Massive, continuous and non-invasive surface measurement of degree of saturation by shortwave infrared images

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Massive, continuous and non-invasive surface measurement of degree of saturation by shortwave infrared images

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ABSTRACT

Short wave infrared (SWIR) images provide an accurate procedure to measure the degree of saturation (Sr) of soils. Changes in Sr result in reflectance changes which were recorded by a special digital camera optimized for a particular range of wavelengths which provide the maximum resolution of the method.

The paper describes the developed methodology, which relies on sample-determined calibration of soil reflectance for a few values of Sr covering the dry-fully saturated range of moistures.

The accuracy of the method was checked by comparing equilibrated profiles of SWIR-determined Sr with other procedures (sensor readings and water retention information).

It was found that the SWIR-based method correlates well with the degree of saturation of the soil but not with its water content, which may change, for a given Sr, when the soil deforms volumetrically.

The transient variations of Sr are also well captured by the method. The recorded evolution of two-dimensional Sr maps of an initially unsaturated soil column was satisfactorily compared with the results of a numerical model.

Keywords: Degree of saturation, water content, infrared image, shortwave infrared (SWIR), laboratory tests.

Introduction and fundamentals

In the experimental field of unsaturated soils, it is of interest to measure the degree of saturation (Sr), water content, and suction because they control their mechanical and hydraulic behavior (Vanapalli and Mohamed 2007, Olivares et al. 2009, Chinkulkijniwat et al. 2016). The measurement of these inter-related variables is traditionally carried out by means of devices (tensiometers, hygrometers, capacitance sensors and dielectric sensors) that collect discrete
data in localized volumes. The placement of these sensors at or near the region of interest has
to be selected a priori. However, the region of interest to measure such variables is, in some
cases, unknown at the beginning of the test. This is, for instance, the case of scaled tests of slope
failures in unsaturated soils in which the position of the failure surface, where the Sr value is of
interest, cannot be specified at the beginning of the test.

As an alternative to sensors, other methods to evaluate the distribution of the degree of
saturation or water content in soil have been explored. Neutron radiography and tomography
were proposed as a non-invasive measurement of the water content (Tumlinson et al. 2008,
on the high neutron attenuation caused by the hydrogen of the water molecule compared to
the interaction with the atoms of soil grains. This technique allows analyzing in 3D the entire
sample, and it is useful to determine the hydraulic properties of granular soils. However, it
presents some limitations for being used in general laboratory experiments. The technique is
restricted to small samples that are placed in front of a neutron’s beam. The procedure is based
on the analysis of the neutrons that crosses the sample; therefore, the neutron penetration
limits the thickness of the sample. The main difficulty is to manage the neutron radiation and
induced radioactivity hazard, which implies the need to perform the experiments in isolated
capsules or chambers.

On the other hand, two geophysical methods are useful to measure the Sr in soils. The electrical
resistivity tomography is based on the different resistivity offered by soil particles and water to
an electric current (Daily et al. 1992, Zhou et al. 2001). The ground-penetrating radar uses
differences in the propagation velocity of electromagnetic microwaves (Greaves et al. 1996,
Huisman et al. 2003). These two methods are well developed and useful for field measurements.
They are capable of providing a 3D model for the soil Sr.
The aim of this study is to develop a method to be used in soil experiments in geotechnical laboratories. The outlined methods are not appropriate for this objective. Neutron radiography and other methods that use waves in the ultraviolet region of the electromagnetic spectrum are dangerous for biological tissues and they need to be performed in specialized laboratories. The ground-penetrating radar and other geophysical methods use long wavelengths. This length limits the maximum resolution physically attainable to centimetric pixel sizes. The sensors for long wavelengths are unable to get enough resolution for the laboratory tests of interest.

The suitable waves to measure the Sr are in the regions of the visual or infrared areas of the electromagnetic spectrum. Some authors have explored the possibilities of different ranges inside that area. The idea is to evaluate the amount of water filling the voids of soils taking advantage of the difference of light reflection/absorbance between water and solid particles. Water is more absorbent to light than solid soil particles, when analyzing the visible and infrared bands. Therefore, the amount of light reflected by a soil depends on its degree of saturation or, alternatively, on its water content. The soil appears darker the higher the amount of water. The physical principles of the light reflection in unsaturated soils are explained below.

Given a soil (characterized by mineral composition, grain size distribution, packing density, grain surface roughness), the presence of the water surrounding the soil grains causes a change in scattering and absorption of the incident light. A comprehensive explanation of the effect of water on the light reflectance was given by Nolet et al. (2014) after briefly describing the theoretical background. Under dry conditions, the reflectance is controlled by the soil mineralogy and structure. When some water is added to the soil (Figure 1a), water is held in the soil as adsorbed water films around the solid grains. At this condition, the optical path length in the water is close to zero, and the decrease of spectral reflectance is almost solely due to scattering. As the water content increases (Figure 1b), water meniscus form bridges between grains, which increase the optical path length, resulting in an increase of absorption. When the
soil becomes fully saturated (Figure 1c) and the free water appears at the surface being evaluated, the optical path length in water is at its maximum, and the reflectance of the soil is mainly defined by the water coefficient of light absorption (Hillel 1998, Lobell and Asner 2002).

The most sensitive bands of the electromagnetic spectrum to assess the amount of water in the soil are a result of the physical principles governing the interaction between light and water. The quantum theory explains that the absorption of light by matter is determined by stable quantum changes in its atomic and molecular energies. The bands of the electromagnetic spectrum whose energy coincide with stable quantum changes would tend to be absorbed.

In the specific case of the water molecule, the wavelength bands, on the visible and infrared area of the electromagnetic spectrum that coincide with stable quantum changes, correspond to changes in the vibrational state of the water molecule ($u$). The water molecule has three vibration modes: symmetric stretch ($\nu_1$), bending deformation ($\nu_2$), and asymmetric stretch ($\nu_3$). Stable vibration excited states correspond to specific combinations of these three modes of vibration. The wavelengths whose energy coincides with one of these stable excited vibration states tend to be absorbed and retained by the water molecule. (Table 1).


Figure 2 plots the results of one of the mentioned laboratory spectroscopy tests as an example (Nolet et al. 2014). The reflectance of sand at different Sr values was measured in the laboratory by means of a full range spectrometer (300-2500 nm). For a given wavelength, the reflectance decreased with increasing amount of water. The magnitude of this variation depends on the wavelength. Figure 2 highlights the bands of light absorbance by water, defined in Table 1 (Wozniak and Dera 2006). The comparison between the two superimposed plots indicates that
the wavelengths where the soil reflectance is more affected by moisture variations coincide with
the bands with higher coefficient of light absorption by water. With the aim of correlating the
reflectance with moisture, it is convenient to select the wavelength ranges most sensitive to
water content. On the visual and infrared areas, the two most convenient wavelength ranges
are 1400 -1550 nm and 1900 – 2000 nm. Notice that the most absorbent bands lay on the Short-
Wave InfraRed (SWIR) part of the electromagnetic spectrum, whereas in the visible part the
absorbance is almost negligible.

The effect of changing soil saturation on the light reflectance has been evaluated in the literature
for different soils (from coarse sand to silty loam). This information is collected in Figure 3. In all
cases, the maximum difference between the reflectance for dry and saturated conditions is
reached in the range of 1400 -1550 nm and 1900 – 2000 nm. This observed response is mainly
controlled by the optical properties of the water, which exhibits an absorption peak for these
two wavelength ranges.

Soranzo et al. (2015) evaluated the degree of saturation in natural soils by means of the analysis
of visual images (wavelengths: 400-800 nm). For the range of wavelengths of the visual
spectrum, the effect of the Sr on the reflectance is not enough to provide a proper precision in
the correlation between reflectance and Sr. To overcome this limitation, Peters et al. (2011),
Siemens et al. (2013, 2014) and Sills et al. (2017) use artificial transparent soils with the same
reflection than the fluid used and a black background. By measuring the light reflected at the
air-fluid contacts, they are able to estimate the amount of air in the sample and, therefore, to
calculate the degree of saturation.

Sadeghi et al. (2015) based on previous theories, proposed a linear physically-based model to
transform the light reflectance from images at different wavelengths to the soil water content.
The technique is especially useful in satellite imaging. Later on, Sadeghi et al. (2017) applied the
method for the characterization and quantification of liquid distribution in porous media from
SWIR images. Their model enables to convert the SWIR reflectance into soil water content. The proposed methodology was successfully validated for soils with different grain size distributions. This paper presents a methodology to determine the continuous variation of Sr in unsaturated porous media by interpreting SWIR images. The procedure can be applied to surface images. It relies on a calibrated set of correlations between light reflectance and the measured Sr of samples of the soil being tested. This correlation was found to be nonlinear unlike previous results by Sadeghi et al. (2015).

At the medium scale of a laboratory experiment (an equilibrated column of unsaturated sand above a zero suction level), the SWIR-based method was consistent with other direct (sensors) and indirect (through the water retention relationship) procedures to find the saturation profile. The ultimate goal of the research presented was to build case records at laboratory mid-scale (1g and eventually ng) to validate the hydro-mechanical behaviour of unsaturated soils under changing boundary conditions. In this regard, there was an interest in determining the moisture-related index, either water content or degree of saturation, offering the best correlation with SWIR images. The results of tests on samples at different void ratios but constant water content will be given.

In a final part of the paper, the experimental transient variation of Sr of an unsaturated soil column, subjected to surface infiltration, is compared with the results of a calculation by means of the finite element code CODE-BRIGHT (Olivella et al., 1996, 2019).

**Experiment description**

The purpose of the test performed is to measure the Sr of unsaturated soil surfaces by correlating the light reflectance with the Sr. The procedure requires previous calibration carried out on samples with a known Sr. Based on the spectrometry studies discussed above, the
wavelength used in this work is 1500-1560 nm. This specific range was selected because of the capabilities of the camera selected.

**Camera**

Images of unsaturated samples are captured by a Short-Wave InfraRed (SWIR) camera. Common SWIR cameras use the InGaAs sensor. This is a specialized and expensive technology. As an alternative, the common sensor used in digital cameras (CCD array charge-coupled device) can be used after a phosphor-coated treatment (which is significantly cheaper). In the experiments presented in this paper, the CamIR sensor from Scintacor is used. The camera should not have any gain or automatic image improvement to avoid additional pixel intensity changes not caused by the soil reflectivity. The sensor (Sony progressive scan interface interline transfer ICX445 1/3” Exview HAD CCDTM), after the phosphor treatment, has two spectral sensitivity peaks at 1512 and 1540 nm (Figure 4).

Energy-efficient infrared lightbulbs of 175W are used as a light source. Other options that could be used are incandescent tungsten light bulbs (dismissed due to the low energy-efficiency) or Sunlight (dismissed due to the lack of intensity control). Normal LED or CFL lights cannot be used as a light source because they emit only in the visible spectrum.

The illumination must be constant throughout the experiment because the light reflected depends on the reflectivity index but also on the amount of incident light. Therefore, all the experiments of a set shall be performed with the same lightbulb arrangement and camera distance.

**Material**

The soil used in the test is calcareous-siliceous fine sand from Castelldefels’ beach (Catalonia, Spain). The properties are summarized in Table 2. The soil-water retention curve (SWRC), under imbibition conditions, was measured by the gravimetric method in a segmented hanging
column. The measured values of Sr and suction are indicated in Figure 5 together with the estimated Van Genuchten model (van Genuchten 1980). Table 2 shows the values of the model parameters.

Measuring the reflectance

The method requires the measurement of the reflectance in granular materials. The pixel intensity, which is a measure of the reflectance, is also known as grey value in the photography field. It ranges from 0 (black color) to 255 (white color).

Consider a homogeneous and unsaturated sample (150x250 mm) of Castelldefels’ sand whose bottom is saturated, and the Sr reduces with height in a situation of equilibrium. Figure 6 shows digital images of this sample taken at visible light spectrum (Figure 6a) and at an infrared wavelength (SWIR) (Figure 6b). The varying Sr results in a gradual color variation from the light color of the upper part of the sample to the darker color of the saturated bottom.

Due to the texture of the soil, the different colors of the sand grains, and the phosphor-coated treatment to transform the visual sensor into a SWIR sensor, the image exhibits “salt-and-pepper” noise. This noise implies that the discrete information from each single pixel (in this case 1x1 mm) does not represent the general reflection of the surrounding area, which depends on the Sr. Therefore, an analysis based on pixel intensity cannot be correlated with the Sr, and a pixel intensity of a representative area for each pixel is required.

In order to wane the salt-and-pepper noise, the intensity of each pixel is calculated as a weighted average of the intensity of the pixels located in the vicinity of a given location by means of a Gaussian filter. The average pixel intensity value \( \xi_{x_0,y_0} \) associated with a pixel located at coordinates \((x_0, y_0)\) is computed by means of the 2-dimensional Gaussian function centered on the pixel evaluated:
\[ \xi_{x_0,y_0} = \sum \xi_{x,y} \frac{1}{2\pi\sigma^2} e^{-\frac{(x-x_0)^2+(y-y_0)^2}{2\sigma^2}} \]  

Equation 1

where \( \xi_{x,y} \) is the pixel intensity of a pixel located at coordinates \((x,y)\), and \( \sigma \) is the standard deviation of the Gaussian function. The suitable value of the standard deviation mainly depends on: the noise from the camera sensor, the grain size and the expected spatial gradient of the Sr.

Figure 7 shows the SWIR image of the sample after applying the Gaussian filter with a standard deviation of 20 pixels. Each point of the filtered image stores the information of the surrounding pixels, weighted by the distance following a Gaussian normal distribution. As a reference, for the indicated standard deviation, weights are 68.27%, 27.18% and 4.28% at distances of 20, 40 and 60 pixels respectively.

**Calibration**

The calibration procedure allows correlating the SWIR reflectance of soil samples with the Sr value. SWIR images of a set of samples of Castelldefels’ sand having the same density and different water contents were analyzed. The calibration will provide a curve correlating the pixel intensity with the Sr.

The samples were prepared in cylindrical containers, 7.1 cm of diameter and 3.6 cm high (Figure 8). The camera and two infrared light bulbs were fixed in position. Zenithal images were taken with the SWIR camera. All the samples were placed under the fixed camera in the same place in order to maintain a constant intensity of incident light.

Eight samples compacted at 1390 kg/m³ of dry density and different degrees of saturation (0, 0.02, 0.07, 0.15, 0.30, 0.44, 0.60, 0.73 and 1) were evaluated. The hygroscopic moisture of the dry sample was assumed to be negligible, and its Sr is indicated as 0. A maximum Sr of 1 was also tested. Sr values over 0.7 are difficult to obtain because the air tends to get trapped.
between the soil grains. Degrees of saturation close to one were reached by pluviating soil particles into water, following a procedure proposed by Ezzein and Bathurst (2011).

Table 3 shows the SWIR images of the samples after applying the Gaussian filter (applying a standard deviation of 50 pixels) and the values of water content, Sr and pixel intensity.

Figure 9, based on Table 3, shows the curves correlating the Sr and the pixel intensity. The correlation curve of Figure 9 depends not only on the type of soil, density and Sr, but also on the intensity of the incident light. It follows that this curve cannot be used to evaluate the Sr of samples of the same soil from SWIR images taken under different light intensity because the light intensity changes the absolute value of the reflectance. However, for a given light intensity, the measured pixel intensity values can be normalized taking into account the extreme cases: dry (Sr = 0) and fully saturated (Sr = 1). The following normalized pixel intensity is defined:

$$\xi_{\text{norm}} = \frac{\xi - \xi_{\text{dry}}}{\xi_{\text{sat}} - \xi_{\text{dry}}}$$  \hspace{1cm} \text{Equation 2}$$

where \(\xi_{\text{sat}}\) and \(\xi_{\text{dry}}\) is the pixel intensity at saturated and dry conditions, respectively. Then the correlation Sr vs normalized pixel intensity \(\xi_{\text{norm}}\) becomes independent of the light intensity. Figure 10 shows the normalized calibration curve for the samples analyzed. The curve was smoothly extrapolated close to the saturation.

Sadeghi et al. (2015) propose another type of model based on the physical equation of reflectance and absorbance that does not require a calibration curve for each soil. This model is useful when the soil cannot be tested, such as remote sensing using satellite images.
Effect of void ratio

An additional set of calibration experiments was performed to evaluate the effect of the variation of void ratio on the SWIR reflectance. The variation of this state parameter was key to discern if reflectance was controlled by the soil degree of saturation or by water content.

Three samples of sand were prepared assigning a certain value of water content to each one of them. The sand was placed in a metallic cylinder, and the top was covered by a glass. The bottom base of the cylinder had a piston to change the volume of the sample. In this way, the void ratio could be controlled. Reducing the void ratio, the Sr increases maintaining constant the water content (Table 5). A SWIR image was taken for each of the cases presented in Table 5. Table 6 shows the average pixel intensity measured on each sample surface.

If the water content controls the reflectance, the pixel intensity should be constant regardless of the void ratio changes. Otherwise, if the Sr controls the reflectance, the pixel intensity should decrease with higher void ratios. The results are plotted in Figure 11 and Figure 12, which show the correlation between the pixel intensity with the Sr and the water content, respectively. In Figure 11 the pixel intensity decreases as the Sr increases following approximately the calibration curve determined in the previous section. It follows that the reflection is not controlled exclusively by the water content but the void ratio has a significant role. This is further illustrated in Figure 12: the samples have different pixel intensity values at the same water content, but varying the void ratio. These figures show that the reflectance/absorbance is determined by Sr, which is the variable assessed with SWIR images.

Figure 13 summarizes the normalized pixel intensity – Sr curves for all the samples tested. The Sr of the samples indicated was imposed by different procedures. The constant dry density (1390 kg/m³) curve plotted (orange) was determined for the calibration procedure (Figure 10). The variation of Sr was imposed by increasing the water content. The second curve (blue), at a higher dry density (1470 kg/m³), was determined following the same procedure. In the three additional
curves (yellow, lime, green) shown in the plot discussed in the previous paragraphs (Figure 11), the variation of Sr was imposed by increasing the density (in the range 1290 – 1560 kg/m³) at constant water content. There is some scatter in the plot, but it is clear that the Sr is the dominant parameter explaining the soil reflectance for the tested densities.

Analysis

Once the calibration is achieved, this section presents the steps to assess the Sr based on SWIR images. The method can be applied to a sequence of images in order to evaluate not only the distribution of the Sr at a certain time, but also its variation in time. The steps are described below and indicated in the flowchart of Figure 14 for a SWIR video recording. The analysis will be carried out for each extracted frame from the video images.

Steps

1. Record the laboratory experiment with the SWIR camera, and extract the frames from the video.
2. Each image is stored as a matrix where each position corresponds to the pixel intensity of every pixel.
3. The Gaussian filter is applied.
4. The Point of Interest (POI) coordinates are selected or imported.
5. The area of interest is selected or imported.
6. The pixel intensity matrix ($\xi$) is created storing the pixel intensity of the points of interest that are inside the area of interest.
7. The normalized pixel intensity matrix ($\xi_{\text{norm}}$) is created, normalizing the values of the pixel intensity matrix ($\xi$).
8a. The Sr and the water content of every point of interest is calculated from the normalized pixel intensity matrix ($\xi_{\text{norm}}$) using the calibration curves.
8b. The calibration curves come from the calibration process performed once for each material.
The curves provide the relationship between the normalized pixel intensity of the calibration images and their Sr or water content.

9. Suction is calculated from the Sr using the Water Retention Curve of the material.

10. The results can be plotted on contour graphs providing the spatial distribution of the variable of interest (Sr, water content, suction) at any time $t$ (Figure 19). The histories of desirable variables may be built at any point of interest (Figure 20).

Validation and evaluation

The proposed method is applied in this section to measure the distribution of the Sr in a column of an unsaturated Castelldefels’ sandy soil using the calibration curve of Figure 10. The experiment is divided into two stages: (a) stationary stage after imposing the saturation of the bottom of the column; and (b) transient stage during a wetting process from the top of the column. In order to validate the method, the measurements of the Sr based on SWIR images are compared with measurements taken by means of conventional moisture sensors installed in the sample at different elevations.

Experimental setup

The experiment was performed on a column of sand placed in a perspex transparent tank except for the frontal side that was made of glass to avoid scratches that could affect the quality of the images. The tank was 400 mm high, 1000 mm long (limited to 200mm by adding a glass wall) and 200 mm deep. The sand sample tested was a column with square cross-sectional area, 200x200mm, and a height of 300 mm (Figure 15). The tank base was filled with a 2 cm thick layer of gravel which was covered with a geotextile to avoid sand penetration into the gravel layer. The top was covered by a plastic film to minimize evaporation without affecting the atmospheric pressure. The sand was placed in the tank by dry pluviation and the density was controlled by
weighting sequentially the amount of soil. The average density of the sample is 1500 kg/m³.

Three capacitive soil moisture sensors (SEN0193) were installed at different heights: 60, 140 and 220 mm.

Two wetting situations (stages) were analyzed:

**First stage**: The bottom of the sample is saturated imposing a stable water level at the top of the gravel layer located at the bottom of the sample. The water rose up through the sand by capillarity until it reached the stationary condition. At this time, the lateral surface of the column was recorded by means of the SWIR camera and the Sr was estimated by analyzing the image.

**Second stage**: The soil column is wetted from the top with a water flow applied, simulating rainfall, using a drip system with nozzles separated 10 mm. The vertical water infiltration process in time was recorded using the SWIR camera. The time evolution of the distribution of the Sr on the sample face will be analyzed.

**Results**

**First stage**

Once the condition of saturation was fixed on the bottom of the sandy column, the water rose up progressively through the sand. Equilibrated and stable conditions were reached two weeks after the saturation of the base.

Figure 16 shows the distribution of the Sr and water content at the stationary condition measured by means of the SWIR image, following the procedure presented before and the calibration curves of Figure 9.

Several vertical profiles of the SWIR-measured Sr are plotted in Figure 17. They are compared with the theoretical vertical profile computed by accepting a linear increase of the suction with height, applying the previously determined retention curve (approximated by the Van...
Genuchten expression, Figure 5). In addition, the values of the Sr measured by moisture sensors are also indicated. The average dry density (1500 kg/m³) was used to compute the water content from Sr measurements.

The results using the calibration curve method and the linear physically-based method (Sadeghi et al. 2015) are plotted in Figure 18. The comparison shows that while the linear method exhibits a satisfactory performance, the results using the calibration curve method fit better the expected water retention curve and the direct measurements with sensors. The proposed method needs the calibration of a specific curve for each soil that is possible inside the facilities of a geotechnical lab, but not in other cases where the linear method would be more useful.

Second stage

The rainfall applied to the second stage of the experiment had an intensity of 0.6425 mm/s (equivalent to a flow rate of 0.0257 l/s on a 200x200 mm area). The infiltration process was recorded with a SWIR camera at 15 frames per second. However, one image per second is enough for the presented application. The time evolution of the SWIR-estimated Sr is plotted in Figure 19.

The measured values by means SWIR images and the values measured by moisture sensors are compared in Figure 20. The evolution of the Sr at three heights, by means of SWIR images, match well the direct measurements by moisture sensors. The evolution of the descending waterfront is also well captured by the image analysis.

Numerical model

The experiment has been modelled using the finite element program Code_Bright (Olivella et al. 1996; 2019). The model only used hydraulic equations for the solution. The water retention curve used in the numerical simulation was the Van Genuchten model (Equations 3 and 4):
\[
S_e = \frac{S_l - S_{rl}}{S_{ls} - S_{rl}} = \left( 1 + \left( \frac{P_g - P_l}{P_i} \right)^{\frac{1}{1-\lambda}} \right)^{-\lambda}
\]

Equation 3

\[
P = P_0 \frac{\sigma}{\sigma_0}
\]

Equation 4

The hydraulic properties of the sand introduced as model parameters are described in Table 4.

The numerical water retention curve is compared with the experimental curve measured in the laboratory in Figure 21.

The liquid phase relative permeability follows Equation 5.

\[
k_{rl} = S_e^5
\]

Equation 5

It is represented in Figure 22. The permeability rises as it gets closer to the saturated level to take into account the reduction of pore volume due to the soil collapse caused by saturation.

The time evolution of the SWIR-measured Sr is compared to the results from the Code_Bright numerical simulation.

The measured values by means SWIR images are compared to the values measured by moisture sensors and to the values calculated by the numerical simulation (Figure 23). The evolution of the Sr at three heights, by means of SWIR images, match the direct measurements by moisture sensors.

Figure 24 shows the spatial distribution of the Sr in certain times and compares the measurements by SWIR images and the results from the numerical simulation. The descent of the waterfront follows the same general evolution. Nevertheless, the measurements on the images show the inhomogeneities on the distribution of the Sr. In the real experiment, the effects of spatial variation of hydraulic properties result in preferential paths for water flow and...
Draft an irregular waterfront which are features not captured by the numerical simulation because there was no attempt to introduce any heterogeneity in the model. The opportunity to measure and map the spatial distribution of the Sr allows a better understanding the real behaviour of the soil during the whole experiment and provides a benchmark for a refined analysis.

Discussion

The results shown in this work were obtained for a fine sand. Correlation between pixel intensity and water content has also been validated for other grain size distribution with satisfactory results (Sadeghi et al., 2017). The procedure presented should be evaluated and validated in different kind of soils in order to define the range of applicability of the method regarding the type of soils and in particular, the applicability in clays.

The methodology presented exhibits the following limitations:

Non-uniform incident light: The method is based on the light reflected by the soil, but the reflection is dependent on the intensity of the incident light. In order to keep the incident light intensity stable through time, the arrangement of the light emitters can be fixed if the experiments are performed in the same location. In spite of having a stable light intensity through time, the intensity cannot be spatially homogeneous because the light comes from point sources (Figure 25). The intensity of light that reaches the experiment surface depends on the distance to the emitter. These factors force to normalize the calibration and the pixel intensity values from the images.

In order to get better control of the incident light is also useful to include distributed targets with known reflectance values in the image. These targets would act as a reference points to normalize the pixel intensity values, instead of using the saturated and dry pixel intensity.

Image edges: The images from the camera should be filtered, as discussed above (using a Gaussian filter) to attenuate the effect of the different grain mineralogy and the sensor noise.
This filter makes the pixel intensity from the background interfere in the filtered values close to the edges. This effect should be taken into account when interpreting the results near the edge. The Sr values close to the boundaries may appear higher than they really are.

**Surface measurements:** The penetration of the SWIR electromagnetic waves into the soil is low. Therefore, the technique is only capable of assessing the Sr of the surface of the soil samples tested.

**Conclusions**

This study presents a method to measure the degree of saturation of unsaturated soil in laboratory experiments by means of the optical sensing of soil reflectance using short wave infrared (SWIR) images. The method accuracy relies on the differential spectral absorbance of water partially filling the soil pores and the solid grains. Among the analyzed range of light wavelengths, the SWIR spectrum is the most absorbent.

An affordable SWIR camera alternative to the most expensive InGaAs sensor cameras is proposed. The performance of the camera is judged to be sufficient for the purposes of determining the soil’s Sr. The testing arrangement of the camera and the light sources must be stable for a proper analysis.

SWIR images interpreted by a filtered and normalized pixel intensity was shown to depend on the Sr (and not on water content). An initial experimental calibration, for a given soil, is required to relate pixel intensity and Sr. A benchmark experiment conducted on an unsaturated soil column in equilibrium with a saturated lower boundary (suction increases linearly with elevation above the base) allowed to compare the derived water retention curve with a direct determination by standard procedures. The agreement was very satisfactory (Figure 17).
In a second benchmark experiment, during a surface wetting (simulating rainfall) of the previous column, SWIR results were compared with the readings of moisture sensors located in the column. Again, the correspondence was very good (Figure 20).

These benchmarks indicate that the method may be as accurate as other known procedures based on “point” sensors. However, the main value of the method is its capability to capture two-dimensional fields of evolving Sr. This is a major advantage to design experiments to validate numerical models in boundary value problems.

References


Table 1. Bands of the electromagnetic spectrum with high absorbance coefficient by water, beside the correspondent vibrational state of the excited water molecule (Wozniak and Dera 2006).

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<thead>
<tr>
<th>Symbol</th>
<th>Wavelength</th>
<th>Assignment</th>
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<td>α</td>
<td>739 nm</td>
<td>$a \nu_1 + b \nu_3$; $a + b = 4$</td>
</tr>
<tr>
<td>μ</td>
<td>836 nm</td>
<td>$a \nu_1 + \nu_2 + b \nu_3$; $a + b = 3$</td>
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<td>ρ σ τ</td>
<td>970 nm</td>
<td>$a \nu_1 + b \nu_3$; $a + b = 3$</td>
</tr>
<tr>
<td>φ</td>
<td>1200 nm</td>
<td>$a \nu_1 + \nu_2 + b \nu_3$; $a + b = 2$</td>
</tr>
<tr>
<td>ψ</td>
<td>1470 nm</td>
<td>$a \nu_1 + b \nu_3$; $a + b = 2$</td>
</tr>
<tr>
<td>Ω</td>
<td>1900 nm</td>
<td>$a \nu_1 + \nu_2 + b \nu_3$; $a + b = 1$</td>
</tr>
</tbody>
</table>
Table 2. Geotechnical properties of Castelldefels’ sand.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particle density</td>
<td>g/cm³</td>
<td>2.665</td>
</tr>
<tr>
<td>Dry density</td>
<td>g/cm³</td>
<td>1.442 – 1.795</td>
</tr>
<tr>
<td>Porosity</td>
<td></td>
<td>0.459 – 0.326</td>
</tr>
<tr>
<td>Particle size distribution</td>
<td></td>
<td></td>
</tr>
<tr>
<td>D10</td>
<td>mm</td>
<td>0.254</td>
</tr>
<tr>
<td>D30</td>
<td>mm</td>
<td>0.3109</td>
</tr>
<tr>
<td>D60</td>
<td>mm</td>
<td>0.3715</td>
</tr>
<tr>
<td>Air-entry value</td>
<td>kPa</td>
<td>0.7</td>
</tr>
<tr>
<td>Van Genuchten parameters: $Sr = Sr_r + \frac{(Sr_r - Sr_s)}{[1 + (\alpha h)^n]^m}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\alpha$</td>
<td></td>
<td>0.07</td>
</tr>
<tr>
<td>$n$</td>
<td></td>
<td>2.2</td>
</tr>
<tr>
<td>$m$</td>
<td></td>
<td>0.545</td>
</tr>
<tr>
<td>$Sr_s$</td>
<td></td>
<td>0.73</td>
</tr>
<tr>
<td>$Sr_r$</td>
<td></td>
<td>0.0</td>
</tr>
<tr>
<td>Saturated permeability at a porosity of 0.4</td>
<td>m/s</td>
<td>$2 \times 10^{-4}$</td>
</tr>
</tbody>
</table>
Table 3. SWIR images after Gaussian filter and parameters of the sample used in the calibration.

<table>
<thead>
<tr>
<th>Water content</th>
<th>0</th>
<th>0.73</th>
<th>2.63</th>
<th>5.26</th>
<th>10.53</th>
<th>15.79</th>
<th>21.05</th>
<th>26.35</th>
<th>30.00</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sr</td>
<td>0</td>
<td>0.02</td>
<td>0.07</td>
<td>0.15</td>
<td>0.30</td>
<td>0.44</td>
<td>0.60</td>
<td>0.73</td>
<td>1</td>
</tr>
<tr>
<td>Pixel intensity</td>
<td>104</td>
<td>92</td>
<td>86</td>
<td>83</td>
<td>78</td>
<td>71</td>
<td>64</td>
<td>54</td>
<td>52</td>
</tr>
</tbody>
</table>
Table 4. Hydraulic properties of the sand.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Units</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pore pressure</td>
<td>$P_0$</td>
<td>MPa</td>
<td>0.0012</td>
</tr>
<tr>
<td>Surface tension</td>
<td>$\sigma_0$</td>
<td>N/m</td>
<td>0.072</td>
</tr>
<tr>
<td>Shape function</td>
<td>$\lambda$</td>
<td></td>
<td>0.8</td>
</tr>
<tr>
<td>Residual saturation</td>
<td>$S_{rl}$</td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>Maximum saturation</td>
<td>$S_{rl}$</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Intrinsic permeability</td>
<td>$K_0$</td>
<td>m$^2$</td>
<td>4e-11</td>
</tr>
</tbody>
</table>
Table 5. Degree of saturation of tested samples. For each water content, three different degrees of saturation are obtained by reducing the void ratio.

<table>
<thead>
<tr>
<th>Water content</th>
<th>Void ratio</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.70</td>
<td>0.82</td>
<td>1.08</td>
</tr>
<tr>
<td>7.1</td>
<td>0.28</td>
<td>0.24</td>
<td>0.18</td>
</tr>
<tr>
<td>14.3</td>
<td>0.56</td>
<td>0.48</td>
<td>0.36</td>
</tr>
<tr>
<td>22.9</td>
<td>0.90</td>
<td>0.77</td>
<td>0.58</td>
</tr>
</tbody>
</table>
Table 6. Average pixel intensity of each sample condition presented in Table 5.

<table>
<thead>
<tr>
<th>Water content</th>
<th>Void ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.70</td>
</tr>
<tr>
<td>7.14</td>
<td>171</td>
</tr>
<tr>
<td>14.29</td>
<td>130</td>
</tr>
<tr>
<td>22.86</td>
<td>106</td>
</tr>
</tbody>
</table>
Figure 1. Schematic representation of the effect of water content on light absorbance and reflectance of a sandy soil sample surface. Changes in degree of saturation lead to different water distribution into the soils: (a) Water films around the sand grains; (b) Capillary menisci between grains; (c) Saturation and continuous water (Nolet et al. 2014).
Figure 2. Curves indicating the measured spectral reflectance of a beach sand over a range of 350-2100 nm in samples with different values of degree of saturation (Nolet et al. 2014). The underlaid grey zone indicates the coefficient of light absorption by water depending on the wavelength according to Table 1 (Wozniak and Dera 2006).
Figure 3. Variation, for different soils, of the difference between the reflectance measured at dry and saturated conditions for varying wavelengths of different soils. Shaded areas (1400 -1550 nm and 1900 – 2000 nm) corresponds to maximum differences.
Figure 4. Sensitivity curve of the camera phosphor treated sensor.
Figure 5 Measured values and calibrated water retention curve of Castelldefels' beach sand.
Figure 6 Images of an unsaturated column of Castelldelvels beach sand in (a) the visible and (b) the SWIR spectra.
Figure 7 SWIR image after a Gaussian filter.
Figure 8 Experiment setup for calibration.
Figure 9 Correlation curve between the degree of saturation and pixel intensity measured in samples.
Figure 10 Calibration curve correlating normalized pixel intensity and degree of saturation measured in samples.
Figure 11 Effect of the void ratio on the reflectance of the soil for the different water contents (7.14, 14.29, 22.86). The pixel intensity for dry and saturated conditions is also plotted as a reference. The average trend is plotted as a dotted line.
Figure 12 Pixel intensity variation of samples having the same water content but different void ratio.
Figure 13 Normalized pixel intensity – Degree of saturation plot of soil samples at constant water content (7.14, 14.29, 22.86) and varying void ratio. Normalized pixel intensity – degree of saturation plot of samples at constant density (1470, 1390 kg/m³) and varying water content.
Figure 14 Flowchart of the methodology.
Figure 15 Experiment setup for validation
Figure 16 Values of (a) degree of saturation and (b) water content of the column measured by the SWIR image.
Figure 17 Comparison of vertical profiles of degree of saturation determined by SWIR images and values computed from equilibrium suction profile and the experimental water retention curve.
Figure 18 Comparison of vertical profiles of volumetric water content assessed by SWIR images compared experimental water retention curve. a) Using a calibration curve developed for this soil. b) Using the linear physical-based method (Sadeghi et al. 2015, 2017).
Figure 19 SWIR-measured degree of saturation at increasing time during the raining sequence.
Figure 20 Comparison between the degree of saturation measured by SWIR images (dashed line) and by moisture sensors at three column heights (60 mm, 14 mm and 220 mm)
Figure 21 Comparison between the experimental and the numerical water retention curve.
Figure 22 Degree of saturation effect on the liquid phase relative permeability
Figure 23 Comparison between the degree of saturation measured by SWIR images (dashed line), by moisture sensors (solid line) and the degree of saturation calculated through numerical simulation (dotted line) at three column heights (60 mm, 14 mm and 220 mm).
Figure 24 SWIR-measured degree of saturation compared to Code_Bright numerical simulation at increasing time during the soil column wetting.
Figure 25 Example of the spatial non-uniformity of the light from 3 emitters when reaches a surface.