Title
Editorial: Coupled processes in fractured geological media: Nuclear waste disposal

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Publication Date
2024-12-01

DOI
10.1016/j.tust.2024.106077

Editorial: Coupled Processes in Fractured Geological Media: Nuclear Waste Disposal

CouFrac 2022, the 3rd International Conference on coupled processes in fractured geological media: observation, modeling, and application, was held November 14-16, 2022, at the Lawrence Berkeley National Laboratory in Berkeley California, and online everywhere else. It aimed at gathering advances in coupled processes relevant to fractured geological media, covering a wide range of applications, such as nuclear waste disposal, energy storage and geothermal reservoir engineering. The CouFrac 2022 conference was attended by over 250 participants from 32 countries.

This Special Issue in Tunnelling and Underground Space Technology contains selected papers from CouFrac 2022 related to deep geological disposal of nuclear waste. All the papers are in one way or the other related to coupled thermal-hydrological-mechanical-chemical (THMC) processes in geological media that can significantly impact the long-term repository performance. Because coupled THMC processes associated with a nuclear waste repository are often thermally-driven by the heat released from waste canisters, adequate thermal management is an important strategy in the design of a repository. Thermal management is one of the themes in most papers in this Special Issue.

Thermal management of deep geological repositories has often been limited to managing the maximum temperature occurring at the waste canisters or in the bentonite buffer surrounding the waste canisters. For example, in the Swedish and Finish repository programs, a maximum temperature limit is set to 100°C to assure long-term stability of the buffer. However, the temperature evolution in the host rock can be equally important as it drives THM processes that can potentially cause unwanted permanent changes in radionuclide transport properties and repository safety.

As an example, Rutqvist and Tsang (2024) show that for the current design and conditions at the Forsmark and Olkiluoto nuclear waste disposal sites, the peak temperature in the buffer is predicted to be well below 100°C, whereas there is still a high potential for thermal–mechanical damage to the underground excavations. To avoid such thermal-mechanical damage, the temperature evolution in the host rock has to be controlled, in addition to considering the maximum temperature limit for the buffer (Rutqvist and Tsang, 2024).

The maximum temperature in the buffer can be reduced by engineering the buffer for high heat conduction as investigated by laboratory experiments in Lee and Yoon (2024). They are using mineral additives to develop optimum bentonite properties, including thermal conductivity, hydraulic conductivity, and swelling properties. It is important to make sure that such additives, while enhancing thermal conductivity, do not significantly reduce swelling capacity, because adequate buffer swelling is important to minimize thermal-mechanical damage to excavations (Rutqvist and Tsang, 2024). Thus, a careful design of the buffer and backfill and the geometry of the repository excavations are all important to minimize thermal damage to the repository barriers.

Thermally driven THM effects can also significantly impact the far field host rock. In the case of disposal in crystalline rocks, this may include shear activation of existing fractures and faults that might lead to enhanced rock mass permeability and potentially induced seismicity. In this context, Seo et al. (2024) performs a far-field analysis of shear slip potential and ground uplift, considering alternative repository designs, such as multi-canister and multi-layer disposal concepts. The highest potential for shear slip would occur near the boundary of a repository, but could also occur inside, in particular on shallowly dipping (e.g. 30°) fractures and faults (Seo et al., 2024).

The potential for thermal shear slip is highly dependent on rock properties, particularly on friction, but also on rock-mass elastic modulus and thermal expansion. Laboratory test results in Sun et al. (2024) show the important role of fault or fracture roughness, not only on slip initiation, but also on thermal stress. For example, the results indicate that thermal stress changes would be relatively smaller across a rough unmated fracture, probably because of a lower stiffness in that case. This indicates that thermal stress changes may be strongly heterogeneous in fractured rocks, depending on local fracture properties and fracture orientations.

If shear slip occurs, then changes in permeability and the potential for induced seismicity will depend on the evolution of friction and dilation with shear. These are parameters that are scale dependent from small-scale roughness to large-scale waviness as described in Zou et al. (2024). They found that surface unevenness notably affects the peak shear strength of unfilled and mated fractures, while the surface waviness controls the residual shear strength. A significant drop in friction with shear can be more prone to induce seismic events (Zou et al., 2024).

Kim et al. (2024) conduct coupled THM analysis for thermal management related to Korean repository designs with the goal of optimizing disposal efficiency, considering three design factors: Decay heat optimization, increased thermal limit of the buffer and double-layer concept. Kim et al. (2024) found that disposal areas can be reduced by 20 % to 40 % compared to the current reference disposal system in Korea (KRS+) when utilizing a combination of the three design factors.

For disposal in tight argillaceous claystone or shales with high clay content, a good understanding of coupled THM processes is important. Fractures might foremost be induced in the disturbed zone around excavations. Shen et al. (2024) studies such phenomena for deep borehole disposal, involving deep large diameter boreholes. Depending on the shale properties, weather stronger or weaker, very different results are obtained in terms of fracturing around the borehole. In the case of weak shale, large breakouts (>1.5 m) are predicted at depths of 1000 m and 2000 m caused by extensive shear fracturing.

Thermally-driven coupled processes in low permeability argillaceous claystone involves thermal pressurization that can induce pore pressures above the lithostatic stress and thereby potentially create new fractures. Thermal pressurization has been studied in field experiments, such as a recent experiment at the French Meuse/Haute-Marne (MHM) Underground Research Laboratory (URL) in Callovo-Oxfordian (COx) claystone (Bumieler et al., 2024). The study presented in Bumieler et al. (2024) shows that the pore pressure distribution due to tunnel excavation plays a role in the thermally induced pore pressure, accentuating the anisotropic THM response of the COx claystone.

The impact of anisotropy in argillaceous claystone is also the subject of Sasaki and Rutqvist (2024), focusing on the effect of anisotropic creep for the long-term THM evolution of a repository. They found that creep in general affects the long-term stress evolution, relieving deviatory stress, and reducing shear induced permeability changes. Anisotropic creep can most accurately predict such changes in comparison to alternative isotropic creep and/or elastic models (Sasaki and Rutqvist, 2024).

Gas generation and migration is another important phenomenon that could lead to strongly coupled processes, including dilatancy controlled gas flow or potentially gas fracturing. Yu et al. (2024) present modeling of such coupled hydro-mechanical processes associated with gas migration within the disturbed zone of a borehole. They modeled a gas injection experiment performed in COx claystone at the MHM URL in France. They successfully modeled the gas injection by considering effects of gas and liquid pressure on the nucleation and propagation of cracks using an extended phase-field method (Yu et al., 2024).

Finally, the impact of coupled processes on radionuclide transport are studied in a modeling study by Chang and LaForce (2024), so far limited to the effects of thermal-hydrological process in the nearfield. The study evaluates impacts of the spatial distribution of heat sources on the spatio-temporal perturbation in hydro-thermal flow quantities and radionuclide transport rate in both near- and far-field of the repository system. Future analysis will include THM effects such as permeability evolution in the excavation-disturbed zone.

The importance of coupled THM processes in thermal management of a repository is highlighted in several papers in this Special Issue. As demonstrated, coupled THM modeling can be applied in repository design and optimization, as well as to estimate potential impact of THM processes on the Safety Assessment. An example is Safety Assessment on changes in properties and near field fluid flow that have an impact on radionuclide transport. Unwanted permanent thermal damage may be avoided by a careful design. In some cases, thermal damage may be unavoidable and/or tolerated, while considered in the Safety Assessment. For example, in the Swedish repository program, a thermal damage zone along deposition holes is currently considered in the Safety Assessment, as full buffer swelling is not guaranteed for all the deposition holes (Rutqvist and Tsang, 2024). These are examples of coupled THM and THMC processes and issues that we expect will be a hot and important topic in deep geologic nuclear waste disposal for many decades to come.

On behalf of the members of the CouFrac 2022 Organizing Committee, we hope that this collection of papers will be interesting to the readers of Tunnelling and Underground Space Technology. We would like to express our gratitude to all the Reviewers who kindly contributed to this Special Issue, as well as the Journal staff who have made this publication possible.

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