



# **2<sup>nd</sup> International symposium on PROTINUS**

## **— The 2nd IROAST Seminar —**

**Date: 2017/7/7**

Place: Engineering research tower I 905

MC: Toshifumi Mukunoki

Registration: Free

Contact Prof. Mukunoki: [mukunoki@kumamoto-u.ac.jp](mailto:mukunoki@kumamoto-u.ac.jp))



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## International symposium on PROTINUS supported by IROAST

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9:30-9:40	Welcome Speech by Jun Otani as a vice-leader of IROAST
9:40-9:50	Introduction of IROAST by Jun Otani
9:50-10:00	Introduction of PROTINUS by Celine Duwig as a project leader of PROTINUS
10:00-10:30	<i>Analysis of the porous structure of an Andosol and the relationship on SPH simulated flow</i> Celine Duwig, IRD, Grenoble University Alpes, France
10:30-11:00	<i>Assessment of soil permeability based on X-ray CT imaging: Definition of a geometrical criterion</i> Patricia Ortega, Laurent Oxarango LTHE, Grenoble University Alpes, France
11:00-11:30	<i>Pore-scale modeling of biofilm growth in porous media</i> Fabrice Golfier, GeoRessources, Université de Lorraine (UL), France
11:30-13:00	Lunch break
13:00-13:30	<i>Comparison between 3D printing methods for granular medium reconstruction</i> Anne-Julie Tinet, GeoRessources, Université de Lorraine (UL), France
13:30-14:00	<i>Image analysis of LNAPL recovery in sand due to injecting air using X-ray CT</i> Toshifumi Mukunoki, Ryo Takenaka and Erika Shiota, X-Earth Center, Kumamoto University, Japan
14:00-14:30	Break
14:30-15:00	<i>Development of a new system of anchorages learned from plants roots structures using X-ray Computed Tomography</i> Bertoni Serena, Jun Otani, X-Earth Center, Kumamoto University, Japan
15:00-15:30	<i>Global vs Local: Performing image segmentation in the Context of Soil Science</i> Patrice Delmas, University of Auckland, New Zealand
15:40-16:30	PROTINUS Meeting and Closing

## **Analysis of the porous structure of an Andosol and the relationship on SPH simulated flow**

A. Gastelum Strozzi<sup>1</sup>, C. Duwig<sup>2</sup>, P. Delmas<sup>3</sup>, L. Oxarango<sup>2</sup>, B. Prado<sup>4</sup>, J. Marquez<sup>1</sup>

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The morphological and topological characteristics of the soil pore network determine the capabilities of the network to transport water, agrochemicals and contaminants. The objective of this study was to evaluate the relation between the pore network shape (morphological and topological) properties with the hydraulic properties obtained through numerical simulation of the flow behavior on them. T

he use of X-ray microtomography to obtain the cross-sections of soil samples provided with the 3D pore network structures (REV) of the sample up to the resolution of the micro-CT scanner. Several Representative Elementary Volumes were calculated using the porosity as a threshold. Soil morphological properties were extracted from the 3D structure in each REV with morphological calculations. The relationship between shape and flow was obtained by comparing the effect of a set of pore morphological and geometrical measurements with the numerical-simulated volumetric flow throughout the pores, using a correlation matrix. In this study, the volumetric flow as simulated with the Smooth Particle Hydrodynamics (SPH) method.

Low connectivity inside the REV was found at the CT resolution. The descriptors most correlated with the flow were pore extend, variability of the cross-section areas, perimeter, and integration of the distance field. For pores with a tubular form, the skeleton form and tortuosity (angle change between skeleton segments) were the descriptors most correlated. However, REV's with similar porosity fraction contained pores with morphological descriptors that had a different behavior across each REV. Porosity as threshold to calculate the size of the REV might not be the best parameter when studying the flow behavior.

**Keywords:** smoothed particles hydrodynamics, micro tomography, pore morphometry

## **Assessment of soil permeability based on X-ray CT imaging: Image resolution and geometrical criterion**

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Micro focused X-ray computed tomography (CT) is becoming a popular method to investigate soil functions in the field of agriculture, geotechnics, or environmental engineering. Among other, the saturated permeability is a property of great interest since it is the main driver of water transfers. The classical approach to compute the permeability relies on computing a numerical solution of Stokes equation with a Computational Fluid Dynamics (CFD) method such as finite volume, finite difference, Lattice Boltzmann Method or Smooth Particle Hydrodynamics. Then the permeability is estimated by computing Darcy's law average pressure gradient and flow rate by numerical integration. In this study, the commercial software package Geodict, based on the Finite Volume approach is used. This software uses the voxel of the segmented 3D CT image as a cubic mesh. The accuracy and quality of the numerical simulation thus improves as the mesh size decreases (*i.e.* as the CT scan resolution increases). On the other hand, studying a complex 3D porous media requires analysing a sample large enough to be representative of the porous structure (Representative Elementary Volume). The ideal situation to estimate properly the permeability thus consists in studying a large region of interest with a fine resolution. However, the numerical cost of such simulations could overcome the available computers. This study aims at defining a geometrical criterion based on the pore size distribution of the sample to estimate the quality of the computed permeability.

A Fontainebleau (NE34) sand sample (Diameter: 8 mm, height: 10 mm) has been scan with a resolution of 4.5 mm. A numerical scaling is applied to the reconstructed gray scale 3D image in order to artificially create images of the same sample with resolutions ranging from 6 mm to 36 mm. A classical image analysis chain is then applied to each image using ImageJ. It consists in a contrast enhancement, a 3D median filter and a threshold based two phase segmentation to discriminate the solid grains and the pore space. The geometrical characterization is based on porosity, Cauchy-Crofton specific surface and pore size distribution (PSD). The PSD is estimated using an original procedure based on the image closure algorithm. Finally, the permeability is computed on each image. The scaling of the image has a small impact on the porosity computation. The specific surface tends to decrease with decreasing image quality and the PSD evolves toward bigger pores while the resolution decreases. The permeability computation proves to be robust but exhibit a 300% increase for a resolution of 36 mm compared to the reference simulation at a resolution of 4.5mm. An overestimation of 35% is observed with a resolution of 9 mm. It suggests that the pore diameter  $D_{50}$  should remain higher than 6 times the voxel size to insure a proper permeability evaluation for the studied sand sample.

## Pore-scale model of biofilm growth in porous media

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In subsurface systems, biofilm may degrade organic or organo-metallic pollutants contributing to natural attenuation and soil bioremediation techniques. Mathematical modeling plays a crucial role in understanding biofilm dynamics and predicting efficiency of these decontamination methods.

Biofilms, which are composed of bacteria and extracellular organic substances, grow on the pore-walls of the porous medium. Biodegradable organic solutes are converted into biomass or other organic compounds by the bacterial metabolism. This evolution of the microbial biomass phase within the porous medium is a complex process due mainly to growth (or decay) and spatial spreading of the cellular phase. Processes such as biofilm sloughing and attachment (or detachment) of cells from the fluid phase may also contribute to the biofilm volume variation. The objective of this work is to model biofilm growth by integrating the various pore-scale mechanisms which favor the bacterial development (bacterial proliferation, assimilation of nutrients to synthesize new cellular materials, attachment of cells) or, conversely, which are responsible for slowing down such dynamics (e.g., detachment of cells, toxicity). An Immersed Boundary – Lattice Boltzmann model is developed for flow calculation and non-boundary conforming finite volume methods (volume of fluid and reconstruction methods) are used for reactive solute transport. A sophisticated cellular automaton model is developed to describe the spatial distribution of bacteria. Several numerical simulations have been performed on complex porous media and a quantitative diagram representing the transitions between the different biofilm growth patterns was proposed. Finally, the bio-enhanced dissolution of NAPL in the presence of biofilms was simulated at the pore scale. The impact of biosurfactants and NAPL toxicity on bacterial growth has also been investigated.

**Keywords** Porous media, solute transport, Biofilm, Cellular Automaton, Lattice Boltzmann method, NAPL biodegradation

## **Comparison between 3D printing methods for granular medium reconstruction**

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3D printing is a more and more popular method to construct 3D complex reproducible shapes. Several technologies are already well developed. The use of 3D printed porous media could provide soil science samples that are reproducible from a structure point of view and remains complex. In this work 3 different printing technologies (Fused Deposition Model, Stereolithography and Powder Bed) were used to reproduce a sand sample. Major hydrodynamical parameters, ie porosity and permeability, were monitored at the different levels of the printing: experimental measurement on the sand sample, calculation from the computed tomography images of the sand sample and of the printed samples. A significant loss of porosity happened to the image preparation for printing, due to constraints in regards to computing performance. Fused Deposition Modelling demonstrated the best results even though a microporosity appeared. Stereolithography led to a poor porosity value and the sample made with Powder Bed was clogged by residual powder.

**Keywords** Porous media, 3D printing, Lattice Boltzmann Models

## **Image analysis of LNAPL recovery in sand due to injecting air using X-ray CT**

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Air sparging method has been well known as one of the effective and proven remediation techniques for this difficult contamination status. The air sparging can be defined as the injection of compressed air into the saturated zone below/within, the contaminated zone. When the air is injected through the saturated zone toward the unsaturated zone, LNAPL dissolved in the groundwater, sorbed onto the soil/ trapped in the soils are strapped into air channels where it is transferred into the unsaturated zone. The engineering design of air sparging has been developed by empirical knowledge, experience and studies. However, although air sparging technique has been well-established, it has been applied with varying degrees of success because of the complicated remediation mechanism of LNAPL because of the effect of air injection rate and capillary force as fluid mechanics of micro scale in ground. More accurate prediction and more developed system designing require advanced understanding of the interaction between injection rate and capillary effect due to remediation process in the ground. Hence there is the necessity to observe and evaluate the inside of contaminated and remediated soil in micro scale, three-dimensionally. Several studies with respect to visualization by micro-focused X-ray CT scanner have been conducted to understand the water and oil behavior in pore scale, and the effectiveness of using CT device has been reported by them.

The objective of this paper is to study on remediation mechanism because of air injection in contaminated sand by LNAPL using micro X-ray CT scanner. In this paper, the three following items should be achieved: 1) to develop the test apparatus of fluid injection into the sandy soil, 2) to find out the scan method using micro-focused X-ray CT scanner and 3) to develop new image processing technique to be able to evaluate the residual fluids in the pore of a sandy soil. Three achievements will give an idea of remediation mechanism due to air injection in contaminated sand by LNAPL, in particular, whether or not the effect of air injection rate and capillary force should be dominant factor to cause effective remediation in the ground. To do so, LNAPL blobs in remediation process are visualized with injected air and KI solution in pore space as multiphase flow. The obtained CT data was analyzed to evaluate each blob quantitatively assuming its displacement condition with injected air.

Key conclusions were summarized as follows:

- 1) The increase of air injection rate could not contribute the reduction of LNAPL saturation in the effect of capillary fingering;
- 2) The different tendency of number and diameter of distributed LNAPL blobs were found with the increase of air injection;
- 3) 2) was attributed to the interaction of frequencies of the LNAPL blobs trapped by KI solution and by capillary pressure;
- 4) LNAPL blobs trapped in pores where KI solution existed in initial condition were found as the cause of slight difference of LNAPL saturation after air injection;
- 5) LNAPL blobs of 4) were trapped by capillary pressure as the constant degree by the dominant effect of capillary fingering.

## **Development of a new system of anchorages learned from plants roots structures**

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Tree roots can be compared with foundations of buildings. They are the anchors allowing plants to resist against stresses. Roots strength depends on many parameters as soil type, nutrient richness and water content, presence of obstacles causing root's deviations, geographic position, species, etc. These factors show the complexity to classify these living being that are constantly evolving. Therefore, a close monitoring throughout their whole life cycle is required to have a perfect understanding of it. Nevertheless, many scientists agree on the existence of three main roots systems which are the plate root system, the heart root system, and the taproot system which is the most efficient system against pull-out loading.

The main objective of this research is to innovate in the field of foundation engineering by drawing inspiration from plant root's models to create new type of anchorage system. Thus, artificial anchors systems were inspired from plants roots structures.

Results from controlled pull-out tests and from the X-ray CT gave quantitative and qualitative information to have a better understanding of roots behaviours and to get the deformation of the surrounding soil before, during and after pull-out loading. These analyses allowed to determine which parts of the plant root system play major role from a geotechnical point of view to create prototypes.

Finally, based on all the results of tests and analyses, it can be said that the proposed models could produce the behaviour of real plant roots. This study could open doors to new foundation systems.

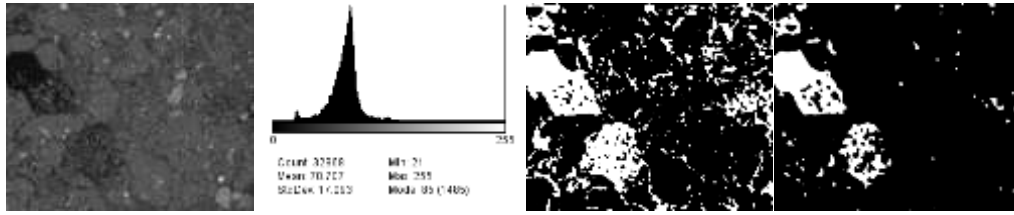
**Key words:** plant roots - pull out loading - X-ray CT- mechanical behaviour

## Global vs Local: Performing Image Segmentation in the Context of Soil Science

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We present here an overview of some of the most popular global and local image segmentation techniques for soil science applications. Image segmentation often refers to assigning pixels to regions based on statistically significant patterns within a given image. This usually results in a binary map separating the feature of interest from the image background. In soil sciences, this may help segment pores and initiate a wealth of mathematical morphology algorithms to compute the pore network geometrical characteristics often referred as morphometrics. Image segmentation may use global or local methods often using a pixel value, a.k.a. a threshold, to set preliminary regions (either background or say pores) within the image. In global thresholding techniques, pixels are classified based on a global attribute, such as the distribution of pixels based on grey level. Otsu, Iterative and Entropy Maximization are the most commonly techniques. The segmented regions are prone to misclassification errors as well as over- or under-segmentation. This is due to: i) Image artifacts and distortion (inherent to CT-scan imaging such as ring artefacts) ii) mis-classified pixels due to arbitrary histogram threshold selection. Local methods instead do rely on image local information and gain spatial awareness. Objects are segmented based on surrounding pixels characteristics (whether intensity or local connectivity for example). Region growing is typical of such methods where seeds (e.g. randomly placed a pixel location throughout the image) grow by including neighbourhood pixels following some uniformity predicate often based on region characteristics (e.g. pixel intensity average or std across the region) consistency. Local methods are in turns prone to segmenting images in more separate regions than expected or being highly dependent on the uniformity predicate settings. Iterative Kriging is an hybrid approach which uses global information within the image to set the number of separate regions expected thus reducing the local segmentation problem to a subset of unclassified pixels. A Kriging indicator function is trained after the image initial classification stage based on the spatial distribution of pixels belonging to one or another region. Typically the number of unclassified pixels vary between 5% and 15% and may be set heuristically or based on the image acquisition settings (CT-scan pixel resolution for example) and the imaged materials properties (e.g. expected porosity percentage). Providing a satisfactory initialisation of the undetermined pixels (using say region determination via the Expectation-Maximisation thresholding algorithm), IK does provide consistent results across a range of soil cores with diverse porosity characteristics as exemplified in the below figure.



*Figure 1. Global vs local segmentation. From left to right: Soil image; image histogram showing a strong unimodal characteristic; Otsu segmentation; Indicator Kriging segmentation.*