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Characterizing water transfer in compacted soils in the context of energy storage, contribution of magnetic resonance imaging (MRI)

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The concept of energy geostructures consists in enhancing existing civil engineering structures from an energy point of view thanks to the insertion of heat exchanger tubes. In order to consider the use of compacted soil embankments for heat storage [1], a good knowledge of water movement is required. Indeed, the increase in temperature of the exchangers leads to a migration of liquid/vapour water to the surface layers [2]. A loss of moisture may alter the thermal capacity of the soil [1] and therefore the system energy efficiency. To determine unsaturated hydraulic properties, the Instantaneous Profile Method (IPM) consists in inducing transient flow in a long cylindrical sample of soil and then measuring the resulting water content and/or pore water pressure profiles at various time intervals [3]. The unsaturated hydraulic conductivity (k_u) is then computed using Darcy's law.

The direct evaporation technique allows the measurement of the suction profile in a soil column submitted to drying [4] using filter papers whose water retention curve is known. This method is quite reliable but requires long equilibrium time. Thus, the tests need several weeks and do not give accurate results at the early stages of drying, as the soil state is close to saturation. The analysis of the results when the soil retention capacity is low is therefore complicated, especially when the flow is coupled with temperature variations.

In this study, this classical method was compared to a faster alternate method using nuclear magnetic resonance imaging (MRI) that allows for non-intrusive, continuous and small-scale monitoring of the effect of thermo-hydraulic solicitations on water transfer within the sample. The use of MRI for monitoring the drying/wetting front progression appeared in 1970 [5]. Simpson et al. [6] presented the successive studies that have made it possible to develop a method for monitoring the movement of water within a sample. These measurements can be 1D, 2D and 3D.

The tests were performed on a sandy lean clay sampled in the Paris region in France. The soil was dried, pulverized, and sieved through a 2 mm sieve before experiments. The compaction state was selected to optimize the heat storage capacity [4] with a water content of 16.3% and a dry density of 1.79 $Mg.m^{-3}$. Ten cylindrical samples of 70 mm in diameter and 20 mm in height were compacted and superimposed with introducing filter paper disks between them. The regular weighting of each sample and each filter paper during three months allowed the derivation of the k_u curve by the IPM method.

For the MRI method, 9 samples of 36 mm in diameter and 10 mm in height were compacted at the initial state then brought to different degrees of saturation. The measurement of the water proton relaxation time using a Bruker Biospec 24/40 superconducting magnet (100 MHz), allowed the definition of a calibration curve which connects MRI signal to the water content of the samples (Figure 1b). A Single Point Imaging pulse sequence [7] was used to obtain the signal intensity (encoding time 75 µs < τ < 200 µs). In an image acquired with the SPI method, the intensity of each voxel (S) is :

$$S = M_0 \exp\left(\frac{-\tau}{T_2^*}\right) \quad (1)$$

Where M_0 is the magnetization in a pixel and T_2^* is the transverse relaxation time.

The calibration curve is shown in Figure 1b. Then, a larger sample of 30mm in height was compacted and exposed to an air flow at 20°C and 30% relative humidity through using a remote humid air generation system. 27 measurements points were monitored

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with an interval of 1.1 mm along the sample. Four examples of the recorded profiles are shown in Figure 1c. The evolution of the water content inside the sample is then calculated using the calibration curve to interpret the water migration in the samples submitted to humidity- and temperature-controlled air (Figure 1a). The pre-established retention curve of the soil will be used to calculate its matric suction. At each depth, the flow velocity and the hydraulic gradient will be calculated from the water content profiles and suction profiles respectively in order to determine the unsaturated hydraulic conductivity.

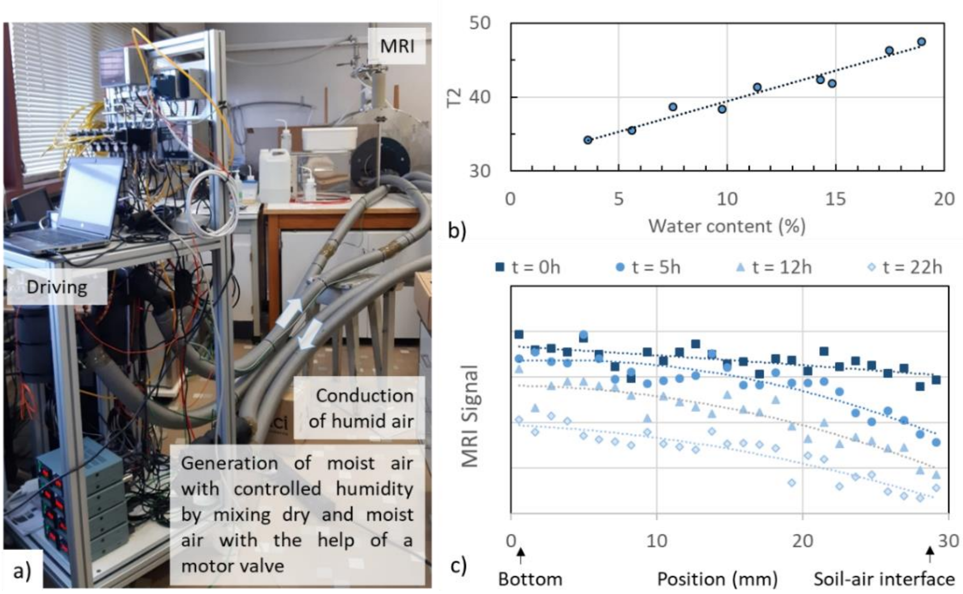

Figure 1: a) photograph of the MRI experimental setup; b) calibration curve ; c) drying example at T=20°C and HR=30%

These experimental developments allow the non-intrusive and continuous quantification of water movement in unsaturated soils during the application of coupled thermo-hydraulic solicitations. The understanding of these fundamental parameters is a key step for studying thermo-hydromechanical behavior of compacted soils considered for heat storage. The results provide insight into the feasibility of these structures in terms of their long-term energy efficiency and stability.

Data Availability Statement: data will be published in Dorel, the University of Lorraine open data repository, at the end of the study

Contributor statement: Editing, article writing, presentation: Rosin-Paumier with contribution of all authors; Laboratory tests: El Youssef; Result analysis: El Youssef, Abdallah, Leclerc, Rosin-Paumier; MRI expertise, technical development: Perrin and Leclerc.

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