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Use of X-ray CT scan to characterize the evolution of the hydraulic properties of a soil under drainage conditions

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ABSTRACT

Characterization of soil hydraulic properties is essential for modelling water flow and solute transport in the vadose zone. These properties are often assessed assuming that the soil is a non-deformable (rigid) porous medium. However, under real conditions, such as those found in agricultural systems, the soil is constantly exposed to external stresses induced by farm machinery and by wetting and drying cycles, which constantly modify the soil hydraulic properties. The main objective of this work was to develop a methodological framework based on X-ray CT scanning to predict the spatio-temporal evolution of the hydraulic properties of a soil under drainage conditions. The methodological framework combines the particle size distribution of a soil and the fractal dimension of its porosity obtained from X-ray CT scans to predict the saturated hydraulic conductivity and volumetric deformation of a soil column. The results show that the proposed framework provides a realistic description of the spatio-temporal evolution of the hydraulic properties of a soil during the drainage process.

1. Introduction

Agriculture has an important influence on soil formation and evolution (Montagne et al., 2008). Several studies have shown that farming practices and crop management can significantly affect soil hydraulic properties (Hu et al., 2009). Indeed, when compared to natural conditions, some water management practices, such as flooding, irrigation, subirrigation, and drainage, may increase the frequency of water table fluctuations (wetting–drying cycles), which may lead to significant changes in the physicochemical soil properties (Huang et al., 2015; Montagne et al., 2009) and induce changes in soil pore size distribution (Bodner et al., 2013a; Bodner et al., 2013b; Mubarak et al., 2009). More recently, the implementation of a drainage system has been shown to promote an increase soil water flow, inducing changes in the soil structure, pore size distribution, and other properties, such as total porosity, water retention properties, bulk density, air entry point, and saturated and unsaturated hydraulic conductivities (Alletto et al., 2015; Bodner et al., 2013a; Bodner et al., 2013b; Frison et al., 2009; Montagne et al., 2009; Montagne et al., 2008). For example, in rice paddies, Zhang et al. (2013) observed that repeating flooding and draining cycles has a significant impact on the percolation properties, soil shrinkage and bulk density. More recently, Périard et al. (2014) have shown that anthropic soil genesis can induce formation of a soil horizon that has hydraulic properties with low drainage capacity, which may have negative effects on crop yields. For a highly drained, sandy soil under cranberry production, Gumiere et al. (2014) found a direct relationship between areas of low crop yields and soil horizons with a low saturated hydraulic conductivity. Anthropic soils, such as those under cranberry production, Anthrosols and Technosols (IUSS Working Group WRB, 2014), are often characterized as soft and unconsolidated materials that undergo rapid and intense early pedogenesis (Séré et al., 2012).

This rapid soil evolution may be explained by flow-induced migration of fine particles, and the ensuing reorganisation of coarse particles during the hydroconsolidation process; modifying the drainage capacity (McDaniel et al., 2001; Pires et al., 2007). The study of these spatio-temporal variations in soil hydraulic properties represents a daunting task that may demand numerous destructive laboratory analyses and field observations (Bodner et al., 2013b). Furthermore, core sampling may affect soil properties, such as bulk density and pore size distribution, leading to differences between in situ and laboratory measurements of soil hydraulic properties (water retention and unsaturated soil hydraulic conductivity curves) (Pires et al., 2007). In fact, Alletto et al. (2015) proposed more than three sampling periods distributed during the season to minimize perturbation of soil samples and capture the spatio-temporal evolution of soil properties. However, the evolution of soil properties after tilling may be very rapid and, thus, it may be difficult to observe with precision using standard soil sampling techniques because of the uniqueness of the soil core (Rab et al., 2014). X-ray CT scanning is a non-destructive imaging technique that can be used for high-resolution monitoring of time-dependent changes in soil properties such as bulk density, tortuosity, porosity, pore network characteristics, permeability,

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volumetric water content, solute transport parameters, fractal properties (Helliwell et al., 2013), soil aggregate characteristics (Garbout et al., 2013; Helliwell et al., 2013), unsaturated hydraulic conductivity and soil water retention curves (Tracy et al., 2015).

The X-ray CT scan has been widely used in the past for characterizing soil hydraulic properties (Rab et al., 2014) and conducting studies on colloidal transport (Chen et al., 2009; Chen et al., 2010; Gaillard et al., 2007; Li et al., 2006), soil compaction (Keller et al., 2013) and soil consolidation by wetting and drying cycles (Keller et al., 2013; Ma et al., 2015; Pires et al., 2007; Pires et al., 2014).

A new framework is needed to characterize the spatio-temporal evolution of soil properties at early stages after tilling or field construction. Therefore, the main objective of this paper is to propose a methodological framework using X-ray CT scans to characterize the evolution of the spatio-temporal soil hydraulic properties (porosity and saturated hydraulic conductivity) of a heterogeneous sandy soil under drainage conditions.

2. Material and methods

2.1. Soil column preparation

The experiment was performed with a repacked cylindrical soil column (56 cm in length and 15 cm in diameter) composed of two different sand layers (Fig. 1). The first layer (sand 705) was 14-cm thick (L1) (Fig. 1) and had a d_{50} (median radius of the particle size distribution) of 150 μm. While the second layer (Flint) was 42-cm thick (L2) (Fig. 1) and had a d_{50} of 500 μm. A characterization of the particle size distribution of the sand was achieved using a Laser Diffraction Particle Size Analyzer (LS 13320 series, Beckman Coulter Canada LP., Mississauga, Ontario, Canada) and 3 replicates of the 705 and Flint soils. The particle size distribution of the 705 and Flint soils are compared to those of fine and coarse sands in Fig. 1. The 705 soil is a fine sand, the Flint soil is medium sand, and both have particles smaller than coarse sand (Fig. 1). To ensure uniform flow conditions and an evenly distributed pressure imposed by a water column (Fig. 1), each end of the column was covered with Nitex (20-μm mesh) to provide good contact between the water film and the diffusion plate. A variable water pressure of 245 to 194 cm (P) was applied at the inlet (on the side of the 705 soil) of the soil column by a reservoir connected to the soil column with a flexible pipe (Fig. 1). The water pressure head boundary (P) is shown in Fig. 1 and was chosen to represent a condition at a position near the drain tile akin to a flooded cranberry field during harvest for protection against freezing. The pressure heads inside the reservoir (R) and in the drainage tank (T) (Fig. 1) were measured using an absolute pressure sensor (Hobo U20 Water Level Logger, ONSET, Bourne, MA, USA) at time intervals of 1 min throughout the duration of the experiment. The pressures were converted into water height by subtracting the atmospheric pressure monitored at intervals of 1 min. The water pressure boundary was obtained by adding the height of the water in the reservoir to height of the water pipe at the soil column level.

A 3-step saturation-drainage cycle was performed to firmly pack the sand within the column. During the first step, we saturated the soil by applying a water pressure at the column inlet of 224 to 234 cm during 2 h (Fig. 2). During the second step, we oriented the soil column vertically and imposed a free drainage condition with constant atmospheric pressure at the inlet and outlet of the soil column. For the last step, we gradually saturated the soil column from the bottom up with a pressure of 56 cm. The soil column was not wet and dried many times so that the soil was more representative of conditions occurring just after the construction of a cranberry field when the soil is soft and unconsolidated. We did not replicate the experiment; thus, this study focuses on the development of the methodological framework to study the evolution of soil properties under drainage rather than on the mechanisms involved in consolidation.

2.2. CT scanning

The experiment was performed at the *Laboratoire Multidisplinaire de Scanographie du Québec* using a Somatum Volume Access CT scanner (Siemens, Germany) (Fig. 1). The energy level used was 140 keV, and the spatial resolution (i.e., a voxel) was 0.06 × 0.045 × 0.045 cm (*x*, *y*,

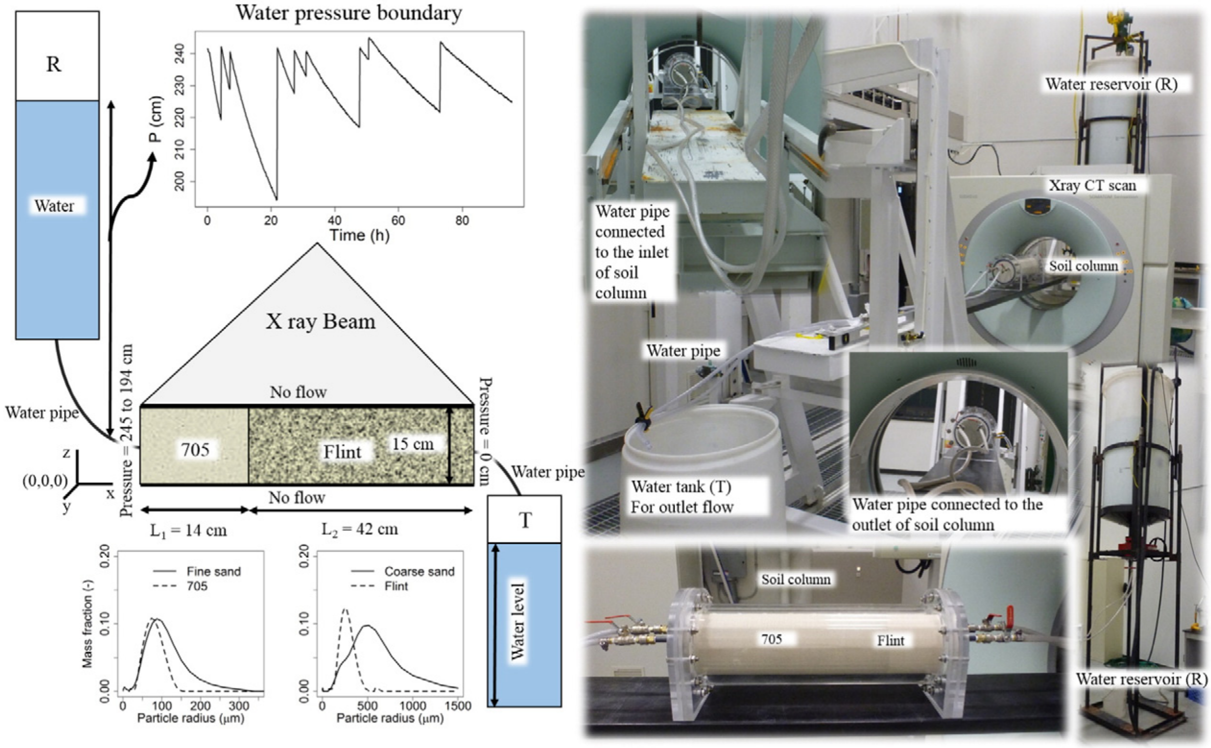

Fig. 1. Schematic diagram and photos of the experimental setup.