Real-time study of capillary rise in soil

Background

Motivation

The world is full of porous materials, natural (soil, rocks, wood, etc.) as well as man-made (food, construction materials, filters, etc.). These materials are often studied in terms of how liquids find their ways into or out of the material. In this experiment, we will use soil material as porous material. Understanding water transport mechanisms in soil is essential to many applications in agriculture, environment protection, and natural hazards mitigation.

Capillary rise in porous media

Capillary rise is the phenomenon you can observe when you dip a porous material into a liquid. The water will be sucked up into the material and sometimes you can even observe the wetting front. The location of the front can be described by Washbourne's equation. You can start reading on Wikipedia (https://en.wikipedia.org/wiki/Washburn%27s_equation) and then complement with the following papers:

L. Fisher, Physics takes the biscuit, 1999.

Lavi et al., "Porous Media Characterization by the Two-Liquid Method: Effect of Dynamic Contact Angle and Inertia", 2008.

Neutron imaging

Neutron imaging is a radiography technique that only considers the neutrons that passes through the sample. The neutron intensity behind the sample is described by Beer-Lambert's law which in its basic form for the observed image, *I*, is

$$I = I_0 e^{-\int \mu(x) dx}$$

Where I_0 is the incident neutron intensity and $\mu(x)$ is the linear attenuation coefficient in the sample at depth *x*. The images mostly are mostly acquired using a combination of scintillator to convert the neutrons into visible light which is then captured using a camera detector. In practice, the optical thickness of the specimen is computed from measured images using

$$\int \mu(x) dx = -\log\left(\frac{D_0}{D}\frac{I - I_{DC}}{I_0 - I_{DC}}\right)$$

Where I_{DC} is an image acquired without radiation to measure the dark current bias of the camera. The dose correction term is the ratio between the neutron dose used during the acquisition of specimen (I) and open beam images (I_0) respectively. The doses are scalars which are mostly measured as the average image intensity of a region which in not covered by the specimen. This correction is needed to take flux fluctuations of the source into account.

So far, neutron imaging is very similar to X-ray imaging. The main difference lies in how neutrons interacts with matter compared to X-ray. <more details>. This has the effect that neutrons are very sensitive to low Z elements like hydrogen and lithium.

In this experiment we are in particular interested in quantifying the amount of water and how it is distributed in the sample over time. The water content can be determined for a single time frame of an experiment sequence using Beer-Lambert's law

$$I_{Wet} = I_0 e^{-(L_{H2O}\mu_{H2O} + L_{Soil}\mu_{Soil} + L_{Container}\mu_{Container})}$$

As you can see here, we also have contributions from the porous medium and the container walls. These contributions can be removed by making an image of the dry sample in the container

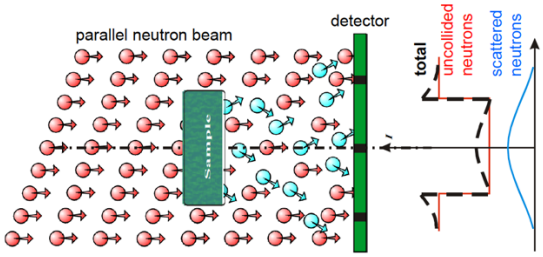
$$I_{Dry} = I_0 e^{-(L_{Soil}\mu_{Soil} + L_{Container}\mu_{Container})}$$

And compute the division of I_{Wet} over I_{Dry}

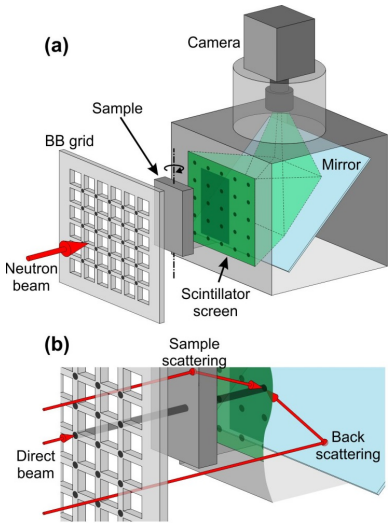
$$L_{H2O}\mu_{H2O} = -\log\left(\frac{I_{Wet}}{I_{Dry}}\right)$$

This equation gives you the optical thickness of the water in the sample. We are however interested in the metric thickness of water; thus, this result must be divided by the attenuation coefficient of water. We will determine μ_{H2O} experimentally.

There is an important complication to be aware of for this task; the attenuation coefficient of water is mainly originating from the scattering cross section of hydrogen. This means that the neutrons are scattered in the sample and hardly any are absorbed. The scattered neutrons contribute to a bias in the image intensity that leads to large errors in the quantified water content.



In the Applied Materials Group, we have developed a method to correct for the biases introduced in a neutron imaging experiment. Details about this correction method, which is an alternative normalization scheme to the one previously described, can be found in Boillat et al. (2018) and Carminati et al. (2019).



From the experiment point of view, this correction requires two additional reference images where neutron absorbing dots are uniformly distributed over the image.

Experiment

Sample preparation

In this experiment we will prepare a collection of samples containing sands with different grain size distributions. The sand will be filled in small boxes with a porous interface at the bottom to allow water to enter the sand packing.

Setting up the experiment

Install the sample environment

During the experiment we will mount the samples at a constant position and then approach the lower side with a water surface. The basin will have sufficient volume to avoid that the water table remains essentially on a constant level.

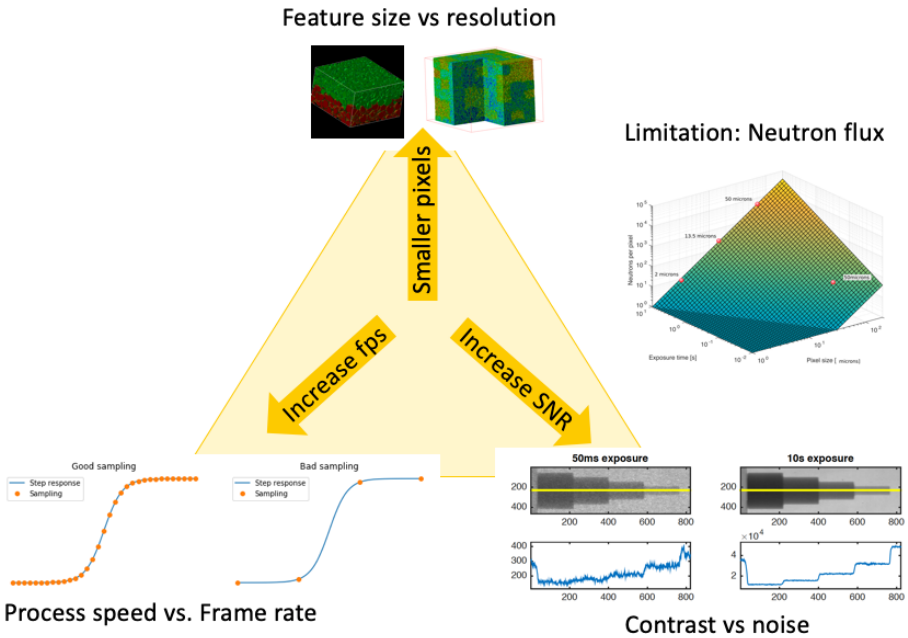
Detector setup

Focusing the camera is usually a task the local contact at the instrument is doing. Here you can follow the steps how this is done.

- Select and install scintillator
- Determine field of view (depend on the sample size), set focal distance on the lens.
- Focus the camera
- Determine pixel size

Experiment tuning

The process we want to study is relatively fast. This means we have to find a balance between frame rate (exposure time) needed to follow the process and the signal to noise ratio in the images. Typically, we need several seconds and sometimes even minutes of exposure time to obtain images with low noise amplitude. The noise is Poisson distributed based on the number of collected neutrons per pixel and the signal to noise ratio is therefore proportional to the exposure time as $\sim\sqrt{t_{exposure}}$ or linearly to the pixel size. The neutron flux can be considered to be constant as it depends on the source. This leaves us with the tuning criteria whether we want to change exposure time or pixel size until we reach a SNR which is acceptable for the task at hand.



Determine μ_{H2O}

Knowing the linear attenuation coefficient is essential to be able to quantify the amount of water in the sample.

We will use a so-called step wedge to determine the attenuation coefficient for water. This is a container which step wise has different thicknesses in the beam direction. The step wedge is filled with water and put in front of the detector to acquires images. The needed images are:

- Dark current image
- Open beam image

- Image with empty step wedge
- Image with black bodies in front of the empty step wedge
- Images with black bodies in front of the detector with the filled step wedge
- Use the linear stages to move the sample out of the FOV
- Images with filled step wedge

Be careful when you remove the step wedge not to displace the black body grid.

Observing capillary rise

The actual experiment will be done as a time series acquisition from the time when bottom end of the samples comes in contact with the water surface. The images
The experiment procedure includes the following steps:

Put the dry samples on the balance.
At the start of each experiment we will get
- Dark current images
- Open beam images
- Open beam with black bodies

Insert the sample (keep the BB grind without touching it)
- BB images with sample inserted

Remove BB grid (keep sample in place)
- Start acquisition at planned frame rate
- Raise the water table to touch the bottom of the sample
- Acquire until the water front stops rising
- Stop acquisition

This procedure will give you five sets of images. The reference image set should contain at least five images of each type. The time series of the water uptake process may vary in amount.
Put the wet samples on the balance.

Data evaluation

The data evaluation is best done using a scripting language like python. You will be provided with a collection of jupyter notebooks containing some python code that can serve as a starting point for your evaluation.

Step wedge analysis to determine μ_{H2O}

Coarsely, the steps required to analyze the step wedge in order to obtain the linear attenuation coefficient for water are:

- Normalization of the images (you can compare the impact of using traditional method and with scattering correction).
- Compute the average optical thickness of each wedge segment.
- Divide these values by the metric thickness
- Plot the results
- Ideally this is a straight line; the slope is the value of μ_{H2O}.

Question: How thick can a water layer be for 10%, 20%, and 50% transmission?

Time series analysis

There are two type of information we can gain from the time series data: (1) The position of the water front and (2) the amount of water at each position in the sample.

Determine the amount of water in the sample

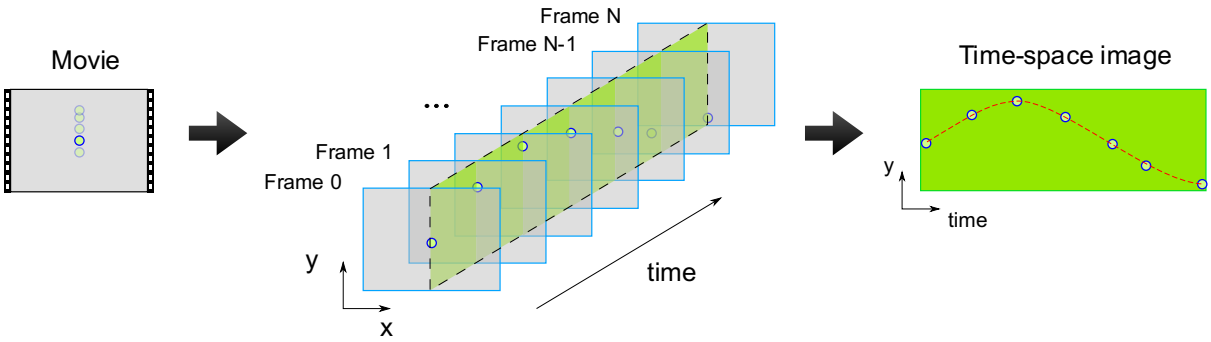
The amount of water is determined by normalization of the images and dividing by the value of μ_{H2O} which was determined in the previous experiment. You can also compute the total amount of water and compare the value obtained from the imaging experiment with the gravimetric measurement. How well do the measurements agree? What are the sources of uncertainty?

Determine the pore size of the soil

We will use Washbourn's equation to determine the average pore size in the sample.

$$L = \sqrt{\frac{\gamma r t \cos(\phi)}{2\eta}}$$

In this equation, we can measure *L* and *t* from our experiment. The time, *t*, we get from the acquisition frame and the height of the wetting front, *L*, will be extracted by means on image processing of the time series. Normally, when we look at a time series, we see a movie. The data can also be considered being a volume image with the axes x, y, and t. This can be used to determine the position of the water front over time.



The data may also be quite noisy if we use framerates below 1fps. The SNR can be improved by means of filtering. You can try the effect of applying different filter strengths to the images.

The steps you need to perform to obtain the height of the water front are:

1. Load the time series.
2. Normalize with open beam images.
3. Possibly apply a filter to improve the signal to noise ratio.
4. Apply a Laplacian of Gaussian filter to identify the front.
5. Find the position of the front for each column. Different methods available
    a. Find the index of the max value (simple, less accurate)
    b. Correlation with an edge spread function (more complicated, higher accuracy)
6. Use the edge position data and the time stamps to fit Washbourne's equation.
7. It you want absolute values of the fitted parameters; it is important to scale the y data by the pixel size and the t data by the frame rate.

It is good if you can have a prototype workflow prepared when we meet, then we will make faster progress. If not, we will look into this part when we meet. You can find some ideas for the analysis on this repository https://github.com/neutronimaging/scripts/tree/master/python