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2D and 3D Morphological and Topological Analysis of a Clay Soil

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Résumé. — L'ultime but de cette étude est de caractériser les propriétés hydrauliques et électriques des sols argileux. Les deux principales applications de nos recherches sont l'étude des écoulements et la décontamination des sols par champs électriques. Par conséquent, nous utilisons les concepts de la morphologie mathématique pour décrire les caractéristiques géométriques, topologiques et texturales d'un réseau de fissures 3D reconstruit par coupes sériées. La comparaison des morphologies bi- et tri-dimensionnelles montre que les géométries sont similaires mais que les topologies sont différentes. En effet, le seuil de percolation est largement sous-estimé en 2D. La détermination du seuil de percolation, associé à la notion de goulot critique, est détaillée.

Abstract. — The ultimate goal of this study is to characterize hydraulic and electric properties of clay soils. The two main applications of our work are understanding of flows and decontamination of soils by electric fields. Therefore, mathematical morphology concepts are used to describe geometrical, topological and textural properties of a reconstructed 3D fissure network from serial sectioning. Comparison between bi- and three-dimensional morphologies shows that geometries are similar even though topologies are different. In fact, percolation threshold is highly under-estimated in 2D. Determination of percolation threshold corresponding to the notion of critical narrowing is explained.

1. Introduction

The behaviour of a soil depends mainly on its structure, *i.e.* the spatial arrangement of voids and solids. So, because of the growth of graphic computers, image processing tools and mathematical morphology concepts [1], more and more researchers have studied geometrical and topological properties of fissure networks in clay soils within the last decade. The ultimate goal of our study is to characterize the electric and hydraulic behaviours of clay soils with accuracy in order first to understand fluid flows when it rains and secondly to know in which conditions removal of contaminants from soil by electric fields can be performed. Until now, most studies of this type have been performed from soil thin sections without knowing whether the 3D morphological properties of the porous medium can be obtained from bidimensional representations. In fact, the use of classical stereological methods [2] is not possible because of complexity and anisotropy of the clay soil fissure network. So this paper presents a two- and three-dimensional morphological analysis of a resin impregnated clay soil sample. In the first part, the reconstruction of the 3D clay soil image is briefly explained using two scanning techniques: X-ray tomography and serial sectioning. The geometrical and topological parameters are then presented. They enable to compare the different representations defined in $\mathbb{R}^2$ and $\mathbb{R}^3$. In the last part, the results are discussed.

2. Materials

Image processings and morphological analysis are performed on a Silicon Graphics Indy workstation. All the softwares used were developed in our laboratory. They used X Window user interface and C language. So they can be run on any Unix workstation. Geological images can be digitalized with three systems:

- a color laser copier connected to an Unix computer which allows to scan and to print 400 dots-per-inch and 16 million color images,
- a Praktica numerical camera linked to a PC micro-computer and piloted by the Photofinish 3.0 Window software. Its resolution is $3\,200 \times 2\,600$ pixels in 256 grey levels,
- a scanning electron microscope to determine microscopical properties of rocks, which is connected to Ethernet so images are directly transmitted to graphic computers.

3. 3D Reconstruction

Most studies of the geometrical properties of porous medium are investigated in two dimensions and use principles of quantitative stereology [2] even though 3D investigations are required to obtain topological information. So it was decided to reconstruct a 3D fissure network binary image to match two and three-dimensional representations. Briefly, the realization of the clay soil sample consists in impregnating the connected pores of a undisturbed soil sample with an opaque epoxy resin containing an ultraviolet fluorescent dye. The 3D reconstruction has been explained by Moreau *et al.* [3]. After the numerical acquisition of the successive cross sections (by tomography or by serial sectioning), the 3D reconstruction consists first in processing the 256 grey level 2D images to enhance the dynamic and to facilitate the segmentation. Then, the images are thresholded with a correlation criterion [4], filtered [1], realigned with reference marks and stored in cubic grid. Because the resolution obtained from X ray tomography is low (500 μm), the study of the volume reconstructed from serial sectioning will be only presented. The distance between each successive cross section along the z axis corresponds to 100 μm. The resolution of cross sections reaches 100 μm to obtain a cubic voxel without interpolating. The reconstructed volume corresponds to $600 \times 890 \times 250$ voxels but the studied volume is finally $600 \times 600 \times 200$ voxels. It seems stationary (asymptotic covariogram) and representative of the studied porous media (larger than REV), but it presents an anisotropy (deformed plane fissures perpendicular to the xy plan). The 3D reconstructed clay soil fissure network and some 2D cross sections selected in x, y and z axis are presented in Figures 1 and 2.

4. Comparison Between 2D and 3D Representations

Morphological analysis enable to characterize the fissure network. In this paper, three 2D and 3D geometrical and topological parameters are compared.

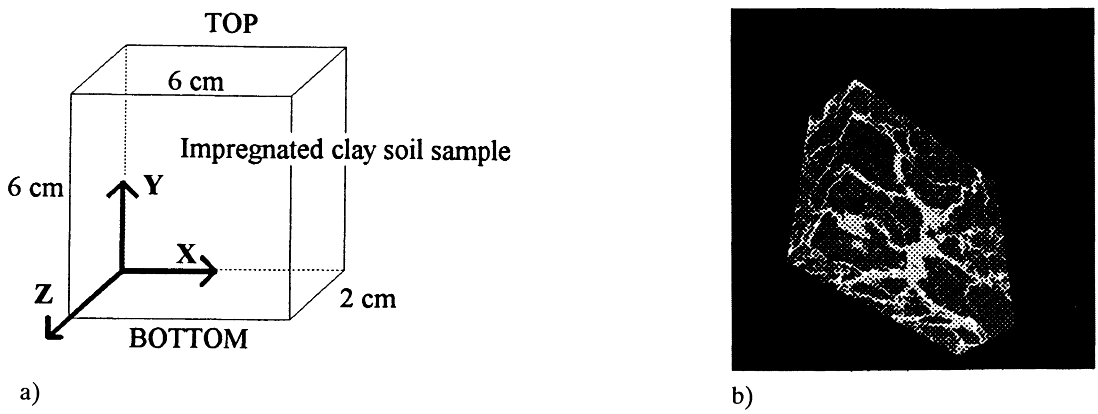


Fig. 1. — The 3D (x, y, z) landmark (a) and a view of the 3D reconstructed clay soil fissure network (b) where clay appears in dark.

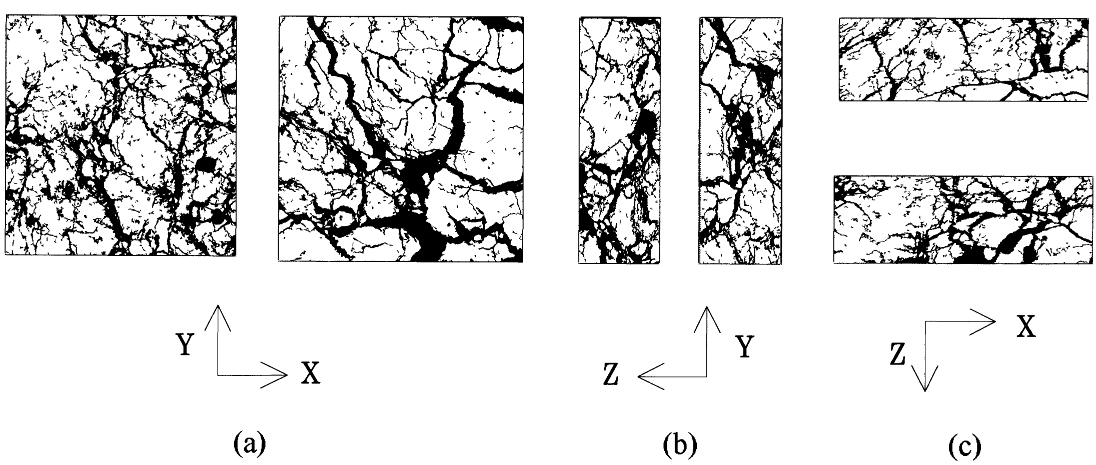


Fig. 2. — Some binary cross sections along the z axis (a), x axis (b) and y axis (c) axis. Fissures are black. Scale equals to 1:2.

Most of these analysis use mathematical morphology concepts, as erosion, dilation and geodesic propagation [5].

Because the volume is represented in cubic grid, erosion and dilation are performed in cubic graph, *i.e.* 6-neighbourhood. So two voxels are neighbours if they are connected by a face, an edge or a vertex; propagation is then carried out in 26-neighbourhood. In 2D, images are represented in square grid, consequently a square graph is used for erosion and dilation even though propagations are realized in octogonal graph. We have shown that fissure interconnectivity does not depend on the graph used for propagation.

4.1 Porosity. — The first parameter compared between 2D and 3D representations is *porosity.* Let X the object which represents the porous set. So the total porosity corresponds to the ratio of the point number belonging to X on the size of the image. The first result confirms the Delesse's law [6]:

$$V_V = A_A$$

where V_V is 3D total porosity and A_A is 2D total porosity. In fact, a statistical analysis shows that 95% of 2D cross section along the x, y and z axis have a porosity A_A as $24.71\% < A_A < 28.7\%$ whereas $V_V = 26.39\%$.

4.2 FISSURE WIDTH DISTRIBUTION. — Secondly, the *fissure width distribution* was studied using granulometry concepts [1], *i.e.* openings with structuring element B of increasing size.
Figures 3 and 4 show that 2D and 3D distributions are similar and can be fitted by a double exponential law such as $F(L) = C_1 \exp(-L/T_1) + C_2 \exp(-L/T_2)$ where $C_2 \ll C_1$ and $T_2 \gg T_1$. Moreover, average width is over-estimated in 2D.

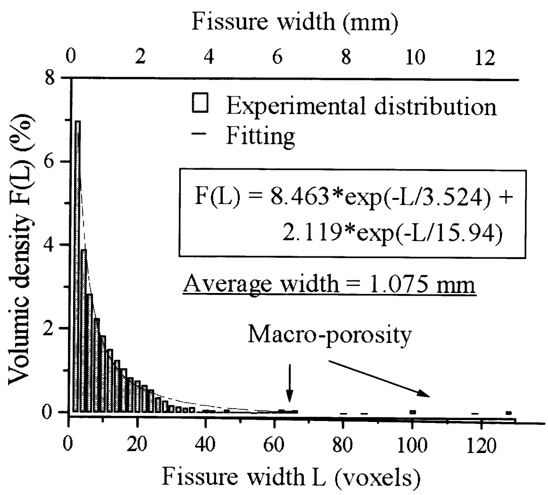


Fig. 3.

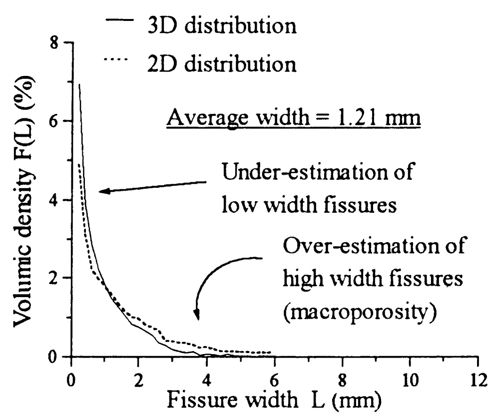


Fig. 4.

Fig. 3. — Behaviour of the distribution of L fissure width of the 3D reconstructed clay soil sample and fitting by a double exponential curve.

Fig. 4. — The average distribution of fissure width of some 2D cross sections is near the 3D distribution but macroporosity is over-estimated in 2D.

4.3 TOPOLOGY. — Topology of porous medium can be characterized by several methods [1, 6]. Because usual interconnectivity parameters give no interesting information in our case, one prefers to study the *percolation* of our clay soil. So an approach which allows to characterize a percolation threshold was defined: it corresponds to a *critical narrowing*. Figure 5 explains the different steps of the algorithm with an example of bidimensional fissure network.
Figure 5a represents the initial network. Let X be the porous set. Porosity is equal to 44%. A geodesic propagation is performed from the upper to the lower edge of the image. So the fissures which are not connected to the percolant network are removed to create a new X′ set (Fig. 5b). The porosity now corresponds to 39%, so the ratio of connected fissures on all the fissures is $F = 0.89$. After one Euclidian erosion $E^B(X)$ of X by the structuring element B of size λ equal to one (Fig. 5c), a geodesic propagation followed by one Euclidian dilation $D^B(X)$ of X by the structuring element B of size λ equal to one are performed (Fig. 5d). The new porosity is 29.5%

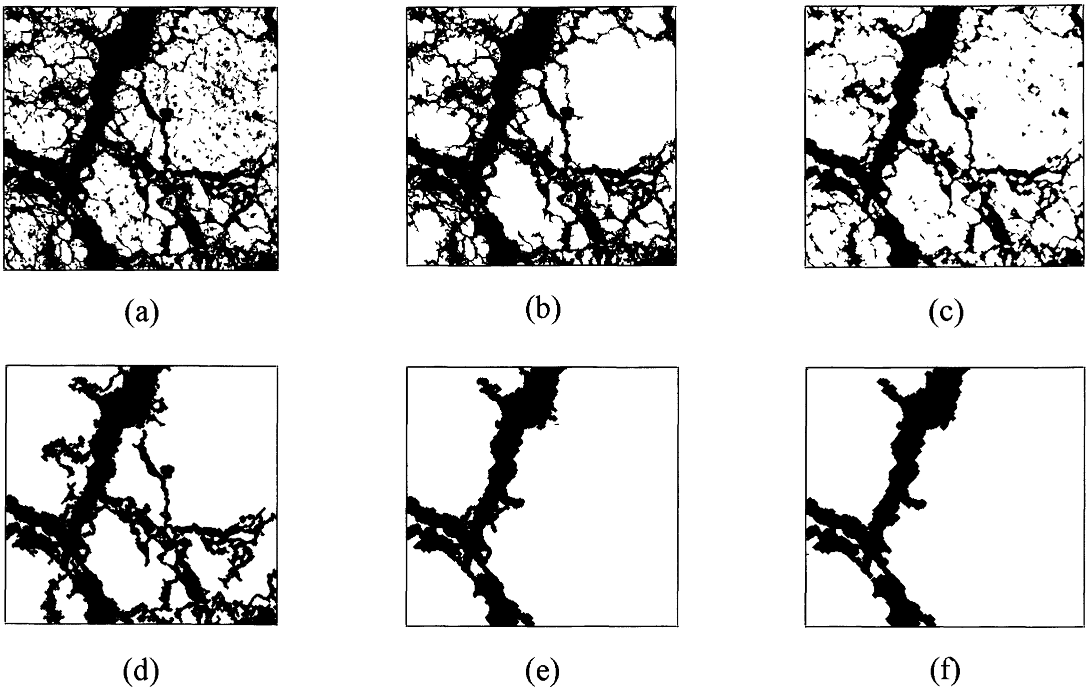
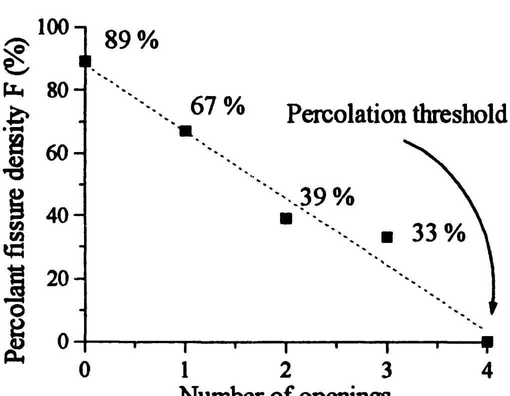


Fig. 5. — Different steps of the 2D critical narrowing algorithm. (a) original X set, (b) corresponds to $P_g(X)$, (c) to $E^B(X)$, (d) to $D^B\{P_g[E^B(X)]\}$, (e) to $D^BD^B\{P_g[E^BE^B(X)]\}$ and (f) to $D^BD^BD^B\{P_g[E^BE^BE^B(X)]$, where B is a square structuring element of size one and P_g is an octogonal geodesic propagation from the top to the bottom of the X set.



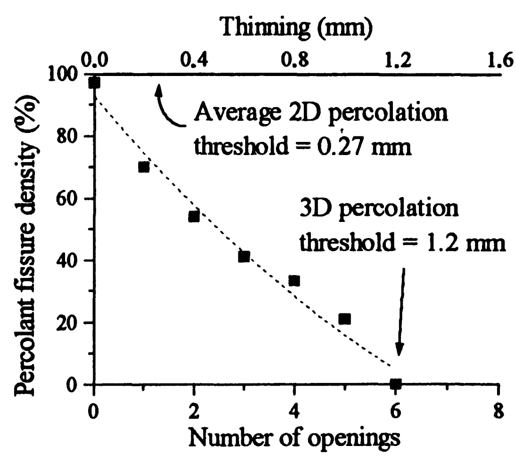


Fig. 6. Fig. 7.

Fig. 6. — The evolution of *F versus* the number *N* of erosions for the 2D example.

Fig. 7. — The evolution of *F versus* the number *N* of erosions. The 3D percolation threshold is equal to 8 pixels so 1.2 mm.

so $F = 0.67$. This erosion-propagation-dilation sequence removed the fissures connected by a narrowing smaller than 2 pixels. Figure 5e represents the network X after a thinning of size two, a geodesic propagation and a thickening of size two as:

$$X = D^B D^B \{P_g[E^B E^B(X)]\}$$

where $P_g(X)$ is a geodesic propagation in set X from the top to the bottom of the image. Under-four-pixels-wide narrowings are removed so $F = 0.39$. Figure 5f, where $F = 0.33$, corresponds to X where fissures connected by under-six-pixels-wide narrowings have been removed. After four erosions, there is no more percolation; percolation threshold is attained.
Then Figure 6 which represents the behaviour of F *versus* the number of Euclidian erosions shows that the critical narrowing is under-eight-pixels-wide, *i.e.* percolation threshold equals to eight pixels.

The analysis of our reconstructed fissure network shows that the 3D percolation threshold equals to 1.2 mm, whereas the average value equals to 0.27 mm in 2D (Fig. 7). So permeability is under-estimated in 2D even though electroosmotic phenomena could be correctly estimated.

5. Conclusion

Knowing that the hydraulic and electric behaviours of a soil depend highly on its structure, mathematical morphology has been used to characterize 2D and 3D geometrical, topological and textural parameters. The analysis of the three-dimensional clay soil sample and some bidimensional cross sections has showed that 3D and 2D porosity and fissure width distribution are similar. Meanwhile, percolation is highly under-estimated in 2D.
Then, it seems that electrokinetic phenomenon could be efficiently evaluated from bidimensional representations even though permeability estimation needs a three-dimensional analysis.

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