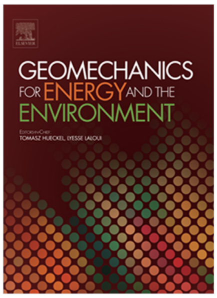

Geomechanics for energy and the environment: Current developments

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Geomechanics for Energy and the Environment: Current Developments

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Abstract

Geomechanics is advancing our understanding of the multi-physical processes encountered in engineering practices involving energy storage and production and environmental protection for which the characterization of the behavior of relevant materials is essential. Trends based on publications in the Geomechanics for Energy and the Environment Journal over the past seven years have revealed that four areas of research are currently of utmost importance: (1) energy geostructures, (2) geological storage of CO2, (3) nuclear waste disposal, and (4) hydrocarbon and geothermal reservoirs. This article aims to emphasize the contributions of the journal to these areas by providing insights into their relevance and the current trends and developments in their design and analytical approaches whilst identifying and presenting current knowledge gaps and new horizons for young researchers.

Keywords: geomechanics, energy, storage, production, environment

1. Introduction

The subsurface offers a large space to store and extract energy and to permanently dispose energy waste. Over the last decades, new subsurface energy storage, production, and disposal systems have emerged to advance the utilization of the subsurface while protecting the environment. These will play a key role in meeting the increasing global energy demand [1] as the world's population and the extensive economic and technological development continues to grow and expand whilst continuing to decarbonize energy systems to meet carbon neutrality goals. However, the complexity in characterizing the subsurface and the involvement of multi-physical processes hinder our ability to benefit from the full potential of these systems and thus provide optimal and sustainable subsurface solutions. To address such complexities, geomechanics concepts are continuously evolving, deviating from the core of geotechnics, and incorporating fundamental concepts in physics, geochemistry, and geo-biology.

In this regard, the journal of Geomechanics for Energy and the Environment (GETE) is actively contributing to bringing forward research advances in geomechanics while promoting cutting-edge, innovative, and creative techniques. In particular, four energy technologies are being currently widely examined according to the trends of this journal: (1) Energy geo-structures, (2) Geological CO2 storage, (3) Nuclear waste disposal technologies, (4) Hydrocarbon and Geothermal Reservoirs to overcome the associated technical and scientific issues.

The use of geotechnical structures as heat exchangers (so-called energy geostructures) to extract geothermal energy from shallow soil depths have been extensively discussed, however, new challenges are arising as these systems are being put into practice and as their use is expanding to different geostructures beyond piles, such as tunnels, anchors and walls[2,3].

The issues mainly arise from the additional thermal loads on the structure itself, the soil-structure interaction, and the surrounding soils in addition to the construction and organizational issues which should be tackled to ensure safe and efficient application. Unconventional reservoirs are offering a long-term potential for energy supply, either oil and gas or geothermal energy. However, these reservoirs pose technological challenges to enhance their permeability in order to reach an economical flow rate with hydraulic stimulation being the most commonly adopted technique nowadays. These challenges are related to the complex properties of the reservoirs (heterogeneity, anisotropy, and high in-situ stress levels) along with complex in-situ conditions that involve high temperatures. Yet, not only multiphase non-isothermal flow in subsurface porous/fractured media under challenging conditions should be considered, but long-term biological effects should also be explored to maximize the production while ensuring the sustainability of operations. To contain energy waste (CO2 and nuclear waste), underground engineered systems are being considered. For the high radioactivity nuclear waste, a series of engineered barriers (buffer material), in addition to the natural barrier (host formation), will retain the radionuclides and isolate the nuclear waste. However, both the engineered barriers and the host formation will be subjected to the heat generated by the waste, water infiltration after excavation, gas migration due to canister corrosion, and the induced chemical interactions which must be taken into account while estimating their short- and long-term performance. As for the CO2, it will be injected in deep high permeability and porosity reservoirs. The long-term, viable storage and reservoir safety will rely on the existence of an overlaying caprock formation that serves as a hydromechanical barrier and prevents CO2 migration to the surface. Technical issues involve fluid flow problems due to the fluid pressure of the reservoirs. As pressure increases, it will affect the permeability of the caprock, along with the chemical reactivity of CO2 with the groundwater within the reservoir and the caprock. This will create chemo-hydro-thermo-mechanical couplings which will alter the behavior of the involved geomaterials. For all these issues, the subsurface resource production operations may have harmful environmental impacts such as inducing earthquakes, surface deformations, change of groundwater, and gas leakage.

Dealing with such technical issues is a priority to ensure safe and efficient implementation of all these emerged subsurface energy technologies but it requires developing our understanding of the basic concepts and methodologies governing the involved multi-physical processes and the geomaterial coupled behavior. This paper will reveal the main trends and developments relevant to these four systems based on the contributions of the journal and highlights accordingly the knowledge gaps and future research opportunities in geomechanics.

2. Current trends and developments

2.1. Energy Geostructures:

Energy geostructures, which are geotechnical structures incorporating geothermal heat exchangers, provide convenient solutions to secure renewable energy for heating and cooling needs with a lower cost than the traditional ground heat exchangers (GHE) [4]. Energy piles are the most common energy geostructure, involved in over 157 projects worldwide [5] but they now include earth retaining structures, shallow foundations, tunnel lining, and anchors. To enable a safe and reliable design and implementation of such structures, the effect of thermal loading on the geostructure itself, the surrounding soils, and the soil-structure interactions should be quantified and best practices for installing geothermal loops should be identified.

In recent years, great efforts have been made to evaluate and optimize the thermal performance of energy geostructures by developing appropriate thermal analysis approaches (analytical and numerical) [2]. Currently, advanced three-dimensional finite element numerical simulations on the long-term thermal response of GHEs, energy piles, energy tunnels, and walls are employed using COMSOL Multiphysics. Such simulations revealed that the efficiency of GHEs improved when incorporating the surface temperature fluctuations [6] which would allow the GHEs to be shortened up to about 11% and helped identify the effect of construction parameters (concrete cover, the distance between shafts, and pile spacing) on the temperature distribution of the cross-section of energy piles and thus accurately estimate the induced axial stresses [7]. Energy tunnels do not only exchange heat with the surrounding ground in the same way as energy piles as they also interact with the air inside the tunnel requiring true three-dimensional models to model and couple the ground, tunnel GHEs, tunnel air, and groundwater [8]. The tunnel thermal performance showed a dependency on the groundwater flow velocity which could assist in ensuring the air ventilation system of tunnels is designed appropriately [8]. Additionally, as different types of energy geostructures are being applied in practice, the thermal interaction between those in close proximity are starting to draw attention. For instance, early insight into the thermal interaction between tunnel GHEs and nearby borehole heat exchangers (BHE) demonstrated that the thermal performance of the BHE are improved by the operations of the nearby tunnel GHEs [9]. Such results reveal a potential to reduce the installation costs of BHEs as fewer or shorter BHEs will be required to achieve the needed thermal energy if placed near the tunnels, especially for heating dominant climate conditions.

The thermo-mechanical response of energy geostructures has been widely investigated using full-scale experiments [3,10,11], centrifuge experiments [12], or numerical models [13,14] to check their serviceability. Coupled thermo-hydro-mechanical finite element simulations validated against full-scale or centrifuge experiments are developed also using COMSOL which include an appropriate plasticity model for the soil and the soil-pile interface to assess the long-term energy pile mechanical response under different energy demand scenarios and soil conditions [13,15]. However, only simplified models for the thermal and themo-mechanical behavior of the thermo-active diaphragm walls are employed nowadays showing that the thermally induced axial stress changes are significant [16]. As such, the effect of thermal cycles on the mechanical response of thermo-active walls should not be ignored. The first investigation on the thermo-mechanical aspects governing the behavior of energy sheet pile walls based on a 3D finite element model and results of full-scale in situ tests lately highlighted the critical role of the initial conditions and thermal boundaries [17].

Full-scale experiments are needed to validate the numerical and analytical design approaches for energy geostructures. The most available ones are for single energy piles [10] which recently indicated that energy piles in soft soils underwent temporal downward movements unrelated to the pile thermal deformations [11] and that their response depends on the end-restraining conditions [3] and the operating periods [18]. Fewer full-scale experiments exist for energy tunnels and walls [2]. These include the two tunnel geothermal plants in Stuttgart–Fasanenhof and Jenbach [19] indicating that the geothermal operations do not impact the subsurface temperature and the energy sheet pile wall in Napoli [17] and the therm-oactive diaphragm wall in Northern Italy [20] which gave valuable insights on the involved heat transfer processes.

Design standards are now available for GHE and energy piles in France, Switzerland, and the United Kingdom but the other energy geostructures mostly require a case-by-case study [2]. Recently, a comprehensive performance-based design framework for energy piles has been established underlining that thermal loads effects should only be considered at service limit states [21].

2.2. Nuclear waste disposal:

Nuclear energy is a scalable and low-carbon energy source contributing to the reduction of our global dependence on fossil fuels. However, nuclear energy production generates radioactive waste that requires special procedures for handling, storage, and disposal [22]. Nuclear waste with elevated levels of radioactivity remains hazardous for thousands of years and thus entails long-term passive safety repositories. Deep geological formations are a suitable disposal option and are being considered by many countries including France, Germany, Switzerland, Sweden, Finland, Belgium, and the United States [22]. Research efforts are directed towards the development of appropriate design concepts for deep geological repositories via multi-barrier systems composed of engineered (buffer material) and natural barriers. It is, therefore, crucial to identify the short and long-term performance of both the engineered barriers and the host formation while considering the involved thermo-hydro-chemo processes induced by the waste and the instalment procedure.

Clayey geomaterials such as Opalinus Clay, Callovo-Oxfordian, and Boom clay are potential host rocks for many nuclear waste disposal programs having favorable thermo-hydro-mechanical properties, self-sealing capacity, and the ability to prevent the migration of radionuclides [23-26]. However, testing such geomaterials is very challenging due to their extremely low permeability, high capillary suction, and brine interactions. Laboratory tests under controlled conditions are required to determine their intrinsic properties and the effect of in-situ conditions (high temperature, high pressure, salinity, gas pressure). Recently, new laboratory practices were developed to overcome these challenges [27], which were proven to be robust and relatively less time-consuming [28] and yielded consistent results compared with other conventional and systematic testing methodologies, as demonstrated by a benchmark experimental study on undrained triaxial tests of Opalinus Clay [26]. These undrained triaxial tests have shown that the elastic and pore pressure parameters of Opalinus Clay are stress-dependent [28] and that the shear strength of the remolded Opalinus Clay samples of different facies is correlated to the clay fractions [24]. Gas injection tests under oedometer conditions demonstrated that gas migration has a significant impact on the intrinsic permeability and water retention properties of Boom Clay [25]. Other than the conventional laboratory tests, a novel experimental-computational approach was proposed to predict the mechanical properties of such geomaterials (particularly, shales), which links these properties to mineralogical observations through a combination of nanoindentation and SEM-EDS testing [29]. This work would help in deriving reliable input data for multi-scale geomechanical modeling of shales, without the need for time-consuming and complicated conventional macroscopic experiments [30].

Similarly, laboratory tests were widely used to investigate the properties of the different potential buffer and backfilling materials as gas permeability tests, swelling and oedometric compression tests, resonant column tests, and triaxial tests [30-35]. Mainly compacted bentonite (e.g., MX-80 and FEBEX) and claystone/sand–bentonite mixtures, recovered from in-situ experiments [31] or prepared in the laboratory, were tested. These tests revealed that the gas permeability of bentonite depends on the water content and dry density, both of which vary with the position of the samples in the barrier [31] and that their compressibility and thermal volume behavior changes with the salinity of the groundwater [32]. They also yielded comparable results to in-situ experiments on the swelling and gas transport characteristics of buffer materials [33]. As such, small-scale laboratory tests can be referred to for the design of nuclear waste repositories.

Full-scale experiments have been implemented and instrumented to examine the behavior of the multi-barrier system under real in-situ conditions and evaluated its feasibility as Grimsel Test Site [34], Mont Terri (Switzerland) [36], Meuse/Haute-Marne Underground Research Laboratory (France) [23,37], and HADES URF (Belgium) [37]. These experiments are limited due to the required large scale and associated high cost. Innovative techniques are lately being employed to characterize both the host rock and the buffer material in-situ, as the active distributed temperature sensing (DTS) to estimate the in-situ dry density profile of bentonite [34] and the Mini-Seismic Methods (MSM) to measure the dynamic elastic rock parameters [37].

Recent advances in this field also included fully coupled numerical models using research code as CODE-BRIGHT to predict the behavior of the whole nuclear waste disposal system. Using a 3D thermo-hydraulic model for the disposal alternative KBS-3H, the presence of a gap between the buffer material and the host rock was proven to impact the behavior of the repository [38]. Fully coupled hydro-mechanical finite element code (also Code Bright) were used to simulate the fracture opening in the host rock by incorporating an integrated fracture permeability model to handle gas flow along variable aperture pathways[25]. Other efforts focused on modeling the excavation-damaged zone (EDZ) with Alcolea Rodríguez et al.[36] presenting an efficient approach to deduce 3D stochastic continuum models of the EDZ from 2D discrete characterizations of the fracture network based on Marked Point Processes.

2.3. Geological CO2 Storage

In our current global efforts to address climate change, carbon capture and storage (CCS) can actively contribute to achieving the net-zero emissions envisioned by the 2015 Paris Agreement. To date, CCS remains the only viable option available to eliminate hard-to-reduce CO2 emissions from heavy industry (such as cement, iron, steel, and chemical production) with many CCS projects already in operation since 1972 [39]. However, CCS technology faces public opposition in some countries as the safety and permanence of geological storage of CO2 remains questionable [40].

The concept is to capture CO2 at source emitters, pressurize it and store it in deep geological formations of high porosity and permeability such as saline aquifers, depleted oil and gas reservoirs, and deep coal seams[41]. Such reservoirs must be overlayed by a caprock formation of low permeability to prevent CO2 migration to the surface such as shale, anhydrite, or low permeability carbonate rocks [42]. To safely store CO2, the effect of CO2 injections and CO2 interactions with the formation brine on the geomechanical and geochemical behavior of the reservoir's rock and caprock must be evaluated. Laboratory-scale experiments under chemical reactive conditions on reservoir rock and caprocks core samples have generally been conducted for this purpose [43-45]. Recent studies revealed that salinity, pH, and temperature control the fracture mechanical properties of shale caprocks and their fracture growth using the double torsion tests [43]. It was also shown that the integrity of the caprocks will be enhanced or impaired depending on their lithology. CO2 injections were found likewise to alter not only the mechanical and hydrological properties of sandstone reservoirs but also the pore network[44]. In addition, the initial microporosity of the reservoir's rock, as oolitic carbonate rocks, directly influences their mechanical strength, failure mode, and elastic properties [45]. Valuable insights into the dominant deformation micromechanism that drives macroscopic compaction in such porous carbonates were also provided [45].

Many issues can arise from the CO2 storage systems which include the CO2 leakage through different pathways (wellbore, caprock, geological faults, and fractures) due to chemical and mechanical effects, the ground heave after caprock deformation and the pressure build-up, the seismicity induced by CO2 injection, CH4 leakage and displacement of brine [46], all of which would put the integrity of the whole system at risk. Many advancements have been achieved lately to predict and prevent such issues. For instance, Wolterbeek et al.[47] assessed both chemical and mechanical effects on wellbore cement behavior, a potential leakage pathway, and found that CO2 reactions induced mechanical healing and permeability enhancement of the wellbore cement. Stormont et al.[48] designed a specialized pressure vessel to measure the gas flow through microannuli (the cement-casing interface) while changing the confining pressure, internal casing pressure, temperature, and pore pressures. New dynamic models of CO2-injection-induced fault rupture are now used instead of the commonly employed quasi-static approach to assess the mechanical behavior and the potential for fault reactivation within CO2 storage system. These models coupled multiphase fluid flow and geomechanical simulators while incorporating for the first time the fault rheology and slip velocity using TOUGH-FLAC 2D [49]. Other models included the effect of thermal stresses induced by cold CO2 injections on fracture propagation into the caprock using Code Bright[50]. CO2 injections would lead to a fluid pressure build-up inside the reservoir, which in turn, lead to poroelastic expansion of the reservoir visualized as surface uplift. Lately, semi-analytical and analytical solutions have been developed to evaluate the surface uplift and the caprock deflection induced by CO2 injections [51-53]. For instance, Li et al.[52] presented a semi-analytical hydromechanical model of a deformable reservoir coupled with immiscible two-phase flow (CO2 and brine). Poroelastic solutions were also derived to predict the surface uplift based on Fourier representation of the reservoir pressure [53] or on superimposing the point source solution to solve fluid injection problems along horizontal and vertical line elements [51]. All these solutions were found to align well with the numerical results and therefore provide a useful first approximation for some CO2 storage problems.

2.4. Hydrocarbon and Geothermal Reservoirs:

Global energy demand continues to grow in order to power the world’s growing population and extensive economic and technological development. The dominant energy sources are still crude oil and natural gas, with shares of 40.8% and 16.2% of global energy consumption respectively [1] which are extracted from both conventional and unconventional reservoirs. Conventional reservoirs are porous and permeable (sandstones and carbonates) while unconventional reservoirs have extremely low permeability, which requires specialized and complex techniques to extract oil and gas (Shale oil and shale gas reservoirs) [54]. On the other hand, as the world moves toward CO2-free energy resources, geothermal energy is gaining increasing attention as an alternative clean energy to oil and gas. Most geothermal resources are also found in unconventional reservoirs leading to the emergence of enhanced geothermal systems (EGS), also referred to as Hot-Dry Rock or petro-thermal systems [55]. Exploration of these reservoirs (oil and gas and geothermal reservoirs) entails first the enhancement of their permeability with hydraulic stimulation is the most commonly adopted technique. However, hydraulic stimulation, as hydraulic fracturing or shear-induced expansion (also known as hydro-shearing), requires careful design and deployment based on the reservoir properties and specifications to ensure efficient and sustainable operations while keeping induced seismicity at an acceptable level [56]. A better understanding of the processes underlying hydraulic stimulation would be gained by monitoring and analyzing tests sites such as Mayet de Montagne and Soultz-sous-Forêts test sites or down-scaled in-situ experiments as Grimsel Test Site (GTS) and Bedretto Underground Laboratory for Geoenergies (BULG)[57,58]. Combining in-situ stress determined at the site with pressure, rates, and microseismicity observed during the stimulation would allow determining the representative volume element in which a continuum linear model could be applied [57]. Based on such results, Cornet [57] recently deduced that the creation of fresh shear zones in a rock mass with its inherently large dilatancy is more stable than the reactivation of pre-existing fractures. This would help in the design of a new shear stimulation protocol to maintain safe levels of induced seismicity. The first findings of the scaled-down stimulation experiments in the Grimsel test site (10 m scale) shed light on one of the main problems of EGS systems, the scalability, by revealing the large variability in permeability enhancement and induced seismicity at this scale [58]. Modeling hydraulic stimulation is also very challenging and still needs improvement with recent contributions targeting the deflection of a hydraulic fracture under a mixed-mode loading (I and II) problem [59] and subcritical cracking in acidized carbonate rocks using coupled chemo-elasticity [60].

To better analyze the hydraulic stimulation and fluid flow and transport in hydrocarbon and geothermal reservoirs, a characterization of the reservoir rocks under different in-situ conditions is underway (temperature, high stresses, anisotropy, heterogeneity). Numerous laboratory studies have recently investigated the effects of temperature and confining pressure on dynamic elastic properties and permeability of unconventional core samples[54,61]. Innovative laboratory tests are thus being used, as true triaxial equipped with acoustic emission sensors, X-ray Computed Tomography (CT), and fluorescence of the crack tip to explore the details of the fluid-dynamics at the crack tip [62] and fiber optic pressure sensors to monitor pore pressure diffusion [61]. A new stress-induced aperture model has been developed to examine the effect of polyaxial stress conditions on the fluid flow in three-dimensional (3D) persistent fracture networks [63], and a new hydro-mechanical simulator (Lagrangian solid mechanics code with an Eulerian fluid flow simulator) has been developed to compute reservoir permeability[64].

It is now well established that injection and extraction of fluids in both shallow and deep reservoirs can induce microseismicity [65]. The different hydro-mechanical coupling associated with the development of seismic motions was recently introduced and detailed by Cornet [66] based on four different pore pressure levels. However, Cornet [66] also pointed out that fluid injections not only induce seismic motions but also aseismic motions. These aseismic motions could affect volumes equivalent to those associated with a magnitude 5 earthquake and may be developed even after the fluid injection is completed and it exists some evidence of such aseismic slides [67-69]. In order to evaluate seismic risk, advanced numerical models have been developed which have revealed the different factors affecting the potential of induced seismicity (injection rate, temperature, injection, and production volumes, reservoir permeability, stratification, rock fault, and fracture orientations, and location of injection wells relative to faults)[65,70]. For instance, Haddad and Eichhubl [70] demonstrated the importance of poroelastic stress changes on the fault stability for different stacked injection-production scenarios after performing three-dimensional fully coupled geomechanical simulations on Abaqus while Haug et al.[71] focused on identifying the potential impact of geologic factors using 2D Abaqus simulations. Numerical models are also used to predict and assess surface subsidence, another environmental issue related to fluid extraction which is calibrated against large in-situ data sets. In this regard, a new 3D constitutive geomechanical model was proposed which describes the time-dependent deformation of deep sediment reservoirs following hydrocarbon or water extraction from the subsurface[72]. Angus et al.[73] also integrated fluid-flow, geomechanical, and seismic modeling to the Valhall reservoir and successfully predicted the surface subsidence. Surface subsidence is also offering insight into subsurface mechanisms initiated by water/hydrocarbon production. Inversion methods have been recently applied to characterize the geomechanical properties of deep reservoirs and provide an estimate of the parameters controlling the subsurface mechanisms (vertical uniaxial compressibility, compaction coefficient, elastic moduli) using assimilation of PS-InSar, multibeam surveys, GPS, well logs, and extensometer data[74,75].

Lastly, wellbore instability during drilling is a serious and costly problem during exploration and production. Current contributions are enhancing the wellbore stability analysis by evaluating the allowable drilling mud pressure while considering an appropriate failure criterion for the rock formation and the effect of a temperature difference between the drilling mud and rocks[76,77].

3. Future opportunities and Emerging priorities

There can be little doubt that the work done so far has had made a profound contribution to our understanding of energy production and storage technologies and their associated benefits and risks and has promoted the development of many applications that help mitigate the environmental impact we are having on our planet today. Yet if we are to be able to solve some of the great challenges presented by the likes of escalating energy use and climate change, there remains a great deal of work to be done in these research areas and technologies. Here we have identified a list of emerging priorities that merit further discussion, research, and action to validate the applicability, safety, and cost-effectiveness of energy technologies.

1. Whilst research on energy geostructures can be regarded as advanced, their deployment is relatively new and limited, especially for energy walls and tunnels. A key step missing that will further stimulate their practical application is the development of standard design and analysis approaches. A few efforts have been made in this regard in the United Kingdom, Switzerland, and France, but limited only to energy piles. This should be done in conjunction with new regulations that consider the interaction between different energy geostructures at the neighborhood or city scale rather than at an individual project scale, allowing for the economic advantages of these interactions to also be quantified. Some of the least developed analytical techniques include those used to evaluate the thermal and thermo-mechanical behavior of energy geostructures. Despite requiring several assumptions, they have been widely adopted within engineering practices. Only a few attempts to develop analytical techniques for energy piles have been made [14,78], BHE [79], and for plane energy geostructures [80]. In contrast, numerical techniques have progressively been

enhanced but still need to be refined for the analysis of tunnel GHEs and energy walls due to the associated complexities and conditions, such as pipe layout, anchorages, heat input, presence of air and groundwater flow. However, with the emergence of new techniques, we should not be restricted to analytical and numerical solutions. The use of computational intelligence algorithms to predict energy geostructures and the surrounding soil responses will open a whole new area of exploration and more importantly, these algorithms may be beneficial in predicting the long-term behavior of these structures which currently are not possible due to the limited availability of full-scale experimental data.

2. Certain fundamental understandings of the effect of thermal loads on energy geostructures and soil behaviors are also still missing. Energy piles have experienced ratcheting settlements unrelated to the pile thermal deformation but most likely due to the soil deformation [11]. These settlements should be accurately quantified as they could surpass the acceptable pile movement and further alter the interface properties. Furthermore, the mechanisms controlling thermally induced soil deformations at the microscopic scale remain unknown [81]. The identification of these mechanisms can help determine macroscopic soil deformations and therefore the design of energy geostructures can be refined. In this regard, using advanced laboratory techniques such as Mercury Intrusion Porosimetry (MIP), neutron imaging, and X-ray diffraction techniques could help the observation of microscopic and mesoscopic changes of the soils under thermal loading[82,83] resulting in new, accurate and robust constitutive models for thermally induced deformation of both fine and coarse soils.
3. The data collected from long-term, full-scale experiments and ongoing lab testing and modeling has progressed our understanding of the implementation of nuclear waste disposal systems, yet more is required to ensure their safe deployment at scale whilst

ensuring their long-term stability. Currently, there is still a lack of a complete characterization of the properties of the buffer material and the host formation as the physical processes involved are not yet fully known. Host formations involved are complex materials with multiscale heterogeneity and anisotropy. To predict the microporomechanical models of the stiffness and strength properties of the host formation, the mechanical microstructure properties must be determined. The methodology of Veytskin et al.[29] of combining grid nanoindentation and scanning electron microscopy (SEM) with energy and wavelength-dispersive X-ray spectrometry (EDS/WDS) was useful for shales, however, this work needs to be upgraded to incorporate 3D correlative X-ray microscopy. This will allow the identification of material phase and porosity distribution in the tested sample volume, which could explain length-scale effects and interaction volumes by adding a new dimensional feature. Further research is required to characterize the form of bonding of clay to quartz and carbonates, as the underlying mechanical, chemical, and physical mechanisms of this bonding are still not understood. More attention should also be paid to the long-term behavior of the buffer material and host formation, which is affected by gas migration processes and can be observed through controlled experimental tests for gas injection to detect whether new fractures will be created, or existing ones will open under gas pressure and how the permeability will be affected. In addition, proper numerical models should be implemented to include the embedded fracture model or more advanced random permeability fields that would enable the heterogeneity to automatically develop fracture patterns, without requiring a predefined fracture zone. Recently, coupling the hydromechanical model with the phase-field method is starting to gain attention for geomaterials, as the method provides a continuous approach to explicitly model the fracturing initiation and propagation within standard FEM [84]. This coupling, along with the thermal behavior of the host formation and the buffer materials needs further experimental assessment. These should be incorporated into elasto-plastic models of these materials in the analysis of formation-liner-buffer systems.

4. CO2 storage knowledge has come a long way, although there is still much to understand. It has been experimentally proven that there is a correspondence between shearing-induced dilation and permeability of porous and permeable reservoir formations owing to the increase of crack density and the opening of microcracks [45]. However, quantitative modeling of the permeability enhancement still needs to be developed. We now have evidence suggesting that caprock fracture response depends on fluid chemistry, rock mineral composition, and rock permeability [43], however, a broader range of rock types should be tested to better understand the effects of mineral composition on fracture growth and fracture initiation under the chemically reactive conditions in a CO2 reservoir and to reach clear conclusions and correlations. In both cases, tracking the evolution of the caprock and the reservoir formation microstructures under different fluid salinity, pH, temperature, and loading conditions would also help to reveal the controlling mechanisms behind the fracture response.
5. Other areas where our understanding can be expanded include the strain rate and time dependencies of the cement response revealed by Wolterbeek et al.[47] which should be further investigated and incorporated into models for this type of porous rock to ensure the integrity of wellbores. CO2 injection-induced seismicity also lacks advanced dynamic numerical models for distinct types of storage formations and different injection scenarios. These models are necessary to determine the conditions that trigger seismic slippage which will help to identify and achieve safe conditions for CO2 injection and storage.

6. While we are making advances in the understanding of unsaturated soils, there remains much to do. The non-equilibrium suction stress effect on the hydro-mechanical behavior of unsaturated soils for instance needs further investigation. This could be achieved by performing both hydraulic element tests lately proposed by Milatz et al.[85] and mechanical tests. Alternatively, these hydraulic element tests could also be useful for accurately estimating soil-water transient characteristic curves together with suction stress characteristic curves.
7. The influence of pore water salinity on the macroscopic behavior of intact clay soil and rocks, especially structured clays, is also a recurrent problem [86]. To date, the presence of diffuse layers has not been considered but could help describe the physicochemical interaction between clay minerals and water. For instance, Tuttolomondo et al.[87] developed a generalized effective stress concept for active clays to highlight the effect of pore water chemistry on the mechanical behavior of saturated active clays.
8. The development of technologies to extract geothermal energy or hydrocarbons from unconventional reservoirs is tied to proving their scalability, accessibility, and controllability. Related research is currently based on scaled tests and laboratory experiments; however, it is still unclear how laboratory experiments can be scaled up to full-scale. Current in-situ experiments performed at intermediate scales may offer a possible solution, such as that presented by Gischig et al.[58]. Larger scale experiments closer to target reservoir depths with detailed monitoring systems would present further opportunities to evaluate the feasibility of these technologies and expand our understanding of the processes involved. In parallel, reliable hydromechanical models to simulate hydraulic fracture and to predict surface subsidence and induced seismicity still must be advanced. Seismic data could help calibrate these models as

they can provide valuable insights into the intrinsic anisotropy, elastic modulus, and in-situ stress sensitivity of the rock formation[73]. It is therefore crucial, to develop new constitutive models that better describe the response of rock formations once the effective stress increases due to hydraulic fracturing. For this, a 3D crack propagation model can capture the brittle deformation response including local concentrations of critically high tensile or differential stresses, as well as the realistic fracture opening and shearing behavior on pre-existing and newly propagated fractures allowing the accurate capture of the 3D flows of fractured rocks [63]. Additionally, the creep deformation explored by Cassiani et al.[72], should be further enhanced by examining deformation induced by fluid expulsion from these low permeability rock formations which would allow for the depiction of the delayed compaction that drives surface subsidence.

9. Previously, the potential for fluid injection to produce damaging earthquakes was not considered significant; but, in recent years, the maximum magnitude of seismic events attributed to hydraulic fracturing has increased reaching M = 4.4 [65]. Attention should therefore be paid to such events as well as to the aseismic events as proposed by Cornet [66] to eliminate any possible risk. Usually, "traffic light" systems are used to monitor the energy release during operation in geothermal and hydrocarbon reservoirs and appropriate equipment should be used to detect even slow aseismic slips to maintain acceptable surface disturbance [66]. In addition, novel approaches for estimating seismic hazards from induced earthquakes should be established [88-91] taking into account the variations in source locations and fluid injection and withdrawal rates and volumes [65].

4. Conclusion

Geomechanics for Energy and the Environment journal has become a forum for the fields of energy production, storage, and environmental protection which is a remarkable achievement. Over its brief history, the journal has attracted prominent papers covering the most rapidly emerging, challenging, and revolutionary areas of research, such as energy geostructures, nuclear waste disposal, geological CO2 storage, hydrocarbon, and geothermal reservoirs. Current developments, as presented herein, are underway to expand the fundamentals of geomechanics by adapting these research area requirements and technical issues where multi-physical processes and coupled phenomena (thermo, chemo and hydro couplings) are involved. These include the use of advanced numerical models, innovative techniques to characterize full-scale experiments sites and new appropriate laboratory practices, and the emergence of several testing methods from other disciplines (such as nanoindentation, MIP, and full-field techniques) which would help identifying the distinct nano and micro-mechanisms that govern the macroscopic behaviour of geomaterials. Despite these considerable advances, there are still many gaps to be addressed in the future.

The journal of Geomechanics for Energy and the Environment will thus continue being at the forefront of all new advances providing the community with innovative and creative international research and applications that enable the future exploration, production, and storage of energy sources and environmental solutions.

5. Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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CRediT author statement:

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Author Agreement

Author Agreement Statement

We declare that this manuscript is original, has not been published before and is not currently being considered for publication elsewhere. We confirm that the manuscript has been read and approved by all named authors and that there are no other persons who satisfied the criteria for authorship but are not listed. We further confirm that the order of authors listed in the manuscript has been approved by all of us. We understand that the Corresponding Author is the sole contact for the Editorial process. He/she is responsible for communicating with the other authors about progress, submissions of revisions and final approval of proofs

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: