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X-ray microtomography: A porosity-based thresholding method to improve soil pore network characterization?

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ABSTRACT

X-ray microtomography, through quantification of soil structure at the microscale, could greatly facilitate the current understanding of soil hydrodynamic behaviour. However, binarisation method and processing choices are subjective and can have a strong impact on results and conclusions. In this study, we test a new method based on the porosity detectable by X-ray microtomography, while validation is achieved through comparison of soil microtomogram information with soil physical measurements. These measurements consist of water retention and unsaturated hydraulic conductivity using two different soil populations with only structural differences. To assess the porosity-based method performances, we compare it to four other methods, namely the global method of Otsu and three recent soil-dedicated local methods. The robustness of the porosity-based method is also tested in regard to different pre-processing procedures. In this paper we demonstrate that soil segmentation through a porosity-based method is an interesting issue. Indeed, it is less demanding in terms of time and computational requirements than its alternatives, and combines robustness and performances broadly comparable with the recent local methods.

1. Introduction

Current challenges in hydrology are linked to the increase in precision of soil structure characterization. Indeed, soil hydrodynamic behaviour modifications are still not well understood, regardless of their origin (i.e. anthropologic or natural). However, they are known to be directly linked to soil structure modifications in the pore network, which in turn influence water flow dynamics. Macroscopic measurements of hydrodynamic parameters do not provide sufficient mechanistic explanations for these changes and the need for microscale characterization is therefore clearly evident. In this context, X-ray microtomography provides the means for studying pore geometry and can help to improve our understanding of soil behaviour.

X-ray tomography has been used in the field of soil science since the early 1980s (Crestana et al., 1985; Hainsworth and Aylmore, 1983; Petrovic et al., 1982, principally). This technique presents many advantages: it allows a relatively quick measurement acquisition; it is non-destructive; and the resolution can reach micron scale or less. An increasing number of publications refer to this technique, along with new algorithms to enhance analyses and perform original measurements, such as pore size distribution, shape, connectivity or orientation. Taina et al. (2008) and Pires et al. (2010) offer an exhaustive state of the art for this field of research.

However, there are almost as many procedures for tomographic data processing as papers about soil tomography. Hence, the relevance of the soil pore network depends on pre-processing and exploitation choices. Indeed, the data require a certain amount of pre-processing before geometric features can be quantified. Tomographic reconstruction produces a 3D grey-level image to which artefact corrections and noise reduction can be applied. Processing of the resulting grey-level images can include a binarisation step, i.e. separating solid phase and pores as two different domains, or the attribution of a permeability level linked to the grey-level values. Both these strategies lead to uncertainty, especially for soil material. Indeed, if we consider the variation of composition in one voxel, an identical grey-level value can correspond to voxels with different proportions and arrangement of each material (mineral and organic), and as a result can lead to different permeability (known as "partial volume effects" (Oh and Lindquist, 1999)). Therefore, in most cases, binarisation is applied because analysis of black and white 3D structures is faster and easier than grey-level ones.

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However, binarisation remains a tricky step. Not only does the choice of thresholding technique have a deep impact on the resulting measurements (Baveye et al., 2010; Taina et al., 2008; Zhang, 1995), but thresholding methods are also abundant (Dey et al., 2010; Sezgin and Sankur, 2004; Zhang, 1996). Ashbridge et al. (2003) and Iassonov and Tuller (2010), for example, propose pre-processing algorithms to facilitate a visual cut-off or the application of automatic techniques. Other attempts adapt threshold values for each pixel using local information: Pierret et al. (2002) propose a method of local thresholding and Al-Raoush and Willson (2005) use a local criterion based on indicator kriging (Oh and Lindquist, 1999). However, owing to the soil complexity, automatic methods as well as visual cut-off lead to highly variable results (Baveye et al., 2010). This is explained by the fact that most thresholding methods are not developed for soil analyses purposes and so, they do not take into account soil images characteristics. To overcome this problem, Schlüter et al. (2010), and more recently Hapca et al. (2013) and Houston et al. (2013a) have proposed new methods directly developed for soil samples. The method by Schlüter et al. (2010) is based on local information through edge detection. Hapca et al. (2013) use Otsu (1979) as a point of departure, and develop a local method by applying the intra-class variance tool after performing a preclassification step. Houston et al. (2013a) adapt the indicator kriging of Oh and Lindquist (1999) by considering in the kriging step a variable window size which adapts to the information in the local neighbourhood. The research of Houston et al. (2013b) shows that these methods are quite robust with regard to scanning and reconstruction settings, and are therefore promising.

So it is evident that plenty of methods exist, global or local, and fully automated or user-dependent. Local methods potentially allow some variation to be taken into account (e.g. variation of porosity and illumination) throughout the sample. Global methods, on the other side, are often easier to implement and need less computational power. The performance of these different techniques often depends on the images' complexity and quality. Besides, segmentation performance is not always related with method complexity. For instance, Wang et al. (2011) show that, in some contexts, the global method of Otsu (1979) is more efficient than the local one developed by Oh and Lindquist (1999). Based on the above, it is apparent that the question of the best technique for soil images segmentation remains unanswered. Indeed, the abundance of thresholding methods is a direct consequence of the lack of a universally acknowledged, reliable method.

The underlying reason for this abundance is also that ground truth information is missing for methods' development and validation in the context of soil analysis. Performance assessment therefore becomes a key point in this field, depending on the choice of both criterion and reference images. For example, Wang et al. (2011) use greyscale images simulation, whereas Baveye et al. (2010) propose the use of a physical benchmark such as porosity. Porosity is indeed a fast and easily measurable property; its measurement doesn't affect the scanning procedure, and it is usually used to validate segmentation techniques (Al-Raoush and Willson, 2005). However, matching the porosity is not a quality guarantee because it is not difficult to adapt the porosity of the images to match the readings. Notably, Oh and Lindquist (1999) are opposed to this method because of the partial volume effects and the uncertainty about sub-volume porosity.

However, porosity has not been tested as a thresholding method since Baveye et al. (2010) proposal. Yet, this perspective makes sense for soil analyses, whereas it demands another strong validation method. Besides porosity, soil is characterized through hydrodynamic behaviour. For instance, retention and hydraulic conductivity curves are representative of this soil hydrodynamic behaviour. Following these statements, we tested the use of the mean porosity detectable by X-ray microtomography, termed “visible-porosity” in this paper (see Section 2.2.2 for a complete definition). Meanwhile, segmentation performance was quantified through a comparison between X-ray microtomography analyses and hydrodynamic characterization. The robustness of the method was tested using different pre-processing procedures, i.e. beam hardening correction and noise reduction. Finally, in the context of soil structural comparison, the aim of this paper is to help determine the best methodology – considering both time and quality factors – for soil images analysis. The porosity-based method is compared with other thresholding methods (Hapca et al., 2013; Houston et al., 2013a; Otsu, 1979; Schlüter et al., 2010) including new local and soil dedicated methods.

After all, we seek to answer the following questions: i) Is visible-porosity a useful and robust benchmark for binarisation? ii) Can visible-porosity be used as the basis of the thresholding method?

2. Material and methods

In the first part of this section, parameters for X-ray microtomography acquisition, pre-processing, binarisation and morphological calculations are detailed.

The second part of the section relates to the methodology of the thresholding methods' comparison and validation. Macroscopic measurements (a term used in contrast with measurements at the pore scale using X-ray microtomography) are presented, and consist of retention data acquisition, and saturated and unsaturated hydraulic conductivity measurements. The first two measurements are used to draw retention and hydraulic conductivity curves in combination with X-ray microtomography, while the latter serves as validation. Principal component analysis (PCA) is additionally performed in order to establish a potential difference in structural parameters depending on thresholding methods.

2.1. Field experiment

The soil was taken from a site near Gentinnes, Walloon Brabant, in Belgium. The soil is mainly composed of silt loam and can be classified as a Luvisol (following the FAO classification by Driessen et al., 2001). Soil measurements come from different plots cultivated in conventional (CT) or reduced tillage (RT), i.e. sowing after stubble ploughing of about 10 cm. In RT, it is the subjacent no tilled horizon (RT2, below 10 cm) that is tested to maximise structural differences between objects. Indeed, although only one type of soil has been tested in terms of textural aspects, structural effects are nonetheless taken into account, since the plots proved to be different from a structural point of view. First, penetrometry performed on the horizons showed different resistance to penetration. Next, hydraulic conductivities were found to be significantly different between objects. Finally, PCA performed with a threshold reference showed a structural differentiation as well (see Beckers et al., 2013 for more information).

2.2. X-ray microtomography

In order to *empty* the pores, samples (5 cm height and 3 cm diameter, 8 replications) were exposed to a 15 kg pressure according to Richards (1948) and DIN ISO, 11274 (2012), before microtomographic acquisition.

X-ray microtomography consists of performing a series of X-ray radiograms under different angles, thereby producing enough information to algorithmically reconstruct a 3D X-ray attenuation map of the sample. The transmitted X-ray intensity depends on the attenuation coefficient, which is related to the material properties, i.e. to the density and atomic number of the studied material (Attix and Roesch, 1968), and the energy of the incident beam.

Samples were scanned using a Skyscan-1172 high-resolution desktop micro-CT system (Skyscan, Kontich, Belgium). The cone beam source operated at 100 kV, and an aluminium filter was used to reduce beam hardening. The detector configuration (16-bit X-ray camera with 2×2 binning, creating 2048×1024 pixel radiograms) and the distance source–object–camera were adjusted to produce images with a pixel