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Combining global and local scaling methods to detect soil pore space

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ABSTRACT

Computed tomography (CT) images provide very useful information to characterize the pore space structure in different porous materials. Being a non-destructive technique, it allows preserving the real characteristics of the analysed samples. Moreover, providing 3 dimensional (3D) information, it also allows making more exhaustive studies on other characteristics of pore space such as connectivity or pore geometry. However, this technique also has drawbacks such as the insertion of errors and distortions from CT reconstruction that could drive to low contrast greyscale images hindering the detection of solid-void interface.

The Singularity-CA (S-CA) binarization method has already proven to be an efficient method when detecting the pore space in CT soil images. This method is primarily based on the existence of self-similar properties in the singularity value (SV) spatial distribution. These self-similar properties derive to thresholds in the singularity map which are used to delimit the pore space. This method detects the medium and large pore sizes with an excellent fit. However, due to its high sensibility to low fluctuations in the greyscale images, some small pores are incorrectly detected and therefore its amount is overestimated.

This work attempts to solve this drawback introducing a new approach named the Combining Singularity-CA (CS-CA) method. This improved method is based on the combination of a global thresholding method, the Maximum Entropy method, and the S-CA method. The CS-CA methodology is fully automatic and did not require human adjustment. A set of soil synthetic images with porosities from 3% to 25% were used to validate the new approach. These images were constructed using the Truncated Multifractal (TM) method, especially useful to simulate CT soil images. Based on parameters such as porosity, relative error and misclassification error, CS-CA method gave better pore detection than the S-CA and the Maximum Entropy method applied individually to the images.

Finally, it was compared the two main methods used to detect slope-change points in plots with several linear segments: the linear regression (LR) method and the wavelet transform modulus maxima (WTMM) method. These methods are very important in the S-CA methodology since they are responsible of defining the threshold in the binarization step. The WTMM method proved to be easier to deal with when using by the new CS-CA method.

1. Introduction

Non-destructive imaging methods, such as X-ray computed tomography (CT), yield three-dimensional representations of porous materials such as soils, rocks or concrete that requires a discrete representation of grain and pore structures. X-ray CT relies on measurement of the attenuation of X-rays passing through a sample from different angles, thereby generating cross-sectional and three-dimensional radiographs that map the spatial distribution of the numerical values of the linear attenuation coefficients of the materials under investigation (Stock, 1999).

However, X-ray CT is not free of artefacts, which complicates quantitative image analysis driving it to misinterpretation of attenuation values of several materials in different image sections (Cortina-Januchs et al., 2011). Reviewing the literature we can find several problems such as high-frequency noise, beam hardening, scattered X-ray (Van Geet et al., 2000; Wildenschild et al., 2002). In addition, there might be errors and distortions from CT reconstruction, for further details see Ketcham and Carlson (2001) and references there in.

In soil science, it is very important to characterize the spatial

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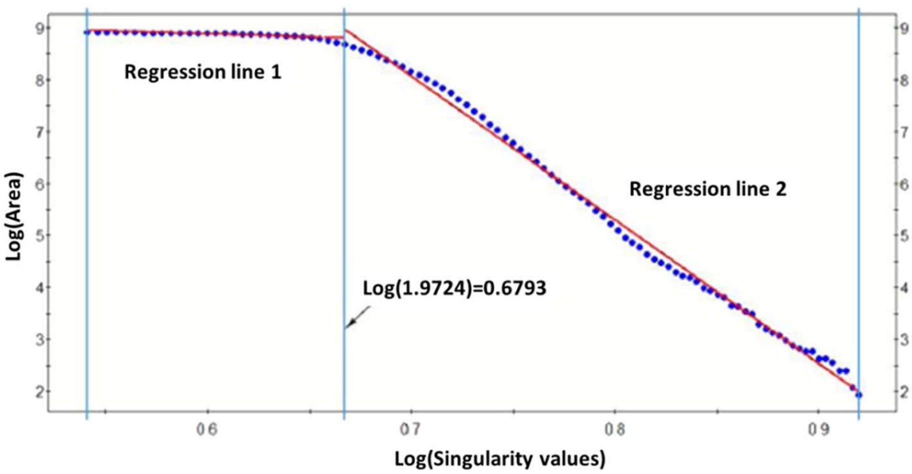

Fig. 1. Log-log plot of CA method with two linear segments calculated by the LR method. The slope-change point is calculated by crossing lines.
Source: Liu et al. (2013).

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). CT-based methods have been applied to study soil structures (Wang et al., 2011; Houston et al., 2013; Ojeda-Magaña et al., 2014) and it has been proven effective for capturing it. Considerable efforts are devoted to the improvement of CT technology; a thorough inspection of recent literature reveals that development and refinement of soil image segmentation methods, mainly binarization, are lagging behind as soil can present a high heterogeneity of materials composing it.

Soil pore structure characterization involves delimiting the pore structure (pore space) from the CT soil images. Different delimitation methods can provide 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 classified two classes of pixels: the foreground class of interest (in this case, the pore space) and the background class. To delimit 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. Additionally, local thresholding establishes local thresholds based on local image characteristics which vary throughout an image.

Hybrid methods can also be found which utilize local image transformations together with a global threshold. An example of the latter is the Singularity-CA (S-CA) method (Martín-Sotoca et al., 2016, 2017). This method is based on the results obtained by Cheng et al. (1994), Cheng (2001, 2012), Goncalves et al. (2001) and Liu et al. (2013). In these works, singularity maps were used to detect anomalous concentrations of specific geochemical elements. These anomaly areas are used as a start point in the search of ore deposits. In this context, the singularity map of the concentration variable $c(x,y)$ of a geochemical element is a function:

$$\alpha: (x,y) \rightarrow \alpha(x,y), \tag{1}$$

where $\alpha(x,y)$ is the singularity or Hölder exponent of the concentration variable $c(\boldsymbol{x})$ at the point $\boldsymbol{x} = (x,y)$. This exponent is a way to quantify the anomaly degree of the concentration variable $c(\boldsymbol{x})$. Formally, the singularity exponent α is defined through a mathematical measure (field) μ as:

$$\mu(B(\boldsymbol{x},r)) = \lim_{r\rightarrow 0} \sum_{\boldsymbol{x_i}\in B(\boldsymbol{x},r)} c(\boldsymbol{x_i}) \propto r^{\alpha(\boldsymbol{x})}, \tag{2}$$

where $\mu(B(\boldsymbol{x},r))$ is a measure over a set of locations $B(\boldsymbol{x},r)$, box-interval centered in $\boldsymbol{x}$ with box-size r, and $\propto$ denotes proportionality. This measure can be interpreted as the total amount of the geochemical element in the box-interval $B(\boldsymbol{x},r)$. When the element is uniformly distributed in space, we will have $\alpha = 2$. Additionally, areas with $\alpha < 2$ correspond to local enriched areas, and areas with $\alpha > 2$ imply local depleted areas (Cheng, 2001). Ore deposits are potentially located in areas with local concentration enrichment ($\alpha < 2$). Additionally, a threshold is necessary to establish anomalous Singularity Values (SV) in the areas with $\alpha < 2$. The Concentration-Area (CA) method was used to separate anomalies from background on singularity maps calculating a SV threshold (Liu et al., 2013). This method is particularly suitable for detecting populations with different self-similar features, giving rise to different power-law relationships. The CA method establishes that the area constituted by SVs (α) greater than a given value C satisfy a power-law relation:

$$Area(\alpha \geq C) \propto C^{\gamma}, \tag{3}$$

where the symbol $\propto$ stands for "proportional to" and the exponent γ may have several values depending on the different populations with self-similar features. If the accumulated SV distribution is depicted in a log-log plot, several linear segments with different slopes appear due to the power-law relations. The most important thing in the CA method is to locate the appearing slope-change points. These points are normally used as thresholds which delimit the potential anomalies in the singularity map. The method generally used to locate these points is the linear regression (LR) method. This method calculates linear lines for each linear segment using the linear regression methodology. The intersection of these lines provides the sought slope-change points. In Fig. 1 it is shown an example of CA method application using the LR method to calculate the threshold. This example comes from the paper Liu et al. (2013), where singularity maps are used to detect tungsten polymetallic deposits.

The S-CA method uses the latter philosophy to delimit the pore space in 2 dimensional (2D) CT soil images. In this case, the pore space corresponds to the local depleted area ($\alpha > 2$). The application of the CA method to the accumulated SV distribution reveals the existence of several linear segments with their slope-change points, meaning that different sets with self-similar properties also exist. One of these slope-change points defines the threshold applying to the singularity map to establish anomalous SVs. In this case, the method used to detect this point is the wavelet transform modulus maxima (WTMM) method. This method detects high curvature points using a second-order wavelet, the "Mexican hat" wavelet (see Appendix A). In Martín-Sotoca et al. (2017) the S-CA method was compared with the traditional thresholding methods, namely, the Otsu, the Iterative and the Maximum Entropy