X-RAY MICRO-TOMOGRAPHY OF PORE-SCALE FLOW AND TRANSPORT

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ISSUES:

• Measurements and modeling of water flow and contaminant transport in soils and groundwater are generally macroscopic (spatial scale range of 1 cm to 1 m or larger);

• Fundamental mechanisms occur at microscopic scales (micrometer or smaller);

• Improved understanding and model predictions require microscopic approach.
WE HAVE COME AT CROSS ROADS WITHIN PORE-Scale FLUID CONTINUUM,

FOR WHICH MEASUREMENTS AND MODELING APPLY TO IDENTICAL SPATIAL SCALES

Note: It was Bear (1972) that presumed that any attempt to describe in an exact manner the geometry of pores and solid surfaces inside a porous medium is hopeless.
X-ray computed micro-tomography (CMT) provides three-dimensional nondestructive and noninvasive measurements of fluid saturation and concentration at the micro-scale.

**AS OPPOSED TO**

**RADIOGRAPHY**

(2-dimensional)

Pore-scale measurements are being developed so that fundamental processes of flow & transport can be studied at pertinent micro-scale range.
$I_{o} (x\text{-rays})$: Intensity (photons/sec) produced by electron ray tube

Characteristic energy levels (Tungsten target)
Procedure for 3-D imaging:

- Cone beam with planar Detector Array;
- Scan object from many different beam directions;
- By rotating scanning object;
- Use reconstruction algorithm to solve for $\mu(x)$. 
\[ I = I_0 \exp \left( -\int_L \mu(x) \, dx \right) \]

\( \mu \): linear attenuation coefficient, and is equal to the probability that photon is removed from the beam (by either scattering or absorption). It is a function of energy of x-ray source.
$I = I_0 \exp \left( - \int_0^L \mu(x) \, dx \right)$

Attenuation coefficient is a linear function of electron density.

In practice:
Conduct a priori calibration to estimate soil density, water content, or soil solution concentration.
For polychromatic radiation, attenuation decreases with penetration depth, due to selected removal of photons of the more strongly attenuated energy levels, hence variations in attenuation are biased.
Detector:

- Planar x-ray-sensitive scintillating detector;
- provides instantaneous 2D radiographic image, that is recorded by CCD camera
**Beam Geometry:** Fan beam (2D)  
Cone beam (3D)  
Parallel beam (3D - synchrotron)

Voxel size controlled by: source and detector size  
photon flux  
acquisition time
Example of CMT for nondestructive 3D plant root measurements

3D Root Image, showing isolines of attenuation

Experimental Setup

Heeraman, Hopmans and Clausnitzer
Plant & Soil, 1997
Representative Elementary Volume (REV) of glass beads Clausnitzer et al (1999)

Noninvasive measurement of 3D material attenuation;

Glass bead diameter is 0.5 mm

Spatial resolution: 20 micrometer
\[ f(\alpha) = \phi_{\text{air}} f_{\text{air}}(\alpha) + \phi_{\text{glass}} f_{\text{glass}}(\alpha) + \phi_{\text{mix}} f_{\text{mix}}(\alpha) \]

\[ \int_{-\infty}^{\infty} f \, d\alpha = 1 \]
Representative Elementary Volume (REV) of glass beads (Clausnitzer et al 1999)
Pore-scale measurements of solute breakthrough (Clausnitzer et al 2000)

- 5 cm long and 4.76 mm diameter plexiglas flow cell
- After saturation and steady flow rate, 90-minute pulse of 0.1 ml/hr NaI solution was applied
- 3-dimensional scans of 0.44 mm thick slice, about 20 mm below inflow end, were obtained during breakthrough
CT SCAN of iodide transport
Spatial resolution: 20 µm
Nr. of voxels: about 2 million
15 scans for a total of 5 hrs
POTENTIAL FOR WITHIN PORE CONCENTRATION MEASUREMENT
SPATIAL DISTRIBUTION OF PORE WATER VELOCITY

Computed from time to peak concentration to pass through each of 17x17 segments
Spatial distribution of total mass breakthrough, with decreasing segment size

\[ \text{Mass} = \int \int c(x, t)v(x) \, dA \, dt \]

- 17 x 17 segments, with 4100 voxels per segment
- Mass balance error: 5%
Synchrotron-produced x-rays

- High photon flux fluence rate (photons mm\(^{-2}\) sec\(^{-1}\));
- Although beam is filtered (monochromator), the fluence rate remains very high;
- Thereby allowing high spatial resolutions (micrometer);
- And fast transient measurements;
- Furthermore, monochromatic beam eliminates beam-hardening;
- Experimental results can be compared with Lattice-Boltzmann simulations
ADVANCED PHOTON SOURCE OF ANL, CHICAGO, IL
BOOSTER, elevating electron energy to 7 billion electron volts (GeV), about equal to speed of light.
Drainage and inhibition of fine sand (median particle size is about 200 micrometer)

Study of Flow Rate Effects on Water Distribution

www.aps.anl.gov/apsimage/porousmediamain.html
Separate solid from water and air phase, and estimate interfacial areas.
LATTICE BOLTZMANN SIMULATIONS

(Don Zhang et al, Geophys Res Letters, 2000)
LATTICE BOLTZMANN SIMULATIONS

- Unique capabilities (advantages):
  - Quantitatively incorporates pore-scale physical and chemical processes
  - For arbitrarily complex pore space geometries
  - Allows direct computation of system characteristics (e.g., permeability, dispersion)

- Links microscale physics to macroscale processes
Neutron Radiography & Computed Tomography

Gadolinium control rods
2.0 x 2.0 cm triangular aluminum sample holders

Increasing thickness

Increasing water saturation
Volumetric Water Content

Attenuation - Saturation

2 cm thick

1 cm thick soil sample

0.00 0.05 0.10 0.15 0.20 0.25 0.30 0.35

Attenuation

0 20 40 60 80 100 120 140 160 180

Saturation (v/v%)
Fast Neutron Tomography

Neutron Imaging

- Aluminum optical table
- Monochromator crystal
- Neutron beam
- Collimating guide
- Neutron converter screen
- Lens
- Sample
- Mirror
- CCD camera
- 1 m

- Development of micro tomography capabilities is approaching spatial and time scales that control flow and transport;
- Capabilities are becoming such that physical, chemical and biological processes at solid-liquid and liquid-gas interfaces can be measured;
- This is especially true for high photon fluxes, such as provided by *synchrotron*;

THERE ARE PLENTY !!!!!!!!