Determination of the thermal parameters of a clay from heating cell tests

Détermination des paramètres thermiques d'une argile à partir d'essais dans une cellule de chauffage

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ABSTRACT: Boom Clay is being studied in Belgium in connection with the design of a repository for radioactive waste. Within this context, thermal impact may play an important role on the behaviour of this low-permeability clay. To evaluate this impact, heating pulse tests on intact borehole samples were carried out using an axi-symmetric and constant volume heating cell with controlled hydraulic boundary conditions. Attention is focused on the time evolution of temperature and pore water pressure changes along heating and cooling paths –i.e., pore pressure build-up during quasi-undrained heating and later dissipation to the applied hydraulic boundary conditions–. A coupled thermo-hydro-mechanical finite element program was used in a first stage to determine thermal parameters by back-analysis and then to simulate the experimental results.

RÉSUMÉ: L'argile de Boom est un matériau actuellement étudié en Belgique dans le cadre de la conception d'un centre de stockage de déchets radioactifs. Dans ce contexte, l'impact thermique est susceptible de jouer un rôle important dans la réponse de la formation argileuse, de faible perméabilité. Afin d'évaluer cet impact, des essais de chauffage par impulsion ont été réalisé sur des échantillons intacts, dans une cellule axisymétrique à volume constant qui permet de contrôler les conditions hydrauliques à sa frontière. Les mesures obtenues en termes d'évolution de température et de pression d'eau lors de cheminements de chauffage et de refroidissement indiquent le développement initial de pression de pores en conditions quasi-non drainées (cas du chauffage), suivi d'une dissipation postérieure vers un régime stationnaire équilibré avec les conditions hydrauliques appliquées. Un programme Éléments Finis couplés thermo-hydro-mécanique a été utilisé pour rétro-analyser, dans un premier temps, les paramètres de conductivité thermique et pour simuler, dans un deuxième temps, les résultats expérimentaux.

KEYWORDS: heating cell, clay, thermal conductivity, back-analysis, experimental results, numerical simulation

1 INTRODUCTION

Thermal impact may play an important role on the behaviour of low-permeability saturated clayey host formations in connection with the design of a repository for 'High-Level Radioactive Waste'. Boom Clay is currently the subject of extensive research on hydrothermal and mechanical phenomena that may possibly affect its performance as potential geological host formation.

There are a number of laboratory results concerning the saturated hydro-mechanical behaviour of Boom Clay under a constant temperature field and studies on this area are described -to cite but a few of them- in De Bruyn (1999), Le (2008) and Lima (2011). Nevertheless, there is less information on clay hydro-mechanical response on heating and cooling paths under controlled small-scale laboratory condition. To this end, the paper presents results from a comprehensive testing program performed on Boom Clay to determine thermal and hydraulic parameters using an axi-symmetric heating cell with measurement of temperature and pore pressure. Pore-pressure built-up and dissipation on fast heating pulse tests have been analysed using experimental results assisted by numerical simulations carried out with a coupled thermo-hydro-mechanical finite element code.

2 EXPERIMENTAL SETUP AND TESTED MATERIAL

Laboratory tests have been performed on Boom Clay (Mol, Belgium). Table 1 summarises the main properties of this Tertiary clay (20%-30% kaolinite, 20%-30% illite and 10%-20% smectite), which is slightly overconsolidated (Horseman *et al*. 1987, Coll 2005, Lima 2011).

Table 1. Main properties of Boom Clay.

Property	Value
Density, ρ	2.05 Mg/m^3
Dry density, ρ_d	1.65 to 1.67 Mg/m^3
Gravimetric water content, w	25 %
Density of soil solids, ρ_s	2.67 Mg/m^3
Void ratio, e	0.60 to 0.62
Degree of saturation, S_r	100 %
Liquid limit, w_L	56
Plastic limit, w_P	29
Vertical water permeability at 20ºC, k_{wv}	2.3×10^{-12} m/s
Vertical water permeability at 80ºC, k_{wv}	6.5×10^{-12} m/s
Horiz. water permeability at 20ºC, k_{wv}	4.5×10^{-12} m/s
Small-strain shear modulus, G_0	347 MPa
Poisson's ratio, ν	0.20

Figure 1 shows a scheme of a constant volume and axi-symmetric heating cell (Muñoz *et al*. 2009, Lima *et al*. 2010, Lima 2011), which has been used to perform heating pulse tests with controlled power supply and controlled hydraulic boundary conditions. Soil sample size is 75 mm in diameter and 100 mm high. A controlled-power heater (*H* in the figure) is installed along the axis of the sample in the lower part of the cell. Different transducers monitor the sample response, as shown in the figure: two miniature pore water pressure transducers (Pw_1 and Pw_2), and three thermocouples (T_1, T_2 and T_3). The cell is equipped with top and bottom valves to apply controlled hydraulic boundary conditions (u_u and u_b). The heater with controlled power supply remains switched on for 24 hours during the heating stage and later it is switched off to perform the cooling phase.

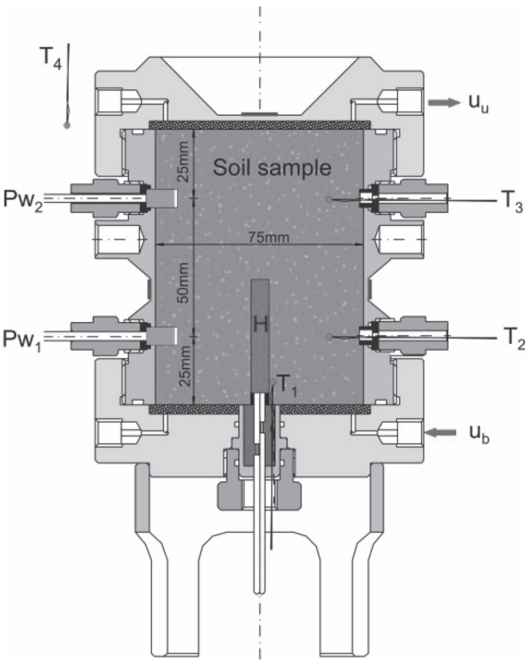

Figure 1. Axi-symmetric heating cell and transducers (Muñoz *et al*. 2009, Lima *et al*. 2010, Lima 2011).

3 EXPERIMENTAL RESULTS

Attention has been focused on the time evolution of temperature and pore water pressure changes during heating and cooling paths –i.e., pore pressure build-up during quasi-undrained heating and later dissipation to the applied hydraulic boundary conditions–. Throughout the course of the heating/cooling paths, the bottom drainage is maintained open at constant water backpressure (1 MPa) using an automatic pressure / volume controller, while the upper valve is kept closed. This backpressure is important since it allows measuring the pore pressure drop during the cooling phase without reaching the negative range (below atmospheric conditions). The initial and external temperatures are regulated by submerging the cell inside a temperature controlled water bath at temperature T_4 (Figure 1). Figure 2a shows the time evolution of temperature for different locations and along a heating and cooling cycle up to a maximum heater temperature of 54ºC. Figure 2b presents the corresponding time evolution of pore water pressures at different locations. During heating, pore water pressure increased due to the larger thermal expansion coefficient of water. The magnitude of the water pressure change depends on the rate of temperature increase / decrease, on soil compressibility and thermal-expansion coefficient, on water permeability and porosity, as well as on the hydraulic boundary condition applied. After the heating path, pore water pressure dissipates at constant temperature towards the hydraulic value applied at the boundary. Pore water pressure Pw_2 dissipates more slowly due to the larger distance to the draining boundary. An opposite pore pressure evolution is observed on cooling: an initial pore pressure drop followed by pressure recovery to the applied boundary condition (again, Pw_2 recovers more slowly).

Figure 3 shows a zoom of the early stage evolution of pore water pressure P_{w1} and temperature T_2 changes during another heating phase. These sensors are located close to the draining boundary (Figure 1). It can be observed that pressure changes develop at a faster rate compared to temperature changes. In fact, pore pressure starts to dissipate towards the applied hydraulic boundary condition well before the temperature reaches its maximum value.

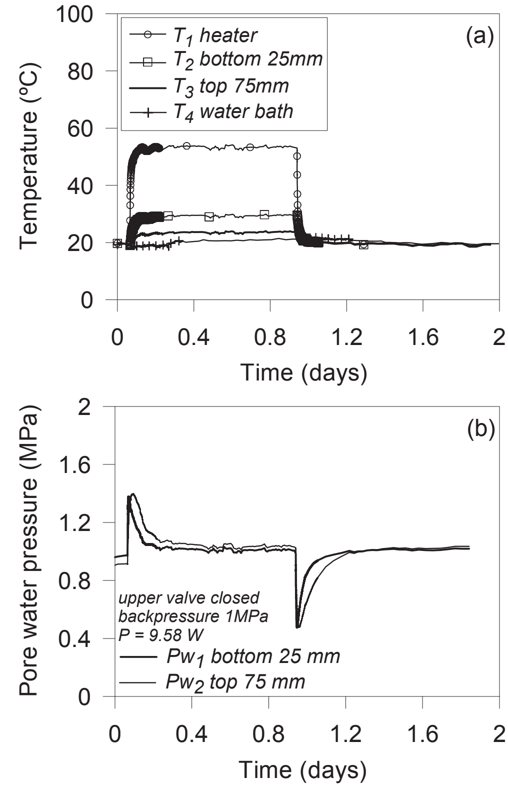

Figure 2. Temperature and pore water pressure evolutions during heating and cooling paths (Lima *et al*. 2010, Lima 2011).

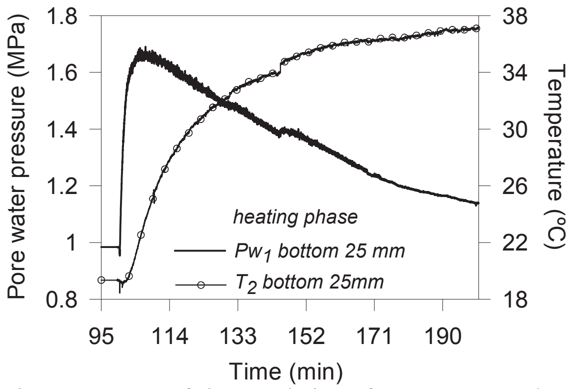

Figure 3. Zoom of time evolution of temperature and pore water pressure during heating (Lima *et al*. 2010, Lima 2011).

4 INTERPRETATION OF RESULTS

In the interpretation of the test results, it was assumed that temperatures and heat flux were not influenced by water pressure and flow, which means that heat convection was assumed to be negligible. The driving process for temperature change during the test is thus conduction only. This assumption is justified by the condition of constant overall volume prevailing in the heating cell that makes the change in porosity and the velocities of the solid phase very small. Moreover, the low permeability of the material prevents the existence of high velocities for the liquid phase. The flux of heat convected by the solid and liquid phases is, therefore, extremely low. In contrast, water pressure and flow were assumed to be influenced by temperature: as a consequence, while the thermal problem was decoupled from the hydraulic one, the hydraulic problem was coupled to the thermal one.

The test was then interpreted in two separated stages. First, a back-analysis of temperature measurements was carried out by performing uncoupled thermal simulations using the finite element program CODE_BRIGHT (Olivella *et al*. 1996); only the balance equation for energy was solved. Heat exchanged by the highly conductive stainless steel cell with the controlled water bath was accounted for as a convection-type boundary condition of the problem. This heat flux was assumed to be proportional to the difference between the temperature of the cell and the temperature of the water bath at each boundary node, through a convection coefficient *h*. Thermal optimisation was then aimed at identifying the values of the saturated thermal conductivity λ and the convection coefficient *h*. Calculations were performed for different combinations of λ and *h*. For each of them, a measure of the least squares difference between temperature simulation results and temperature experimental measurements ε was computed for different elapsed times. The three-dimensional plot in Figure 4 shows the least squares differences ε between simulation results and experimental observations. The best agreement was obtained for parameters λ=1.6 Wm^{-1}K^{-1} and h=24 Wm^{-2}K^{-1}.

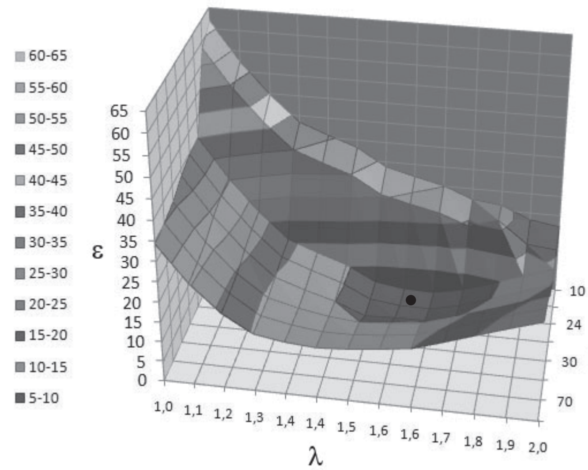

Figure 4. Three-dimensional graph showing the differences in temperature between observations and calculations in the back-analysis of the heating pulse test. Determination of thermal conductivity λ and convection coefficient *h* (Lima 2011).

Back-analysed thermal parameters were used to study the coupled thermal and hydraulic results. Water permeability and elastic soil parameters used in the simulations, which are reported in Table 1, were obtained from independent tests. Controlled-gradient tests at different temperatures and constant volume conditions for water permeability, as well as small-strain shear moduli with resonant column and bender element tests, have been reported by Lima (2011). Figure 5 displays the time evolution of temperature and pore water pressure (experimental and simulated results) during the same heating and cooling paths presented in Figure 2. A good agreement is observed in the pore water pressure response, which shows the consistency between the back-calculated and directly measured parameters from independent laboratory tests.

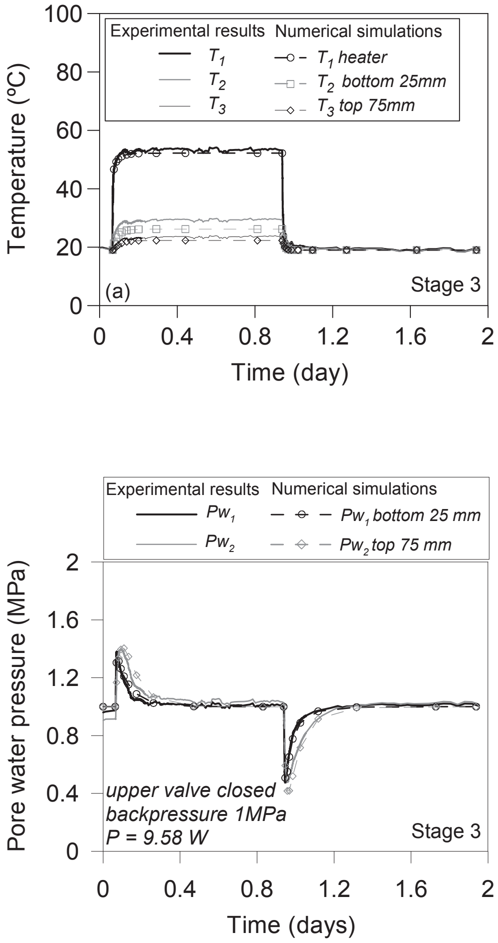

Figure 5. Time evolution of temperature and pore water pressure: experimental and simulated results (Lima 2011).

5 CONCLUSIONS

A series of heating and cooling paths were performed on Boom Clay –a reference host formation for potential geological disposal of 'High-Level Radioactive Waste' in Belgium– to study the impact and consequences of thermal loads on this low-permeability clay formation. Tests were performed in a fully-instrumented heating cell –with several thermocouples and pressure transducers– under constant volume and controlled hydraulic boundary condition: constant water pressure at the bottom drainage and top end with no flow condition. Selected results of a comprehensive experimental programme on intact borehole samples have been presented and discussed in terms of the joint measurements of temperature and pressure changes during the application of heating-cooling cycles.

Thermal and hydraulic results were calibrated and simulated using coupled thermo-hydro-mechanical analyses performed with a finite element code (CODE_BRIGHT). In particular, the thermal conductivity of the clay was determined by back-analysis of the thermal response. The coupled thermal and hydraulic results were also successfully simulated using parameters that had been back-calculated from previous heating pulse tests and also directly from independent laboratory tests. An overall examination of the results obtained allows the identification of the main features of the hydro-thermal coupling under the test conditions.

6 ACKNOWLEDGEMENTS

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