The Through Porosity of Soils as the Control of Hydraulic Conductivity

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Abstract

The prominent contribution of macropores to water flow and solute transport points to the need for thorough characterization of soil void structure. Undisturbed soil columns need to be studied to infer topological properties of macropores. Three undisturbed soil columns (7.5 cm ID, 16 cm length) of the Taylor soil were taken at a grassed floodplain in Franklin County, PA. The FlashCT - 420 kV system and supplied software (HYTEC Inc.) were used for X-ray CT scanning and image reconstruction in the columns. A MatLab® software was developed for the 3D reconstruction and analysis of pores larger than 110 µm in diameter. The saturated hydraulic conductivity was measured on the 16 cm long columns and then on 8, 4, and 2 cm-thick columns obtained by consecutive slicing of the original columns. The macropore network was reconstructed from the imagery and the through pores were identified in each section as voids open to top and bottom of columns and column sections. Saturated hydraulic conductivity was affected by the column length and the minimum size of through pores. The increase in overall macroporosity did not necessarily translate into large hydraulic conductivity of columns. Introducing a novel parameter - the through macroporosity - was useful to quantify the effect of differences in pore space structure on the differences in hydraulic conductivity.

Key words

Macropore structure, computed tomography, water conductivity, sample size.

Introduction

Soil hydraulic properties are essential inputs of water flow and chemical transport models. Typical measurement scale for soil hydraulic characterization is in order of 10 cm. Soil parameters obtained from a decimeter-scale measurements are often used in numerical models with a grid ten times as large, with the numerical results extrapolated to the field scale. It has been shown in numerous publications that saturated hydraulic conductivity (K_s) can vary with sample size. Shouse *et al.* (1994) and Haws *et al.* (2004) have observed an increase in average K_s values with increase in area of measurement. Other researchers have shown that K_s values decreased as the sample length increased (Anderson and Bouma 1973; Mallants *et al.* 1997; Fuentes and Flury 2004). The changes in K_s with the sample size were attributed to soil spatial heterogeneity and to the effect of macroporosity on saturated flow at larger scales.

The concept of effective porosity (φ_e) as the pore volume fraction that dominates the flow of water when the soil is saturated has been introduced by Brooks and Corey (1964). Ahuja *et al.* (1984) used this concept to derive a power law relationship between K_s and φ_e by generalizing the Kozeny-Carman equation (Carman 1956). Replacing the effective porosity (φ_e) with the macroporosity (φ_{ma}) Messing and Jarvis (1995) developed the equation:

$$K_s = B\varphi_{ma}^n \quad (1)$$

where B and n are empirical parameters. The values of parameter n were 7.17 and 4.24 for different soil layers in their study. Although the authors did not study soil pore structure, the difference in n was attributed to difference in tortuosity, pore size distribution, pore continuity and presence of “necks” in flow pathways between these layers.

The X-ray computed tomography (CT) has recently become available for the noninvasive study and the 3-D quantification of macropore structure in soils (Perret *et al.* 1999; Luo 2008) and made it possible to relate soil hydraulic properties to the pore structure. Objectives of our study were: (a) to use CT to search for parameters of soil pore space affecting saturated hydraulic conductivity, and (b) to evaluate the core length effects on saturated soil hydraulic conductivity as related to macropore structure.

Materials and methods

Three undisturbed columns (7.5 cm ID, 16 cm length) of the Taylor soil were taken at a grassed floodplain in Franklin County, Pennsylvania from A horizon. Soil texture was loam. The cores were carved out with acrylic rings using a core sampling device. Some soil cores had visible macrospores, which presumably served as water conduits. The columns were X-ray CT scanned using the FlashCT - 420 kV system (HYTEC Inc.) and images were reconstructed using the FlashCT-DAQ, the FlashCT-DPS, and the FlashCT-VIZ software. About 1500 cross-section images with resolution of about 110 microns were obtained for the columns. The images were binarized, and 3D pore structure was reconstructed using a software written in MatLab® (The MathWorks, Inc.).

The soil cores were saturated from the base during a period of 24 hours and the saturated hydraulic conductivity was measured using the constant pressure method (Reynolds *et al.* 2002). Then soil cores were drained overnight and sliced into two 8-cm sections with a band saw. The sliced core sections were saturated and K_s measurements were repeated as described above. The 8-cm core sections were cut into 4-cm and later on into 2-cm sections for measurements at smaller scales.

The porosity value was calculated as a ratio of number of pore voxels to total number of voxels in core sections. The through pores were identified in each section as the voids which are open to both sides of the core sections. Total and minimal volumetric contents were calculated for each through pore individually. Parameters B and n were estimated by fitting Eq. (1) to the experimental data.

Results and Discussion

The visual inspection showed that circular pores dominated in pore structure of column 1, planar pores dominated in column 3, and circular and planar pores were equally presented in column 2. In general, the total measured porosity and complexity of the pore network increased with the depth in all columns. The number of through pores also increased with depth and with the decrease of core height indicating discontinuity of large pores (Figure 1). The through porosity was zero in 16-cm long columns, and the maximum porosity was found in the bottom 2-cm cores. Both an increase and a decrease in core porosity were observed with a decrease in core height (Figure 2a), so that the standard deviation of porosity tripled while core height decreased from 16 to 8 cm.

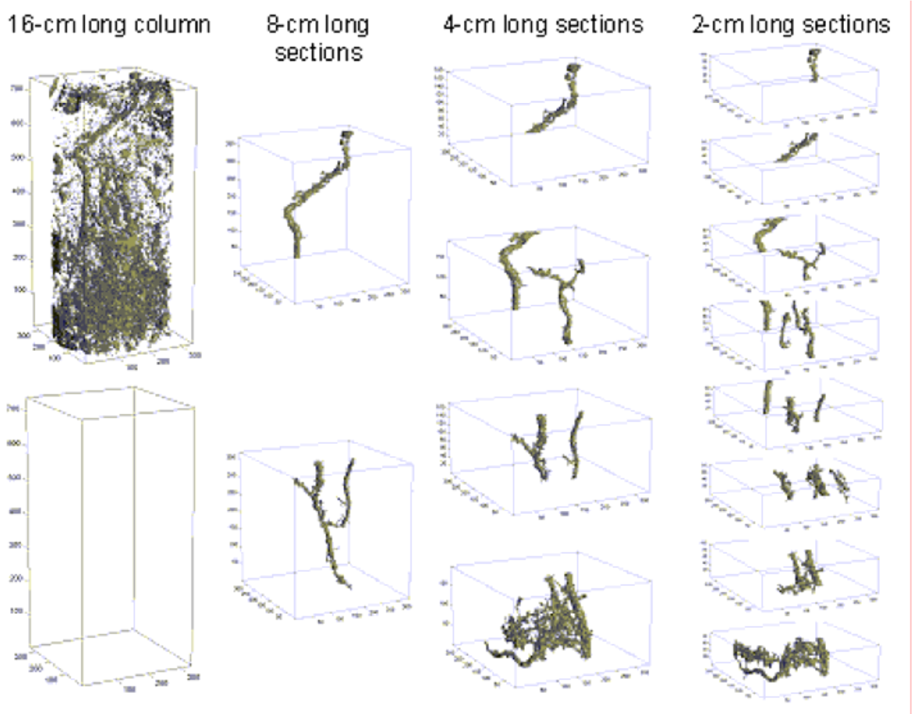

Figure 1. A three-dimensional visualization of the total porosity (top left) and trough pores large than 110 μm in soil sections of column 1.

The through porosity averaged among each core height group decreased with the increase in the height, while the standard deviation remained about the same and was in the range from 0.016 $cm^3\ cm^{-3}$ to 0.018 $cm^3\ cm^{-3}$ (Figure 2b). Changes in the core height affected soil saturated hydraulic conductivity (Figure 2c). Smaller values of K_s corresponding to $\log(K_s)=0.32\pm0.40$ were observed in 16-cm columns as compared to 2-8 cm high cores where $\log(K_s)$ varied from 0.75 ±0.82 to 1.00±1.20 (mean ± standard deviation). Equation (1) was fitted to the values of different porosities paired with K_s in each column (Figure 3). High R^2 values were obtained only for the relationship between K_s and minimal through porosity in the soil cores (Figure 3c). Values of the parameter n were 0.72, 0.55 and 2.02 in columns 1, 2 and 3, respectively, and reflected the differences in pore shape. Smaller n values were observed in columns with circular pores, and with both circular and planar pores; maximum n was in column with dominated planar pores in pore network. These results are consistent with the experimental results and theoretical model developed by Anderson and Bouma (1973), and imply sharp changes in K_s for planar pore systems caused by changes in size of pore necks that restrict water flow.

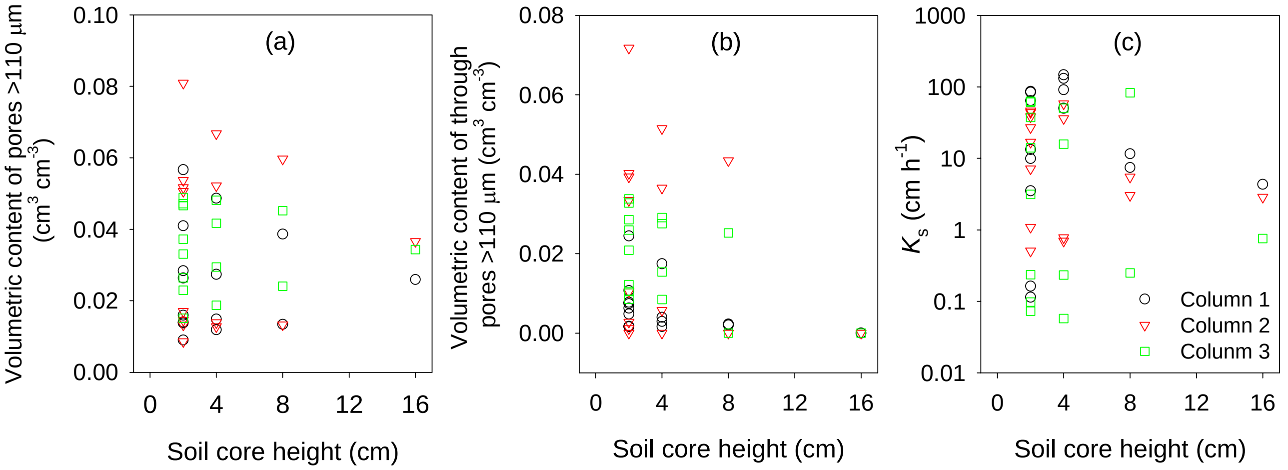

Figure 2. Changes in the volumetric content of all pores larger than 110 µm (a), the volumetric content of through pores larger than 110 µm (b), and the saturated hydraulic conductivity K_s (c) with the soil core height.

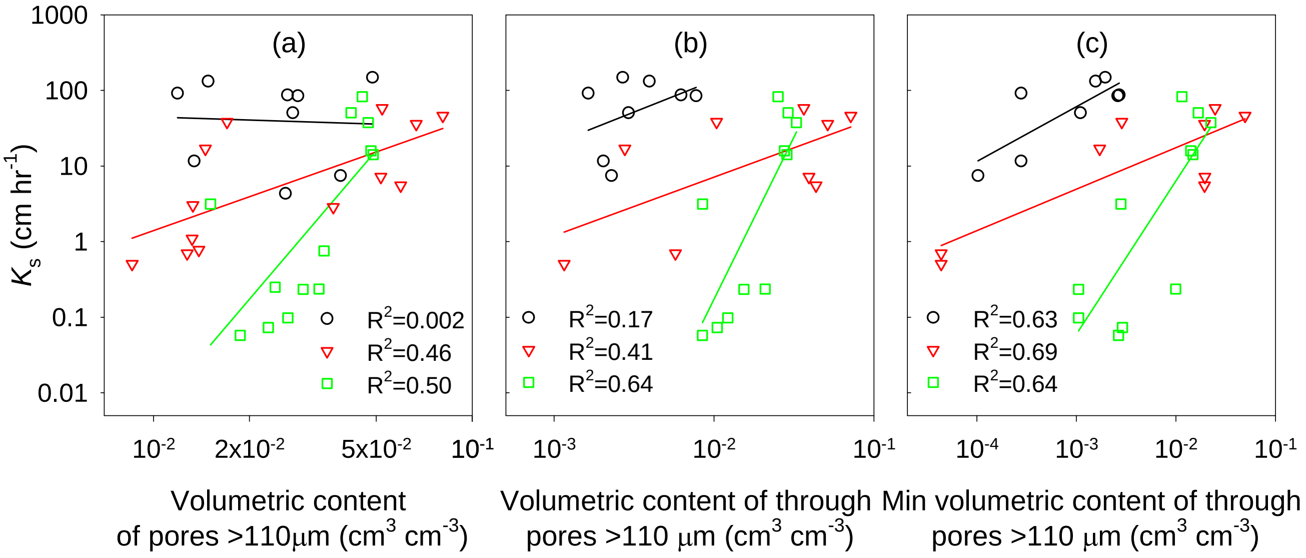

Figure 3. Relationships between saturated hydraulic conductivity (K_s) and volumetric content of different pores for columns: (○) – 1, (▽) – 2, and (□) – 3.

Conclusions

This study showed that, due to discontinuity of soil macropores, larger macroporosity did not necessarily translate into the larger hydraulic conductivity. The CT provided the quantification of the soil through macroporosity and the insight into observed differences in slopes of the log-linear regressions "minimal through porosity vs. saturated hydraulic conductivity". Changes in K_s with scale could be attributed to the differences in macropore continuity and to changes in minimial through porosity with the core thickness.

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