-sized grains. Salt rock's mechanical behavior is affected by defects in its crystal lattice, which allow for creep, a well-known time-dependent deformation mechanism [238, 239]. Creep deformation occurs in three stages: primary, secondary, and tertiary as shown in Fig. 10-a when a constant deviatoric load is applied. During primary creep, dislocation movement of the lattice structure occurs rapidly, but the strain rate decreases as dislocations pile up and create barriers. In the secondary stage, a recovery process takes place, and the strain rate stabilizes at a constant level. Depending on stress conditions, tertiary creep can eventually occur, characterized by micro-crack propagation, leading to brittle failure.

The secondary creep stage is particularly important in salt caverns for assessing their long-term applicability. Two different deformation mechanisms induce secondary creep, namely dislocation creep and pressure solution creep. The so-called dislocation creep accounts for most deformation under moderate stresses. The dislocation creep is proportional to the magnitude of stresses raised to the power 3.5-5.0 [239] (see Figure 10-b). The pressure solution creep mechanism [240], on the other hand, is inversely proportional to salt grain size and directly proportional to the stress level, and is important in low-stress regions (Figure 10) (< 5 MPa) such as regions far from the cavern walls. Dislocation creep is dominant in higher-stress regions, like near-cavern areas. Predicting strain rates only with a dislocation creep mechanism underestimates creep strain rates for low stresses.

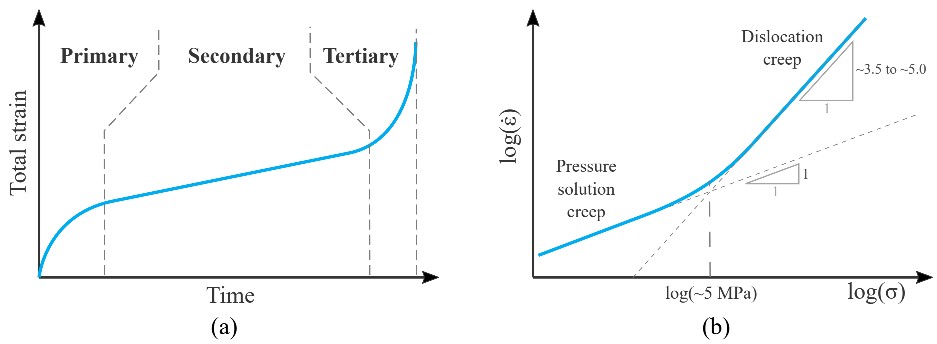

Figure 10: (a) Creep stages at constant stress and (b) strain rate during secondary creep for different stress levels.

Experiments with salt rocks [241, 242, 243, 244, 245] show two distinct regions in the stress space where salt rocks exhibit different behaviors, as shown in Fig. 11 for $I_1 - \sqrt{J_2}$ stress space, I_1 and J_2 being the first stress invariant and second deviatoric stress invariant, respectively. In the compressibility region, irreversible volume decrease occurs (recovery process), and micro-cracks tend to close, preventing long-term failure (point A in 11). By increasing confining pressure and/or deviatoric stress, the salt-rock moves to the dilatancy region (e.g. point B), as indicated in Fig. 11. The dilatancy region, on the other hand, is characterized by irreversible volumetric strains caused by micro-crack openings, allowing for long-term failure due to tertiary creep.

The Compressibility/Dilatancy (C/D) boundary is a band [242] that spreads at higher confining pressures, separating compressibility and dilatancy regions. This band is represented in Fig. 11 by the shaded area. The short-term failure boundary is where the material can fail without going through all stages of creep. The dilation boundary is important for designing minimum working pressure in salt caverns to avoid long-term failure due to accelerated creep [246]. Ideally, salt caverns should always operate inside the compressibility region to avoid the opening and propagation of cracks on the cavern walls. In practice, this is achieved by increasing pressure inside the cavern, as it alleviates compression of the surrounding rock salt. However, too much pressure can cause tensile stresses, and since salt rocks have low tensile strength, they can experience short-term failure and ultimately lead to roof collapse.

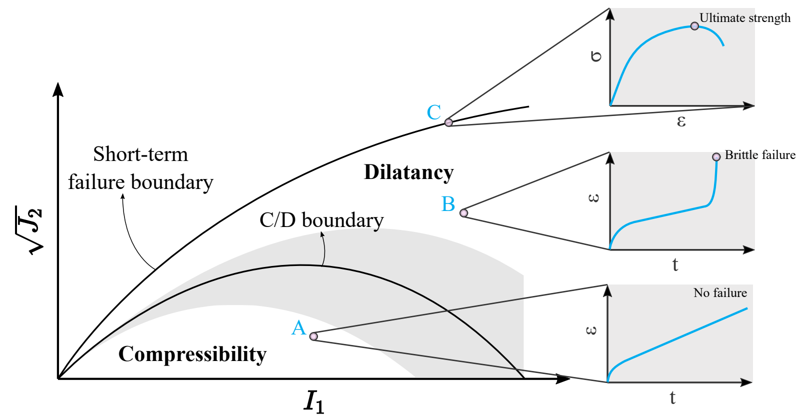

Figure 11: Compressibility and dilatancy regions. Points A and B illustrate the mechanical behavior of salt when operating in the compressibility and dilatancy regions, respectively. Point C depicts the brittle failure when the stress reaches the short-term boundary.

4.4. Particularities of UHS in salt caverns

As discussed before, the application of salt caverns for either energy storage or waste disposal has a long history with significant experience accumulated throughout many decades. Although H_2 storage has been carried out since the 1970s, the small number of H_2 plants and the specific conditions of each one do not allow for a thorough understanding of all the aspects related to large-scale H_2 operations. In the following subsections, we discuss possible issues that can arise during H_2 storage in salt caverns.

4.4.1. Cyclic loading

When CO_2 is disposed of in salt caverns, the interior pressure on the walls rises during injection and gradually decreases over time. Long-term creep effects should be the primary concern unless one chooses to recover this CO_2 (for reinjecting into oil reservoirs, for example). The loading signature for natural gas operations is more closely related to energy usage on a seasonal basis. Natural gas availability is largely stable because it is primarily generated from gas reservoirs, so salt cavern internal pressure tends to follow a moderate frequency of injection/production (periods from weeks to months). On the other hand, the production of compressed air (CAES) and H_2 from renewable sources are inherently intermittent, as they depend on weather conditions. Therefore, in these applications the cyclic loading frequency tends to be much higher, ranging from some hours to a few days [247]. As mentioned before, only three CAES plants are currently in operation. The Teesside H_2 storage project in the UK is operated at constant pressure by injecting brine to displace H_2 from the salt cavern. No literature was found about the operating conditions of the other plants in the US. The bottom line is that, although the use of salt caverns for storage purposes is a well-known technology, in very few cases the cyclic loading conditions match those of H_2 storage operations.

Experimental investigations have been conducted to study the effects of fast cyclic loading on salt rocks, although practical experience in this area is limited. Cyclic loading can affect not only elastic properties but also reduce/increase short-term peak strength, modify the C/D boundary, and accentuate tertiary creep. Researchers have shown that the elastic modulus tends to degrade with increasing cycle number, but independent of the stress conditions [248, 249]. Viscoplastic deformations such as transient and steady-state creep are highly affected by cyclic loading frequency [248]. The position of the dilation boundary is not affected by cyclic loading, and the creep rate is not significantly affected unless the stress condition is in the dilation region [250]. However, cyclic loading can reduce the peak strength of salt by up to 30% [246], and the maximum applied stress has a major influence on the fatigue life of salt rock [251, 246, 248]. Fatigue failure can only occur in the dilation region [80, 249, 248], and the closer the stress is to the short-term failure boundary, the shorter the fatigue life [251]. The fatigue limit is suggested to be at 75% of compression strength, below which the number of cycles does not influence the accelerated creep [251]. Temperature seems to increase the fatigue life of salt rocks. More recently, numerical simulations of caverns operating under cyclic loading have shown that cavern volume convergence without considering fatigue effects is approximately 6%, whereas volume shrinkage is almost 29% when fatigue is considered [252]. The results available in the literature suggest that high-frequency cyclic loading, which is associated with UHS, and fatigue effects have a strong influence on the safety and stability of salt caverns.

4.4.2. Thermal effects

Temperature variations within salt caverns can have detrimental effects on mechanical stability, warranting careful investigation. Two mechanisms can disrupt temperature distribution during cavern operations. The first is caused by the Joule-Thomson effect, resulting in temperature shifts due to pressure changes. Most gases, like natural gas, display a positive Joule-Thomson coefficient, causing cooling during pressure drops. However, gases like hydrogen experience heating with pressure reduction (negative coefficient) [253]. In-depth thermodynamic comparisons between natural gas and hydrogen are provided in [254, 255]. Consequently, the gas temperature is anticipated to fluctuate during the injection and production phases. For natural gas, fewer cycles per year allow pressure-related temperature disturbances to permeate cavern walls more deeply. In contrast, frequent hydrogen cycles tend to limit temperature effects to a thin layer at the wall [256]. The second mechanism concerns natural convection streams that can develop within the cavern. This phenomenon heavily relies on injected gas temperature, brine temperature at the cavern base, and the mass rock's geothermal gradient. Cooling gas at the cavern base ascends due to buoyancy, transferring heat upwards. Despite its significance as an efficient heat transfer mechanism, it's often overlooked [257].

Temperature fluctuations impact various deformation mechanisms. For instance, creep is highly dependent on temperature, which is usually described by Arrhenius law [239]. Additionally, short-term failure boundary can also be affected by temperature [258, 259]. Although it is not entirely clear to what extent these two effects are significant – considering that only a thin layer close to the cavern wall is affected by temperature variations – thermal stresses can still play an important role. This is because temperature drops induce tensile stresses tangential to the cavern walls that can easily exceed salt rock tensile strength, thus potentially creating spalling and fractures normal to the cavern walls [257]. For natural gas, this happens during the withdrawal phase, where both pressure and temperature go down. This leads to two opposing mechanisms, where pressure decrease induces compressive stresses along cavern walls, whereas temperature decrease induces tensile stresses. For hydrogen, however, temperature decreases occur during injection, where pressure builds up reducing compressive stresses. Therefore, the possibility of fracture propagation and spalling might be even higher when the cavern is cyclically operated with hydrogen.

4.4.3. H_2 percolation

Although salt rock is regarded as being inert when in contact with H_2 [260], the possibility of H_2 percolation is still a concern as it would represent the failure of containment and could potentially alter the mechanical behavior of the surrounding salt rock. Permeability of undamaged salt rock is extremely low, with the atomic space in the crystal lattice of halite in the order of 30 pm [261]. Because H_2 atom size is in the order of 100 pm, permeation by diffusion through salt rock lattice could not occur [262]. Nevertheless, the concern still holds mainly based on the fact that H_2 is known to cause embrittlement in metals due to the percolation of H_2 protons through the metal lattice. However, as pointed out in [262], the production of H_2 protons through ionization is not possible in the presence of halite, so this should also not be a problem.

H_2 percolation only happens when there are open cracks on the cavern walls, so avoiding operations in the dilatancy region prevents both H_2 percolation and long-term failure due to accelerated creep. As mentioned in subsection 4.4.2, thermal stresses can create fractures in the cavern walls, which could potentially be an additional pathway for H_2 leakage. If H_2 percolation occurs through open cracks, there could be mechanical impacts, such as additional pore pressure that modifies the effective stress on the salt rock structure [263]. Pore pressure affects the peak strength and permeability of rock salts [264]. The effect of pore pressure on the dilatancy boundary has also been investigated in [265], where the Biot's coefficient for Asse rock salt was also measured.

Salt rocks may contain small amounts of water that enable pressure solution creep [240]. H_2 percolation through salt grains can suppress pressure solution creep by causing water desiccation [266]. However, this is more likely to occur in the near-wall region, where pressure solution creep is not a dominant deformation mechanism. Water content also promotes the healing ability of salt rocks (or recrystallization) [267], so reducing water content in cavern surroundings can suppress healing where it is most needed. Failure to recover micro-cracks can aggravate H_2 percolation, potentially creating a vicious cycle. The effects of water desiccation in salt rocks due to H_2 percolation have not been reported in the literature, making it difficult to predict the extent of these effects and their impact on salt cavern operations.

4.4.4. Heterogeneity

As mentioned before, salt domes are composed of pure halite, so heterogeneity is not expected to be prominent in this environment. Salt domes are in general considered as being suitable for UHS [11]. On the other hand, the presence of non-salt interlayers in bedded formations introduces a strong heterogeneity that should be considered to study the geomechanical behavior of the salt cavern. However, from a purely mechanical perspective, the effect of heterogeneity for H_2 operations should not differ from the storage of other gases. Nevertheless, one should keep in mind that while non-salt interlayers with permeability higher than the surrounding salt rock would not compromise containment of other gases (e.g. natural gas, air, CO_2), they could potentially represent leaking pathways for H_2 due to its low viscosity and small molecular radius [224, 268].

4.4.5. Microbial activity and geochemical reactions

Salt rock is known to be inert concerning H_2, so no undesired reactions should be expected in this regard [269]. Following the debrining phase, a residual brine quantity lingers within the cavern's sump. This residual brine can evaporate and potentially mix with H_2, necessitating surface treatment for H_2 dehydration. Furthermore, sulfate-reducing bacteria (SRB) can generate H_2S in the presence of sulfate (primary electron acceptor) and H_2 (electron donor). Sulfate is typically present in anhydrite layers on cavern walls or within the sump [270]. Consequently, for H_2S prevention, salt formations with highly pure halite are preferable. Essentially, bedded salt formations are more susceptible to H_2S production compared to caverns constructed within dome salts. Furthermore, findings indicate that microbial activity can be limited by factors such as low temperature, low pressure [231], and high salinity [271]. Analogous to water vapor, H_2S production compromises H_2 purity, necessitating its removal at surface facilities. Speculation has arisen about whether the presence of H_2S might diminish the self-healing capacity of salt rock [151] or other mechanical properties. Nonetheless, salt caverns have been employed for H_2 storage over extended periods, and no related issues have been reported thus far.

4.5. Multi-cavern storage systems

Salt cavern size is limited by mechanical stability and the salt formation they are built in. Storage volume can range from 10,000 m^3 to 1,880,000 m^3 [272]. To put it into perspective, the Groningen gas field in the Netherlands has a storage volume of approximately 2 billion m^3 [273]. In a recent study [274], it has been shown that 28 thousand caverns could be constructed in Australia to store 14 thousand PJ of hydrogen energy. As the need for large-scale energy storage increases, it is important to develop systems of multiple salt caverns. However, the interaction between adjacent caverns must be carefully considered. Several researchers have examined the minimum safe distance that should be maintained between two caverns. Wang et al. [275], studied safe pillar widths for caverns constructed in bedded salt formations and suggested that a distance of 2 to 2.5 times the maximum diameter should be kept between two adjacent caverns. The distance between a salt cavern and possible faults should also be at least two times the cavern's diameter [276]. However, more conservative approaches have suggested that a distance of three diameters should be sufficient to eliminate most mutual interactions [277]. It has been shown that the proximity between two caverns can increase damage when compared to a single cavern operation [277], and damage evolution in a double cavern layout has been studied in [278], who adopted a small distance of 0.3 times the diameter. The authors demonstrated that damage slowly evolves over time, mainly affecting cavern walls that are close to each other, and that its effects tend to be minimized for higher internal pressure. Recently, Peng et al. [279] investigated the mutual interaction between two caverns in bedded formations concerning pillar width, number of inter-layers, thickness and dip angle of inter-layers, and the pressure difference between the caverns. Although numerical simulation is the primary method for investigating cavern systems, experiments with physical models can provide valuable information for understanding the complex physics involved and for the verification of numerical models. For example, Zhang et al. [280] conducted experiments with a system of four reduced-size caverns built from the Jintan salt mine. They investigated gas injection/extraction rates, gas loss impact, pillar width, the pressure difference between caverns, and tertiary creep.

In recent years, there has been an increasing interest in researching multi-cavern systems for gas storage, but the literature in this field is still relatively limited. There is a particular lack of research on systems of salt caverns suitable for UHS. As shown in Table 6, most of the works found in the literature consider either constant internal pressure or cyclic loads with periods ranging in the order of months (most of them refer to natural gas storage). Only one study, by Wang et al. [252], has investigated cyclic loads with daily injection/production of gas in the context of compressed air energy storage (CAES), which is more similar to the cyclic loads associated with H_2 operations. Although research specifically dedicated to fast cyclic loading for H_2 storage is still needed, the existing investigations on systems of caverns for different cyclic loading frequencies can still provide valuable insights.

Table 6: Types of salt formation and loading conditions investigated in different works.

Reference	Salt formation	Loading condition	Period	Summary
Wang et al. [252]	Dome	Cyclic	Days	Investigated the influence of fatigue in cyclic operations. Concluded that fatigue can significantly enhance cavern closure.
Bruno et al. [277]	Bedded	Cyclic	Months	Considered systems with different cavern shapes and loading conditions. The goal was to identify a minimum safe distance.

Wang et al. [275]	Bedded	Cyclic	Months	Studied safe width of pillars between caverns. Concluded that asynchronous injection/production in adjacent caverns is harmful for stability.
Wang et al. [276]	Bedded	Cyclic	Months	Analyzed the interaction between cavern/cavern and cavern/fractures.
Yang et al. [230]	Bedded	Cyclic	Months	Presented a feasibility study to use abandoned salt caverns for UGS. Proposed safe operational conditions.
Yin et al. [281]	Bedded	Constant and cyclic	Months	Studied the influence of microleakage interlayers (MLI) in the system of caverns and concluded that they have little effect.
Deng et al. [278]	Dome	Constant	–	Stability analysis using deformation reinforcement theory (DRT)
Peng et al. [282]	Bedded	Constant	–	Analyzed stability for a system of caverns with interlayers. Proposed a comprehensive stability evaluation index.

4.6. Numerical simulations

Understanding the mechanical behavior of salt rocks allows for devising and implementing constitutive models in numerical simulators. Salt cavern simulation is a crucial tool for managing and planning operations, by enabling the testing of different scenarios. While the literature on salt rock models is vast, this subsection provides a brief overview of some main constitutive models for salt rock mechanics. In the sequence, a review of different approaches for full-scale salt cavern simulation is provided.

4.6.1. Rock salt constitutive modelling

Salt rocks exhibit complex behavior with different deformation mechanisms, but the significance of specific phenomena depends on the intended application. For instance, in salt cavern waste disposal, secondary creep (dislocation and pressure solution) and possibly accelerated creep are dominant deformation mechanisms, making transient creep less significant. Some researchers thus develop constitutive models to account for specific processes rather than complete models.

A well-known example is the (Norton) power-law model for dislocation creep [239], which takes temperature effects into account via the Arrhenius law, and it has been extensively applied [266, 247]. A specific model for pressure solution creep has also been proposed in [240], which is formulated similarly to Norton's creep law, but with a linear dependency on stress and inversely proportional influence of the grain size. It has been shown that Mohr-Coulomb and Drucker-Prager criteria are not able to accurately capture short-term failure boundary [283]. Instead, the Hoek-Brown [284] and the Generalized Hoek-Brown [285] show better agreement with experimental results. The viscoplastic model proposed in [286], in addition to describing the short-term failure boundary, also provides a model for the dilation boundary and a dependency on the stress condition, characterized by Lode's angle. The tertiary creep stage is usually modeled by damage mechanics, and several models have been proposed for salt rocks [283, 287, 288] and also including fatigue effects [289, 290, 291]. The Kelvin-Voigt element is employed in the extended Nishihara model [292] to model transient creep and the generalized Kelvin-Voigt model is adopted in [288]. Similarly, the Kelvin-Voigt element with a stress-dependent viscosity dashpot is adopted in the LUBBY2 model [293], and a fractional derivative model is developed in [294]. In a different approach, the viscoplastic model proposed by [286] has been employed in [247] for modeling transient creep behavior. Other models that should not go unmentioned are the Hou/Lux model [295, 296], the Multi-mechanism Deformation (MD) model [297, 298], the double mechanism creep law [299, 300], and many others [301, 302, 303, 304]. A more detailed review of constitutive models for salt rock is presented in [263].

The fast cycles associated with H_2 operations constantly change the stress conditions applied to the salt caverns, which causes the transient creep stage to be always present. As a consequence, an effort should be made to employ constitutive models that appropriately consider this type of deformation. Moreover, the constitutive model should also comprise fatigue effects, in case the salt rock operates in the dilatancy zone (the effects of cyclic loading and fatigue are discussed in the next section).

Existing models in salt rock mechanics encompass physical phenomena such as short-term/long-term failure, various creep stages, healing, and cyclic loading fatigue. However, uncertainties (e.g. heterogeneity of the salt formation, non-salt interlayer characteristics, in situ stress conditions, etc) must also be considered for underground applications. In addition to a proper calibration against laboratory experiments on field samples, uncertainty quantification, and sensitivity analysis to identify the impact of different parameters are also important to ensure realistic simulations. Nonetheless, proper constitutive models in numerical simulators already provide a powerful tool for predicting salt cavern behavior for storage.

4.6.2. Salt cavern modelling

In addition to appropriate constitutive models for salt rock mechanics, the simulation of UHS in salt caverns also requires geometrical information (cavern shape) and operational conditions (internal pressure). Moreover, sufficiently detailed geological characterization of the site – which includes salt formation type, underburden and overburden conditions, and presence of non-salt interlayers – is also necessary. Several numerical models have been developed to study gas storage in salt caverns, and they differ from each other according to the specific application goals. For instance, damage models are included when long-term failure is to be investigated [296, 288, 252]. For other applications, the focus lies on long-term effects [278, 252], such as pressure solution creep [305] and cavern closure [306]. The presence of non-salt interlayers [307, 226, 308, 281, 266, 282] and the interaction of multiple caverns [275, 230, 281, 266, 282, 252] are also often investigated. Of special interest for hydrogen applications is the behavior of salt caverns under fast cyclic loads. In this regard, studies can be found in which fast cycles are applied to the simulations [248, 309, 252], mainly in the context of CAES. Although these simulations are performed after proper validation against laboratory experiments (e.g. triaxial and uniaxial tests), very few of them perform validations with in-situ field measurements [310, 308, 280].

4.7. Hazards and preventive measures

The use of salt caverns for storage or disposal purposes can cause undesirable consequences with varying degrees of severity. For instance, there are reports of salt caverns that lost 30 to 40% of their initial storage volume due to creep closure [234, 233, 235]. While this, in principle, might not represent an environmental or safety risk, it results in major financial impacts. More severe accidents, such as explosions due to leakage of liquefied petroleum gas have also been reported [311]. As suggested in the literature [312], risks associated with salt cavern operations can be grouped into three major categories: cavern failure, gas leakage, and ground subsidence. Cavern failure includes excessive cavern closure, spalling and crack propagation in the cavern walls, and interaction between adjacent caverns due to insufficient pillar width. All of these problems can be prevented by appropriate cavern design and operational conditions (pressure and temperature). Ground subsidence is also a matter of concern when it comes to underground operations. For salt caverns, however, subsidence is relatively small [311] and within acceptable ranges [312]. On the other hand, gas leakage can bring – in addition to the loss of storage product – serious consequences such as contamination and even explosions. The stored gas can either leak due to equipment failure (damaged valves and/or casing shoe, human error, etc.) or cavity cracks [312]. Included in the gas leakage problem is the possibility of blowouts, which are characterized by uncontrolled gas flow through the well, often followed by a jet fire. Such a phenomenon occurred in 2004 at the Moss Bluff facility in Texas, and it lasted for six days until the fire was finally extinguished. A theoretical study on blowout predictions for salt caverns is presented in [313]. When the leakage occurs through wall cracks, the gas can contaminate aquifers or accumulate below buildings, which can cause catastrophic explosion [63]. These problems can be avoided by proper maintenance of the equipment and regularly subjecting the cavern to mechanical integrity tests (MIT).
Hydrogen operations might bring additional challenges when compared to natural gas or CO_2, for example. Firstly, hydrogen mobility is much higher and molecules are considerably smaller than natural gas. Therefore, the risk of leakage is greater for hydrogen operations than natural gas [269]. For the same reason, well embrittlement can also be a serious issue for hydrogen (see Section 5). Additionally, hydrogen can ignite at much lower energy than natural gas, and it has a much higher flame propagation speed, which could more easily result in explosions [273]. Subsurface safety valves are usually adopted to prevent blowouts, but they are not proven for hydrogen storage. Finally, the cyclic loading conditions and temperature variations associated with hydrogen operations must be carefully studied to avoid crack propagation in the cavern walls that could compromise gas containment.

4.8. Research recommendations

Although salt caverns have been used for many years for storage purposes and the understanding of the mechanics of rock salt has matured, there are still some particular unknowns when it comes to H_2 operations. Most of these issues are related to the H_2 properties and the loading conditions associated with intermittent energy production. In what follows, we list some topics that would require further investigation.

Because of its low viscosity and small molecules, H_2 can percolate through the cavern walls, especially in regions operating in the dilatancy zone. Based on this scenario, we suggest the following topics for further research:

- If H_2 percolates the cavern walls, there will be a pore pressure build-up. Consequently, it affects the effective stresses acting on the salt rock. This effect should be characterised and quantified to keep stress levels under control.

- As mentioned before, the presence of H_2 around salt grains can dry up the water-bearing grains. Although it can substantially reduce pressure solution creep, this is not expected to be important in the near-wall region. However, the healing effect is important and it can be highly affected by the presence of H_2. Therefore, further research on the salt healing capacity in the presence of H_2 would be of high interest.

- It is also not clear how the presence of H_2 can affect the position of the long- and short-term boundaries of rock salt. If the area of the compressibility region is reduced, the cavern could undergo, for instance, unexpected long-term failure (tertiary creep).

The main reason for developing hydrogen storage systems is to use them as a buffer for the intermittent energy produced from renewable sources. Consequently, the cycles of injection/production for hydrogen operations are much faster than for other storage materials. These loading conditions are relatively new for salt cavern operations and need to be carefully taken into account. Some related topics for further research are listed below.

- Additional lab experiments considering cyclic loads with frequencies compatible with field operations are still of interest. Not only concerning load levels (maximum and minimum pressure) but especially in terms of loading rates. This is important to establish the maximum injection or production rates that can be imposed inside the cavern.

- The cyclic pressurization of H_2 inside the cavern can cause temperature variations. It is not clear how the fatigue life of rock salt is affected by temperature, so this would also be of interest.

- As mentioned before, to meet the energy storage demand, multi-cavern systems may be developed. The effect of fast cyclic loading on multi-cavern systems is an important aspect to investigate to ensure safe operation.

5. Wells and borehole integrity

Wells ensures safe injection and production of H_2 into depleted reservoirs or salt caverns. Damage in wells is known to lead to the contamination of the water table [314]. It is crucial to maintain the integrity of wells and borehole infrastructure over several decades during the planning and operation phases of cyclic injection and production. Extensive research has been conducted on the integrity of wellbore infrastructure to prevent leakage during hydrocarbon production [315]. However, a lack of available monitoring data for active and abandoned wells and insufficient public data for comparing the well failure mechanisms hinders a comprehensive understanding of the system. Ensuring the safety of wells is paramount for various subsurface applications such as UGS, CCUS, geothermal energy, and lastly UHS. Although these storage technologies involve different fluids and operating conditions, the main causes of wellbore integrity loss remain the same. These causes include time-dependent leakage through fluid flow, solute transport, chemical reactions, mechanical stresses, annulus quality, and integrity, casing and seal deterioration, and improper abandonment operations [316].

In the context of geothermal energy, potential sources of well barrier and integrity failure include mechanical damage during well development, corrosion resulting from increased chloride concentration in drilling fluids [317, 318], thermal stresses caused by the cyclic injection of cold pore fluid into a hot reservoir [319], metal fatigue, and expansion of trapped fluids [320, 316, 321]. The high reservoir temperature and low injection fluid temperature cause differential thermal stress between the casing and cement which can reduce the shear bond strength resulting in leakage pathways [319, 316]. Thermal stresses could be avoided with proper cementing, slow preheating of the well before production, and good casing design [322, 323]. To tackle the issue of expansion of trapped fluids, a tieback liner was suggested in the casing to casing annulus [320]. A detailed review of different cement failure mechanisms in geothermal wells can be found here [323].

These sources have the potential to overlap with the UHS because of the cyclic loading nature and temperature difference between injected H_2 and the reservoir. In the context of CCUS, to avoid leakages, well design, construction, operation, evaluation, and abandonment are critical measures to be taken into account [324]. The utilization of abandoned wells for CCUS is not widely considered due to the potential creation of leakage paths caused by the degradation of well infrastructure materials over time [30, 325]. Materials used in well construction such as cement or polymers are chosen based on their resistance to corrosion from CO_2. The wells also undergo thermal stresses due to the injection of supercritical CO_2 in the subsurface [326]. The cyclic injection can cause fracture growth which results in the debonding between the cement and formation [327, 328].

Salt precipitation and scale formation have been found to have an insignificant impact on CO_2 storage [329]. Formation of ice-like crystalline compounds caused by trapping CO_2 in cages created by H_2-bonded molecules posed significant hazards like rapid pressurization and loss of injectivity [330, 329]. The role of contaminants (depends on the concentration) in the stream of CO_2 can change the rate of dissolution and precipitation rates which can react with cement and further degrade it [328]. There are a few studies that have reported casing corrosion caused by CO_2which depends on the temperature, pressure, salt concentration, pH, flow rate, and partial pressure of the injected CO_2 [331, 332, 333]. Carbonation product ($Ca(OH_2)$)can also be released when the cement reacts with CO_2 which could decrease the permeability, and porosity and further reduce the strength of the cement [334, 335, 336]. The introduction of CO_2 during injection can lead to a cooling effect, which in turn reduces the radial, axial, and tangential stresses within the composite system [337, 338, 339].

Underground gas storage offers similar technology (cyclic) as H_2 subsurface energy storage. Cyclic mechanical and thermal loading is imposed which can result in interface debonding and cracking, weakening of cement sheath and tubing connections [340], channels of mud at the contact surface, and layering in deviated wells weakens the cement integrity [341]. Sand production is another critical effect caused by changes in pore pressure and stresses, leading to erosion inside the wellbore and wellhead [342, 343]. The effects observed in gas storage can also occur in underground hydrogen storage due to cyclic loading. Leakage of H_2 can occur through various pathways when stored underground, as depicted in Figure 12. These pathways include cement, casing, packer, and around cement plug-ins in the abandoned wells [48].

The primary concerns regarding H_2 in wells pertain to its molecule size, chemical reactivity, operational cyclicity, and compatibility with materials and equipment. Due to its small size and high diffusivity, hydrogen is more prone to leakage compared to natural gas, presenting challenges for designing effective well barriers. Its high reactivity can lead to chemical interactions with rocks and reservoir fluids, potentially resulting in Microbially Induced Corrosion (MIC) of well components. Frequent injection and extraction of hydrogen cause pressure and temperature cycling, which can fatigue well components and the reservoir near the well. Ensuring compatibility with hydrogen and H_2S exposure may necessitate the use of new materials and solutions to ensure long-term operational efficiency.

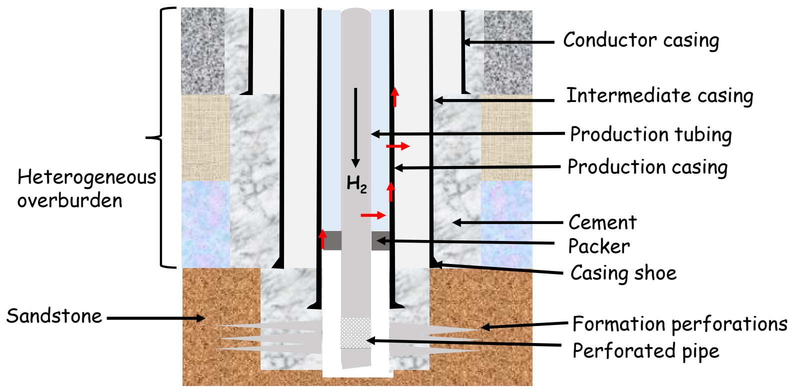

Figure 12: Simplistic illustration of a typical well indicating the possible H_2 leakage pathways (red arrows) through the tubing, through inside and outside of the casing, and around the packer. Modified after [30, 48, 344, 345]. Additional pathways in the sheared well-bore and cement plug-in in the case of an abandoned well are not shown here.

However, there is limited documentation on the impact of cyclic H_2 flow in wells. H_2 can react with sulfurous minerals in the subsurface, resulting in the formation of water, and contaminants such as a highly corrosive weak acid that can corrode the well infrastructure [203]. H_2 blistering and H_2 induced cracking can also take place in steel alloys, depending on the concentration of injected H_2 and operating conditions [48]. The cement bond between the rocks and casing needs to be stronger in comparison to traditional underground gas storage (UGS) sites, as the leakage effects could be more pronounced due to the small size of H_2. Rapid gas decompression of elastomers in sealing assemblies and degradation of elastomers from sulfide-reducing bacteria are potential issues in underground hydrogen storage (UHS) [346, 48]. Recent CT-scan experiments have revealed that H_2 bubbles can become trapped in the cement, leading to a decrease in cement strength through the formation of small fractures within the cement [347]. Aside from the decrease in cement strength, changes in permeability and reduced leak tightness can also occur due to prolonged exposure of H_2 resulting in multiple leakage pathways. Microbial reactions with H_2 can contribute to H_2 loss within the wellbore through metabolic activities. Moreover, the formation of biofilms that block the wellbore at the areas of contact between brine and H_2 can result in a loss of injectivity.

Further research should be conducted to investigate the impact of cyclic H_2 on various grades of cement. This research could lead to the development of new materials that can be added to cement to enhance the strength of well infrastructure, thereby reducing the risk of H_2 corrosion and long-term leakage. It may also be necessary to employ more advanced monitoring techniques to identify H_2 leakage pathways and assess well integrity. By carefully selecting the appropriate materials for well components such as casing, tubing, and cement through thorough laboratory research, significant cost savings can be achieved while ensuring the safety of H_2 storage. To gain a deeper understanding of wellbore integrity, it is beneficial to integrate laboratory experiments, modeling studies, and field-scale data from wells.

5.1. Research recommendations

- Geochemical and microbial reactivity of H_2 can release sulfides and other reactants. This effect on the wellbore components should be studied at a laboratory scale and with numerical models implementing the kinetics of the chemical reactions because of the additional products caused by longer timescale reactions of H_2.
- Effective low-cost continuous monitoring methods to detect H_2 leakage from the wells should be researched upon, which helps in identifying the weak regions in the well infrastructure and further avoid losses.
- Develop standards for different materials and admissible flow velocities used in the wellbore infrastructure relevant for UHS based on the required mechanical and thermal properties to avoid leakage.
- Explore alternative materials and coatings for the casing of existing (legacy) wells, particularly those designated for Underground Hydrogen Storage, when installing new tubing is not feasible.
- Simulation studies on the effect of repetitive cycling of pressure and temperature on cement for longer periods will help in determining suitable mechanical and thermal properties of cement sheath along with its durability.
- Investigate the compatibility of standard equipment for measurements and monitoring in the presence of hydrogen to ensure its safe and efficient implementation.

6. Geomechanical aspects for UHS

Considering several geomechanical challenges associated with UHS, guidelines relevant to safe storage are recommended in this section. A learn-as-you-go approach is suggested similarly as proposed for CO_2 storage [30]. The general guidelines are

- Choosing depleted reservoir sites preferably with thick and low-permeable caprock layers to avoid any leakage of H_2 to the ground and the water table. For salt caverns, large-volume caverns are preferable because of the more homogeneous mechanical properties of salt avoiding heterogeneity. For this reason, preference should be given to salt domes instead of bedded formations.

- Geological characterization of the available fields with InSAR monitoring data of uplift/subsidence on the ground and sonar surveys to closely monitor the salt cavern shapes is extremely useful.

- Selecting the samples from the chosen storage site to perform cyclic experiments and further study the effect of rock degradation due to bio-geo-chemical reactions with H_2 by imposing a similar stress signature as planned in field scale. This information will help in designing the operating conditions.

- Prior to injecting H_2, injection and production of water in the chosen site at the same operating conditions as the future UHS operations to study the possibility of induced seismicity and in addition study the suitability of constitutive models of the rocks [30] is needed.

- Continuous field-scale monitoring of the quality of the produced H_2 from the 1st long-term cycle (months) can reveal the possibility of rock degradation and help identify the possible underlying chemical reactions in the subsurface and losses.

- Based on the risks identified after 1st cycle and the quality of H_2 produced from the chosen site, the imposed pressures of injected H_2 can be increased but constrained by the limits of the site.

- Assessment and monitoring of the effects of operating multiple caverns in the same region continuously need to be undertaken.

If at any point during that process, evidence is found that indicates the possibility of leakage or possibility of a major accident, then the storage operations have to be halted.

7. Concluding summary

Underground Hydrogen Storage (UHS) is a complex interdisciplinary field that demands a comprehensive grasp of geological, mechanical, and geo-chemical processes to ensure safe operations. A brief overview of geomechanics was introduced. Further, a detailed review of the geomechanical aspects of UHS in depleted reservoirs and salt caverns, specifically in relation to H_2 operations. The use of subsurface storage has a history spanning several decades, during which significant experience has been gained, particularly in natural gas storage and more recently in CO_2 storage. This paper delves into the history of storage sites, their relevance to prior storage knowledge, experimental studies, analytical models, and numerical simulations that are pertinent to UHS. It emphasizes the lessons learned and identifies existing research gaps critical for the future of H_2 storage. The integrity of the wellbore is also discussed in the context of UHS. Based on the literature review, geo-mechanical guidelines were suggested to choose a particular site for UHS.

While there is a substantial accumulated experience that can be readily applied to H_2 applications, the practical field experience is still relatively limited, particularly concerning the loading conditions expected for the storage of green H_2 and its intermittent production. As a result, certain key points demand specific attention. These points are summarized below.

- H_2 exhibits greater mobility compared to other gases, resulting in faster diffusion and a higher susceptibility to leakage. As a result, the reservoir selection criteria used for CO_2 or natural gases cannot be directly applied to potential H_2 reservoirs. To ensure safe storage in the subsurface, it is essential to develop a comprehensive understanding of fault reactivation with H_2, following similar protocols used for CO_2 or natural gas storage. Additionally, significant attention should be given to comprehending the mechanical response of heterogeneous reservoir rocks and caprocks during the cyclic injection and production of H_2. Special emphasis should be placed on prior knowledge of the in-situ reservoir stress configuration and magnitude during case-specific studies.

- It is essential to create laboratory-based experimental procedures aimed at understanding the memory effect of reservoirs and caprocks during continuous operation. Ensuring the pressure fluctuation is optimized becomes crucial for achieving longer and safer operations. In this regard, it is vital to develop constitutive models that consider the transferability of experimental findings from specific reservoir rocks to similar rock types.

- Further research is necessary to comprehend the bio-geo-chemical reactions resulting from interactions between H_2, brine, and cushion gas with reservoir rock and caprock. A particular focus should be placed on understanding the microbial interactions and the subsequent impact of biofilms on the stability of the reservoir. In the context of salt caverns, the percolation of H_2 through the cavern walls could raise concerns as it may lead to H_2 loss and mechanical changes in the salt rock, particularly in damaged zones with open cracks. This potential consequence can affect the mechanical stability of salt caverns due to pressure build-up and a decrease in the healing capacity caused by water desiccation, which requires investigation. Moreover, it is crucial to investigate the degradation of components in the well infrastructure resulting from geo-bio-chemical reactions to ensure the continuous operation of the site.

- Performing coupled hydro-mechanical-chemical simulations involving cyclic injection and production of H_2 using field-scale simulators, while considering subsurface heterogeneity and lithology, can offer valuable insights into the prevailing physics over various timescales and in different reservoir regions. Similarly, for designing secure and effective operational conditions in salt cavern storage systems, numerical simulations play a significant role. Given the cyclic loading characteristics, it is advisable to utilize constitutive models that accurately incorporate transient creep and fatigue effects.

UHS is an emerging high-priority topic to counter the impending global temperature rise. As a final point, that goes beyond the discussion of technical results, open sharing of field-scale trial data, laboratory scale experimental as well as numerical simulations will accelerate the understanding of the mechanics of H_2 reservoirs and will enable faster and safer commercialization of UHS shortly.

Author contribution

K.R: Conceptualization, Methodology, Writing original draft, and editing. He.Ho: Conceptualization, Methodology, Writing original draft, and editing. D.C: Conceptualization, Methodology, Writing original draft, and editing. M.L: Writing: revision and editing. H.H: Conceptualization, supervision, Grant acquiring, Writing: revision and editing.

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