Predicting Soil Hydraulic Properties from Particle Size Distribution and X-Ray Tomography.

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Introduction

- Knowledge about soil hydraulic properties are fundamental
- Characterization of these properties is very time-consuming
- Requires many sample manipulations
- Advances in the field of tomography imagery allow for the characterization of a number of soil hydraulic properties (Wildenschilds and Sheppard, 2013)
- The use of the µCT-scan is limited to very small sample (<10 cm³), which is inappropriate to study a representative volume of soil (soil profiles).

Objective

- The main objective of this work is to propose a framework to predict soil hydraulic properties from the combination of particle size distribution with X-ray tomography of a porous media.

Materials & Methods

1. Soils characterization

- Soil sample contained in a 15-cm long, 5-cm wide cylinder
- Unconsolidated Ottawa sand
- Curves of water retention and hydraulic conductivity obtained using the instantaneous profile method

2. Particle distribution

- Particle size distribution = LA950v2 Laser Particle Size Analyzer (Horiba)
- *n*th moment

$$m_n = \exp\left(n\mu_y + \frac{n^2\sigma^2}{2}\right)$$

- Cumulative mass fraction

$$M(R) = W\left(1 - \frac{1}{2}erfc\left(\frac{\ln R - (\mu_y + 3\sigma_y^2)}{\sqrt{2}\sigma_y}\right)\right) + (1-W)\left(1 - \frac{1}{2}erfc\left(\frac{\ln R - (\mu_{2y} + 3\sigma_{2y}^2)}{\sqrt{2}\sigma_{2y}}\right)\right)$$

- μ_y = mean of ln R
- σ_y = standard deviation of ln R
- W = weighting factor for the *i*th sub-distribution

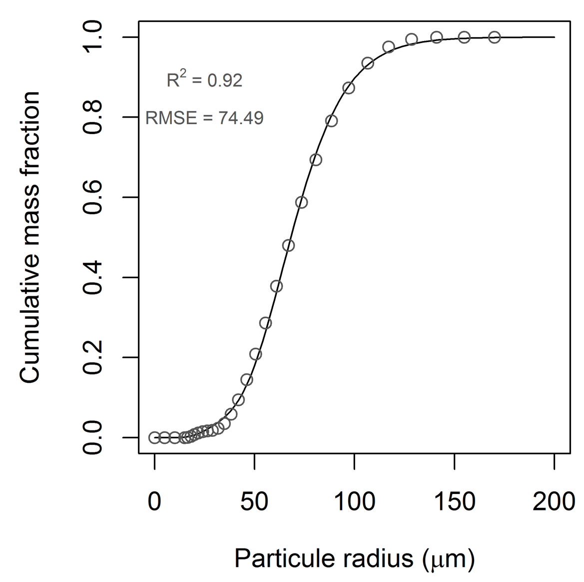

Figure 1. Cumulative mass fraction of particle sizes (R)

Materials & methods

3. Derivation of soil hydraulic properties

- Carnahan–Starling approximation of void nearest-surface complementary cummulative density function (Chan and Govindaraju, 2004)

$$e_{vn}(\delta) = (1-\eta)\exp\left\{-\eta S\left[a_0\left(\frac{\delta}{m_1}\right)^3 + a_1\left(\frac{\delta}{m_1}\right)^2 + a_2\left(\frac{\delta}{m_1}\right)\right]\right\} \text{ where } S = \frac{m_1 m_2}{m_3} \quad \eta = 1-\phi$$

$$a_0 = \frac{(m_1^2/m_2)(1-\eta)(1-\eta+3\eta S) + 2\eta^2 S^2}{(1-\eta)^3}$$

$$a_1 = \frac{6(m_1^2/m_2)(1-\eta) + 9\eta S}{2(1-\eta)^2} \qquad a_2 = \frac{3}{1-\eta}$$

- Coefficients a_0, a_1, a_2
- S = surface ratio
- η = dimensionless reduced density

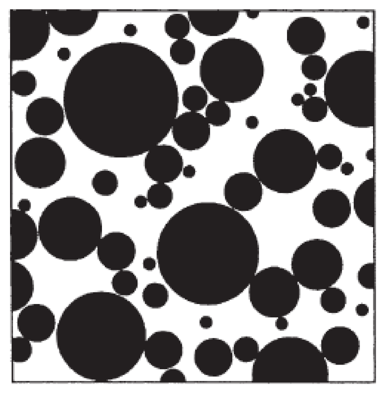

Figure 2. Polydisperse impenetrable hard spheres systems in 2D
(Chan and Govindaraju, 2004)

- Nearest solid surface

$$\delta = ae^{br} \qquad r = \frac{2\sigma\cos\Psi}{\rho g h}$$

- Coefficients a, b
- σ = interfacial tension
- Ψ = contact angle
- g = gravitational acceleration
- ρ = density of the fluid
- h = soil matric potential

- Effective saturation

$$S_e = W\left(1 - \frac{e_{v1}}{\phi}\right) + (1-W)\left(1 - \frac{e_{v2}}{\phi}\right)$$

- Relative hydraulic conductivity (Mualem, 1976)

$$Kr = S_e^{\tau}\left(W\left(\frac{\int_0^{S_{e1}} \frac{1}{\psi(S_{e1})} dS_{e1}}{\int_0^{w} \frac{1}{\psi(S_{e1})} dS_{e1}}\right) + (1-W)\left(\frac{\int_0^{S_{e2}} \frac{1}{\psi(S_{e2})} dS_{e2}}{\int_0^{1-w} \frac{1}{\psi(S_{e2})} dS_{e2}}\right)\right)$$

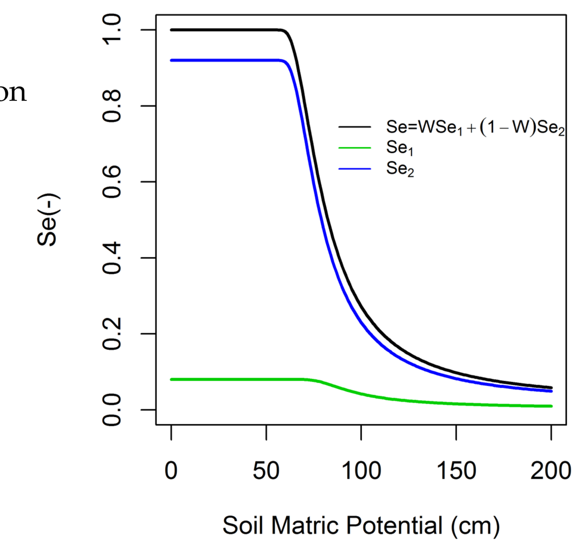

Figure 3. Dual model of effective saturation

4. Tomographic analysis

- The study was done at *Laboratoire Multidisplinaire de Scanographie du Québec de l'INRS-ETE.*
- Type of Medical CT scan : Somatum Volume Access (Siemens, Oakville, ON, CA).
- Energy level of 140, 120, 100 and 80 keV
- Voxel resolution of 0.1x0.1x0.6 mm

Figure 4. Medical CT scan

Determination of the porosity

Beer-Lambert law

$$I = I_0 \exp(-\mu x)$$

$$\phi = \frac{Hu_{quartz} - Hu}{Hu_{quartz} - Hu_{air}}$$

- Hounsfield scale

$$HU = 1000(\mu - \mu_w)/(\mu_w - \mu_a)$$

- *Hu* = attenuation coefficient of the sol
- Hu_{quartz} = attenuation coefficient of quartz
- Hu_{air} = attenuation coefficient of air

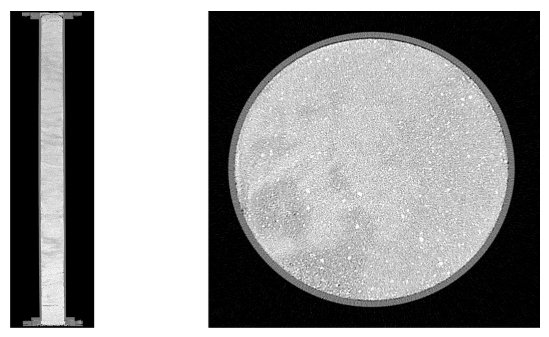

Figure 5. Vertical and horizontal slices

Conclusion

- Used and analysis of Medical CT scans clearly show the variability of soil hydraulic properties in the sample.
- The framework provides a good prediction of the mean soil hydraulic properties.
- The framework provides an opportunity to study the variability of soil hydraulic properties over a monolith.

Results

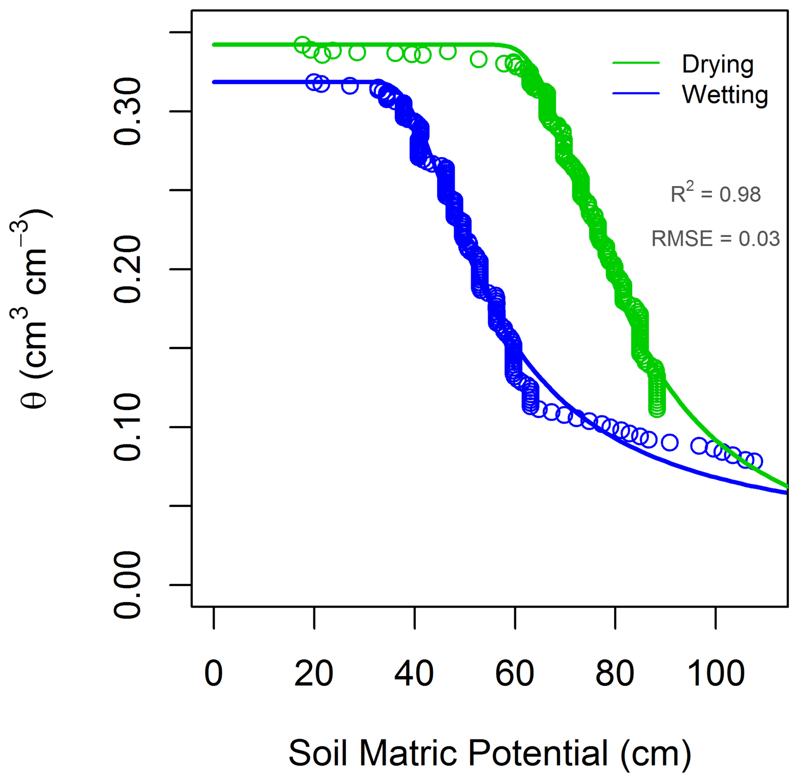

Figure 6. Soil water retention curves

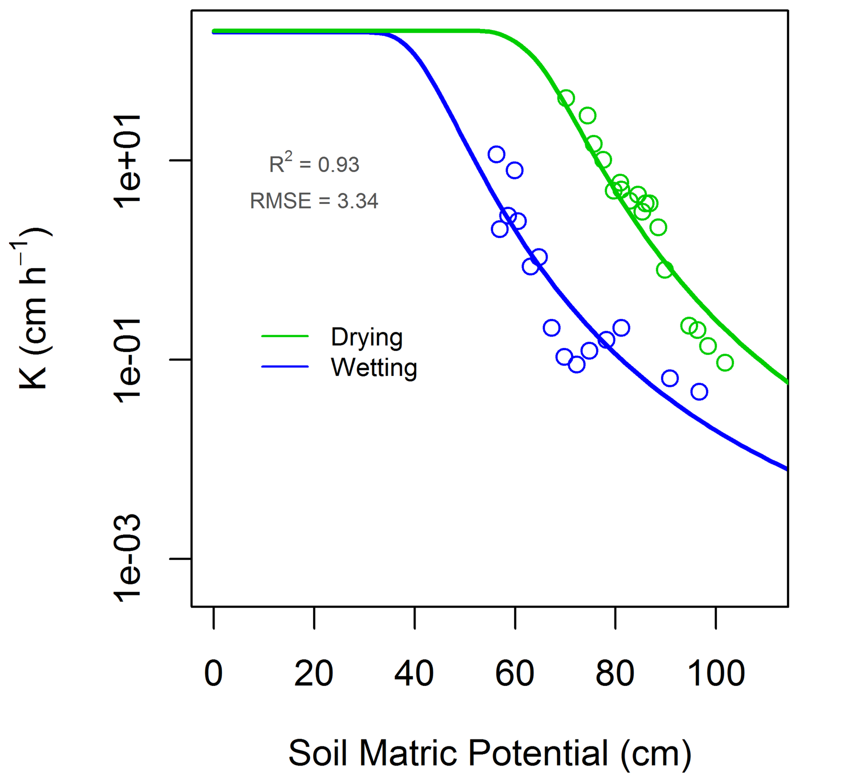

Figure 7. Soil hydraulic conductivity curves

- Good performance of the models to predict soil hydraulic properties (Figures 6 & 7)

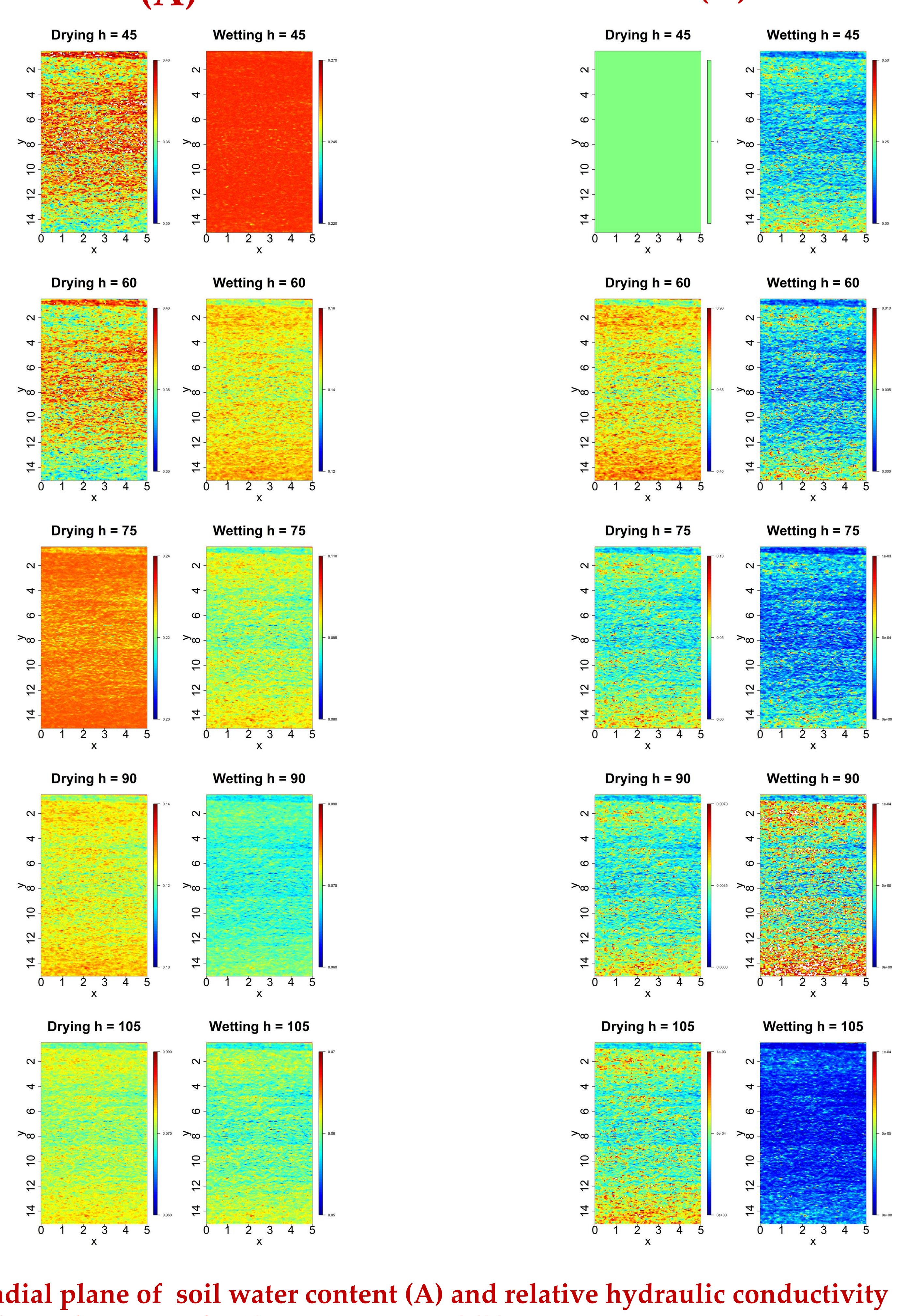

Figure 8. Radial plane of soil water content (A) and relative hydraulic conductivity (B) as a function of soil matric potential (h).

- High variability of soil hydraulic properties (Figure 8)
- Specifically in position of the curve with high variation of water content and relative hydraulic conductivity according to the matric potential (h).

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