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Digital Image Analysis (DIA) for Estimating the Degree of Saturation of The Soil-Water Characteristic Curves (SWCC)

SWCC의 포화도를 구하기 위한 DIA 적용

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요 지

본 연구에서는 불포화토의 포화도를 구하기 위해 디지털 이미지기법(DIA)을 적용하였다. 실험을 위한 시료는 주문진 표준사를 사용하였다. 1차원 모래기둥 시험을 실시하여 일정수위상태에서의 디지털 이미지의 colour number(C_n)와 포화도(S)와의 상관식을 구하였다. 함수특성곡선(SWCC)을 구하기 위해 Buchner funnel이 부착된 hanging water column test를 실시하였으며, C_n - S 관계식을 이용하여 각 suction head 단계에 따른 average colour number로부터 포화도를 산정하였다. Hanging water column test와 DIA기법으로부터 산정된 포화도를 비교해 본 결과, DIA기법을 이용하여 SWCC을 효과적으로 예측할 수 있음을 보였다.

Abstract

The aim of this study was to validate the suitability of an digital image analysis (DIA) method to measure the degree of saturation in the unsaturated conditions. This study was carried out on the Joo-Mun-Jin standard sand. A one-dimensional sand column test was used in the constant water level condition to get the correlation equation between the color number (C_n) and the measured degree of saturation (S). In addition, the hanging water column technique to determine the soil-water characteristic curve (SWCC) was performed in a Buchner funnel. The average degree of saturation (S_{ave}) in the SWCC could be obtained by substituting average color number at each suction head value with the C_n - S correlation equation. Comparisons were made between the measured results by the hanging water column test and those obtained from DIA method. Results showed that the DIA method tested here provided fairly good saturation distribution values in the drying and wetting processes.

Keywords : Average color number, Correlation equation, Degree of saturation, DIA, SWCC

1. Introduction

The further development of studies on soil-water required a more general concept to express the state of water in soil. Studies of the suction and hydraulic conductivity models could not ignore the existence of SWCC. The SWCC relates the gravimetric water content, w, or volumetric water content, θ_w (defined as the volume of water in the soil divided by the total volume of the soil, V_w/V), to matric suction. This curve presents the basic characteristics of a partially saturated soil. Gallipoli et al (2003) and Buisson and Wheeler (2000) indicated that the relationship

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between the degree of saturation, S, and matric suction head, h_m, for a given soil is non-unique because the variation of the void ratio in deformable soils results in changes of the void dimensions and also in changes of the connecting passageway between them. This, in turn, causes corresponding variation in the SWCC. Hence, determination of the degree of saturation is one of the key factor in that relationship.

Numerous approaches have been proposed for mathematical representation (i.e., fitting) or prediction of the degree of saturation. Table 1 summarizes the commonly used soil-water models for estimating the degree of saturation. In Table 1, the equations are written in $S_e(h)$ functional form. S_e, the effective saturation to describe the water content in the soil, can be calculated using equation (1).

$$S_e = \frac{S - S_r}{1 - S_r} \tag{1}$$

in which S is the calculated water saturation; S_r is the residual saturation. From Eq.1 and the $S_e(h)$ functions in Table 1, the soil-water characteristic functions for the models are obtained. One of most widely used relation to represent the SWCC is the one proposed by Van Genuchten (1980), as it is simple, requiring only two parameters and gives the good results in case of granular material. In this study, van Genuchten equation's form was used to get the correlation equation for the sand column test and estimate the degree of saturation in the hanging water column test. Substituting Eq.1 with van Genuchten model in Table 1, the SWCC is defined as the relationship between degree of saturation and suction head, and can be expressed as

$$S = S_r + (1 - S_r)[1 + (\alpha h)^n]^{-m} \tag{2}$$

in which n is a curve fitting parameter which reflects the pore-size distribution of the porous medium, and m = 1 - (1/n); α (L^{-1}) is a scaling parameter which is related to the displacement suction head. The parameter α can be represented by two limiting values, one applied to drainage curves and other applied to imbibitions curves.

Table 1. Summary of Empirical and Macroscopic Equations for Modeling Unsaturated Degree of Saturation Function

Model name	Model
Brooks and Corey (1964)	$S_e = \left(\frac{h}{a}\right)^{-n}$
Brutsaert (1966)	$S_e = \frac{1}{1 + (h/a)^n}$
Van Genuchten (1980)	$S_e = \frac{1}{\left(1 + (\alpha h)^n\right)^m}$
Tani (1982)	$S_e = \left(1 + \frac{a-h}{a-n}\right)\exp\left(-\frac{a-h}{a-n}\right)$
McKee and Bumb (1987) (Fermi)	$S_e = 1/(1 + \exp((h-a)/n))$
Fredlund and Xing (1994)	$S_e = \frac{1}{(\ln(e + (h/\alpha)^n))^m}$
Kosugi (1994)	$S_e = Q\left[\frac{\ln(h/h_m)}{\sigma}\right]$

Note: definition of variables: h is soil suction; α, a, n and m are fitting parameters; Q is a cumulative normal distribution function; σ is standard deviation of lnh

Degree of saturation can be measured either with destructive methods or with non-destructive methods. The gravimetric method, which leads to a soil-water content on the basis of weight or volume, is the most widely used destructive technique. Non-destructive techniques that have proved to be applicable under field conditions are: neutron scattering (Gardner, 1986), gamma-ray attenuation (Bertuzzi et al. 1987), capacitance method (Dean et al. 1987 and Halbertsma et al. 1987) and time-domain reflectrometry, TDR (Heimovaara and Bouten 1990).

Up to now, DIA has become popular approach to quantitatively determine static and dynamic flow of water in an unsaturated/saturated soil. Investigators have utilized DIA to predict such parameters as dye concentration and LNAPL (Light Non-Aqueous Phase Liquid) saturation in laboratory experiments (Schincariol et al. 1993, Van Geel & Sykes 1994). Furthermore, S.B. Coskun and N.C. Wardlaw (1994) proposed an empirical method for estimating initial water saturation by DIA. R.S. Sharma et al. (2002) represented a method to predict the degree of saturation from the average color number in the column test. Philip Gachet et al. (2003) also applied DIA to study the hydromechanical behavior of unsaturated soil.

The rapid development of inexpensive high resolution digital cameras and the availability of high performance digital image processing software open new possibilities of the DIA method in the field of unsaturated soils. The main aim of this paper is to estimate a degree of saturation in the relationship with the matric suction head by combining S-shape curve fitting equation with the DIA results from the hanging water column test. And then, these results are validated by the results of the degree of saturations from the hanging water column test.

2. Material and Methods

2.1 Materials

In this investigation, Joo-Mun-Jin sand was used. The index properties of this sand are C_u = 1.65 and C_c = 1.08 with D_{50} range between 0.50 and 0.55 mm. The sample was classified as poorly graded sand. The porosity of the sample was found to vary in a narrow band, 45 (+/-1)%. The majority of the sand particles had the mean diameter of 0.55 mm and the rest of the particles were very close to the mean diameter.

2.2 Methods

2.2.1 Column Tests for DIA Application

Figure 1 shows the schematic diagram of the sand column test commonly used for measuring the degree of saturation in unsaturated soil testing applications. The sand column is 0.4 m in height, and the interior is 0.19 x 0.19 m wide. The walls are made of 5 mm thick Plexiglas. A fine mess of 5 mm thickness was placed at the bottom of the column. Details of designs of the column test are given in Sharma et. al 2002.

In order to reduce the angle of friction and color differences at the interface (soil mass and Plexiglas), the oil films have been applied. This lubricant will reduce the adhesion at the interface and make the local flow behavior remains unchanged between interface areas and areas inside the soil mass. In this study, the commercial product: WD40 spray (containing MsO2, silicone, Teflon, and other constituents) was chosen. WD40 spray was almost as good as silicone, being more fluid and progressively reducing its effect on the interface (Gachet et al. 2003).

Prior to measure, well-sorted sand samples by air pluviation method were used to fill the column. Saturated samples were initially prepared by pouring dry sand into a partially water-filled container. Although it is unlikely for air to be trapped in the pore voids since dry sand

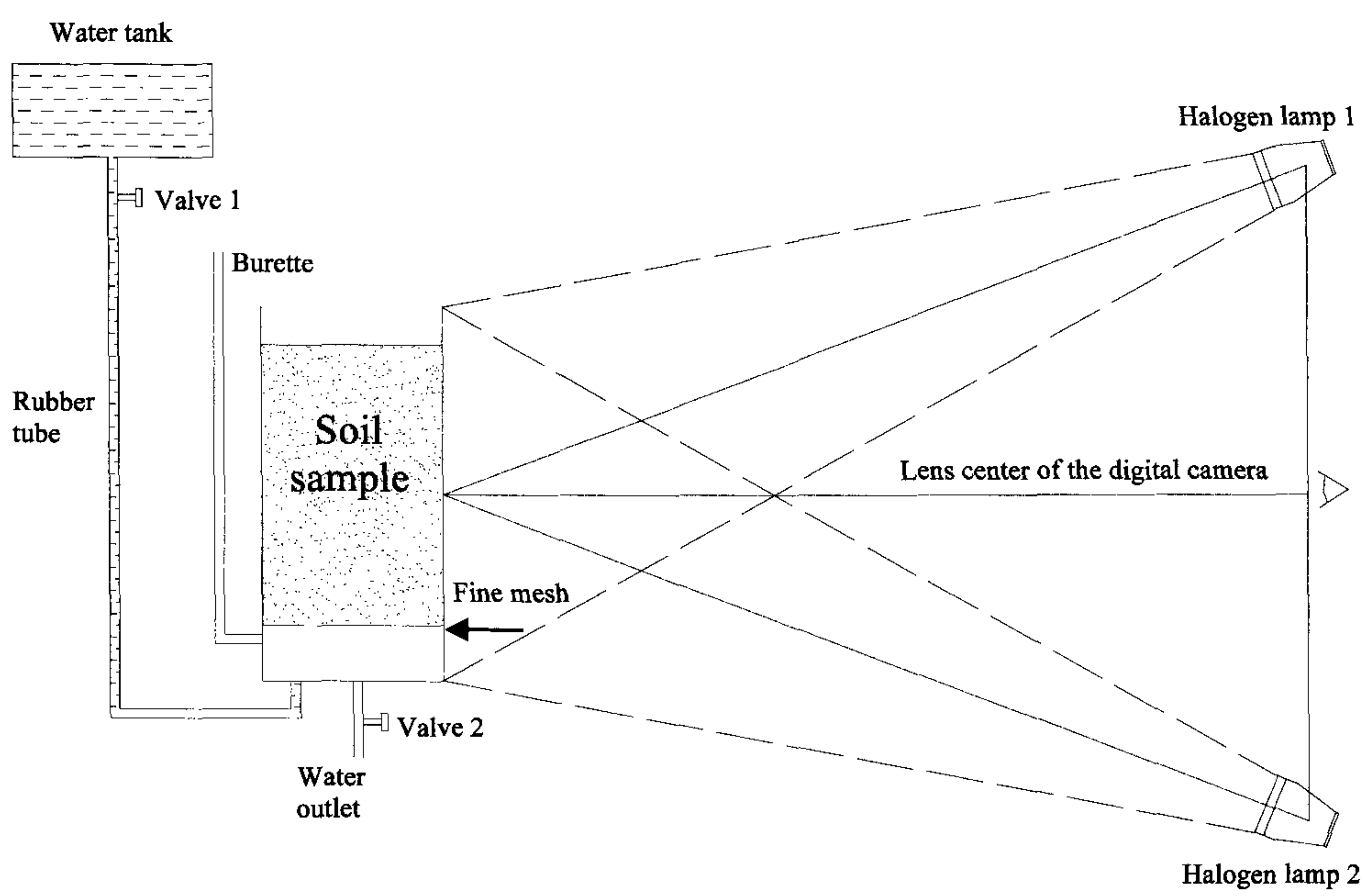

Fig. 1. Schematic diagram of sand column test

was always poured in water, the prepared samples were left for at least 24h with water above the sand surface to ensure that the samples initially reached full saturation.

After a day, the water level decreased to 0 cm and it was left one more day before taking the image. After taking the image, the sand column was brought to measure water content by suctioning method. The sand sample in each 2.0 cm was taken out and then water content can be estimated using an estimate of oven dry weight. The images and the experimental water content results are used to make the relationship between color number and degree of saturation following the height of the sand column.

2.2.2 Suction Tests Using the Hanging Water Column Method

A hanging water column setup was used for determining the matric suction head in the relationship with the degree of saturation. This apparatus consists of three parts: a specimen chamber, an outflow measurement tube and a column of water. The specimen chamber is placed on a fine mesh, which is connected to the outflow measurement tube below. The end of this tube is connected to the column of water. The column of water is used to control the suction at the base of the sample. The specimen chamber has internal dimensions of 19 cm x 19 cm x 15 cm. Figure 2 shows the experimental setup of the hanging water column. A principle that applies to the design of this apparatus is based on the method in ASTM D 6836-02 (2004).

A digital camera was used to take the RGB (red-green-blue) images. The images presented in this paper were captured using an inexpensive Canon PowerShot S400 digital still camera which provides a max pixel resolution of 2272 x 1704. Two 500-W halogen lamps were used to illuminate the column front.

Lighting considerations must also be regarded as a high priority item since the outcome of the analysis will depend greatly on the quality of the recorded images, which are in turn influenced by the quality and arrangement of the lighting system. Several tests were carried out with different setups of the lights and different kinds of lights in order to obtain the one that yielded the crispest images of the soil sample. The height of camera was adjusted so that the centre of the lens was at the same height of the centre of the column (Sharma et al. 2002). Additionally, the lights were arranged at equal space above and below the centre of the camera with light rays going to the centre of the column as shown in Figure 2. Furthermore, all room

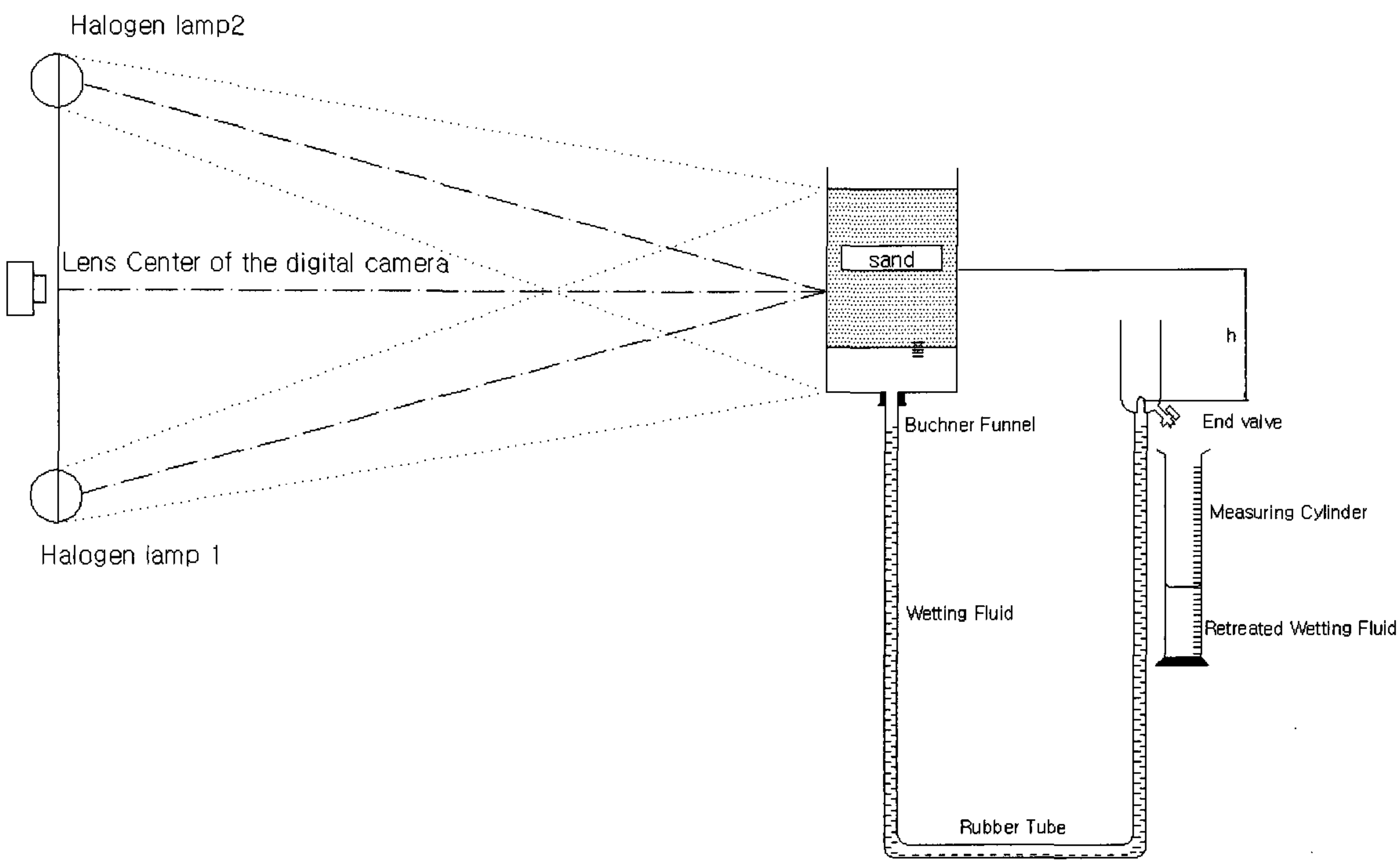

Fig. 2. Schematic diagram of hanging water column test

lights were switched off and also the test area was covered to eliminate any light interference.

Specimen preparations are the same as the sand column test above. The top of the specimen chamber was covered with perforated PVC film to prevent evaporation. The samples were then subjected to varying values of the matric suction head according to the test objectives. Drying and wetting main curves were achieved by lowering and raising the burette to a given height in stages, respectively (see Fig. 2). In each stage, the sample was left for a sufficient time to reach equilibrium, which is marked by no further flow of water from or into the sand sample and then the images were taken. The time given was varied depending upon the value of the suction head and the soil properties. Details of calculations of the degree of saturation and the suction head are given in Sharma and Mohamed (2003b).

From the consecutive outflow and inflow volumes the degree of saturation for each hm value was determined to obtain the soil-water characteristic curves (SWCC) during the main drying and wetting processes. The images which were taken combining fitting correlation equations from the column test will be considered and analyzed to predict the degree of saturation for the SWCC.

2.2.3 Digital Image Analysis (DIA) Methodology

The procedure to determine the degree of saturation of the SWCC by DIA and corresponding algorithm of computer software are summarized in Figure 3. After taking the image, image correction technique was applied to calibrate the image in terms of physical measurement units (e.g., mm). The images consisting of 190 x 300 mm (539 x

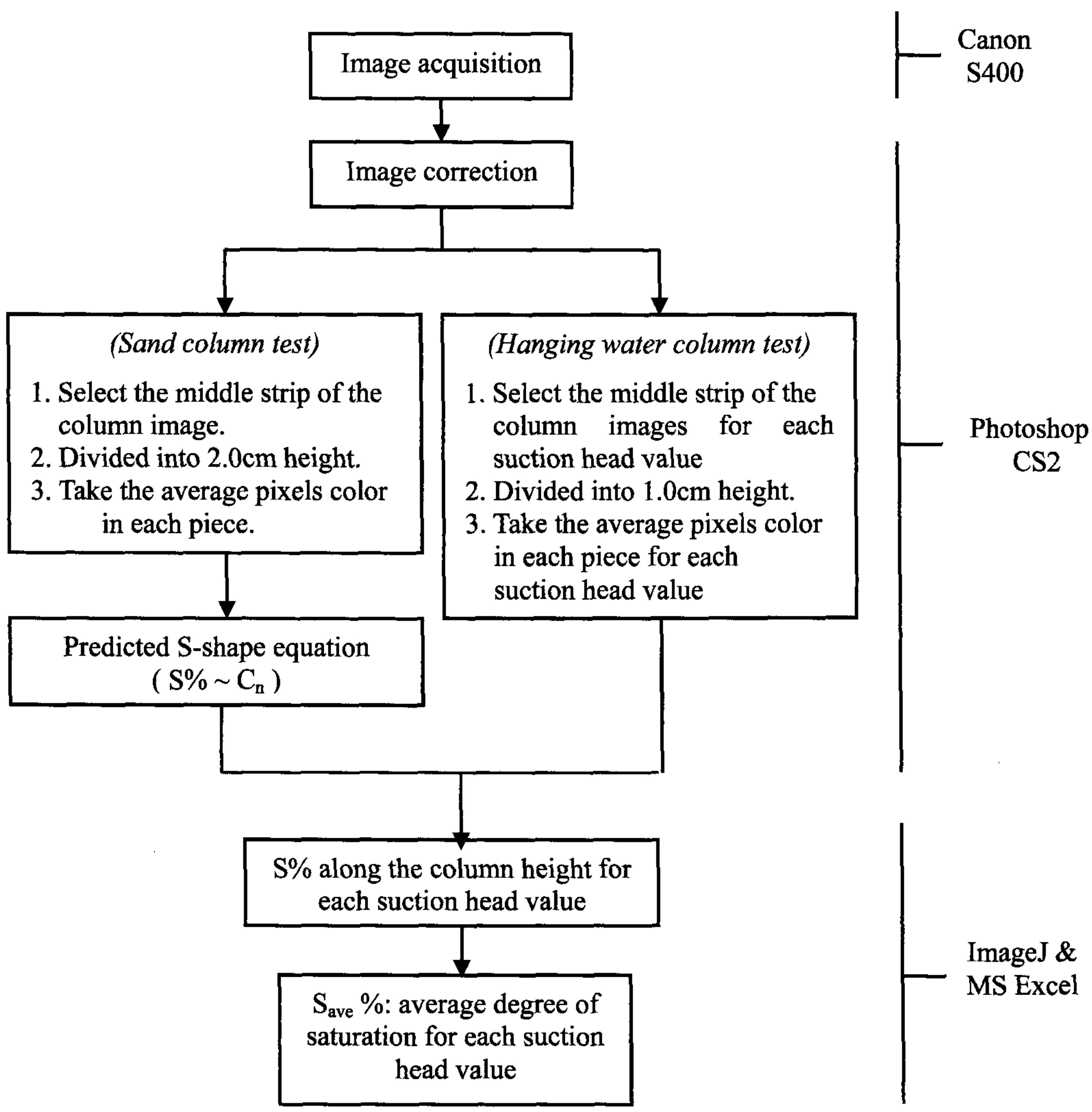

Fig. 3. Flowchart of DIA procedures and corresponding computer softwares

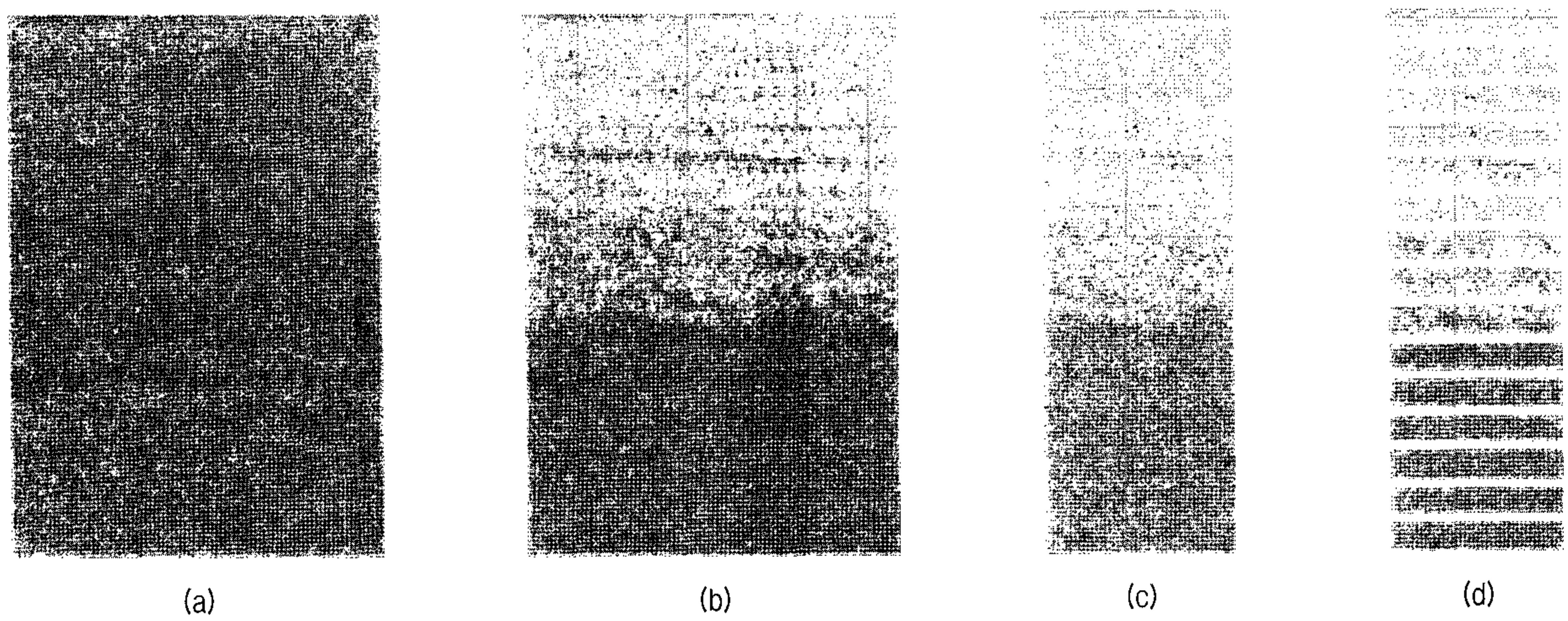

Fig. 4. Typical image in the hanging water column test during drying process : (a) saturated case, (b) unsaturated case, (c) the middle strip was selected from b, (d) after partition step

850 pixels) in the sand column case and 190 x 150 mm (539 x 425 pixels) in the case of the hanging column test were created.

And then, following the sand column test, in order to avoid the light variation on the border of the column, the middle strip of the column image was selected. The average color number for each 2.0 cm piece was automatically calculated by commercial Photoshop software in the expanded view of the histogram option. The correlation equation will be derived from the relationship between these color values and measured degree of saturation.

The step above also has been repeated in the hanging water column test, but corresponding to each suction head value with 1.0 cm pieces. Figures 4a through 4d show the typical images from the hanging water column test during drying process. After these processes, the average color numbers were calculated for each 1.0 cm height. Substitution of the color number in the hanging water column test with correlation equation gives the degree of saturation along the column height for each suction head value.

In this study, the degrees of saturations in the SWCC that means the average degree of saturation at any arbitrary value of suction head were defined as the ratio between the area of the hatched part and the total area of the hatched and unhatched part. Figure 5 shows the procedure for measuring average degree of saturation. This procedure is performed for each of the suction head value in the hanging water column test. Finally, the SWCC is obtained from predicted degree of saturation and measured matric suction head.

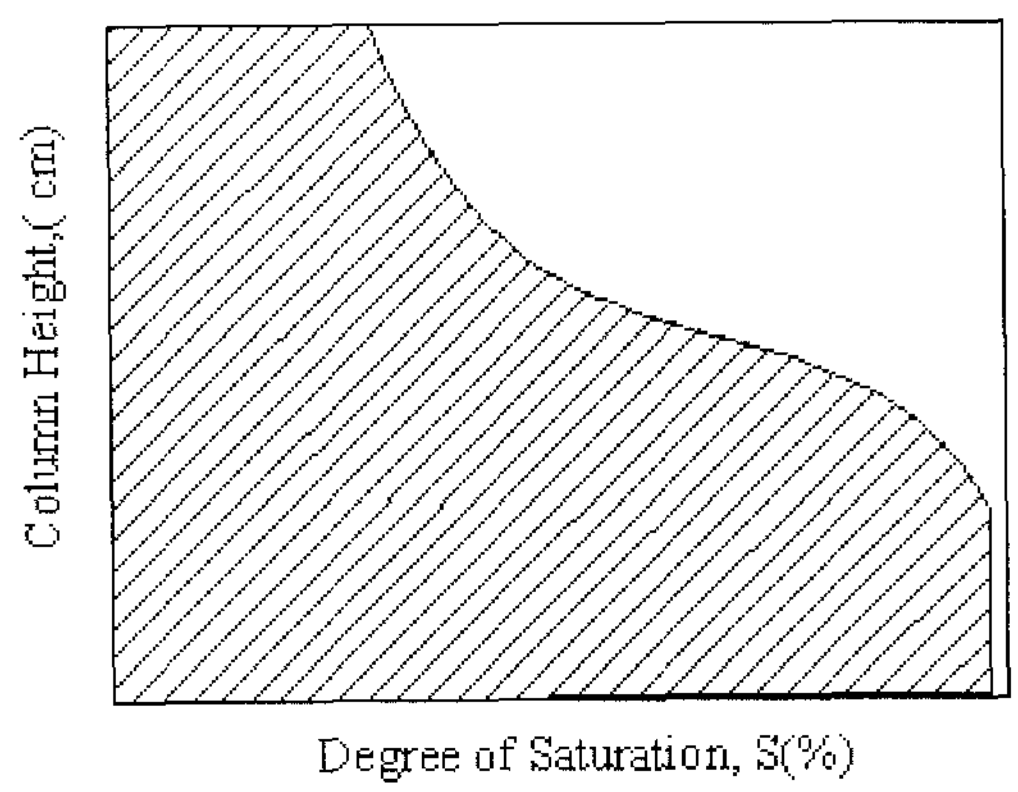

Fig. 5. Procedure for measuring average degree of saturation

3. Results and Discussion

3.1 Column Test Results and S-shape Curve Fitting Equation

The results from the sand column test in the Joo-Mun Jin sand samples are presented in order to find out the S-shape correlation equation between degree of saturation and color number. Figure 6 shows the relationship between color number and column height, in this case the constant water level at the 0 cm. The color distribution curve varied from dark in the capillary zone to bright in the upper zone. Typically, the two ends were pure black and pure

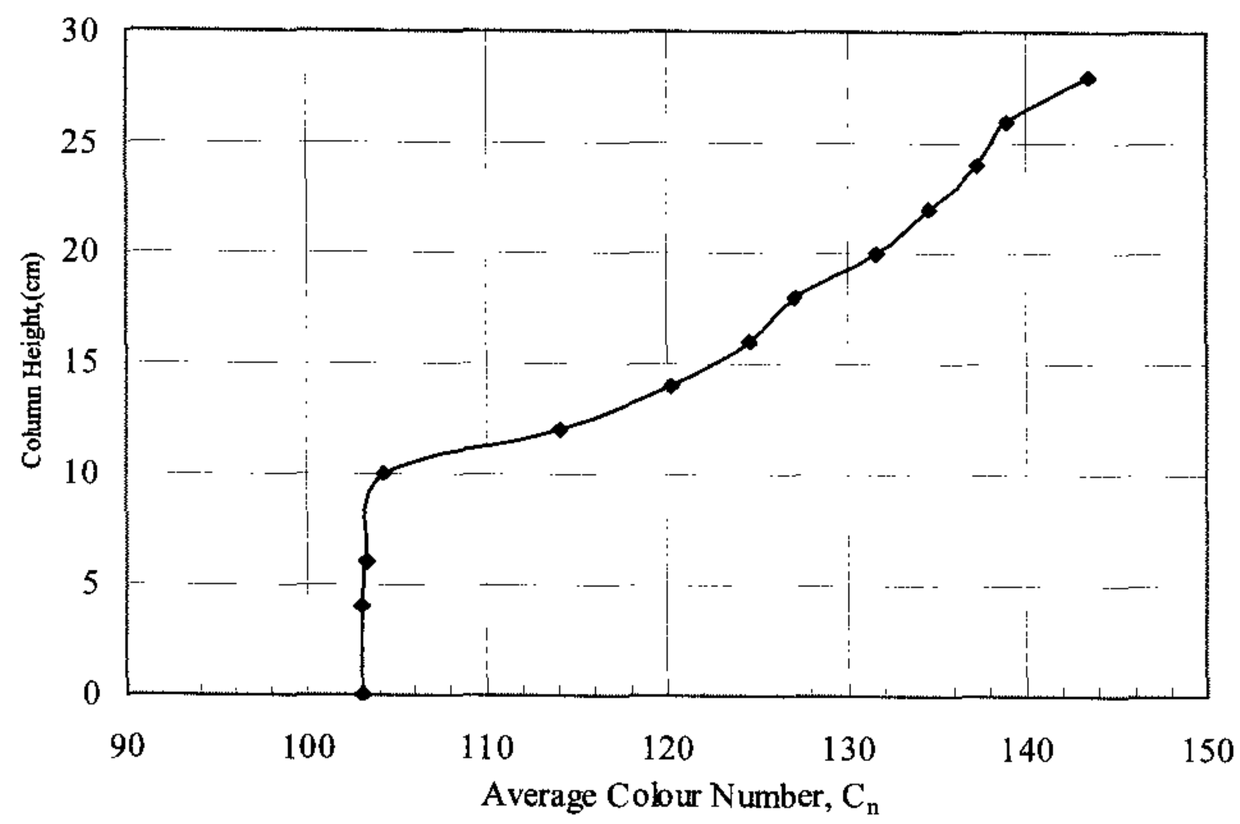

Fig. 6. Color distribution versus column height

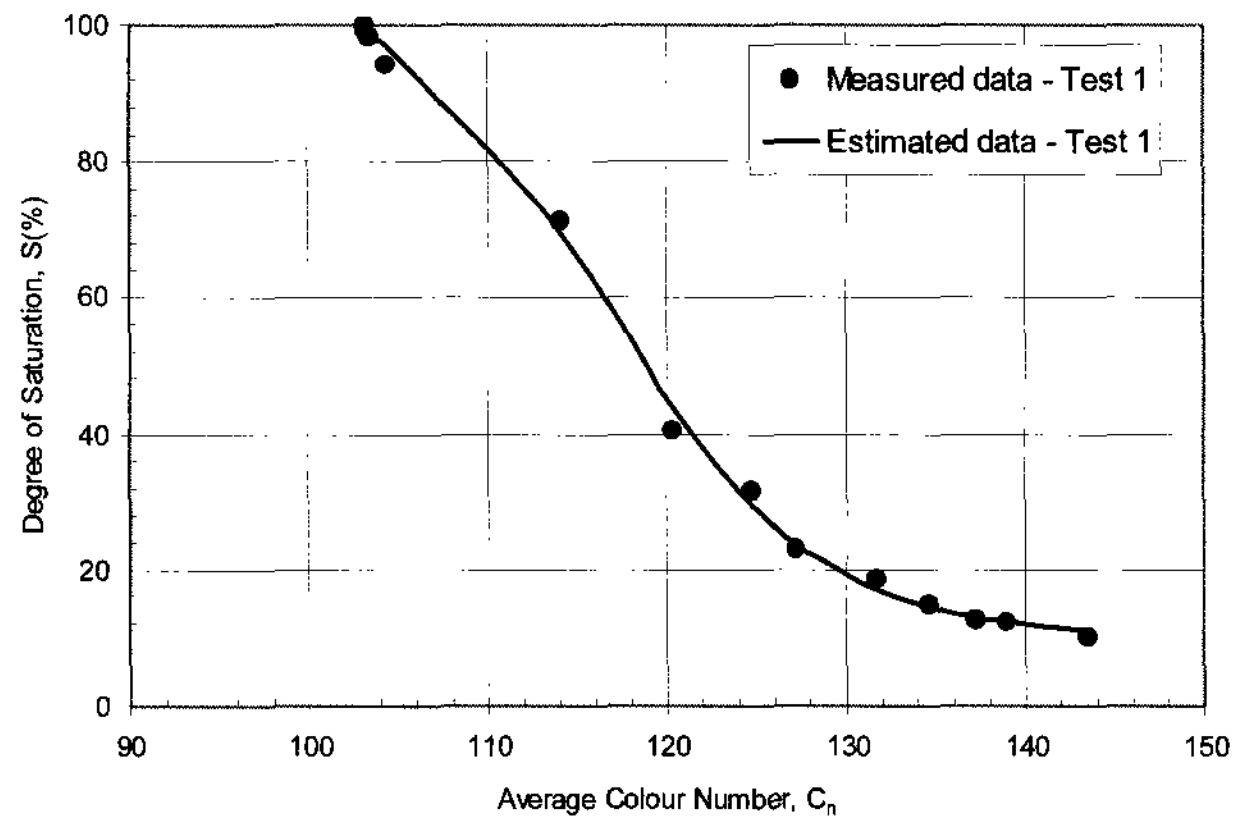

Fig. 7. Measured and estimated degree of saturation, using Eq.3

white, 0 and 255, respectively. In this case, our color results varied from 100 to 150. This distribution looks quite similar to the degree of saturation distribution in unsaturated zone.

Following Sharma et. al 2002, the vadose zone is divided into three zones based on the degree of saturation of water. These zones are: pendular zone, where water is at residual degree of saturation, capillary fringe, where the degree of saturation of water is close to 100%, and funicular zone, where the degree of saturation varies from residual to almost full saturation. From the above distribution, in order to simulate this situation, a form of the van Genuchten's equation (Eq.2) can be applied. In this case, the matric suction head value (h_m) has been replaced by the average color number (C_n). Hence, the relationship between the degree of saturation and color number as shown in equation 3, is similar to those presented by Sharma et.al 2002.

$$S = S_r + (1 - S_r)\left[1 + (aC_n)^b\right]^{-c} \quad (3)$$

in which S is the estimated degree of saturation, S_r is the residual degree of saturation, C_n is the average color number (measured from the test); a,b and c are the fitting parameters with c=1-(1/b).

Table 2 summarises the fitting parameters for this equation for the color number results in Figure 7. These parameters were used to present the correlation equation

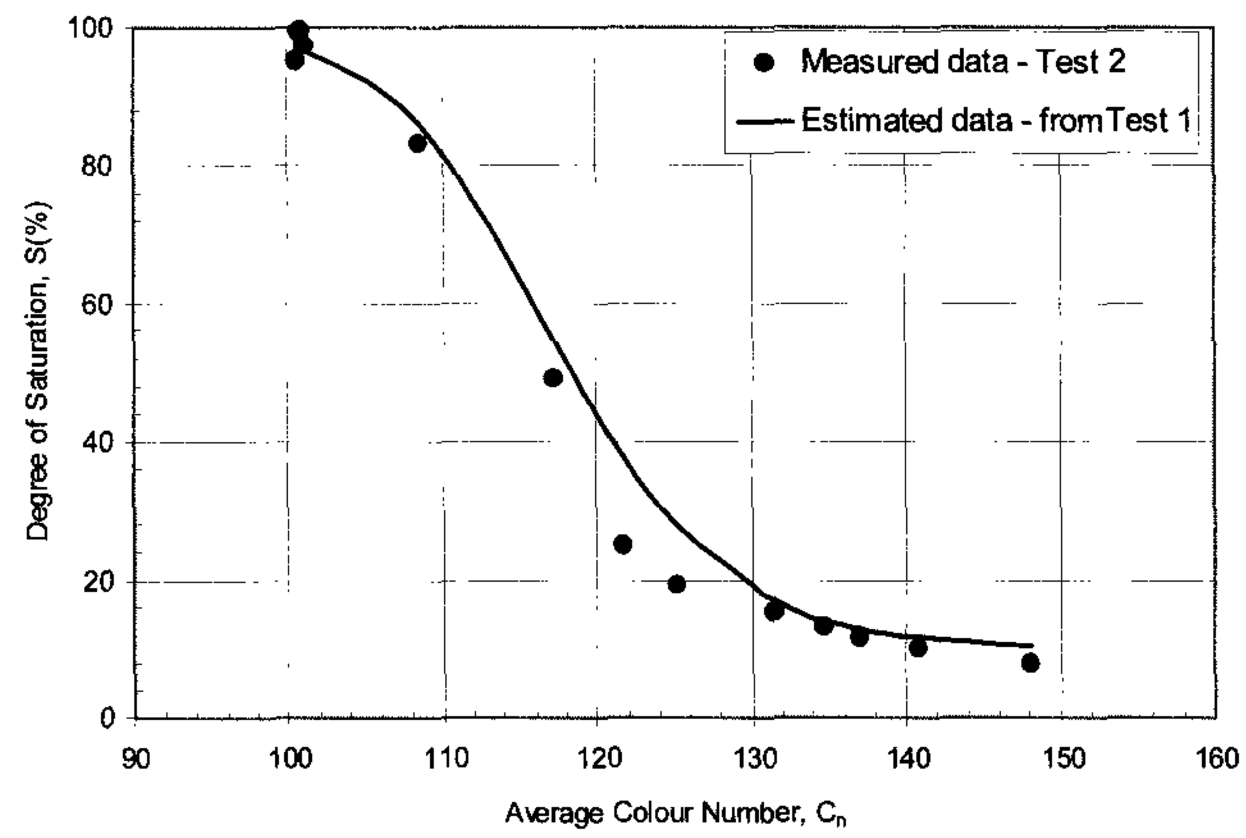

Fig. 8. Validation using S-shape curve equation (Eq.3)

Table 2. Fitting parameters for S-shape equation

S_r	a	b	c	r^2
9.634	0.00856	21.474	0.9534	0.998

between the average color numbers and the degree of saturations. Figure 7 shows the results of measured and estimated degree of saturation using Eq.3. It should be noted that the fitting values in the capillary and residual zone are very close to the measured values.

To validate the results and the above fitting parameters, another measured data have been used for checking. Figure 8 shows the validation results. In that figure, the symbols show the measured data in test 2 and the solid line is the estimated curve by inputing the measured data - Test 2 into Eq.3 with the parameters in Table 2. It is observed from Figure 8 that the estimated curve is close to the measured data, especially in the capillary and residual zone, though it is not so for some points in the transition zone. Based on these results, the above correlation equation (Eq.3) can be used for estimating the degree of saturation and was applied to the following part in this study.

3.2 Suction Test Results

The hanging water column technique to determine SWCC is performed in a Buchner funnel, which is also known as a Haines apparatus (Haines, 1930). Figure 9 shows the comparison between the soil water characteristic curves for measured and estimated values during main drying and wetting processes. The symbols show the measured data and the solid line is the estimated curve. It was observed that just a small amount of water drained in the capillary zone. Once the value of the applied suction head increased over bubbling pressure head, a considerable amount of water drained out of the sample. The bubbling pressure head is highlighted on this figure.

In addition, it can be seen from Figure 9 that a minimum degree of saturation of 20% was reached at a value of suction head of 27 cm. This degree of saturation did not decrease anymore even with further increase in matric suction head, which means this is the residual saturation.

In the wetting path, the degree of saturation reached 84% although the matric suction head had dropped to zero. This suggested that 16% of air was trapped inside the sample. It is clear from these results that there is a hysteresis in the relation between the degree of saturation and matric suction head. The amount of hysteresis is described here by the difference between the values of matric suction head in drying and wetting. The amount of hysteresis is 8 cm. The estimated values have been calculated by using van Genuchten's equation (Eq.2) and the fitting parameters for drying and wetting paths are also presented in Table 3.

It should be noted that there is a little discrepancy in the residual zone between calculated and fitted values. Furthermore, based on Fig. 9 and the error rate values in the Table 3, the estimated results from the wetting process can be obtained better than the results from the drying process.

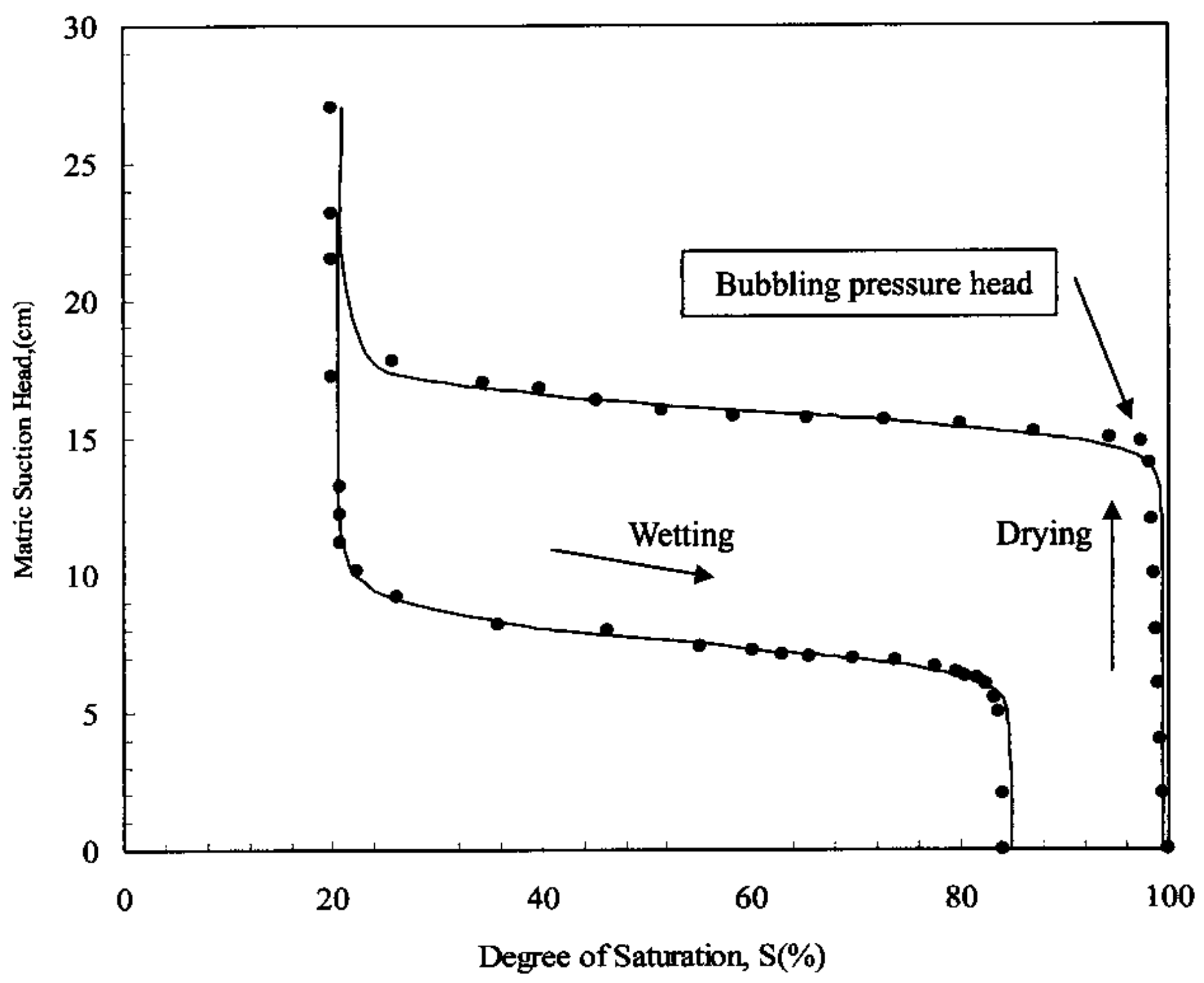

Fig. 9. Measured and predicted the degree of saturation versus matric suction head for the main paths

Table 3. Fitting parameters for S-shape curves from Van Genuchten's equation (1980)

Processes	S_r (%)	α	n	m	r^2
Dry	20.967	0.0628	31.06	0.9678	0.986
Wet	20.52	0.1327	13.686	0.9269	0.996

3.3 Predicting the Degree of Saturation in the SWCC Using DIA Method

Fig. 10 and Fig. 11 show the color distribution results in the hanging water column test for drying and wetting processes, respectively. The legend boxes in these graphs show the free outflow level of water in the burette. The results indicated that the color numbers vary along the column height corresponding to the variation of water

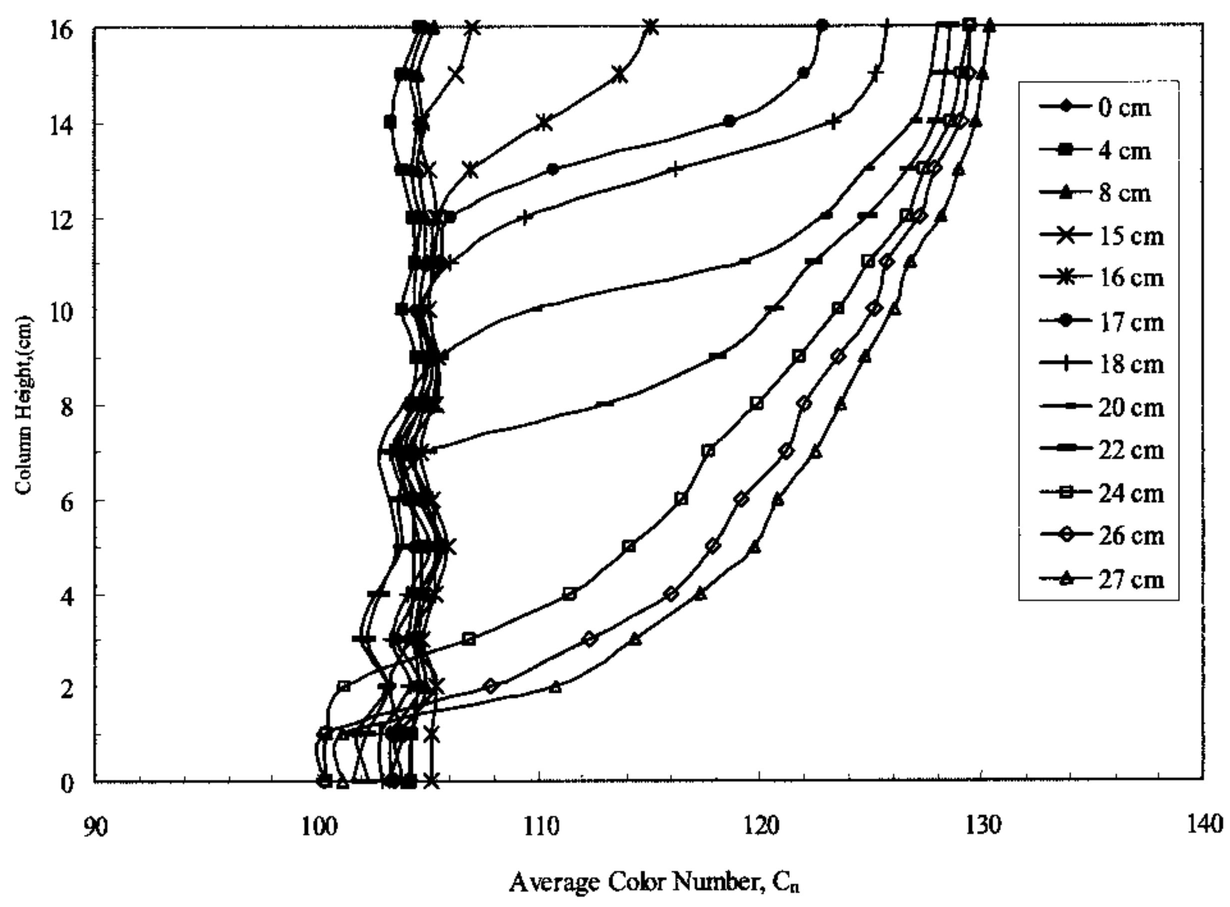

Fig. 10. Color distribution versus column height in drying process

content from wet to dry condition and inversely. The shape of these results are the same as those which are obtained from the constant water level (refer to Fig. 6).

In the saturated condition, the variation of the average color numbers are insignificant, but once the free outflow level of water reaches to 16 cm the distribution curves begin to move to the right side and gradually shape the transition zone. The transition zone continually increases with the decrease in capillary zone and then gradually shapes the residual zone at 24 cm. As shown in Figure 10, the distribution curves from 24 cm to 27 cm are very close in the top part. This means the residual zones are already shaped. On the other extreme, the variation of the average color number along the column height in the wetting process presented imbibition condition. Refer to Fig. 11. These processes can be realized from the

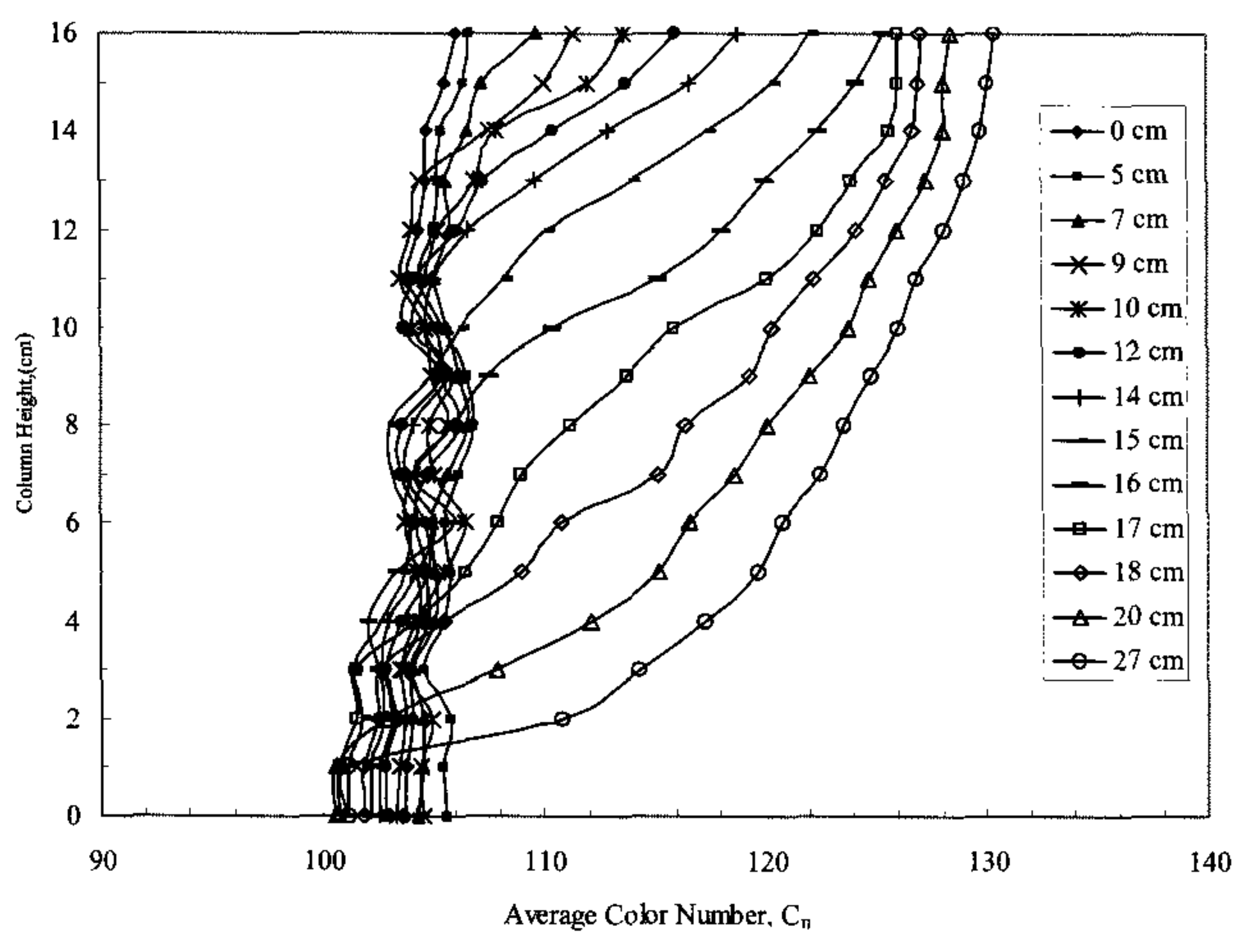

Fig. 11. Color distribution versus column height in wetting process

movement of the color distribution curve from the right to the left side.

Fig. 12 and Fig. 13 show the estimated degree of saturation in drying and wetting processes by using the correlation equation. Substituting the average color number in Fig. 10 and Fig. 11 with Eq.3, the relationship between the degree of saturation and column height can be estimated. The results show significant variations of the conditions of soil sample from the saturated, unsaturated to the dry conditions. As it may also be seen from these graphs, in the saturation case, the degree of saturation can get to 97% - 99% (~100%) and in the residual condition, the residual degree of saturation can reach to 19%.

In addition, in Figure 12 and 13, the variation of the slope of the transition zone can be also realized. When the free outflow level of water slightly increases, the slope of the transition zone is gentle. On the contrary, if they sharply increase, the slopes are very steep. Furthermore, these curves are parallel with one another with a difference distance before they reach at the residual level in the transition zone. This implies that a considerable amount of water drained out and was absorbed in this zone in the drying and wetting processes. Besides, this amount of water also equals with one another corresponding to each process on the transition zone.

The measured and the estimated degree of saturation values for the SWCC are shown in Figure 14. In this figure the round symbols show the measured data from

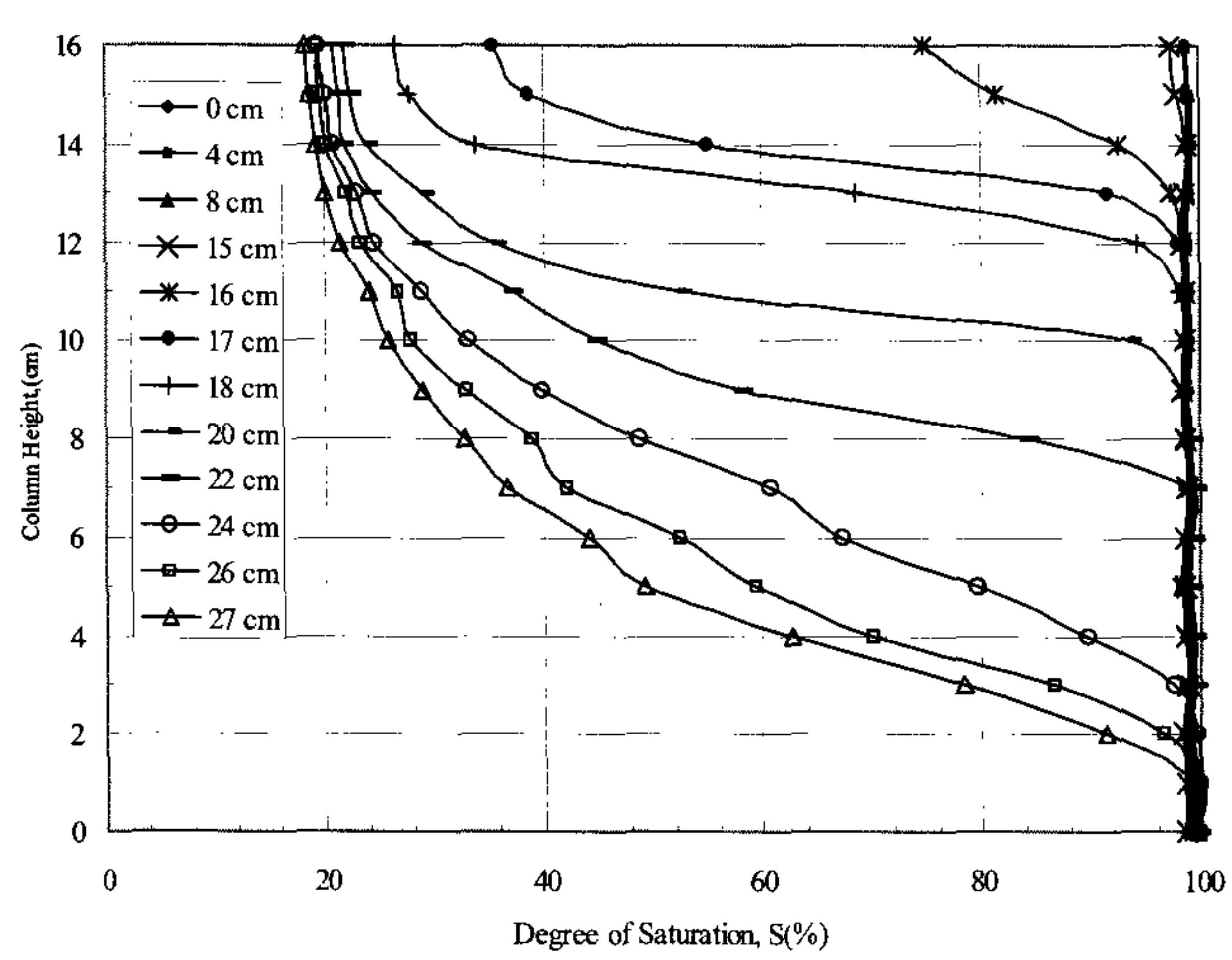

Fig. 12. Estimated degree of saturation in drying process using S-shape curve equation

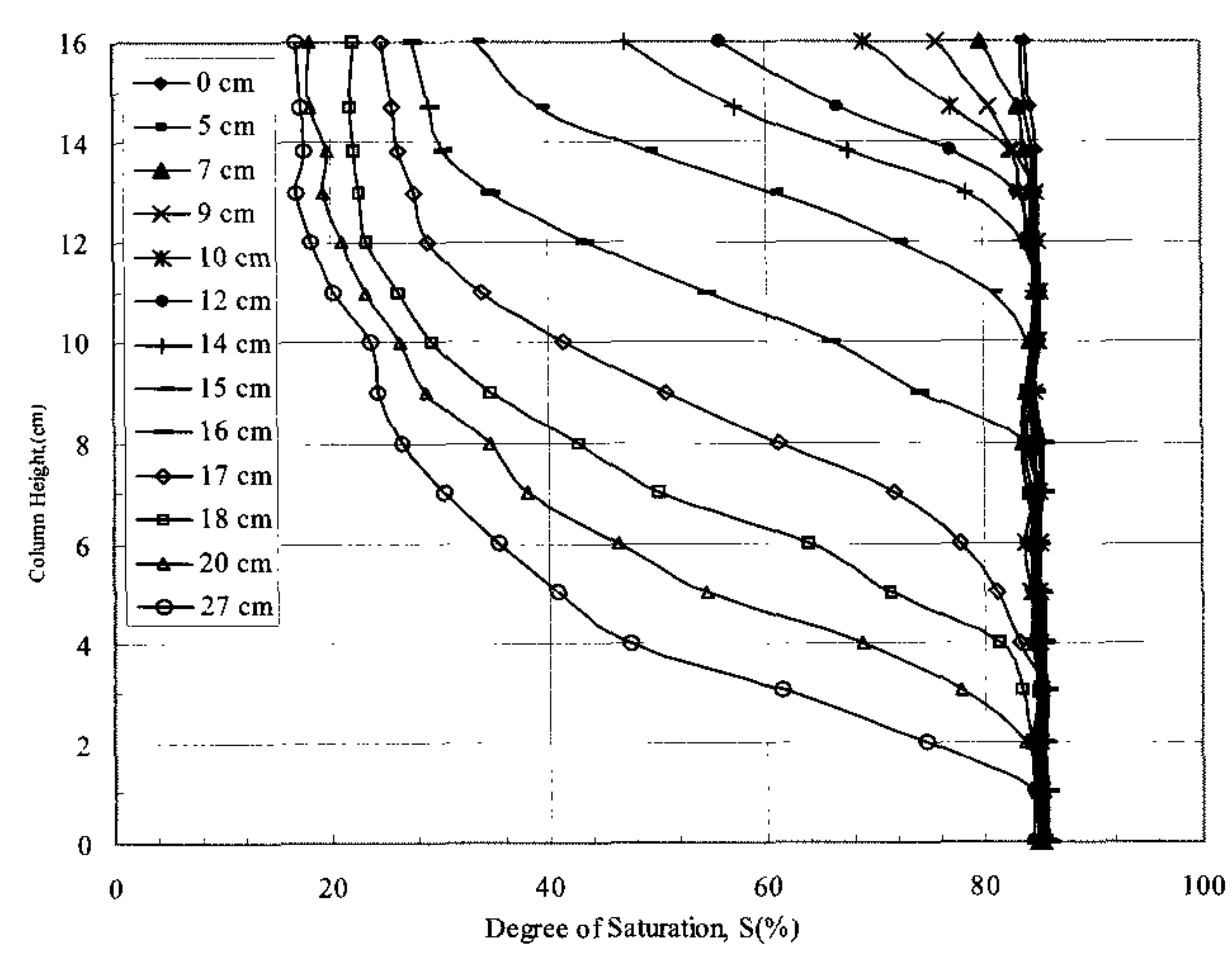

Fig. 13. Estimated degree of saturation in wetting process using S-shape curve equation

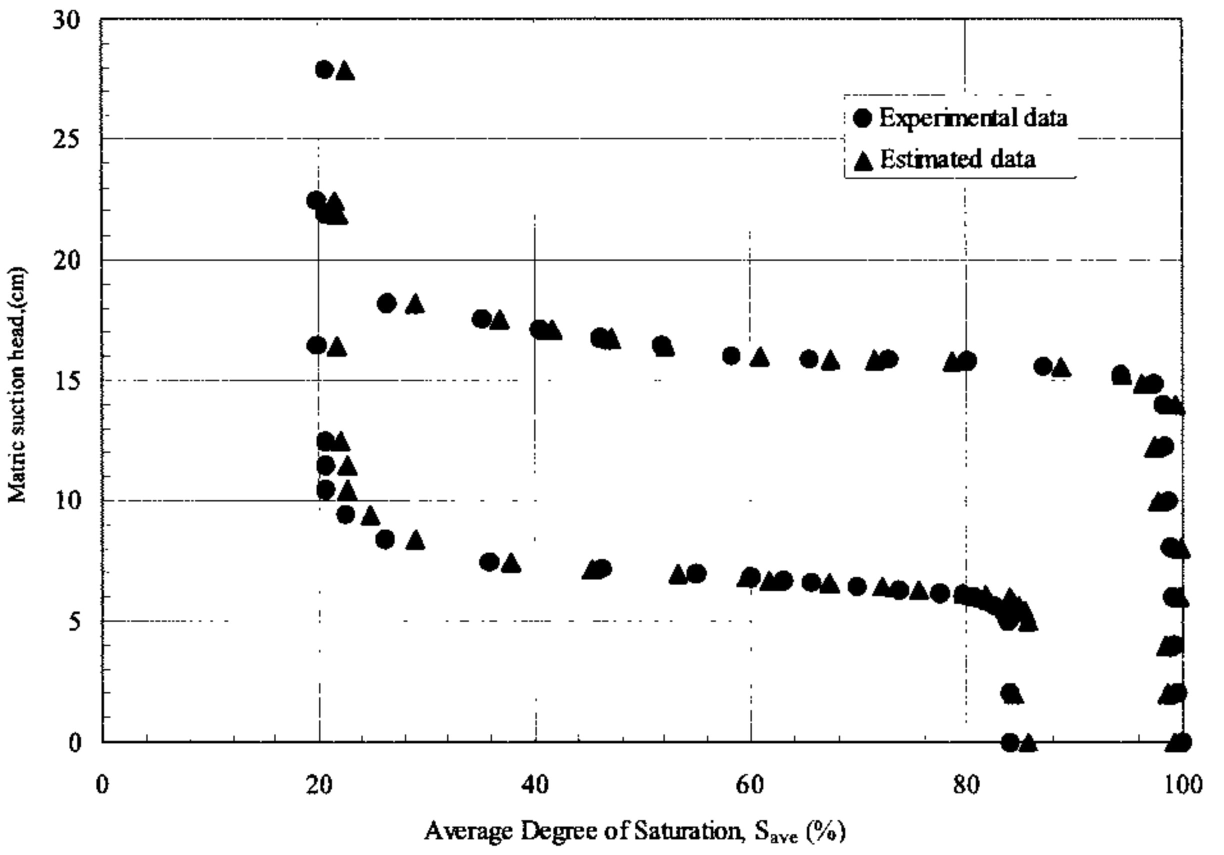

Fig. 14. Measured and estimated degree of saturation for main drying and wetting curves

the hanging water column test and the triangle symbols show successive estimated data from the DIA method. The estimated degree of saturation for drying and wetting SWCC is close to that from the experiment. But its shape does not fit the experimental data very well in the pendular zone. Also the similarity between the estimated air entry value and those which are obtained (refer to Fig. 9) in the experiment is clearly expressed. These results show that in the main paths of the SWCC the application of the estimated curve equation can be used and gives us the good agreement.

4. Conclusions

(1) Based on the sand column and the hanging water column test results during wetting-drying cycles, the DIA method for estimating the degree of saturation has been established.

(2) Comparisons between experimental and estimated results show that the DIA method was effective and could give the degree of saturation results in the drying and wetting SWCC rapidly at low suction cases.

(3) The determination of the degree of saturation of an unsaturated soil is time consuming and sometimes difficult. Hence, DIA has become a conventional engineering practice to estimate the unsaturated degree of saturation. To obtain reliable estimation of the degree of saturation, it is important to take into account some factors such as the arrangement of the lighting system, an evaporation of water and the shape of the air-water interface.

The results of this study are encouraging to use DIA method for the determination of the degree of saturation of the SWCC for granular materials. Furthermore, DIA method can be a useful tool for the future estimation of unsaturated problems, taking the place of complicated or expensive instruments.

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