Measurement of the degree of saturation of ground by image analysis

Mesure du degré de saturation de la terre par analyse d'image

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ABSTRACT

The degree of saturation of ground is conventionally measured at discrete points using transducers, soil moisture sensors, etc. In this paper, a novel method was developed to directly measure the degree of saturation of a continuous region of ground by noting the variation in colour of the ground as the amount of moisture in the soil changes. From photo images taken at various soil moisture contents, the colours of the images were converted into numerical values which were then related to known degrees of saturation. The method was validated through vertical seepage tests, where good agreements were obtained between the measured degrees of saturation by tensiometers and those estimated from the proposed method.

RÉSUMÉ

Soustraire le degré de saturation de la terre est par convention mesuré aux points discrets au moyen de capteurs, de sondes d'humidité du sol, etc. Dans ce document, une méthode originale a été développée pour mesurer directement le degré de saturation de la terre entière en notant la variation de la couleur de la terre lorsque la quantité d'humidité dans le sol change. Des photos ont été prises à de diverses teneurs en eau du sol, les couleurs des images ont été converties en valeurs numériques qui ont alors été liées aux degrés connus de saturation. La méthode a été validée par les essais verticaux d'infiltration, où de bonnes concordances ont été obtenues entre les degrés de saturation mesurés par des tensiomètres et ceux prévus à partir de la méthode proposée.

Keywords : degree of saturation, image analysis, soil moisture, seepage test, luminance value

1 INTRODUCTION

The amount of water in soil, often expressed in terms of the degree of saturation, S_r, plays an important role in defining many soil properties, such as strength and permeability. Conventionally, S_r is determined in the laboratory by taking small amount of soil samples and comparing their volumes before and after drying (e.g. Luthin & Miller 1953). In the field, S_r is measured directly using soil moisture sensors based on either time domain (TDR) or amplitude domain reflectometry (ADR) principles (e.g. Nissen et al. 1998; Nakajima et al. 1998). Indirectly, it can be estimated from water retention curve based on measured matric suction of the soil, which in turn can be obtained using tensiometers, high air entry value ceramic disk, etc. A major drawback of these methods is that only the S_r at discrete points can be measured, and do not give an indication of the amount of water over a large region of the ground.

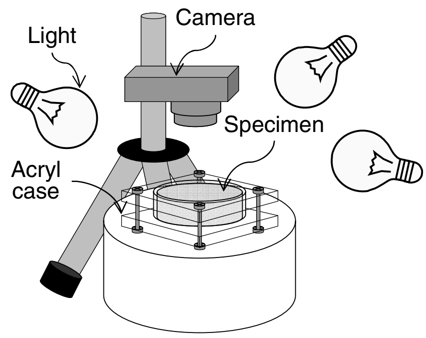
In this research, an innovative way of measuring the degree of saturation of ground is proposed based on the changes in the colour of the ground as the water content is increased. Thus, by taking photos of the ground using a digital camera and converting the colours of the photo images into numerical values which can be associated to known degrees of saturation, S_r of a larger region of the ground can be determined more easily. To validate the method, vertical seepage experiments were performed on model grounds and the results showed good agreement with the values obtained using conventional method.

2 DEVELOPMENT OF METHOD

2.1 *Equipment and test set-up*

In order to develop a method to measure the degree of saturation of ground, different factors need to be examined and therefore, specimens that can be prepared quite easily were preferred. For this purpose, an acryl-type container, 5 cm high and 2.1 cm in diameter, was employed. Moreover, in order to

(a)



(b)

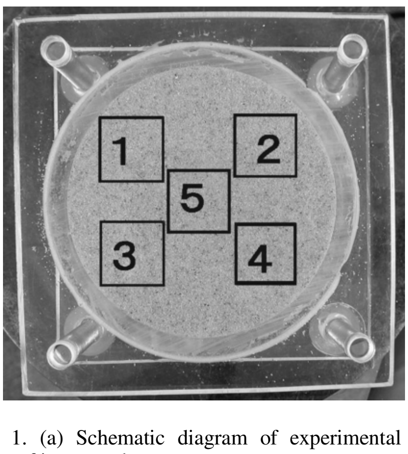


Figure 1. (a) Schematic diagram of experimental set-up; and (b) location of images taken

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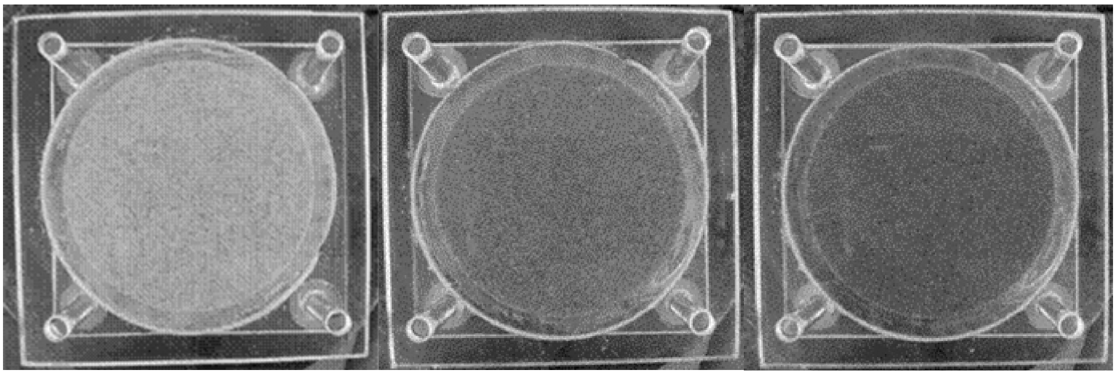


Figure 2. Real images of Toyoura sand (from the left: S_r=0%, 30% and 60%)

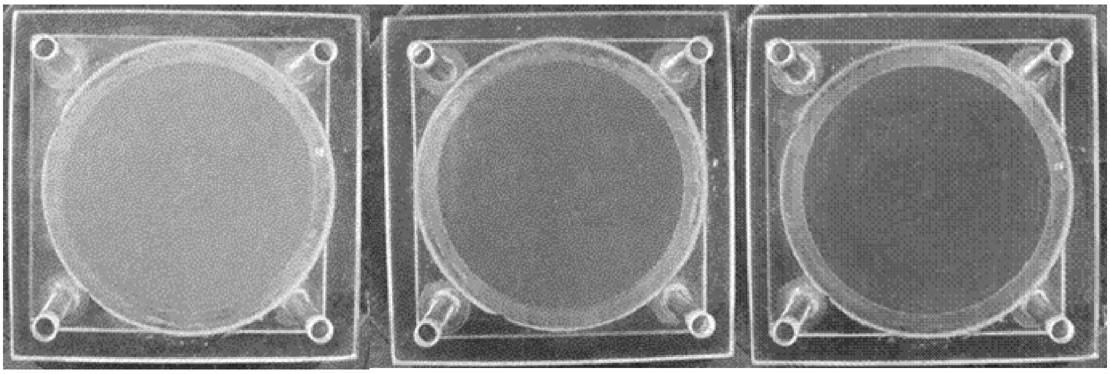


Figure 3. Real images of Tottori silt (from the left: S_r=0%, 30% and 60%)

maintain the amount of light constant, the locations of the three desk lamps used were adjusted and curtains were employed to shade the worksite from unnecessary lights which may affect the images taken (see Figure 1a). An ordinary digital camera commonly available in the market (Canon PowerShot S60) was used for taking digital photos. In this study, the following settings were adopted: shutter speed, T_v=1/20 sec; aperture value, A_v=4.5; image resolution=2592×1944 pixels; and camera effective pixels=approximately five million.

2.2 *Experimental procedure and results*

Two types of soil samples with different grain colours and grain size distributions were employed in the tests: Toyoura sand and Tottori silt. As shown in Figure 1(a), the soil sample was placed inside the acryl container with its water content adjusted to a prescribed degree of saturation (S_r=0%, 30%, 60%) and compacted to attain a relative density, D_r=80%. The container with the sample was sealed, set on the photo stand, and images of the upper surface were taken from the top using the digital camera fixed in position. Careful attention was placed on the colour of the specimen as the amount of water in the sample was varied, and the change in colour was converted into digital value which could indicate the S_r of the soil. Note that each pixel of the digital image has RGB scale values, which are the red, green and blue scale values, and the colour in each pixel is expressed as mixture of the RGB colours in each pixel, which can range from 0 to 255. In this study, the average of red, green and blue scale values in each pixel was used to represent the intensity of colour, referred to as the *luminance value*, in each pixel. A high luminance value indicates that the image is bright while a low value refers to a dark image. In order to take vivid images, red food colouring was added to the water used.

Images of samples were taken five times for each degree of saturation. In order to get the luminance value for each photo, the images of five sheets (size: 200×200 pixels) were cut out from the photo, as shown in Figure 1(b). The average of the

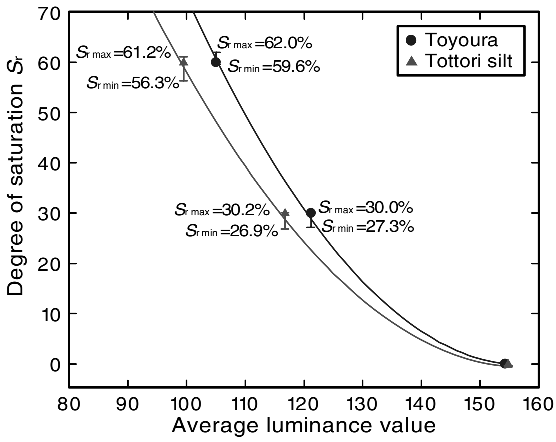


Figure 4: Relation between luminance value and degree of saturation for both Toyoura sand and Tottori silt.

luminance values of these five sheets was taken as the luminance value of the image. Figures 2 and 3 show the real images obtained for Toyoura sand and Tottori silt, respectively. These images, originally in colour, were converted to grey-scale in order to allow for black-and-white printing. Note that the colour of the sample turned darker with increasing S_r.

Figure 4 plots the maximum and minimum luminance values of the images taken for both Toyoura sand and Tottori silt, with the approximation curves drawn. Based on the plots, if the degree of saturation is high, the luminance value is low. Thus, it is possible to estimate the degree of saturation of a sample from the luminance value using the approximation curve. Note that there is little dispersion of data in the plot which, if expressed in terms of degree of saturation, indicates about ±5% accuracy. For both types of soil, the data points can be approximated by a second-order curve which can be expressed as follows:

$$S_r = a \times RGB^2 - b \times RGB + c \quad (1)$$

where S_r is the degree of saturation (%) and RGB is the luminance value. For Toyoura sand, the values of the constants obtained from the tests are as follows: a=0.0223, b=7.0121, c=551.10. On the other hand, for Tottori silt, the values are a=0.0178, b=5.6021, c=440.17.

3 VALIDATION TESTS

In order to confirm the validity of the proposed method and to examine the unsaturated seepage characteristics of Toyoura sand and Tottori silt, vertical seepage tests were performed.

3.1 *Apparatus*

The vertical seepage test apparatus, shown in Figure 5, was constructed based on the concept that the degree of saturation can be determined from the luminance value of the photo image of the sample. Moreover, to verify whether the saturation levels obtained during the infiltration are accurate, tensiometers were attached to the sample through the side of the apparatus and the monitored readings were compared to those obtained using the proposed method.

The size of the acryl case used was 5 x 10 x 70 (cm), and the height of sample employed was 60 cm. In this test equipment, desk lamp and cameras can be fixed at prescribed locations and the experiment was conducted by changing only the sample. Moreover, tensiometer can be attached on the side of the box and the internal degree of saturation can also be measured. It was possible to attach 6 tensiometers and the locations of these are referred to as No. 1 - No. 6 from the bottom.

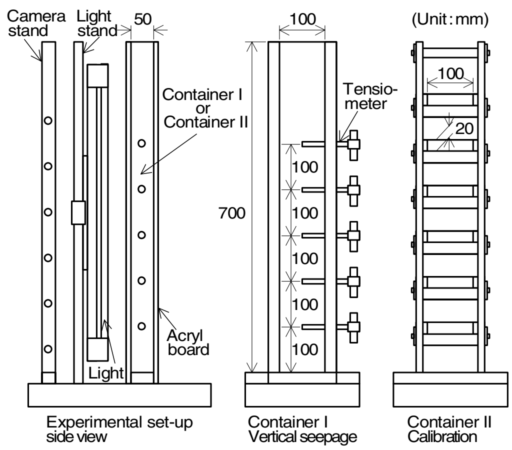


Figure 5: Diagram of the apparatus used for vertical seepage tests.

3.2 *Test procedure and discussion of results*

In the method discussed earlier, it was necessary to obtain the relation between the degree of saturation and luminance value of the sample beforehand and to formulate the appropriate second-degree approximation function. This was referred to as the calibration stage. It was also necessary to fix the position of the camera, lamp, and sample throughout the whole time the above-mentioned relation was being obtained.

Once the appropriate relation for each soil was obtained from calibration tests, vertical seepage tests were conducted while maintaining the same conditions as adopted during calibration. New set of samples (with initial S_r of about 30% and relative density of D_r=80%) were prepared in the soil container and once the set-up was completed, fully-saturated tensiometers were inserted into the model ground through the side of the container. The locations of the transducers were set equal to the vertical positions of the cameras. After insertion, water containing dissolved food colouring agent was percolated through the model ground from the top of the container, maintaining a fixed head above the surface of the ground. The drainage conditions (for both air and water) at the bottom boundary of the ground, as well as the fixed water head at the top, were varied. The experimental conditions are listed in Table 1. During infiltration, photo images were taken continuously by the cameras, which were connected to a personal computer for controlling the time interval between picture-taking (set at t=30 sec intervals).

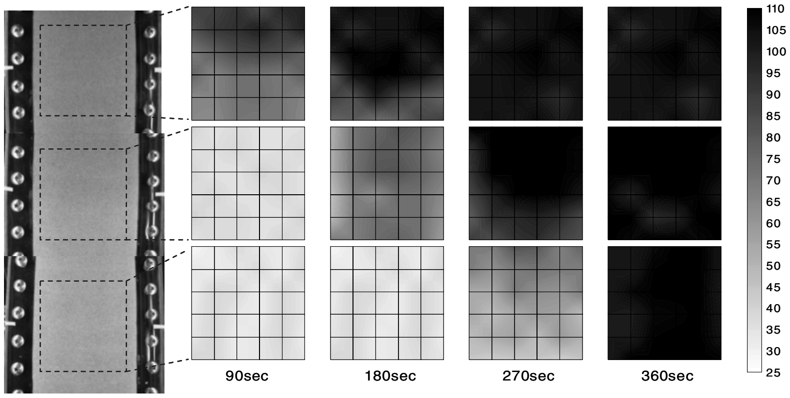
Table 1. Test condition

Sample	Drainage condition	Initial S_r (%)	Rel. density D_r (%)	Water level (cm)
Toyoura sand	Drained	30	80	2
	Drained	30	80	5
	Undrained	30	80	5
Tottori Silt	Drained	30	80	5
	Undrained	30	80	5

Due to space limitations, only the test results for Toyoura sand are presented here. Figure 6(a) corresponds to a typical image taken with the lower boundary having drained condition and the water level at the top set at 2 cm. The photo image is 30 cm high and corresponds to the range from 5 - 35 cm measured from the bottom of the model ground where the 3 cameras were placed (Nos. 1-3 from the bottom). From the sequence of photos, it was possible to visualize the flow as water gradually infiltrated the ground from the top with the passage of time. After 360 sec, the whole ground was coloured black in almost uniform fashion. Based on the images taken, the degrees of saturation at various points were calculated from the luminance value, and contour diagrams showing the distributions of S_r at various times were produced, as shown in Figure 6(b). The contour diagrams showed similar patterns as the photo images, with the S_r increasing significantly in the upper region and changing gradually in the lower part as the infiltration process continued. After 360 sec, the whole ground reached almost the same saturation level of 100%. Similar pattern was observed in the vertical seepage tests involving Tottori silt.

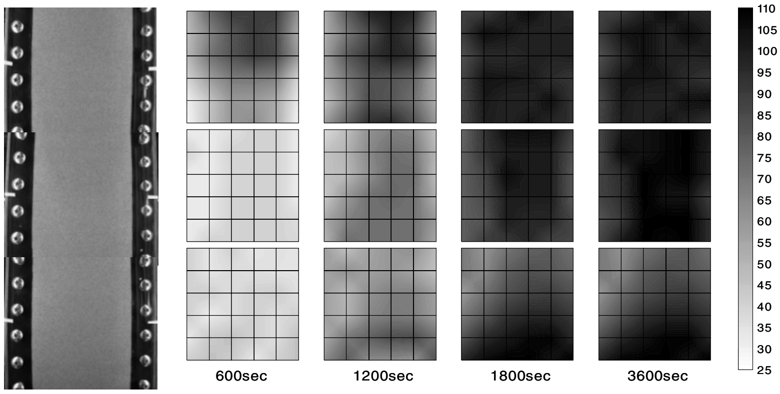
Figure 7 shows the test results with the drain valves closed, corresponding to undrained condition at the bottom boundary. The image shown in Figure 7(a) is also 30 cm high, but corresponds to the range between 15 - 45 cm from the bottom of the model ground (with cameras at Nos. 2-4). Comparing with the previous results for drained condition, which showed almost one-dimensional seepage from top to bottom, the pattern observed this time showed that the entire ground gradually turned black. The corresponding contour diagrams of S_r are shown in Figure 7(b) to quantitatively express the results. Unlike the patterns shown in Figure 6(b), where the saturation level was initially high in the upper portion followed by the gradual increase in S_r in the lower portion with the passage of time, it seemed that in this case, the whole ground showed almost the same distribution of S_r with the passage of time. Furthermore, it appeared that the degree of saturation was lower at points near the sides of the container. The reason for this was that air, which was present in the voids of initially unsaturated ground, tried to escape as the infiltrating water travelled downward; since the bottom boundary was closed, the trapped air was displaced to the sides and attempted to travel upward. Therefore, the S_r within the whole model ground appeared to rise comparatively slowly and evenly because the infiltrating water exchanged places with the air in the voids.

The relations between the degree of saturation obtained by tensiometers and those estimated from the processed images at the same locations are shown in Figure 8 for the drained case of Toyoura sand and Tottori silt. As shown in these figures, there is generally a good agreement between the S_r measured by tensiometers and by image processing, confirming the validity of the proposed method.



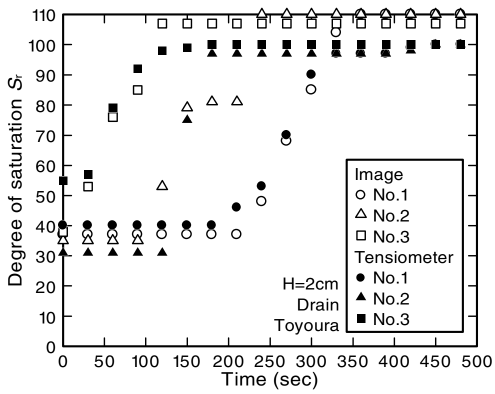
(a) (b)

Figure 6. (a) Real image of Toyoura sand in drained condition (after 180 sec); and (b) contour diagrams of degree of saturation for Toyoura sand under drained condition (from left: after 90 sec, 180 sec, 270 sec and 360 sec)

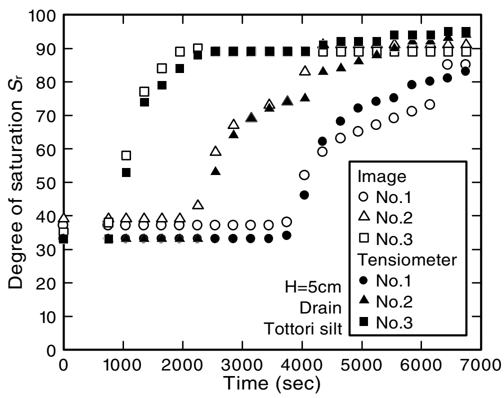


(a) (b)

Figure 7. (a) Real image of Toyoura sand in undrained condition (after 3600 sec); and (b) contour diagrams of degree of saturation for Toyoura sand under undrained condition (from left: after 600 sec, 1200 sec, 1800 sec and 3600 sec)



(a) Toyoura sand



(b) Tottori silt

Figure 8. Comparison of measurements obtained by tensiometers and estimates based on the proposed method for drained condition

4 CONCLUDING REMARKS

In this paper, a series of experiments was conducted for the purpose of developing a method to measure the degree of saturation of ground by processing digital images. Based on the results, the following conclusions can be made:

1. From the test results presented, it is possible to measure the degree of saturation of ground by image processing. The relation between degree of saturation and luminance value can be expressed in terms of a second degree function.
2. Good results were obtained for two soil samples with different colours and grain sizes. The margin of error was in the order of $\pm 5\%$.

The method illustrated the possibility of measuring the S_r of a continuous region of ground, which is difficult to perform using conventional procedures. With this method, contour diagrams of degree of saturation can be produced, making it possible to visualize the propagation of the saturated region. Moreover, not only the flow of water but also the movement of air can be evaluated under drained and undrained conditions.

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