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Advances in Soil Structure Diagnoses*

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ABSTRACT

It is difficult to understand soil microstructure due to the complexity of the related soil processes. To better understand soils, morphological features should be investigated in greater details with the use of advanced technology. New developments and of their combination provide contribution for better evaluation of soil morphological properties and relationships between soil structure and water movement. In multiphase porous materials, qualitative and quantitative information can be collected non-invasively by these methods. With the computer-assisted and nondestructive advanced technology such as computer microtomography (µCT), models which could give more reliable results have been used in the last years. In this regard, microCT isused to display 3D morphological properties of undisturbed soil samples in the greatest detail. 3D-printed structures of undisturbed soils are obtained with a resolution of 80 µm with this tecnique. Experiments showed that more successful results were obtained compared to 2D and/or direct observations and provide high quality images. The results indicated that new technologies would contribute to understanding the micro-heterogeneity of soils and its relation to soil-water dynamics. In this way, using a 3D for imaging of soil structure would be a good tool to develop soil hydraulic models. In this paper, we discussed use of advanced technology in soil structure diagnosis.

Keywords: Soil morphology, soil water dynamics, 3D-printed soils, X-ray computed microtomography

Toprak Strüktürü Analizinde Gelişmeler

ÖZ

Toprak mikroyapısının anlaşılması ilgili toprak süreçlerinin karmaşıklığı nedeniyle zordur. Toprakları daha iyi anlamak için, morfolojik özellikler ileri teknolojilerin kullanılması ile daha detaylı araştırılmalıdır. Bu teknolojilerin yeni gelişmeleri ve kombinasyonları, toprak morfolojik özelliklerinin ve toprak yapısı ile su taşınımı arasındaki ilişkilerin daha iyi değerlendirilmesi için katkı sağlar. Çok fazlı gözenekli materyallerde, nicel ve nitel bilgiler bu metotlar ile bozulmadan toplanabilir. Son yıllarda, bilgisayar mikrotomografisi (µCT) gibi bilgisayar destekli ve zararsız gelişmiş teknoloji ile daha güvenilir sonuçlar verebilecek modeller kullanılmıştır. Bu bağlamda, mikroCT bozulmamış toprak numunelerinin 3D'li morfolojik özelliklerini en ayrıntılı şekilde görüntülemek için kullanılmıştır. Bozulmamış toprakların 3D baskılı yapıları, bu teknikle 80 µm'lik bir çözünürlükle elde edilir. Deneyler, 2D ve/veya doğrudan gözlemlere kıyasla daha başarılı sonuçların elde edildiğini ve yüksek kaliteli görüntüler verdiğini göstermiştir.
Sonuçlar, yeni teknolojilerin toprakların mikro-heterojenliğini ve toprak-su dinamiği ile olan ilişkisinin anlaşılmasına katkıda bulunacağını belirtmektedir. Bu şekilde, toprak yapısının görüntülenmesi için bir 3D kullanmak, toprak hidrolik modellerini geliştirmek için iyi bir araç olacaktır. Bu makalede, toprak yapısının teşhisinde ileri teknolojilerin kullanılması tartışılmıştır.

Anahtar kelimeler: Toprak morfolojisi, toprak-su dinamikleri, 3D-baskılı topraklar, X-ray bilgisayarlı mikrotomografi

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1. Introduction

New technologies may help through understanding of soil processes inmicro-scales. In multiphase porous materials, qualitative and quantitative information can be collected non-invasiveley. Until recently, the concept of the soil capillary tube bundle and processes built on this concept varies as a result of implementation of the new methods with developing technology. Water flow in unsaturated soils occurs in all direction therefore capillary bundle models in porous media may be missing in defining the water flow and water retention properties. Hunt et al.(2013) reported that difficulties of bundle of tube model concept was described according to the relationship between the pore size distribution and the water retention curve, hydraulic conductivity as a function of water content, and dispersion as a function of fluid velocity and soil properties. All of these processes are closely linked to soil structure. Computer-assisted and nondestructive advanced technology such as computer microtomography (CT) and X-ray computed microtomography (XCT), yielded more detailed information on soil structure and its relations to dynamic soil processes. The aim of this study is to discuss the apllication of advanced technology in soil science, specically in soil structure diagonis.

2. Working principles of CT in 3D imaging

The arrangement of the soil particles determines the quantity of existing pores. The soil pores vary in size and shape and are interconnected (Beraldo et al., 2014). Bouma (1982) highlighted the importance of the continuity of the pore network for the flow of water in soil, and small pores may lead to better water conduction since they form a continuous network, while larger pores may not contribute to the flow, if they present a discontinuity.

Evaluation of research over the past years reveals the need to fully understand the processes within the entire soil medium (Kumi et al., 2015). According to Calistru and Jităreanu (2015), 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 for observing and quantifying soils in 3D. In addition, it has been used in studies for investigating spatial distribution of soil pores, bulk density, macropore network structure, layer detection, permeability, calculated fractal properties, solute breakthrough, root system development etc.

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). The visualization of the interior elements of an opaque sample is made possible by the principle of electromagnetic wave attenuation (Mooney et al., 2012). It is positioned in between an X-ray source and X-ray detector (Cnudde et al., 2006).

An X-ray CT scanner consists of three common parts. These are;

An X-ray source,
A sample manipulation stage
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 source of X-ray radiation in micro-tomography (Figure 1) is the tip of a vacuum tube which contains an anode and a cathode (Wildenschild & Sheppard, 2013).

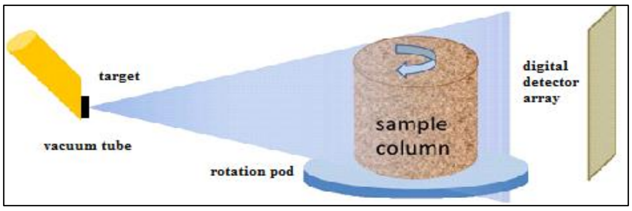

Figure 1. Micro computer tomography cone-beam x-ray. Electrons are falling back then energy in form of X-rays with characteristics of the target material is released. When they strike a sample, the beam can be absorbed, reflected in various ways or transmitted through the material and the sample becomes a source of secondary X-ray radiation and electrons (Wildenschild & Sheppard, 2013)

Each image taken from the rotating sample is a 2D projection from the side of the sample, which faced the detector screen at that moment. The transformation this series of projections from different angles into a 3D-image is called image reconstruction (Fig. 2) (Gonzalez & Woods, 2009).

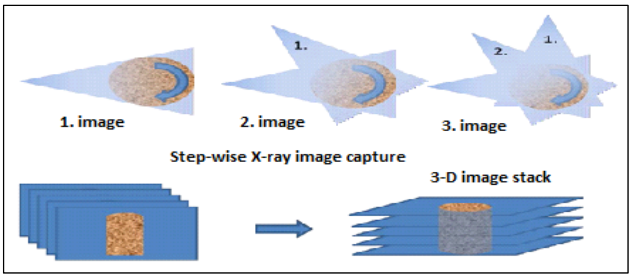

Figure 2. Image reconstructions frm image series (Gonzalez & Woods, 2008)

The spatial resolution of the images depends on factors such as the magnification, focal spot size of the X-ray tube, pixel size of the detector and other physical factors such as X-ray scattering and interaction among detector pixels. The attenuation coefficient of the material under investigation to X-ray also depicts its density density (Kumi et al., 2015). The intensity is expressed as:

$$I = I_0 \exp(-\mu_m \rho_x) \qquad (1)$$

Where, x is the penetrating length of incident X-ray; ρ is the density of material; µm is the absorbing coefficient per unit mass of detected object; I is the intensity of X-ray after penetrating object; I0 is the intensity of X-ray before penetrating object (Wu et al., 2008).

3. Use of CT in soil science

Pore geometry imaging and its quantitative description is a key factor for advances in the knowledge of physical, chemical and biological soil processes (Matrecano et al., 2009). Studies related with pore size distribution models assumed cylindrical pore shapes. However these models can not adequate for defining some soil hydraulic functions such as the tortuosity, continuity, and connectivity of pores. Until recent years, imaging with 3D of the soil structure has been obtained using medical tomographic systems although they have limited resolutions.

Physical models have been used for many years to simulate water flow through porous materials (Karadimitriou&Hassanizadeh, 2012). 3D-printing is now an established technology in prototyping and miniature production but has not been applied widely in flow models. The production of an artificial soil pore model is carried out by 3D-printing technology, which shapes computer graphics into real 3D-objects from a wide choice of materials (Bacher, 2013).

X-ray computed tomography (XCT) is a powerful tool for detecting the micro-scale pore structure and has been applied to many natural and synthetic porous media (Peng et al., 2012). Firstly, Orsi & Anderson (1995) successfully characterize the sediment morphology by X-ray CT. Then the CT and X-ray CT methods were used in many researches such as soil constituents and organic matter (Sleutel et al., 2008 ; Quinton et al., 2009; Kettridge & Binley, 2011; Elyeznasni et al., 2012), soil compaction and porosity (Delerue et al., 2003; Rogasik et al., 2003; Elliot &Heck, 2007; Sander et al., 2008; Peth et al., 2010; Aravena et al., 2011), soil structure modification analysis (Torrance et al., 2008; Elliot et al., 2010; Flavel et al., 2012; Mairhofer et al., 2012; Schmidt et al., 2012; Tracy et al., 2012), water content, and water and solute transport (Perret et al., 2000; Kasteel et al., 2000; Mooney, 2002; Anderson et al., 2003; Wildenschild et al., 2005; Carminati et al., 2009), Gantzer and Anderson (2002), and evaluation of the effect of different soil management systems (Atkinson et al., 2009; Papadopoulos et al., 2009), soil-root research (Koebernick et al., 2014; Tracy et al., 2015; Paya et al., 2015) in approximately last 25 years (Calistru and Jităreanu, 2015)(Kumi et al., 2015). The CT technique used on 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).

Three-dimensional (3D) spatial distribution of X-ray absorption coefficient is measured in the µCT technique. In 2007, Kutilek and Nielsen recommended a combination of advanced hydrological and micropedological approaches which could lead to a better understanding of the real pore and water properties in soil. Khan et al., (2012) simulated the heterogeneous fluid velocity field in the matrix pore space of saturated soil aggregate by applying the lattice Boltzmann Equation (LBE) solver to its X-ray computed nano-CT image as geometrical data input (Figure 3). Porous media properties for the soil aggregate were summarized in Table 1.

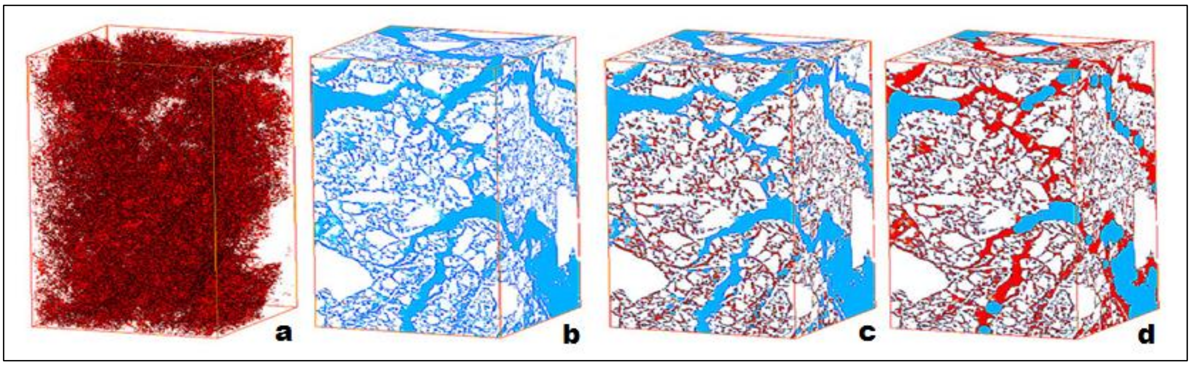

Figure 3.3D imaging of soil sample ROI #1 porosimetry, with a pore size of D10 (without solid matrix which is not clearly discernible when integrated with the void network), b same with solid matrix representation. Blue color represents mercury distribution in pores, while red color depicts pores size; c and d represent the same images for D50 and D90 PSD, respectively. Soil sample height is 0.74 mm (=1,000 voxels) (Khan et al., 2012)

Table 1. Estimation of 3D geometrical parameters of the soil aggregates (Khan et al., 2012)

	Pore size distribution, µm			Total Porosity, cm^3cm^{-3}	Grain size disribution, µm			SSA, m^2gr^{-1}
	D10	D50	D90		L10	L50	L90	
1	3.0	7.3	30.0	0.390	4.4	10.7	59.1	0.11
2	3.0	8.6	32.8	0.406	4.4	9.0	17.5	0.11
3	3.0	6.5	33.6	0.408	4.1	9.2	31.8	0.12
Mean± SD	3.0±0.0	7.6±0.9	32.6±1.5	0.401±0.008	4.3±0.1	9.7±0.8	44±17	0.11±0.01

SSA: Spesific Surface Area, D: Diameter of pore, L: Lenght

Binary images based on the segmentation of the pores with the threshold grayscales were imported to image to generate 3D view of the pore structure (Fig. 4). The extracted pore structure is plotted in pink and green for the low and high resolution X-ray images, respectively. More details on pore structure can be observed in the high resolution images, including the large amount of intraparticle pores and the roughness of the pore surface; while the pore structure in low resolution can be more representative with respect to porosity(Fig. 4a,4b) (Peng et al., 2012).

Peng et al., (2012) reported that conceptually, the porosity determined from the XCT images is the total porosity including both accessible and isolated pores. The actual smallest and largest pore lengths measured with Blob3D are found to be 16.1 µm and 425 µm by the low resolution XCT images, and 0.25 lm and 25 by the high resolution XCT. Therefore, the XCT-based porosity is actually the total porosity in the corresponding detecting pore size range. They said that pore connectivity is another critical property of the pore structure which defines how well the pores are connected and therefore will affect the local fluid flow. Accessible fraction was used to express the pore connectivity and a 3D binary XCT image was applied to determine the accessible fraction.

Porosity, pore size distribution, and pore connectivity are the key parameters which define the pore geometry and topology; therefore, the resolution effect of XCT on these parameters is critical in the results. Both low and high resolution XCT can generate misleading results of either less accurate or less representative. Therefore, the selection of resolution must be a compromise between the accuracy and representativeness. High resolution images can reveal more details of the pore structure and were more accurate in describing of porosity and pore size, while the field of view was limited and thus result in non-representative results. By contrast, low resolution images provide larger field of view and are able to capture the large-pore porosity (D > 16.1 µm), while they overestimated the pore size and pore connectivity. For example diffusion will occur in both small and large pores, while larger pores contribute predominantly to permeability over smaller pores. Therefore, for the same sample, the resolution selected for diffusion analysis should be higher than that for the permeability analysis (Peng et al., 2012).

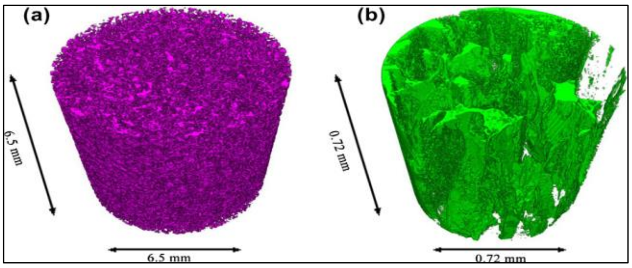

Figure 4. Reconstructed 3D pore structure from XCT images with resolution of 12.7 lm (a) and 0.35 lm (b) (Peng et al., 2012)

Beraldo et al. (2014) collected undisturbed soil sample in the field (Va), several slices (planes) of the cross-sections. It was defined a region of interest for analysis due to the large number of images. The central portion of the sample was chosen to be analyzed, because it consist a region where no disturbances occur in the sample (Figure 5). Maintaining the ratio between the height and the diameter of the cylinder close to one, this volume (Vb) was 39.7 cm^3. To avoid disturbances near the cylinder wall, the same proportion of the volume calculated in Va for Vb was maintained, and was obtained the volume of the central portion of the sample (Vc) of 22.9 cm^3. From this volume (Vc), it was calculated the number of slices containing in it (Figure 5), and thus it was possible to calculate the volume of each slice (Vd).

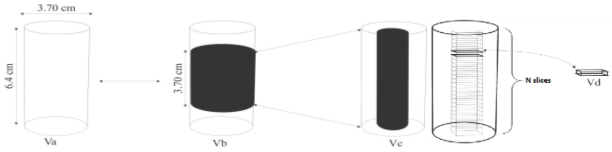

Figure 5. Schematic diagram in the area of interest for analysis with X-ray microtomography (Beraldo et al., 2014).

According to Paya et al., (2015), it is very important that the sample is firmly fixed in its holder to avoid any relative movement between the two during scanning (Figure 6).

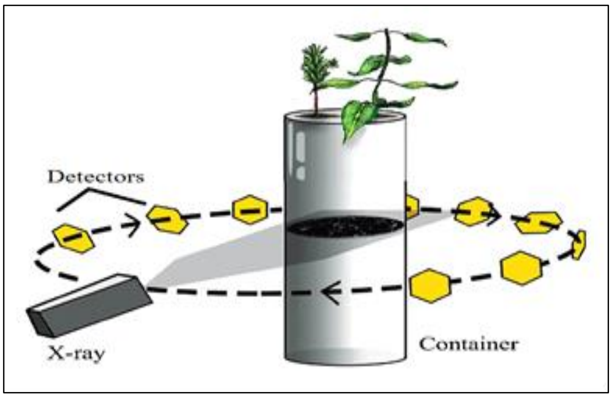

Figure 6. Illustration of the principle of CT in imaging slices of plant soil (Paya et al., 2015)

Dal Ferro & Morari (2015) have used X-ray computed microtomography (microCT) to display 3D morphological properties of undisturbed soil samples in unsaturated conditions and a soil-derived model at the same spatial scale (Figure 7). They showed that 3D printing technology was able to retain the basic features of the macropore network with comparison between morphological characteristics of replicated small prototypes (Figure 8). Generated prototypes was found so enough to identify morphological properties of pores.

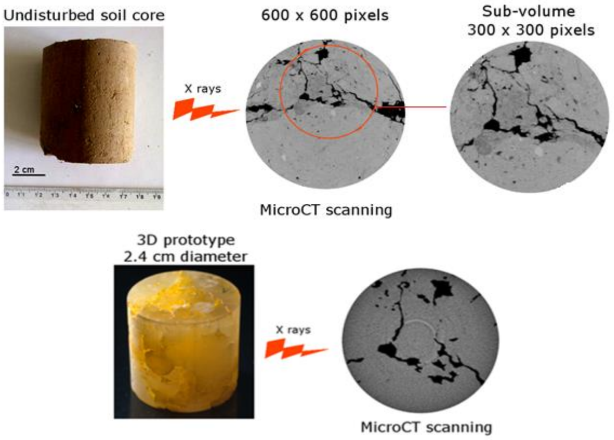

Figure 7. Display of X-ray computed microtomography (microCT) from undisturbed soil sample and 3D prototype (Dal Ferro & Morari, 2015)

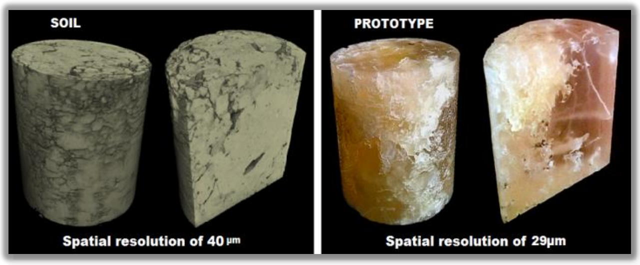

Figure 8. 3D representations of a large soil sample as a result of XCT analysis(Dal Ferro & Morari, 2015)

4. Discussion and conclusions

Field assessment of soil structure is difficult, and X-ray CT studies are only possible in the laboratory (Garbout et al., 2013; Sander et al., 2008). Electrical resistivity as a non-destructive mapping technique can be applied to map the soil structure (Samouëlian et al., 2005; Tabbagh et al., 2000). No tools have been developed that can rapidly, or even slowly, measure or quantify the grade, shape or size of soil structural peds in the field.

The technology has improved continuously so that even complex structures like overhanging structures with no direct connection to the layer below can be printed (Otten et al., 2012). An artificial soil pore network can help to analyse preferential macropore flow which is important for pollutant leaching and degradation in the environment. Reproducing soil macro pores in an artificial, durable material offers the opportunity of repeating experiments in contrast to real soil pore networks. Therefore potential and limitations of reproducing an undisturbed soil sample by 3D printing can be evaluated. For example; the mathematical equivalent of a cylindrical pore has a different effect on pore water flow than the real shapes and geometry of pores. Therefore (Luo et al., 2010) recommends using the pore volume instead of the equivalent pore radius. Instead of a statistically estimated pore size distribution, the real number of pores with a specific diameter can be determined when the exact geometry is known. The 3D-print offers the possibility to shape or modify individual pores as desired; cutting off dead end branches of the macropore or blocking connections with the soil matrix can be all done by editing the 3D-printing master's image (Bacher, 2013).

3D-printing of undisturbed soil to reproduce macropores at the original scale is in principle possible, but the selection of the proper material and 3D-printing technique is crucial. The downside of printing connected macropore-networks in 3D-printing material lies in the smaller scale. Bends and bottle-necks of macropores with an equivalent diameter of 300 microns have smaller diameters which are not printable or might easily become clogged. Therefore, at this stage of research in 3Dprinting of artificial undisturbed soil for hydrological research, fully connected macropores throughout the sample are required (Bacher, 2013).

According to Bacher (2013), 3D-X-ray analysis of the soil avoids disadvantages of other techniques such as small resolution or complicate handling of common techniques as photography or thin sectioning. For analysing the relationships between soil pore systems and flow and transport processes in soils, which can hardly be determined on scales below two or three centimetres, the resolution of X-ray instruments limits the main field of application to pores larger than smaller macropores. Nevertheless the range of applications of x-ray analysis is virtually endless, for example Vogel & Roth (2003) measured the bulk density and Luo et al., (2010) quantified and compared soil pore networks in different soil types. Macropore networks in 3D-printed structures exhibit well-known properties regarding geometry and dimensions. 3D-printing will offer a wide range of possibilities for future research when the available printing resolution improves sufficiently to print even smaller macropores.

Compared to other analysis methods, the short time requiered 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 (Calistru & Jităreanu, 2015). In comparison with classical methods used in soil science, computed tomography has the following advantages: it is a non-evasive and non-destructive technique; allows measuring the heterogeneity in the soil and where it occurs; allows measuring soil density and water content at a high resolution; it is possible to obtain images of soil samples in two and three dimensions independent of the geometry and shape of each sample (Cruvinel et al., 2009; Pires et al., 2010).

The use of soil-like materials will be able to model the physical-chemical interaction between water and the pore surface (Dal Ferro &Morari, 2015). Experiments showed that more successful results were obtained with these techniques compared to 2D and/or direct observations. New technological developments should be explored and used to obtain better results in application of 3D printing technology in many field. Moreover, these simulation tools provide better understanding of macroscopic fluid flows.

Utilization of such tools and modeling procedures will be useful in providing more detailed soil-root and root-root sensitivities and response reactions. The current fast advancement in CT technology will lead to the full understanding of the dynamic processes within the soil (Kumi et al., 2015).

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