Applications of X-Ray Computed Tomography for Examining Soil Structure: A Review

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ABSTRACT

In this paper we present a review of the application of X-ray computed tomography in soil science, a modern technique for structural analysis. The quantification of internal soil structure is the key in understanding the processes that lead to its development. The current analytical and traditional methods for exploring soil structure do not fully cover the needs of the researchers, in order to characterize the soil system and its properties. In the last decades, X-ray computed tomography has provided a non-destructive means in order to observe and quantify soils in 3D. It has been used in researches regarding the spatial distribution of soil pores, bulk density, macropore network structure, layer detection, permeability, calculated fractal properties, solute breakthrough, root system development etc. Compared to other analysis methods, the short time required for a CT scan (within the order of minutes) and the accuracy of the data provided, recommend this technique for the characterization of soil systems.

Keywords: *physical properties, soil structure, X-ray CT.*

INTRODUCTION

Computed tomography (CT) is an efficient technique which is nowadays used in many soil studies. At first, it was used in medicine, starting with the late 1960s, when Cormack and Hounsfield built the first computed tomography scanner, for which they received in 1979 the Nobel Prize for Medicine (Losano et al., 1999). The last decades brought a development of the range of areas where it can be applied. In 1974, Fourie used for the first time the CT in his researches of paleontology, and after that *Conroy* and *Vannier* (1984) and *Houbitz et al.* (1988) also used it with great success. In sedimentology, it was used by researchers for the analysis of sedimentary structures (*Kenter*, 1989; *Peyton et al.*, 1992; *Zeng et al.*, 1996). It was also used for the study of rock porosity, material density and fractures (*Jacobs et al.*, 1995; *Keller*, 1997; *Jacobs et al.*, 1997; *Klobes et al.*, 1997). The researches regarding the use of X-ray CT in soil science focused on the spatial distribution of

soil properties (*Young et al.*, 2001; *Rogasik et al.*, 2003; *Nunan et al.*, 2006), layer detection (*Lipiec and Hatano*, 2003), pore network structures (*Al-Raoush and Willson*, 2005), permeability (*Ketcham and Carlson*, 2001; *Mooney*, 2002), solute breakthrough (*Clausnitzer and Hopmans*, 2000), seedbed preparation (*Atkinson et al.*, 2007) and calculated fractal properties (*Gantzer and Anderson*, 2002; *De Gryze et al.*, 2006; *Papadopoulos et al.*, 2008).

The aim of this study is to present a review of the application of X-ray CT in soil science, as a modern technique for structural analysis.

Overview of the X-ray CT technique

X-ray CT is a non-invasive technique that can be used to visualize the interior of objects in 2D and 3D based on the principle of attenuation of an electromagnetic wave (*Helliwell et al.*, 2013). A typical scan involves the collection of a series of radiograph images of a sample acquired at

incremental angular positions, normally over 360°. Generally, X-ray CT scanners consist of three common parts: an X-ray source, a sample manipulation stage and a detector. X-rays emitted from the source pass through the sample and are progressively attenuated by absorption and scattering as the object itself becomes a secondary source of X-rays and electrons through atomic interactions (Mooney *et al.*, 2012). The characteristic of a material to either absorb or scatter a photon is known as attenuation coefficient. Attenuation coefficients are related to the density of the absorbing material, electron density of the voxel of interest and incident X-ray energy, but are predominantly controlled by four dominant processes: photoelectric absorption, Rayleigh scattering, Compton scattering and pair production (Helliwell *et al.*, 2013). However, it should be noted that pair production occurs at X-ray energies (1.022 MeV) far greater than conventional X-ray CT systems. Integration of the linear X-ray attenuation coefficient values from the multitude of radiographic images form the basis of tomographic reconstruction (Taina *et al.*, 2008). It is based frequently on mathematical filtered back-projection algorithms, through which cross-sectional 2D image slices are generated from radiograph projection images (Wildenschild *et al.*, 2002; Stock, 2008). Each non-invasive tomographic 'slice' consists of discrete units known as voxels (3D pixels), the size of which reflects the spatial resolution of the scan.

Applications in soil science

Soil constituents and organic matter

Sleutel *et al.* (2008) used scan data from four X-ray CT systems, which used different X-ray sources of various energy spectra, detectors of differing sensitivity and beam filters of different thicknesses in order to threshold images of a sand-organic matter mix.

X-ray CT has also been used by Quinton *et al.* (2009) and Kettridge and Binley (2011) in order to study highly organic soils such as peats.

Elyeznasni *et al.* (2012) recovered part of the discontinuous pattern of organic matter fragments in the macro-porosity of the soil after detecting coarse-sized organic matter concentrations in X-ray CT images.

Mineral classification by X-ray CT has been widely made in petrological studies done by Van

Geet *et al.* (2000), Ketcham (2005) and Stock (2008).

Twenty years ago, in 1994, the first who applied medical X-ray CT in order to analyze offshore sediment cores non-destructively were Orsi *et al.* (1994), and so they were able to successfully characterize the sediment morphology (Orsi and Anderson, 1995).

Using a medical system for spatially mapping the 3D distribution of quartz, feldspar and micas based on their radiological densities, Geraud *et al.* (2003) compared the radiological densities of the main mineral phases with measured values on macroscopic crystals, confirming mineral presence in the sample.

In the year 2000, Kalukin *et al.* successfully used principal components analysis (PCA) of images from X-ray scan in order to enhance the contrast between individual minerals more clearly than was possible in single-energy X-ray CT scans.

Feeney *et al.* (2006) and Wang *et al.* (2012) used voxel with sizes <15 µm allowing interpretations of fractions finer than sand.

Soil compaction and porosity

Various studies have used X-ray CT to quantify properties of macropore network morphology, including pore diameter (Anderson *et al.*, 1992; Zeng *et al.*, 1996), crack formation (Peth *et al.*, 2010), pore network structure (Baveye *et al.*, 2002; Aravena *et al.*, 2011) and pore circularity (Gantzer and Anderson, 2002).

In order to demonstrate a clear advantage of X-ray CT over other invasive techniques, Al-Raoush and Willson (2005) used skeletonization algorithms (thinning operations, which systematically remove voxels from an object until a minimal but topologically identical structure is produced) to extract pore-bodies, pore-throats and size distributions in physically realistic pore network structures, that enabled the discrimination of active and inactive pores and the characterization of redundant pore throats.

In their researches, Delerue *et al.* (2003) successfully developed a pore network directly from soil images by integrating pore size and connectivity parameters, which enabled calculation of the equivalent hydraulic conductivity from a 3D image of any porous soil.

Elliot and Heck (2007) compared the optical and the CT method for the determination of

void space, using four thin section samples. After registering the two imagery types, they extracted for analysis an identical region of optical and CT imagery. The results showed that the optical method was proficient in identifying continuous and linear void features, whereas CT readily identified a greater number of voids with higher circularity. The data also suggested that the CT method identified a greater degree of void space in thin section than was evident to the optical classification, fact that prove that CT is a great complementary technique to the soil micromorphology tool set.

Sander *et al.* (2008) used the X-ray CT to visualize the size and connectivity of structural pores including arrangement of aggregates and to quantify the vertical bulk density distribution in the upper soil horizons affected by cultivation in paddy fields. Undisturbed soil columns of 10 cm diameter (5–42 cm and 0–38 cm depth) including the plough pan transition down to the subsoil were scanned using a medical X-ray CT. Vertical bulk density profiles were calculated from Hounsfield Units (HU) and gravimetric water contents measured in 10 mm and particle densities in 20 to 50 mm vertical intervals. Secondary pores were separated using 2 HU-threshold values and described by 3D plots of 'air-filled' and 'low-density' regions; the matrix structures were analyzed by 2D CT-images.

In their studies, Rogasik *et al.* (2003) assessed macropore length, size and connectivity of pores under different agricultural practices at the spatial scale of 0.25×0.25×1 mm.

The effect of soil compaction on 3D macropore geometry was characterized by Kim *et al.* (2010) in undisturbed field cores. They were able to reveal the total macro- and mesopore numbers associated with an increase in surface compaction, by using X-ray CT in addition to recording decreases in overall porosity and bulk density. They were also able to assess the degree of correlation between additional CT-measured pore characteristics, including largest pore circularity, fractal dimensions and pore area.

Luo *et al.* (2010) used the X-ray CT to quantify 3D macropore networks in intact soil columns using an improved approach and to investigate the effects of soil type and land use on soil macropore characteristics. They used samples from two soils with contrasting textures and

structures from two land uses (row crop and pasture). Intact soil columns, 102 mm in diameter and about 350 mm in length, were taken for each soil type-land use combination. The soil columns were scanned using X-ray computed tomography at a voxel resolution of 0.234 mm x 0.234 mm x 2.000 mm. The characteristics of the macropore networks were quantified, including continuous macroporosity change along depth, macropore size distribution, network density, surface area, length density, length distribution, mean hydraulic radius, tortuosity, inclination (angle), and connectivity (path number and node density). The results of the study provide improved evaluation of soil macropore characteristics with important implications for non-equilibrium flow prediction and chemical transport modeling in field soils.

Soil structure modification analysis

In order to interpret soil structure, there have been used destructive techniques and observations in 2D, including thin sections and electron microscopy (Young *et al.*, 2001). X-ray CT has been used in many studies to describe the spatial nature of soil constituents in undisturbed systems (Perret *et al.*, 2007; Torrance *et al.*, 2008; Elliot *et al.*, 2010; Flavel *et al.*, 2012; Mairhofer *et al.*, 2012; Schmidt *et al.*, 2012; Tracy *et al.*, 2012).

Peth *et al.* (2010) quantified the effect of hydraulic stress on the dynamic rearrangement of solid particles at a resolution of 38.4 µm, providing a good example of the potential of X-ray CT as a good means of investigation. They used digital image reconstructions to quantify local structural pore space characteristics and local soil deformation by 3D morphological and correlation analysis of grayscale tomograms. Swelling and shrinkage resulted in a complex heterogeneous soil structure which proved to be very stable when mechanical loads were applied. The mechanism of soil deformation for both structure formation by internal hydraulic stresses and structure degradation by external mechanical stresses were in both cases controlled by pre-existing microstructures. Especially during wetting such structures served as a core for subsequent structure evolution. The results demonstrate the potential of more detailed non-invasive analysis of soil deformation processes which could improve the conceptual understanding of the physical behavior of soil systems.

Water content, and water and solute transport

The CT method was also used to investigate the water movement in soil, which accounts for the 3D interconnected void space (Perret *et al.*, 2000; Kasteel *et al.*, 2000; Mooney, 2002; Wildenschild *et al.*, 2005).

There have been used tracer solution of iodide (NaI or KI) or bromide (CaBr₂) for the assessment of solute transport in porous media, due to their high contrasting X-ray attenuation of iodine and bromide ions (Clausnitzer and Hopmans, 2000; Anderson *et al.*, 2003).

In order to visualize and quantify the soil macroporosity and water flow pattern, Mooney (2002) used undisturbed samples of various soil textural types that were scanned using a fourth generation Picker PQ6000 whole-body X-ray CT-scanner, with no pretreatment of the samples. The X-rays were generated with an exposure factor of 120kV and 100mA using a standard spiral scan routine. Images were collected at c. 0.5 mm intervals with a slice thickness of c. 0.5 mm. The resolution of the scanners output device was 512 x 512 and the final spatial resolution of each volume unit (voxel) was 0.46 mm x 0.46 mm x 0.46 mm. The results showed that in general, the pore space was characterized by low densities and the mineral material had high densities. The soil porosity was predominantly comprised of horizontally orientated angular cracks and irregular shaped pores.

Baveye *et al.* (2002) revealed the dependence of macroscopic soil properties such as volumetric water content, bulk density and air content on sampling volume, positioning and shape. They showed that properties in small volumes can exhibit erratic fluctuations in measurements, which can be stabilized as sampling volume increases.

The research conducted by Carminati *et al.* (2009) shows the appearance of a so-called 'gap' between lupin roots and the soil along with the decrease of the transpiration rate, indicating that the gap was the result, not the cause of water limitation to the plants.

Evaluation of the effect of different soil management systems

Gantzer and Anderson (2002) assessed the impact of different agricultural tillage practices on the mechanical stability of soils and the resulting

seedbeds. The study carried out on intact soil samples from conventional chisel-disc plough and no-tillage systems revealed that the chisel-disc system had higher number of macropores and a 94% and 62% increase in macropore circularity and perimeter, respectively.

The X-ray CT has been also used by Atkinson *et al.* (2009) to describe the temporal evolution of a seedbed at the mesoscale, from pre-through to post-cultivation. Their research revealed that the use of disc and rolling treatments can lead to porous seedbeds, which can reduce crop establishment because of poor seed-soil contact.

In a study carried out by Papadopoulos *et al.* (2009) are compared stable and unstable aggregate fractions from organically and conventionally managed soils in order to evaluate the role of management on aggregate stability and structure.

Future expectations

Even if the last 25 years, the CT technique has evolved, being used on a wide range of areas, there are still a lot of studies to be done, regarding not only the soil structure, composition and its modifications, but also on the influence of the multiple scanning on the same sample (Tracy *et al.*, 2012; Sun *et al.*, 2012).

Also, is needed an improvement of the sample size, image contrast and resolution. When source energy is too high, the sample becomes transparent to the X-rays, and when is too low, there are insufficient X-rays passing through the object and the results are not conclusive (Wildenschild *et al.*, 2002; Helliwell *et al.*, 2013).

An interesting technique is 'region of interest' scanning, providing high resolution CT images of a region in the interior of an object. It requires high resolution acquisition for the region of interest, combined with a second scan of the same plane for the full width of the object, at low resolution; the second scan is used to provide information about the part of the object that is outside the field of view during acquisition for the high resolution scan (Mees *et al.*, 2003).

It is expected that in the next years, CT will become a routine research tool, used on a higher number of samples, with better results.

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