Oral Session 10B

THM experiments in the opalinus clay

Chair: Tilmann Rothfuchs - Yannick Wileveau

MONITORING AND MODELLING OF THERMO-HYDRO-MECHANICAL PROCESSES - MAIN RESULTS OF A HEATER EXPERIMENT AT THE MONT TERRI UNDERGROUND ROCK LABORATORY

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ABSTRACT

The long-term safety of permanent underground repositories relies on a combination of engineered and geological barriers, so that the interactions between the barriers in response to conditions expected in a high-level waste repository need to be identified and fully understood. Co-financed by the European Community, a heater experiment was realized on a pilot plant scale at the underground laboratory in Mont Terri, Switzerland. The experiment was accompanied by an extensive programme of continuous monitoring, experimental investigations on-site as well as in laboratories, and numerical modelling of the coupled thermo-hydro-mechanical processes.

Heat-producing waste was simulated by a heater element of 10 cm diameter, held at a constant surface temperature of 100°C. The heater element (length 2m) operated in a vertical borehole of 7 m depth at 4 to 6 m depth. It was embedded in a geotechnical barrier of pre-compacted bentonite blocks (outer diameter 30 cm) that were irrigated for 35 months before the heating phase (duration 18 months) began. The host rock is a highly consolidated stiff Jurassic clay stone (Opalinus Clay). After the heating phase, the vicinity of the heater element was explored by seismic, hydraulic, and geotechnical tests to investigate if the heating had induced changes in the Opalinus Clay. Additionally, rock mechanic specimens were tested in the laboratory. Finally, the experiment was dismantled to provide laboratory specimens of post-heating buffer and host rock material.

The bentonite blocks were thoroughly wetted at the time of the dismantling. The volume increase amounted to 5 to 9% and was thus below the bentonite's potential. Geoelectrical measurements showed no decrease of the water content in the vicinity of the heater during the heating phase. Decreasing energy input to the heater element over time suggests hence, that the bentonite dried leading to a decrease of its thermal conductivity.

Gas release during the heating period occurred most pronouncedly in a borehole closest to the heater (0.5 m), where after an incubation period of about 6 months after the beginning of heating bell-shaped release curves of carbon dioxide and hydrogen sulphide developed over 10 months indicating that chemical reactions in the Opalinus Clay are restricted. Metal corrosion caused by Opalinus Clay (as it occurred in the rock mechanic laboratory) is probably restricted as well by the supply of a reactant such as oxygen.

Gas release data also suggest that the gas permeability of the Opalinus Clay may be inhomogeneous.

Bentonite and Opalinus Clay show only very weak modifications induced by the heater experiment.

Numerical calculations were done with axisymmetric as well as with anisotropic models. The input data for the anisotropic properties of the Opalinus Clay were provided by the rock mechanic tests. Data of anisotropic creep properties were determined in the laboratory and inte-grated in a Burgers model (but have not yet been used in the Finite Element modeling). Mineralogical analysis shows that the mechanical properties of the Opalinus Clay depend on microstructure rather than mineralogy.

The match between monitored and calculated time series of temperature and pore pressure is good. The pore pressure development shows the impact of transition processes in the Opalinus Clay caused by watering of the bentonite, heating, and cooling. The hydraulic conductivity has considerable influence on the magnitude of the pore pressure values.

The long-term steady stress field does not appear to be affected by the heating and cooling. The bentonite blocks insulate the heater element so that the host rock was only moderately heated (about 65°C at the interface buffer-rock). The temperature field extended to a maximum radial distance of about 5 m only.

THE RESPONSE OF OPALINUS-CLAY DUE TO HEATING: A COMBINED ANALYSIS OF *IN-SITU* MEASUREMENTS, LABORATORY INVESTIGATIONS AND NUMERICAL CALCULATIONS

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ABSTRACT:
In a clay host rock water content rises up to about 30%. Due to the fact that the coefficient of thermal expansion of water is at least one order of magnitude higher than those of minerals a careful evaluation of these effects seems to be an important issue in design, construction and operation of a repository, especially in case of disposal of heat generating waste in extended emplacement fields containing a large amount of disposal boreholes or drifts. Main objective of the research activities are to characterize the THM response of the clay host rock and the effect of thermal expansion on the deformation of underground cavities by a combination of measurements and mathematical calculations in a clay environment as a basis for a repository layout for extended borehole or drift disposal of heat generating waste.

DBE TECHNOLOGY participates in a heater experiment at the Mont Terri underground laboratory in Switzerland. The heater experiment called HE-D is performed by Andra and one major objective is to investigate the host rock behavior in case of directly being heated without any buffer material between heater and host rock.

The heater experiment consists of a horizontal heater borehole equipped with two electrical heaters and a couple of observation boreholes drilled in several direction to the heaters. In one of the boreholes, drilled perpendicular to the heaters, DBE TECHNOLOGY performs deformation- and temperature-measurements based on fiber optic Bragg grating technology. Rock temperature and displacements are measured at several distances to the heaters as a function of time. This allows for evaluating the temperature induced rock deformation due to the heating process.

From the same observation borehole several drill core samples have been taken to perform laboratory investigations on the thermo-physical rock properties. The investigations include the thermal conductivity, thermal diffusivity, specific heat capacity and linear thermal expansion. For all rock properties the temperature dependence has been investigated completed by measurements of pressure dependence of the thermal conductivity. Special attention has been turned to the effect of anisotropy. The rock properties of the opalinus clay are known to show a strong anisotropic behavior. Thus, measurements on drill core samples have been performed in different directions to the bedding of the clay aimed at determination of the factor of anisotropy.

The fiber optic *in-situ* measurements have been accompanied by three dimensional numerical calculations for the purpose of analysis and description of the rock behavior. Due to the strong anisotropic rock properties, the geological situation and the location of the drifts, a full 3D model was necessary to apply. The calculations have been performed with FLAC3D which is a 3D continuum code based on the finite difference method for modeling soil, rock and structural behavior. In order to consider anisotropic thermal conductivities an additional module has recently been developed and implemented into the source code

by Itasca Consultants. The rock properties determined in the laboratory have been used as basic input parameters for the model calculations.

This presentation will show the results of the fiber optic temperature- and deformation- measurements describing the time dependant temperature distribution as well as the corresponding rock displacements. The thermo-physical rock properties determined in the laboratory will be presented and the importance of the parameters with regard to the test analysis will be outlined. The numerical calculations will as well be presented and a parameter configuration will be given, which fits best to all the measurements resulting in a final description of the thermo-mechanical rock behavior.

MODELLING OF AN *IN-SITU* HEATER EXPERIMENT IN OPALINUS CLAY

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ABSTRACT

The safety and long-term performance of underground repositories for radioactive waste rely on a combination of several engineered and geological barriers. The properties of the geological barrier depend on the site conditions of the host formation, but the performance of the engineered barriers is a result of their design and construction and of the interaction between both barriers, specifically when heat generating waste is emplaced. These interactions need to be identified and quantified in order to provide models which describe reliably the long-term performance of a repository. The basic objective of the HE Experiment at Mont Terri, which is the scope of this project, is to gain knowledge about the coupled thermo-hydro-mechanical processes developing in the host rock and in a bentonite buffer as a response to a heat load.

This paper presents some modelling work for the heater test. The calculations are performed with a newly developed three phase (air, water, solids) non-isothermal code THM-Mehrlin. The code is based on a continuum formulation of mass and momentum as well as energy balance equations and uses pressures, displacements and temperature as unknowns.

The THM coupled modelling covered heating and cooling phases of the test, with 2D and 3D isotropic and anisotropic calculations. Starting from a reference case with literature parameters, a series of parameter variations in both 2D and 3D has been performed in order to assess the impact of the temperature changes on the rock mass in the "far field".
The simulations reveal a major dependency of the results on the heat conduction value of the Opalinus Clay. In the simulation, the heat conduction tensor was considered to be either isotropic or anisotropic (larger heat conduction in the direction parallel to the bedding planes than perpendicular to the bedding planes). For the isotropic case, a 2D configuration was chosen, whereas for the anisotropic case a 3D configuration was necessary. The results are summarised and discussed.
A reasonable fit with the measured temperature curves could be obtained with differences between measured and calculated values of a few 1/10 K with the following parameters for the Opalinus Clay: intrinsic permeability = 8×10^{-19} m^2 , thermal conductivity = 2.1 W/m/K, heat capacity of 920 J/kg/K and assuming isotropic conditions. These values represent a best estimate which lies within the reported range of values issued from the literature.

The temperature field was found to be very sensitive with respect to thermal conductivity of both the buffer and –to a lesser extent– the formation. In particular, the buffer thermal conductivity has a large influence, even if the buffer-thickness is small compared to the surrounding rock: a low thermal conductivity leads to much higher temperatures close to the heater (insulation effect). The impact of the thermal conductivity of the Opalinus clay is pronounced and leads to higher pressure level near the heater. The influence of heat capacity of the Opalinus Clay formation on the temperature field is not negligible but not as large as that of the hydraulic conductivity. The effects of mechanical parameters like thermal expansion of the rock or rock stiffness are found to be less important, but still have an influence. The feedback from hydraulic and mechanical conditions on the temperature field is not very important.

As far as the heating effect is concerned, it was found to be limited to a comparatively small volume around the heater (radial extension of the order of less than 5 m for temperature difference less than a

few degrees). Overall, the rise in temperature a few 10s of cm away from the heater was found to be small: at the location of BHE4, i.e. 0.65 m from the heater axis, the temperature reached a stable value at about 314 K.

The porewater pressures were, according to the calculations, significantly influenced by the heating with increased pore pressures developing even in regions that were only slightly affected by the rise in temperature due to compressibility and thermal expansion effects. After the temperature reached steady state, the overpressures dissipated, due to flow within the bentonite buffer / Opalinus Clay. The porewater pressures, however, did not fall back to their original level during the heating test duration, but levelled off to a more or less constant value. The early time pore pressure increased up to 10 MPa and the rock permeability is a major parameter influencing the level of overpressure reached through the heating as well as the porewater pressure dissipation. The calculated pressure level is very sensitive not only to the rock permeability but also, to a lesser degree, to the thermal parameters of the rock. It was found that the volume of rock undergoing a rise in temperature more than a few °C was relatively small. The pore pressure rise due to heating however was found to be significant with respect to in-situ stress level and also probably with respect to the stress level found around underground repositories.

The induced changes in effective stress are equally important and clearly can not be neglected, both regarding mechanical stability (where applicable) and changes in volumetric rock deformation and/or damage, with associated consequences for rock permeability and the creation of preferential features in the vicinity of emplacement tunnels.

MEASUREMENT OF THERMALLY-INDUCED PORE WATER PRESSURE INCREASE AND GAS MIGRATION IN THE OPALINUS CLAY THE HE-D EXPERIMENT AT THE MONT TERRI ROCK LABORATORY

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ABSTRACT
In order to gain a better understanding of coupled thermo-hydro-mechanical processes in indurated clays as host rock for the disposal of high-level radioactive waste, a heating experiment named HE-D is being conducted by Andra, GRS and other partners in the Opalinus clay at the Mont Terri Rock Laboratory in Switzerland [Wileveau & Rothfuchs, 2003]. Figure 1 shows an overview of the test field. Two electrical heaters were installed in a horizontal borehole of 30 cm diameter and 13 m length drilled from the HE-D niche parallel to the existing MI niche. Since April 2004, the surrounding rock has been heated by electric power input of 650 Watt in the first heating phase and 1950 Watt in the second phase. A third heating phase may be carried out for reaching a maximum temperature of 150°C at the interface between heater and rock, depending on the conditions of the testing equipments. Finally, after heater shut-down, the rock will cool down to ambient temperature. To observe responses of the clay rock to the thermal loading, a large number of measuring instruments was installed in the near field around the heaters to measure temperature, pore water pressure, gas migration and deformation of the clay during the experiment. For the design and interpretation of the experiment, numerical modelling work was conducted by different institutions using different codes. This paper presents results of the *in-situ* measurements of temperature, pore water pressure and gas migration in the clay rock during the experiment.

Before drilling the heater borehole BHE-D0, eleven GRS mini-packer systems with sensors for measuring temperature and pore pressure were installed into slim boreholes of 20 mm diameter drilled from the MI niche to different positions up to 11 m deep in the rock, while other sensors of the Métro-Mesures were set up in a borehole parallel to the heater borehole. Figure 2 illustrates a typical example of the measurements at a position 1.35 m distant to heater 2. From this figure, it can be seen that:

(a) The initial pore water pressure of 1.2 MPa was constant over 3 months before drilling the heater borehole;
(b) Drilling the heater borehole BHE-D0 caused an insignificant sudden decrease of the pore water pressure, and then it remained unchanged;
(c) The constant power input of 650 Watt from both heaters to the rock generated a gradual increase of the temperature from 15 to 23.5°C over 3 months, and a rapid increase of the pore water pressure over the first month, and then maintained relatively constant at 2.3 MPa over further 2 months;
(d) The second heating phase with a power input of 1950 Watt increased the temperature to 40.5°C over about 3 months. At the very beginning of the heating phase, a transient drop down of the pore water pressure was observed. Afterwards, it increased to a maximum of 4 MPa and then decreased slowly to 3.7 MPa over about 1 month.

For investigating thermally-induced gas migration in the clay rock, two injection and four extraction boreholes with a diameter of 76 mm and a length of about 10 m were drilled from the MI niche

perpendicular to the heater borehole. The injection boreholes pass the heater borehole at a distance of 0.8 and 1.5 m, respectively. The extraction boreholes have a horizontal and a vertical distance to the injection boreholes of 20 cm. In all six boreholes quadruple packer systems were installed. The central sample intervals of the injection boreholes were inflated to 0.9 MPa prior to heating and the gas pressures were recorded in all intervals electronically. These measurements indicate that the Opalinus clay in the vicinity of the heaters is almost impermeable because, so far, no significant pressure decrease was observed, neither before nor during the heating phases.

The rock mass response to heating has been blindly predicted by GRS with use of the THM computer code CODE_BRIGHT developed by UPC. Generally, the modelling results agree satisfactorily with the *in-situ* measurements.

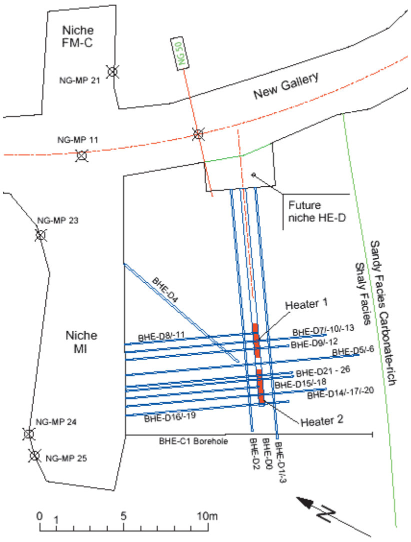

Figure 1: Up view of HE-D experiment

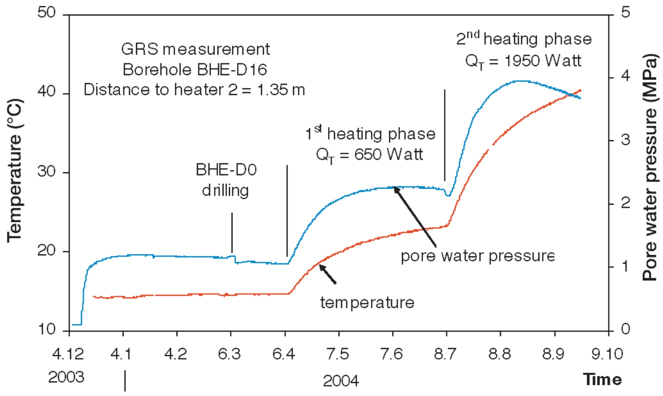

Figure 2: Measurements of temperature and pore water pressure during the heating experiment in the Opalinus clay at Mont Terri

References:

Wileveau,Y., Rothfuchs, T. (2003): HE-D Experiment: Test Plan for Study of the Thermo-Hydro-Mechanical Behaviour of the Opalinus Clay. Mont Terri Project, TN 2004-20.