REM (Resaturation test at metric scale)
Preliminary hydraulic simulation

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Andra's experiment REM consists in the artificial resaturation of a mixture of pellets and powder of bentonite at a metric scale (Conil et al., 2016). It started around one year ago and evidenced the partial hydration of the lower part of the core. Blind simulations had predicted a full resaturation time of 30 to 60 years. No mechanical response (i. e. swelling pressure) has been measured so far. Hydraulic simulations have been conducted for a first comparison with measured relative humidity at some points. The computed hydration appeared to be consistent with reality at the macroscopic scale but local comparison proved to be difficult because of the still high heterogeneity of the partially hydrated bentonite at this early stage of resaturation. Longer measurements and further hydraulic and coupled hydro-mechanical modelling will be needed for deeper investigation.

1 Background

Andra's experimental participation to the DOPAS project is mainly twofold. The Full Scale Seal (FSS) demonstrator and a satellite experiment called REM. FSS is one of the various experiments implemented by Andra within the frame of the Cigeo Project (the French Deep Geological Repository) development, to demonstrate the technical construction feasibility and performance of the seals to be built in order to close the repository galleries and alveoli (shafts, access ramps, drifts, disposal vaults). The REM (Metric Scale Resaturation) experiment has been designed to study the water saturation of a bentonite mixture of 32 mm diameter pellets and crushed pellets used in FSS (Conil et al., 2015). The originality of this mock up is its scale. The cylindrical cell where the bentonite mixture is placed has a one meter height and one meter diameter. Water is injected at the bottom of the experiment at a very low controlled rate so as to simulate the natural resaturation flow from the clay host rock. REM contains several tens of gauges measuring pore pressure, total pressure, relative humidity and the swelling induced total strength on the experiment top cover. In-laboratory tests (at centimetric and decimetric scale) have been performed by the CEA/LECBA laboratory before the beginning of the REM experiment itself to get a better understanding of the bentonite behaviour under several conditions (water composition, dry density) and to characterize its hydro-mechanical properties. The REM results will be used to consolidate the representation of seals in the whole of CIGEO repository TH-Gas transient assessment and in safety analysis. To help this purpose, one mean is numerical simulations of the experiment.

2 Scope and objectives

REM metric-scale cell was installed and hydration started in September 2014. So far significant changes in relative humidity were measured at the bottom of the core whereas any significant changes in total pressure were measured. Uncoupled simulations (i. e. only hydraulic) have been done to assess water distribution within the core using a simple approach so as to quickly get a preliminary interpretation of its early resaturation. A coupled hydro-mechanical modelling will be conducted later on basis of in-laboratory tests results and REM future measurements in order to get a better understanding of its whole behaviour.

3 Modelling

The phenomenological model used for these hydraulic simulations was a generalized Darcy flow coupled with Van-Genuchten/Mualem empirical formulations to represent the non-saturated behaviour (i.e. retention and relative permeability curves). Due to resaturation the remaining porous air within the bentonite is driven out of the core and collected at the top of the cell where air flow is measured continuously. As a first approximation it was considered that air is perfectly mobile and thus any air pressure increase occurs within the core. Hence the Richards' theoretical approach was followed. No gravity was taken into account since capillary forces are much higher.

Despite its initial heterogeneity (pellets & powder) the bentonite core was modelled as a homogeneous material. Some of the physical and hydraulic data were taken from in-laboratory tests on samples conducted by CEA (porosity, initial saturation, intrinsic permeability). The parameters of retention curve were calibrated so as to fit the initial low relative humidity measured within the core (according to Kelvin's law) and to be consistent with data taken from previously laboratory tests conducted on similar bentonite mixtures (Gens et al, 2011). A classic law was chosen for relative permeability. All parameters are listed in Table 3-1.

Table 3-1. Hydraulic parameters

Constitutive law	Parameter	Value
	Porosity (-)	45 %
	Initial liquid saturation (-)	15 %
	Intrinsic permeability (m^2)	2.10^{-21}
Retention curve $S_e = \frac{S_l - S_{lr}}{S_{ls} - S_{lr}} = \left[1 + \left(\frac{s}{P_0}\right)^{1/(1-\lambda_0)}\right]^{-\lambda_0} \left(1 - \frac{s}{P_d}\right)^{\lambda_d}$	P_0 (MPa) λ_0 (-) P_d (MPa) λ_d (-) S_{ls} (-) S_{lr} (-)	50 0.43 800 4 1 0
Relative permeability $k_r = S_e^{\lambda}$	λ (-) S_{ls} (-) S_{lr} (-)	3 1 0

Water is injected at a constant rate of 50 mL per day through a porous disc below the core in order to make the inflow uniform. Hence a 2D-axissymetric model was chosen as a first geometrical modelling approach.

4 Results

Results in terms of relative humidity changes were compared during the early resaturation of the core (~ 300 days) at some points located in the lower part of the core – No significant change was measured at more than 15 cm from the lower boundary. The relative humidity was calculated from the computed liquid pressure according to Kelvin's law. The main results are depicted on Figure 4-1.

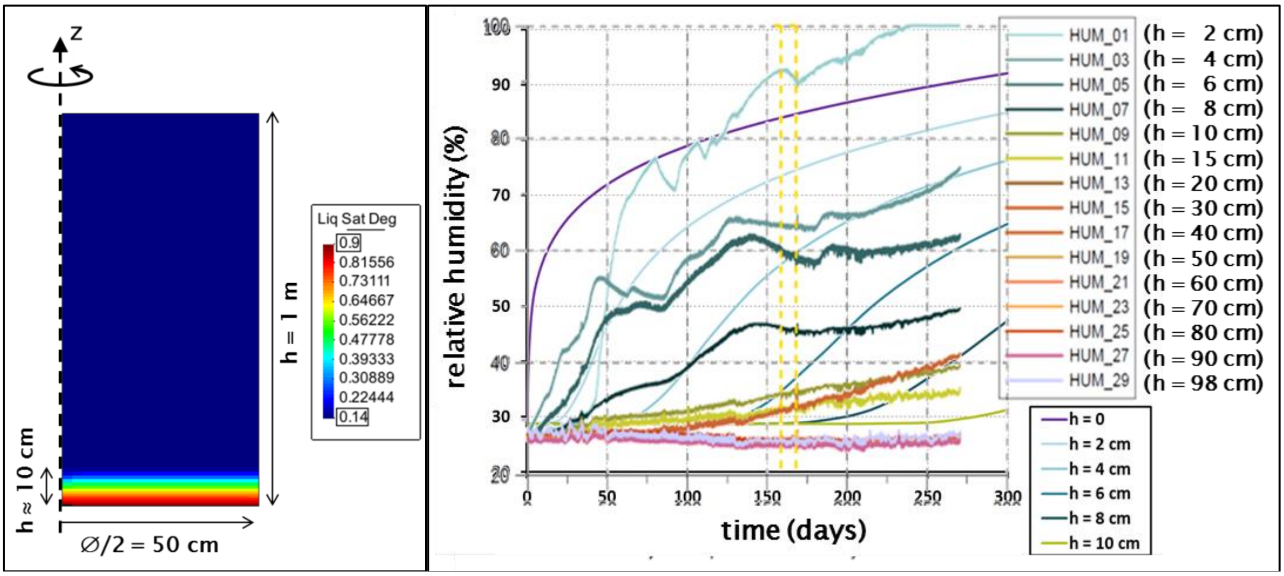

Figure 4-1. Liquid saturation field at time 265 days and relative humidity changes at different heights in the lower part of REM: Comparison between measurements and preliminary 2D-axissymetric simulations

The kinetic of computed relative humidity increase depends mainly on the distance to the bottom boundary of the core. The corresponding curves start to go up after a certain time (for instance 150 days at 8 cm height) thus showing a gradual progress of a saturation front. As the latter moves forward within the core the increase in relative humidity declines quite quickly because hydraulic diffusion increases with saturation. In particular the simulated relative humidity does not reach 100 % at the lower boundary. After 275 days of hydration it ranges from 30 % to 90 % within the ten first centimetres of the core.

The measures evidence a more complex evolution. Some of the sensors located in the first few centimetres show a very early increase of relative humidity whereas others show a later one. Thus no saturation front is evidenced. Afterwards relative humidity does not increase regularly within the ten first centimetres of the core. The sensor located at 2 cm height reached 100 % after 230 days of hydration, suggesting a full resaturation of the two first cm of the core already occurred. The other sensors show a relative humidity range between 35 % and 75 % after 275 days of hydration, which correspond to the order of magnitude of the results of simulations. However the local correspondence between measurement and simulation is very difficult.

5 Discussion

The results show the difficulty to compare computed and measured relative humidity so far with precision because of the important heterogeneity of the mixture at early resaturation (especially concerning retention properties). It seems that water flows locally quicker especially within bentonite powder where macro-voids are predominant. On the opposite bentonite pellets may be slower hydrated. Consequently a double porosity approach might bring deeper understanding in the hydration process. It has also to be noticed that longer measurement is needed to allow for a robust comparative analysis: According to blind hydraulic simulations the full resaturation time is estimated between 30 and 60 years (Robinet et al, 2014) whereas the REM hydration started only one year ago.

The absence of mechanical response so far may seem odd since the amount of water injected so far is not negligible compared to the initial available pore volume within the first 10 cm of the core (14 L vs ~30 L). Usually in most high scale experiments a partial resaturation of bentonite induces early and non-negligible increases in swelling pressure. To explain this apparent inconsistency it has been first assumed that a part of the injected water has been filling the porous disc (initially empty) since the beginning of the experiment. However this hypothesis has been rejected because the very high capillary forces in the bentonite coupled with a relatively low flow rate (2 mL per hour) enable bentonite to catch every water bubble as soon as it is injected in the porous disc, so it is unlikely that the latter has been accumulating significant amounts of liquid water. This conclusion was confirmed by 3D hydraulic simulations based on the same hypothesis as in 2D instead the modelling of the very permeable porous disc and local water injection through pipes (see Figure 5-1).

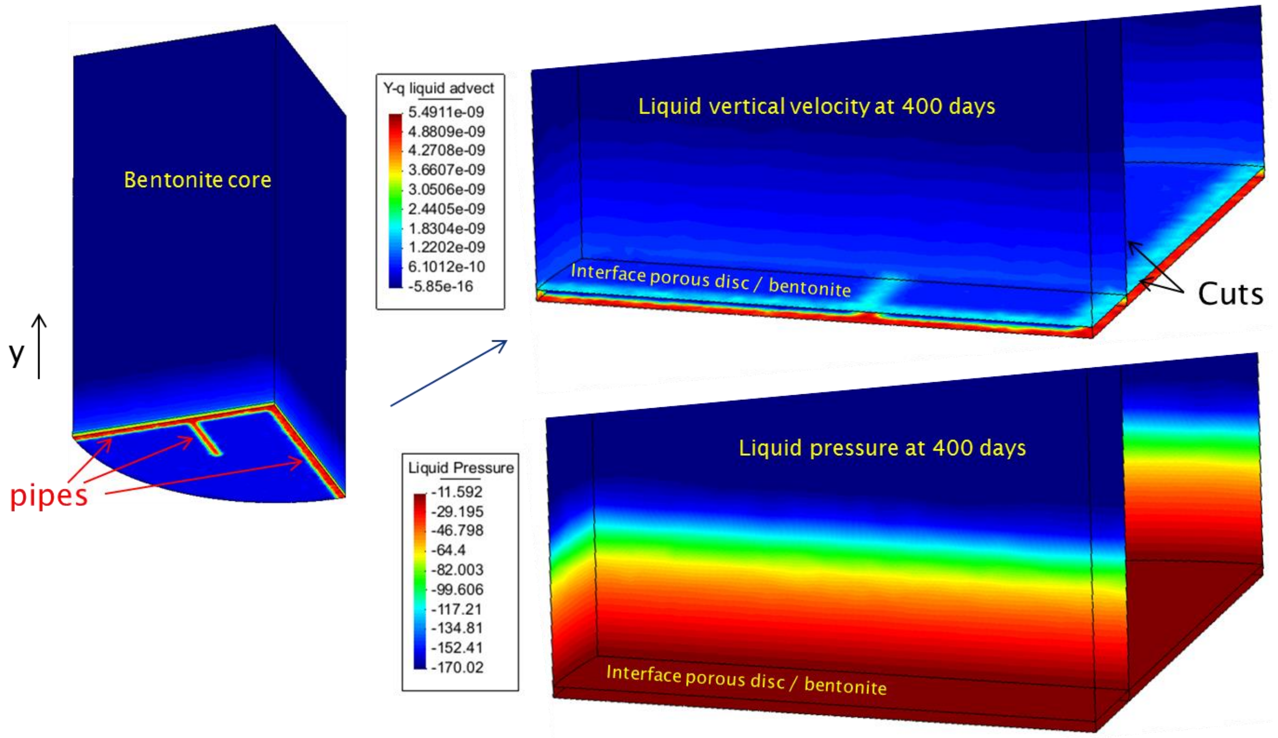

Figure 5-1. Computed liquid vertical velocity and liquid pressure field at time 400 days taking into account the porous disc through which water is injected

Another hypothesis to explain the absence of mechanical response is that the swelling potential may be weaker at this scale for (very) low degrees of saturation within the core. In-laboratory tests on samples seem to show that the early increase of swelling pressure is slower when scale is higher (Gatabin et al, 2015). Anyway and again it is difficult to conclude on this point at this stage regarding the very early state of the core hydration. Longer observations are needed for deeper investigation.

The constant imposed injection flow rate may become a problem when the bottom of the core is fully resaturated (filling of the porous disc instead of bentonite then risk of slight overpressures): bentonite may not be able to absorb it all as pores to be filled become more distant. According to predicting simulations fully resaturation of the bottom boundary of the core may occur between 500 and 700 days from the start of injection (depending on the considered value of intrinsic permeability

– 2.10^{-14} or 3.10^{-14} m/s). Thus later one may have to reconsider the experimental boundary condition (for instance change it into an imposed liquid pressure) to avoid problems in the injection circuit.

6 Conclusions

REM experiment started in September 2014 and is expected to last several decades for full resaturation of the instrumented metric scale bentonite core. Some relative humidity sensors evidenced a partly hydration of the lower part of the core and no mechanical response was detected so far. Preliminary 2D hydraulic simulations gave quite consistent results at the macroscopic scale but local comparison proved to be difficult probably because of the still strong heterogeneity of the mixture at this stage of very early resaturation. Longer measurements and further hydraulic and coupled hydro-mechanical modelling will be needed for deeper investigation.

7 References

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