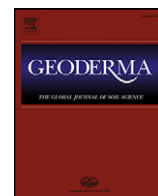




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Local 3D segmentation of soil pore space based on fractal properties using singularity maps

Juan J. Martín-Sotoca^{a,b,*}, A. Saa-Requejo^{a,c}, J.B. Grau^d, A.M. Tarquis^{a,b}

^a CEIGRAM, ETSIAAB, Universidad Politécnica de Madrid (UPM), Ciudad Universitaria, sn, Madrid 28040, Spain

^b Grupo de Sistemas Complejos (GSC), ETSIAAB, Universidad Politécnica de Madrid (UPM), Ciudad Universitaria, sn, Madrid 28040, Spain

^c Grupo de Valoración de Recursos (GVR), ETSIAAB, Universidad Politécnica de Madrid (UPM), Ciudad Universitaria, sn, Madrid 28040, Spain

^d Grupo de Automatización de Señales y Comunicaciones (GASC), ETSIT, Universidad Politécnica de Madrid (UPM), Ciudad Universitaria, sn, Madrid 28040, Spain

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ABSTRACT

Over the last decade, major technological advances in X-ray computed tomography (CT) have allowed for the investigation and reconstruction of three-dimensional (3D) natural porous media architectures at very fine scales. Soil scientists can use the internal structure information to develop predictive models for a range of physical, chemical and biological processes in soil. Image segmentation and thresholding are crucial steps when applying these methods to extract complex pore space geometry information from images. Traditional thresholding algorithms face challenges related to the heterogeneity of soil samples, noise and artefacts introduced during the image acquisition process.

This study proposes a new segmentation method using local greyscale value (GV) concentration variabilities based on fractal concepts. Singularity maps were created to measure the GV concentration at each point. The C-V method was combined with the singularity map approach (Singularity-CV method) to define thresholds that can be applied to binarize CT images.

This study also introduces a new method for creating 3D synthetic soil images based on truncated multifractals that simulate low-contrast and non-bimodal GV histograms. A synthetic soil image was created with the objective to compare traditional segmentation methods (Otsu and maximum entropy) with the Singularity-CV method. We obtained better results in porosity and more amount of pores at all scales than traditional methods, although some small pores were incorrectly identified due to the ability to amplify every anomalous GVs. Misclassification error (ME) was low and similar to Otsu.

Two different 3D CT soil images were also used in this analysis, corresponding to samples of the same soil with 1.2 and 1.6 g cm⁻³ bulk densities. After applying the Singularity-CV method to the GV images, the results were compared with the aforementioned traditional segmentation methods. The image comparison was based on the porosity, pore size distribution (PSD) and cumulative pore size distribution (CPSD). The Otsu method achieves a higher porosity than the Singularity-CV method because it defines the largest pores. However, the Singularity-CV method detected more pores at all sizes. The maximum entropy method always yielded the lowest porosity.

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1. Introduction

In soil science, it is very important to characterize the spatial distribution of soil pore structures. The parameters obtained from this distribution provide the essential variables required as inputs in water flow models (Vogel, 2000; Dullien, 2012) or microbial growth processes (Rockhold et al., 2004; Young et al., 2008; Pajor et al., 2010; Kravchenko et al., 2011). The most widely used pore characteristic is pore size distribution, which can be used to calculate other parameters,

such as total porosity and the mean and maximum pore size. In addition, pore characteristics, such as the pore connectivity and pore surface area, can be used to quantify parameters related to soil morphology and hydraulic properties (Dullien, 2012).

The first step in pore structure characterization is obtaining soil images that best approximate reality. Early studies used soil thin sections where 2D greyscale images were taken using different types of cameras. The main disadvantage of this method is that it is destructive in nature because soil samples must be mechanically sliced. More recent scanning techniques are based on 3D computed tomography (CT) images, which combine numerous X-ray images taken from different angles. CT-based methods have been applied to study soil structures (Wang et al., 2011; Houston et al., 2013b; Ojeda-Magaña et al., 2014). This technique,

* Corresponding author at: CEIGRAM, ETSIAAB, Universidad Politécnica de Madrid (UPM), Ciudad Universitaria, sn, Madrid 28040, Spain.

E-mail address: juan.martin.sotoca@alumnos.upm.es (J.J. Martín-Sotoca).

which has been widely used in medicine, has been proven effective for capturing 3D soil structures. Additionally, this technique does not change the internal solid structure of the soil and attains high resolution images. The main disadvantage of the technique is that the images may provide low contrast at the solid-void interface (Cortina-Januchs et al., 2011).

The subsequent step in pore structure characterization involves delimiting the pore structure (pore space) from the CT soil images. Different delimitation methods can result in different spatial distributions of pores, which can result in substantial variation in the estimation of important parameters, such as total porosity or pore connectivity. Binarization methods are generally used to delimit the air-filled pore space in 2D and 3D CT soil images. A binarization method is a segmentation technique in which only two classes of pixels/voxels are distinguished. These classes include the foreground class of interest (in this case, the pore space) and the background class. To separate the pore space (object) from the solid space (background), the binarization relies mainly on thresholding methods (Sezgin and Sankur, 2004) in which global or local thresholds are calculated. Global thresholding calculates a unique threshold that is applied to the entire image. Local thresholding establishes local thresholds based on local image characteristics which vary throughout an image.

A review of different threshold calculation strategies is provided by Sezgin and Sankur (2004). The authors classified thresholding methods into six groups: histogram shape-based methods, clustering-based methods, entropy-based methods, object attribute-based methods, spatial methods and local methods (the first five groups define global thresholding methods). A literature review reveals that the most popular clustering-based methods are the iterative method (Ridler and Calvard, 1978) and the Otsu method (Otsu, 1979). The maximum entropy (Kapur et al., 1985), the maximum Renyi's entropy (Sahoo et al., 1997) and the minimum cross-entropy methods (Li and Lee, 1993) are the most commonly used entropy-based methods. The best known local thresholding method is the indicator kriging (Oh and Lindquist, 1999), which is based on local spatial correlations. Recently, a new indicator kriging method called "Adaptive-Window Indicator Kriging" (Houston et al., 2013a) has significantly improved the segmentation results in soil images. These authors have utilized other local strategies, e.g., extending Otsu's method by minimizing the greyscale intra-class variance (Hapca et al., 2013), to improve upon the performance of the original method.

When we attempt to compare the performance of different segmentation methods, we can follow different strategies. One of them may be making independent measurements of porosity and pore size distribution. Independent methods for measuring porosity are: (i) calculation from bulk density, (ii) water saturation, and (iii) gas pycnometry. Independent methods for measuring pore size distribution are: (i) water desorption and (ii) mercury porosimetry (Flint and Flint, 2002). Another alternative strategy is to have "real" information from the soil samples. The problem is that in many cases, this information is not available. Currently, to address this problem, the use of simulated or synthetic soil images is common. We can find examples of 2D and 3D synthetic soil images in the studies by Zhang (2001), Schlüter et al. (2010), Wang et al. (2011) and Martín-Sotoca et al. (2016).

Recently, some studies analysed the internal soil structure from a fractal point of view. Multifractal analysis (MFA) has been applied to greyscale soil images to determine parameters such as generalized fractal dimensions, singularity exponents and multifractal spectra (Tarquis et al., 2008, 2009, 2012; Piñuela et al., 2010; Zhou et al., 2011). The results obtained for different types of soils suggest that quasi-multifractal behaviours exist within a certain range of scales. Research and discussions on this topic are ongoing.

In the context of detecting certain geochemical elements in mineral deposits, some studies applied a fractal approach to delimit the mineralized areas. The first studies to use such an approach were Agterberg et al. (1993) and Cheng et al. (1994). In these initial studies, a

segmentation method known as the concentration-area (C-A) method was applied to element concentration maps to calculate mineralization thresholds. This method aims to determine the fractal properties that appear in systems with complex spatial distributions. The fractal properties are visualized through a log-log plot in which several linear segments may appear. A 3D version of the C-A method known as the concentration-volume (C-V) method must be used to analyse 3D concentration maps (Afzal et al., 2011). Element concentration maps were eventually replaced by element "singularity maps" because the singularity exponents, $\alpha(x)$, can be interpreted as a measure of the local concentration (Goncalves et al., 2001; Cheng, 2012). Cheng (2001, 2007) defined "positive singularities", with $\alpha(x) < 2$, which correspond to high values of concentration in a geochemical map, and "negative singularities", with $\alpha(x) > 2$, which correspond to low concentration values. Therefore, calculating the singularity map for a geochemical concentration map may be used to characterize concentration patterns which provide useful information for interpreting anomalies related to local mineralization processes.

The goal of this paper is to utilize the geochemical anomaly detection methodology, based on the singularity 3D maps and the C-V method, to extrapolate the air-filled pore spaces in 3D CT soil images. This study can be considered an extension of the previous work by Martín-Sotoca et al. (2016) in which a two-dimensional analysis was developed. In this paper, we used the C-V method to establish the threshold that separates the 3D pore space from the 3D solid space. As a result of this work, a new segmentation methodology is proposed for 3D CT soil samples. Hereinafter, this method is named the "Singularity-CV" method. A comparison with traditional segmentation methods was performed to illustrate the main differences between methods. In this study, we chose the Otsu and maximum entropy methods for comparison. We justify the use of these methods for two reasons: i) currently, the Otsu and entropy-based methods continue to be the reference methods of comparison for new techniques and ii) the statistical approaches of both techniques greatly differ.

This paper also introduces an alternative method to create 3D synthetic soil images: the "Truncated Multifractal Method" (TMM). This new method is mainly based on enhancing the scaling nature of the pore space in the 3D synthetic images. This method was previously introduced by Martín-Sotoca et al. (2016) to create 2D synthetic soil images.

2. Materials and methods

2.1. Description of the soil samples

An arable sandy loam soil from a field in Scotland was packed into polypropylene cylinders with diameters of 6 cm and heights of 5 cm. The bulk densities were 1.2 Mg/m³ (sample 1) and 1.6 Mg/m³ (sample 2). For further details, see Harris et al. (2003).

The soil samples were imaged using a Metris X-Tek X-ray micro-tomography system at 160 kV and 201 μ A, producing 3003 angular projections. An aluminium filter (0.10 mm) was applied to minimize beam hardening. A reconstruction process also provided several corrections. Radiographs were reconstructed into a 3-D volume using CT-Pro (Nikon). They were then imported into VGStudio Max software (Volume Graphics, 2015) and converted into 8-bit binary TIFF images.

Two image stacks of 260 $\times$ 260 $\times$ 260 voxels and resolutions of 30 μ m (voxel length size) were used in this study. For further details, see Pajor et al. (2010). The two samples (two image stacks) were selected from an image-stacked set by choosing samples with different spatial patterns (different degrees of compaction) and GV histograms with non-bimodal shapes. Threshold calculations are typically easier using bimodal histograms compared to non-bimodal histograms because two obvious objects can be identified in the histogram. We chose non-bimodal shapes to test the Singularity-CV method in the most demanding situation.

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