Editorial

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As well as being an efficient source of energy, nuclear power is a clean source of energy, as, unlike fossil fuels, nuclear energy production does not generate greenhouse gas emissions. However, spent fuel which has been removed from nuclear reactors remains radioactive for thousands of years and therefore suitable management plans must be developed. Deep geologic repositories are, currently, the most realistic option for the final disposal of high-level, spent nuclear fuel. This special issue is focused mainly on the KBS-3 disposal concept (Figure 1; Posiva and SKB, 2017a), where the spent nuclear fuel is packed in copper canisters, placed in deposition holes (KBS-3V) or deposition drifts (KBS-3H) and surrounded with blocks of compacted swelling clay (buffer). The deposition tunnels (present only in KBS-3V) and the central tunnels are backfilled with swelling clay (backfill) and a mixture of crushed rock and swelling clay respectively. Deposition tunnels and drifts are embedded in bedrock at a depth of 400–450 meters.

In Finland, a license for the construction of a spent nuclear fuel disposal facility in Olkiluoto has been granted and an operational license application will be submitted in the near future. The operational phase will occur during the first 100 years and during this window, spent nuclear fuel remains retrievable. In Sweden, a construction license application for a spent nuclear fuel disposal facility in Forsmark has been submitted. Many other countries (e.g. France, Belgium, Canada, Japan, China and South Korea) are actively pursuing deep geologic disposal options as well.

In order to achieve safe disposal of spent nuclear fuel in a deep geologic repository, the design of the facility must provide for long-term isolation and containment of the radioactive material. Long-term in the case of spent nuclear fuel disposal implies no releases of radionuclides for periods up to more than 100 000 years. Such times far exceed the existence of any, currently known man-made structures.

Demonstrating that a spent fuel disposal facility will meet and maintain its long-term safety purpose is extremely challenging and requires that an adequate scientific and technical understanding of the disposal system and its environment be developed. With respect to high-level spent nuclear disposal featuring bentonite materials in the construction of engineered barrier system components, it is necessary to reliably assess not only such performance factors – such as saturation times, maximum temperatures, swelling pressure evolution and the chemical and physical stability of bentonite barriers – but also the evolving load conditions acting on the disposal system (e.g. changing groundwater composition, seismic events, microbial activity and glacial cycles).

High-level spent nuclear fuel disposal is the special theme of this issue and is presented in the twelve included papers. Six of

the papers are focused on modelling studies, two on laboratory investigations, two on ‘in situ’ testing, one on the production of an engineered barrier system component and one on the management and leadership of high-level spent fuel disposal programs.

This issue has been divided in two parts due to the number and size of the contributions. This is part I and it is dedicated to modelling.

Constitutive models are implemented in computer codes which can simulate TH, THC, THM and THMC processes at different levels. In order to generate stable, numerical results, various geometric (e.g. 1D, 2D plane strain and axisymmetry), modeling (e.g. elastic models instead of plastic models in mechanical analysis) and coupling (e.g. using thermal analysis for the definition of the distances between canisters instead of fully coupled modelling) simplifications must be implemented. Balancing the accuracy of the simulations with the simplifications needed for carrying out these simulations is, possibly, the main challenge in modelling work.

Abed and Solowski (2020) present two numerical applications of a newly developed, fully coupled thermo-hydro-mechanical-chemical (THMC) finite-element code. The first one involves the modelling of a large-scale mock-up test as a validation exercise and the second one corresponds to the solution of the Elder problem, which is related to hydro-chemical coupling, as another verification exercise.

Abootabeli *et al.* (2020) discuss the effect of barrier saturation on the dissipation of thermal energy in a generic Canadian placement room. They study this effect for upper and lower bound scenarios which are believed to constrain short-term thermal loads under hydraulically static conditions. Bentonite temperatures should not exceed 100°C in order to avoid potential alteration effects.

It is well-known that the deformability of bentonites is strongly affected by salinity conditions. De la Morena *et al.* (2020) present an analysis of the formulation used to calculate the activities of the species dissolved in the aqueous solutions present in bentonite pores for vertical free swelling test simulations under different salinity conditions.

Rodríguez-Dono *et al.* (2020) have updated the modeling evaluation of the 18-year-long FEBEX ‘in situ’ test from previous modelling efforts (Gens *et al.*, 2009). The new model incorporates the dismantling operations and has been compared with the ‘in situ’ measurements performed during dismantling of the test. Once the model was calibrated, the long-term response was analyzed. The double structure model was considered assuming also two different levels of suction (microstructural and macrostructural with an interchange term).

Figure 1. KBS-3 disposal concept. KBS-3V (left) and KBS-3H (right). Courtesy of SKB (www.skb.com). Illustrator: Jan Rojmar

Schäfers *et al.* (2020) describe the verification of various computer codes that are used in the simulation of high-level spent nuclear fuel repository designs. A benchmark case is defined and different teams using different computer codes carried out simulations of this case. The results obtained are compared, and the differences assessed.

Toprak *et al.* (2020) performed thermal-hydro-mechanical simulations of barriers constructed with bentonite pellets using the Barcelona Expansive Model (BExM) (Gens and Alonso, 1992). This model was developed for studying the behavior of swelling clays and takes into account the double porosity structure of these materials. Pellets will be used for filling gaps between bentonite blocks and rock walls.

This issue touches on some of the different tasks necessary for the design and construction of a high-level spent nuclear fuel repository: the development of constitutive models and implementation of these models in computer codes, the performance of laboratory tests, the validation of laboratory test results and modelling efforts through ‘in situ’ tests, the verification of computer codes used to generate model results and best practices for the management and leadership of disposal programs. It is my sincere hope that this issue of *Environmental Geotechnics* will be interesting for readers and that they are able to find useful information for their own work.

Finally, the Guest Editor would like to acknowledge the authors for their contributions, which will serve to increase knowledge and allow for better response to the challenges posed by nuclear waste disposal.

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