EURAD SCHOOL FOR RADIOACTIVE WASTE MANAGEMENT | GAS & HITEC

MULTIPHYSICAL COUPLINGS IN GEOMECHANICS: A FOCUS ON THERMAL EFFECT AND GAS TRANSFER IMPACT ON THE BEHAVIOUR OF GEOMATERIALS

January 22 - 24, 2020 | Liège University

EXTENDED PROGRAMME

Day 1 | Wednesday, January 22, 2020

09:00 – 09:30 h	**Welcome, registration and coffee**
09:30 – 10:00 h	**Introduction**
	General aspects, *Frédéric Collin & Robert Charlier, Université de Liège*
	Challenges addressed by HITEC WP, *Markus Olin, VTT Technical Research Centre of Finland*
	Both clay host rock and bentonite buffer, and their behaviour at high temperature are included. For clay host rock temperatures under 120°C and for bentonite buffer temperatures under 150°C (even 200°C) are considered. Mechanical behaviour is the focus area, while chemical conditions will be taken care of whenever possible by some simplified couplings. Clay host rock: Formation of overpressure, stresses caused by the overpressure, fractures caused by these stresses and propagation under thermal load, propagation of excavation induced fractures under thermal load. Clay buffer: Influence of high temperature on material: changes, characterisation, safe temperature level determination; influence of high temperature on processes inside buffer – processes at high temperature, Development of coupled THM models at high temperature. Chemical conditions will be only taken care of whenever possible by some simplified couplings.
	Challenges addressed by GAS WP, *Séverine Levasseur, ONDRAF-NIRAS*
	The WP GAS of EURAD is dedicated to the mechanistic understanding of gas transport in clay materials. The main objectives of this WP are (1) to improve the mechanistic understanding of gas transport processes in natural and engineered clay materials, their couplings with the mechanical behaviour and their impact on the properties of these materials; (2) to evaluate the gas transport regimes that can be active at the scale of a geological disposal system and their potential impact on barrier integrity and repository performance. Within this WP, knowledge gained from new and past lab and in situ experiments will be put in context for configurations that are commonly found in current repository designs with the aim to address the key questions from the end-users: How could gas migrate within the repository and which water soluble and volatile radionuclide transport could be associated with it? How and to what extent could the hydro-mechanical perturbations induced by gas effect barrier integrity and long-term repository performance?
10:00 – 10:30 h	**Coffee break**

10:30 – 12:30 h	**Fundamentals on geomechanics and multi-physical couplings** *Antonio Gens, Universitat Politècnica de Catalunya*
	The basic thermo-hydro-mechanical (THM) phenomena occurring in saturated and unsaturated porous media are reviewed, with special attention to their interactions. A theoretical formulation that encompasses the most relevant THM phenomena and their couplings is developed. The description of the formulation is divided into balance equations, constitutive equations and equilibrium restrictions. Governing equations include solid mass balance, water mass balance, air mass balance, energy balance and momentum balance (equilibrium). Constitutive equations are proposed for the various THM phenomena that are deemed most relevant. The specific form of each constitutive equation generally includes information on the nature of the interactions between different phenomena. Equilibrium restrictions provide conditions for processes that are considered fast with respect to the characteristic times of the overall THM problem, notably phase changes. Examples of application to field cases related to nuclear waste disposal are described.
12:30 – 13:30 h	**Lunch**
13:30 – 15:00 h	**Experimental evidences of high temperature effect, at lab scale** *Pierre Delage, École des Ponts Paris Tech*
	Since the pioneering work of Mitchell and Campanella (1968), further attention has been given with the seminal experimental and theoretical contributions of Hueckel and co-workers in the 90's, who evidenced the change in volume, under constant stress, of clays specimens submitted to temperature elevation. They showed for first time the thermo-elastic response of over-consolidated clays and the thermo-elasto-plastic one of normally consolidated clays, also extended to the thermal response of compacted bentonites and claystones, with, in the last case, the evidence of a thermal hardening phenomenon based on the maximum temperature supported by the claystone during its geological history. Temperature elevation also appeared to have little effects on elastic properties, and to reduce a little bit the shear resistance of clays and claystones. Another important aspect is linked to the THM coupling that governs, in clay and claystones, both thermal consolidation and thermal pressurisation, that results from the large difference in thermal expansion coefficient between water and minerals. All these features are important for better understanding and modelling the effects of temperature in the close-field in radioactive waste disposal.
15:00 – 15:30 h	**Coffee break**
15:30 – 17:00 h	**Constitutive modelling for thermomechanical behaviour of geomaterials** *David Masin, Charles University Prague*
	The lecture will cover basic principles of constitutive modelling of geomaterials subject to elevated temperatures. In particular, the following concepts will be covered. (1) Heating-induced compaction and heating-induced expansion, depending on the relative density of soil specimen. (2) Incorporation of volumetric response of mineral grain particles and water into constitutive models. (3) temperature-dependency of matric suction and the effect of temperature on soil water retention behaviour. (4) temperature-dependency of bentonite microstructural behaviour. Subsequently, incorporation of these concepts into two main modelling frameworks (elasto-plasticity and hypoplasticity) will be explained, with examples of models from both groups. Finally modelling concepts of double (and triple) structure will be introduced. Enhancement of existing models by elevated temperature will be explained and model predictions will be compared with experimental response of bentonite.
17:00 – 17:15 h	**Closure**

Day 2 | Thursday, January 23, 2020

09:00 – 10:30 h	**FE numerical modelling of THM couplings in geomaterials** *Frédéric Collin, Université de Liège*
	A good understanding of the interacting thermo-hydro-mechanical phenomena (occurring in the engineered barrier and adjacent rock) is necessary for the design of the disposal. To this end, a multiphysical formulation is described that allows the performance of coupled THM analyses capable of reproducing observed phenomena. An introduction to numerical modeling of coupled problems in geotechnical engineering is presented. It aims to provide an overview both of the techniques and the difficulties encountered when modeling this type of problems. The different couplings are introduced step by step, in the context of finite element techniques.
10:30 – 11:00 h	**Coffee break**
11:00 – 12:00 h	**Microstructure of bentonites: characterisation and evolution under mechanical and environmental loads** *Anne-Catherine Dieudonné, TU Delft*
	Bentonites exhibit a complex behaviour under repository conditions, owing to the high sensitivity of the material to mechanical and environmental loads. This sensitivity of bentonites to external factors arises from both the mineralogical composition and the multi-scale structure of the material. This lecture aims to provide the fundamental keys necessary to better understand the observed macroscopic behaviour of bentonites. The mineralogical composition, structure and physicochemical properties of bentonites are presented and used to explain hydration and swelling mechanisms. The effect of mechanical and environmental loads on the material structure is then described and analysed. Modelling challenges and prospects are finally addressed.
12:00 – 13:00 h	**Lunch**
13:00 – 14:30 h	**Experimental evidences of advective gas transfers at lab scale** *Jon Harrington, British Geological Survey*
	Understanding the processes governing the advective movement of repository gas has long been the subject of debate and conjecture within the radioactive waste community, in order to define process, approach, and treatment of gas in safety assessment. Two approaches are usually proposed to describe the advective movement of gas, (i) classical two-phase flow models, where one fluid displaces another, with the process described by the water retention curve, and (ii) dilatancy flow where gas is unable to move within the original porosity because of capillary restrictions, creating new 'dilatant' features, which open and close in response to the gas pressure. This module focuses on the importance of laboratory scale measurements and their role in defining process understanding, reviews the different methods available for the determination of advective gas flow properties and examines some of the data obtained during 25 years of laboratory measurements to assess which mechanism is dominant in repository clay-based materials. This information is combined with natural analogue studies to provide an insight into the fundamental processes governing advective gas flow in low permeability clays.
14:30 – 15:00 h	**Coffee break**
15:00 – 16:30 h	**Modelling for gas transfers in geomaterials** *Sebastia Olivella, Universitat Politècnica de Catalunya*
	Basic properties of gases such as density, viscosity, diffusivity, solubility will be reviewed briefly. Migration of gases in geological materials involves several transport mechanisms, and mathematical representations are required for each one. Conservation equations and the corresponding boundary conditions will be presented in the context of geological materials. The theoretical and numerical approach includes saturated-unsaturated flow; multi-component mixture of gases; non-isothermal multiphase flow in deformable media; and preferential path formation. The coupling with thermo-hydro-mechanical equations will be described in detail. Examples of modelling of laboratory and in situ experiments will be presented and the challenges encountered discussed.
16:30 – 16:45 h	**Closure**

Day 3 | Friday, January 24, 2020

09:00 – 10:00 h	**In situ thermos-hydro-mechanical experiment on poorly indurated clays** *Arnaud Dizier, EURIDICE*
	In the frame of RD&D on the geological disposal of nuclear waste in Belgium, the thermo-hydro-mechanical (THM) behaviour of Boom Clay has been studied over several decades through small-scale laboratory tests and in-situ experiments at different scales in the HADES underground research laboratory (URL) in Mol (Belgium). The intermediate-scale in situ heating tests ATLAS allowed to observe the impact of the heat on the Boom Clay beyond the zone affected by the drilling of the borehole hosting the heater. In November 2014, the in situ large scale PRACLAY Heater test, carried out in the PRACLAY gallery of the HADES URL, was started. Its purpose is to ensure, on a scale representative of a geological disposal facility, that the heat released by high-level radioactive waste does not affect the favourable properties of the clay. The large scale of this experiment allows for studying the thermo-hydro-mechanical behaviour of the clay in the near field, i.e. within the excavation damaged zone, and in the far-field of a heated gallery. An extensive monitoring network installed around the PRACLAY gallery allows to observe the evolution of temperature and pore water pressure in the Boom Clay. In this lecture, the main observations that have been made within ATLAS and since the start of the heating of the PRACLAY Heater test will be presented. These observations combined with a comparison with numerical modelling generally confirm the knowledge gained previously from past experiments at different scales (laboratory and in situ).
10:00 – 11:00 h	**In situ testing of gas transfer in clayey rocks** *Jean Tallandier & Rémi de La Vaissière, ANDRA*
	R&D program has been developed for more than 15 years by Andra to improve the understanding and representation of the physical processes associated with gas migration in clay environments. Andra has actively participated in the European programs FORGE (Fate of Gas Repository) and Gasnet (A Thematic Network on Gas Issues in Safety Assessment of Deep Repositories for Radioactive Waste), in experimental programs developed in underground laboratories (Aspö, Mont-Terri, Hades). Andra has been conducting its own experiments first in a deep borehole in 2004 and then in the Meuse/Haute-Marne underground research laboratory since 2009. This presentation summarizes the various gas injection tests carried out in situ. The behavior of the Callovo-Oxfordian claystone under gas stress was studied at different gas injection pressure levels as well as swelling clay-based sealing plugs (compacted mixture of MX80- sand and pure MX80 in pellet and powder form).
11:00 – 11:30 h	**Coffee break**
11:30 – 12:30 h	**In situ testing of gas transfer in crystalline rocks** *Patrick Sellin, Svensk Kärnbränslehantering AB*
	There are still l uncertainties around the gas migration process in bentonite and the findings from laboratory have to be verified in a large scale experiment. The objectives of the Lasgit test is to undertake a large-scale gas injection test to provide data to improve process understanding and test/validate modelling approaches which might be used in performance assessment. This relates in particulate to issues relating to up-scaling and its effect on gas movement and buffer performance. The test has been in operation since 2005 and several gas injection tests have been performed. The observation so far is that gas pathways are formed in the bentonite at a gas pressure similar to the total stress in the test.
12:30 – 13:30 h	**Lunch**
13:30 – 14:30 h	**In situ testing of ESBs in crystalline rocks** *Edgar Bohner, VTT*
	The safety concept of Posiva, the Finnish expert organisation responsible for the final disposal of spent nuclear fuel, is based on the KBS-3 design of the geological repository and the characteristics of the Olkiluoto site, which have been studied since 1980's and monitored for more than 20 years. Important elements of the KBS-3 concept are engineered barrier systems (EBS), including canister, buffer, backfill and deposition tunnel plugs, and closure, with its different backfill and plug types. In the lecture, three different in situ tests of EBS will be presented. Next to the design of the tests, the used materials, the

	different components and their manufacturing, as well as various instrumentation and monitoring systems will be discussed. The presented demonstrations allow for identifying the trigger values for evaluating EBS performance. Therefore, they are essential tools to observe and evaluate performance and safety of EBS.
14:30 – 15:00 h	**Challenges and open questions – Numerical and experimental investigations on gas and under high temperature**
	Xavier Sillen(ONDRAF–NIRAS) & Robert Charlier (Université de Liège)
15:00 – 15:30 h	**Feedback of the participants at the end of the school**
15:30 – 16:00 h	**School closure**