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IJIE

http://penerbit.uthm.edu.my/ojs/index.php/ijie
ISSN : 2229-838X e-ISSN : 2600-7916

The International Journal of Integrated Engineering

Estimating Unsaturated Hydraulic Conductivity in Unsaturated Soil Using Soil Moisture Sensors

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DOI: https://doi.org/10.30880/ijie.2023.15.01.024
Received 23 April 2022; Accepted 20 December 2022; Available online 31 March 2023

Abstract: Unsaturated hydraulic conductivity (*K*) is a measurement of soil water-retaining ability in unsaturated soil. The unsaturated hydraulic properties are necessary to predict the movement of water in unsaturated soil. The current study aims to create an alternative experimental device to estimate the *K* using soil moisture sensors. The experimental set up was designed and fabricated in order to measure the volumetric water content using GS3 (Campbell) sensors at different heights. The data obtained from the sensors was validated using mass of moist sand column measured from electronic balance. The *K* was estimated with the help of retention and conductivity functions. The primary materials used in the study were solute-free water and sand. It was found that the reading from the sensors was in good match with the reading of the volumetric water content calculated from the mass of water in the sand column with a root mean square error of 0.0091. Soil water retention curve and hydraulic conductivity were plotted using Peters-Durner-Iden (PDI) model. The results were compared to the van Genuchten function. The *K* prediction was initially equivalent for both models, but the later overpredicts the falling rate of hydraulic conductivity with the increasing soil matric suction before underpredict after 200 cm matric suction on a sandy soil. PDI function was able to extrapolate the hydraulic conductivity film flow region of sandy soil.

Keywords: Soil water content sensor, characteristic curve, hydraulic conductivity function, MP6 and GS3 sensors

1. Introduction

Many soil scientists have been working on developing a reliable model with high accuracy in simulating the moisture movement in both engineering and agriculture applications since the 1960s [1]–[7]. However, due to the high temporal and spatial variability, information to describe the hydraulic properties in the unsaturated zone is inadequate in current soil physics theory [8]. Peters-Durner-Iden (PDI) model [5], [6] is one of the recently developed hydraulic conductivity model [9], which is simple, consistent, and able to link the capillary and film conductivity to capillary and

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adsorptive water retention [5]. According to Iden & Durner [6], this model has great potential in modeling water flow in the dry range, which is crucial for the study of evaporation and root water uptake phenomena.

The estimation of the unsaturated hydraulic conductivity (*K*) would improve the simulation model of the movement of water in unsaturated soil [10]. Water movement simulation is important because it can be used to predict the amount of water in the soil with time and depth [11], especially, the first 1.5 m from the soil surface that is crucial for plant growth like the palm tree, vegetation, and fruits tree [12]. An accurate surface and depth soil water distribution in the soil with time would improve agricultural land management [13].

K can be measured using HYPROP. The instrument is a commercially available measurement unit from Meter Group Inc. [14]. However, the instrument is not readily accessible to farmers due to the relatively high cost involve in owning the instrument. Hence, the exploration of a cost-effective measurement device is needed.

The current study aims to estimate the *K* through a fabricated measurement unit. Thus, a vertical sand column was designed and fabricated to measure volumetric water content (θ_L) using soil moisture sensors at different depths. The sensors' reading was validated by comparing it with the drying column mass loss due to evaporation. Finally, *K* was estimated with the help of retention and conductivity functions. Sand has been selected as the medium of investigation because the soil type is abundantly available in the coastal area of the east side of peninsular Malaysia, and it has been used by farmers in the area for plantation such as vegetable plant and fruit trees [15].

2. Methods and Materials

2.1 Design and Fabrication of the Experimental Setup

An open-top vertical sand column was designed and fabricated to allow the measurement of the θ_L and temperature (*T*) using GS3 sensors from Meter Group Inc. The image of the sensor is shown in Fig. 1. A sandy soil type is collected from the surrounding coastal area that is similar to the soil type used in the Agricultural Centre at Rhu Tapai, Department of Agriculture, Terengganu, Malaysia [12]. The site has 0.8% of clay, 1.8 and 97.5% for silt and sand, respectively. The sand column was then fabricated with an acrylic board below to support the weight of the column (Fig. 2).

Fig. 1 - GS3 sensor from Decagon [16]

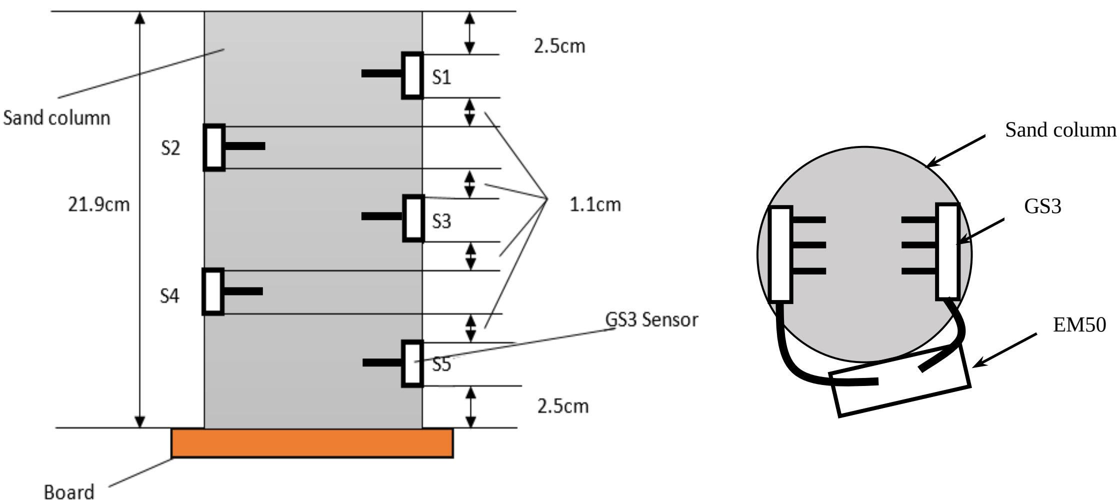

Fig. 2 - Cross-section side (left) and top (right) view of the sand column designed. The S1 to S5 are the soil moisture sensor (GS3). Note that the inner diameter of the column was 21.9 cm.

2.2 Data Inputs

Saturated hydraulic conductivity (K_s) was obtained from the falling head experiment. The K_s was calculated from the equation below:

$$K_s = \frac{2.3al}{At}\log_{10}\frac{h_1}{h_2} \tag{1}$$

where a (cm^2) is the area of the tube, l (cm) is the length of the soil height in the soil column, A (cm^2) is the area of the soil column (cm^2), t (s) is the time that the water takes to flow from the first marking on the tube to the second marking right below it, h_1 (cm) is the height of the top mark and h_2 (cm) is the height of the bottom mark where $h_1 > h_2$.

Bulk density (ρ_b) of soil is highly dependent on soil structural conditions such as compaction [17]. It was calculated using:

$$\rho_b = \frac{m_s}{V_t} \tag{2}$$

where m_s (g) is the mass of sand and V_t (cm^3) is the total volume occupied by sand, water, and air.

Saturated soil water content (θ_s, cm^3 cm^{-3}) is the measurement of maximum water content that can be contained in all the pore spaces. It is indispensable in the estimation of K [18]. In this study, θ_s was calculated from the experiment using:

$$\theta_s = \frac{m_w}{\rho_w v_t} \tag{3}$$

where m_w (g) is the total mass of water occupied the saturated soil, and ρ_w (g cm^{-3}) is the density of water estimated from the water temperature, which was measured by the GS3 sensor.

The θ_L at time step i was computed from the mass of the column using:

$$\theta_{L(i)} = \frac{m_i - m_t}{\rho_w V_t} \tag{4}$$

where m_i (g) is the mass of the sand column at a time step i, m_t (g) is the mass of empty column and sand, ρ_w (g cm^{-3}) is the density of water and V_t is the total volume occupied by sand, water and air. The computation of θ_L allowed the comparison between data obtained from sensors and electronic balance. This has made the validation of the data possible.

Matric suction (ψ), that is, the soil suction pressure was obtained through an experiment. A sand column with a height and diameter of 15 cm was built. Two GS3 sensors and water MPS6 sensors from Meter Group Inc., were inserted into the sand column. Data of matric suction (ψ) was collected from the experiment and computed using [19]:

$$\psi = \psi_e(\theta_L / \theta_s)^{-b} \tag{5}$$

where θ_s (cm^{3}cm^{-3}) is saturated water content calculated using Eq. (3), ψ_e (cm) and b (dimensionless) are curve-fitting parameters obtained by regression from retention data (θ_L and ψ) in the experiment.

2.3 Estimation of the Unsaturated Hydraulic Conductivity (K)

Retention function used was developed by Peter [5] and Iden & Durner [6], it is known as Peters-Durner-Iden (PDI) model:

$$\theta_L(\psi) = (\theta_s - \theta_r)S^{cap} + \theta_r S^{ad} \tag{6}$$

where θ_L (cm^3 cm^{-3}) is volumetric water content obtained from the experiment and ψ (cm) is matric suction obtained from MPS6 sensor. θ_s (cm^3 cm^{-3}) is saturated water content calculated from Eq. (3). θ_r (cm^3 cm^{-3}) is residual water content for water adsorption. S^{cap} is the saturation of capillary water retention and was solved using constrained function of van Genuchten [4]:

$$S^{cap}(\psi) = \tau(\psi) = \left[\frac{1}{1+(\alpha\psi)^n}\right]^{1-\frac{1}{n}} \tag{7}$$

Where α (cm^{-1}) and n (dimensionless) are curve fitting parameters. S^{ad} is the saturation of adsorptive retention. It was solved using function [6]:

$$S^{ad}(x) = 1+\frac{1}{x_a - x_o}\left\{x - x_a + b\ln\left[1+\exp\left(\frac{x_a - x}{b}\right)\right]\right\} \tag{8}$$

where $x = \log_{10}(\psi)$, $x_a = \log_{10}(\psi_a)$ and $x_o = \log_{10}(\psi_o)$. ψ_a and ψ_o are suctions at air entry and suction when water content is 0, respectively. b is parameter that depends on capillary saturation function in Eq. (7) which was given by:

$$b = 0.1+\frac{0.2}{n^2}\left\{1-\exp\left[-\frac{\theta_r}{\theta_s - \theta_r}\right]^2\right\} \tag{9}$$

Function with the sum of capillary and film conductivity [5] used was:

$$K = K_s\left[(1-\omega)K_{rel}^{cap}(S^{cap}) + \omega K_{rel}^{film}(S^{ad})\right] \tag{10}$$

where K_s (cm s^{-1}) is the saturated hydraulic conductivity obtained with the help of Eq. (1), K_{rel}^{cap} is relative conductivity for capillary flow and was given by:

$$K_{rel}^{cap} = (S^{cap})^{\tau}\left[1-\left(1-\left(S^{cap}\right)^{\frac{n}{n-1}}\right)^{1-\frac{1}{n}}\right]^2 \tag{11}$$

where K_{rel}^{film} is relative conductivity for adsorptive flow [5] and it was given by:

$$K_{rel}^{film} = \left(\frac{\psi_o}{\psi_a}\right)^{d(1-S^{ad})} \tag{12}$$

where d (dimensionless) defines the slope of the graph and it was fixed at value -1.5 [5], [20].

3. Results and Discussion

3.1 Soil Water Retention Curve

Fig. 3 shows the vertical soil column. Soil, water, and column properties are shown in Table 1. The sandy soil saturated water content of 0.42 m^3 m^{-3} falls within the normal range of sand porosity from 0.3 to 0.5 m^3 m^{-3}. The bulk density of 1.54 g cm^{-3} is well within the acceptable limit for planting, which is less than 1.7 g cm^{-3} that limits drainage [21]. The soil water content in the soil column was allowed to dry by evaporation at room temperature, 30°C. The parameters of θ_L and ψ were measured in a vertical sand column as the mass loss of water was recorded with a digital balance. Data of θ_L and ψ throughout time were respectively measured by GS3 and MPS6 sensors. The data were stored in a data logger (EM50 Decagon). The collected data of soil water content and soil matric suction is shown in Fig. 4. The values of Campbell constitutive equation fitting parameters ψ_e and b, as in Table 2, were obtained from curve fitting (RMSE of 1.149).

Fig. 4 shows the typical graphical illustration of the water characteristic curve, which relates soil water content and soil matric suction. A soil has less attraction for water when the soil is wet. In dry conditions, the soil matric has more surface area for water adsorption. Hence, the soil in region of higher ψ was low in θ_L than the one low in θ_L region.

The PDI retention function is the sum of capillary and adsorptive water retention [5], [6]. The soil water retention curve of the experiment was produced by curve-fitting the Eq. (6) to the data from the graph in Fig. 4. The result is showed in Fig. 5. In addition, the van Genuchten function was included for comparison. It was apparent that a discrepancy was found at ψ greater than 100 cm. This region was possibly dominated by film flow region. Table 3 shows the value of the parameters obtained from the regression with the data. θ_s was calculated using Eq. (3), and the adsorptive water retention (θ_r) was fixed at 0.045 [5]. Fitting parameters, α and n were solved using excel solver. Matric suction when the water content is zero (ψ_o) was set at $10^{6.8}$. Air entry suction (ψ_a) was treated as fitting parameter and solved using add-in function of excel. The RMSE of the regression is 0.013.

Table 1 - Information on the column and experiment

Parameters	Value
Initial mass of sand column (g)	9819.2
Total volume, v_t (cm^3)	3810.2
Mass of sand, m_s (g)	5867.7
Total mass of water used, m_w (g)	1594.3
Temperature of the water (°C)	30.1
Density of water, ρ_w (g cm^{-3})	0.996
Bulk density, ρ_b (g cm^{-3})	1.54
Saturated water content, θ_s (cm^3 cm^{-3})	0.42

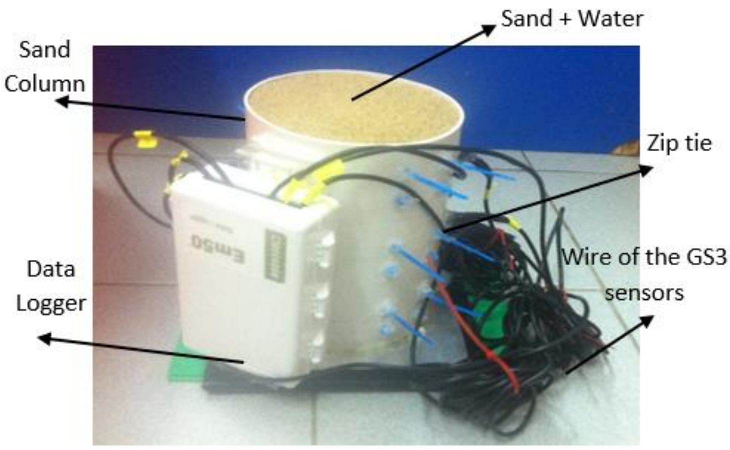

Fig. 3 - Vertical sand column

Table 2 - Parameter of Campbell [19] function

Parameters	Values
ψ_e (cm)	57.885
b (dimensionless)	0.2195

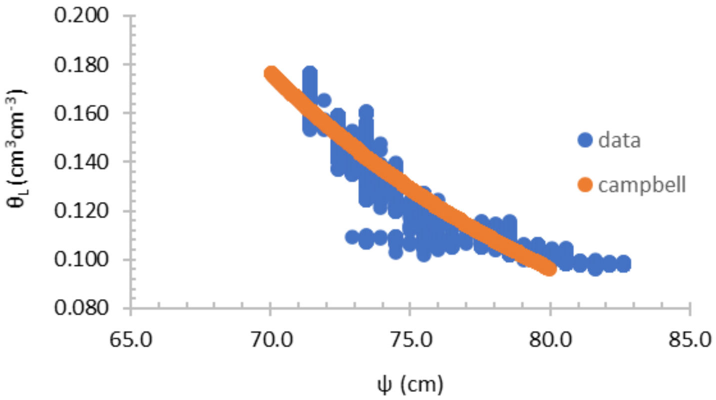

Fig. 4 - Soil water retention curve using Campbell (1974)

Table 3 - Parameters of retention function

Parameters	Values
θ_s (cm^{3}cm^{-3})	0.42
θ_r (cm^{3}cm^{-3})	0.045
α (cm^{-1})	0.01531
n (dimensionless)	18.659
ψ_a (cm)	28.936
ψ_o (cm)	$10^{6.8}$
b (dimensionless)	0.09999

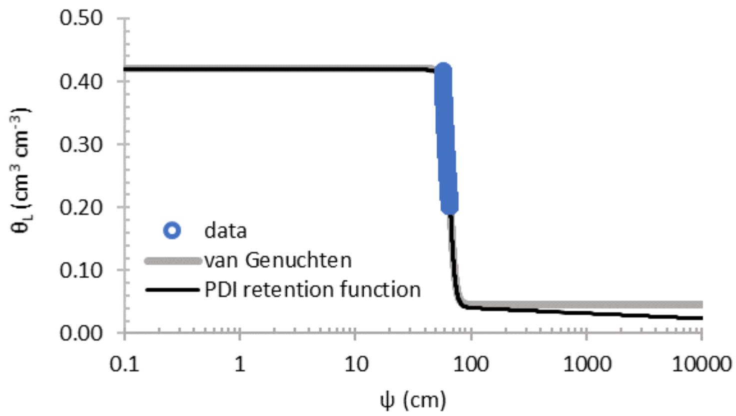

Fig. 5 - Soil water retention curve

Fig. 5 shows a typical θ_L and ψ relation of a sandy soil that the θ_L remained relatively constant with increasing ψ. Further increasing the ψ results in sudden drop of θ_L from 0.42 (that is the θ_s) to 0.05 as given by van Genuchten function, but further decreasing value was expected for PDI function, which was the film flow region. Hence, the Fig. 5 shows a good match between experimental data and curve-fitting and the matric suction at a drier range of soil is not investigated in the current studies.

3.2 Hydraulic Conductivity Curve

The K_s is one of the essential parameter in order to predict K. In this study, it was estimated using falling-head approach [22]. Soil bulk density affects the K_s [23]. The K_s of different ρ_b were calculated using Eq. (1). The graph of the relationship of K_s and ρ_b was plotted (Fig. 6). The relationship was described using linear equation with a R^2 equals to 0.8786.

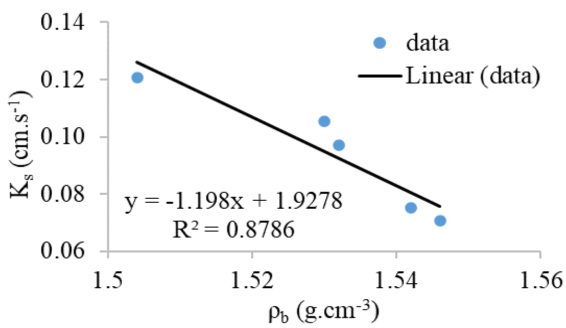

Fig. 6 - Saturated hydraulic conductivity (K_s) versus bulk density (ρ_b)

The K_s in the experiment was estimated using the linear equation in Fig. 6 according to the ρ_b used in the experiment (Table 1). It was found that the K_s was 0.081 cm s^{-1} when the ρ_b of the experiment was 1.54, which was the bulk density of the vertical sand column. The K_s was found comparable to the one shown in Fig. 7.

The K of sand from van Genuchten function was compared to the one from PDI conductivity function based Eq. (10). The result is showed in Fig. 7. The K values from both conductivity functions appeared similar up to 70 cm ψ

before starting to decline more abruptly for PDI conductivity than the van Genuchten conductivity function. From the 70 to 200 cm ψ, the van Genuchten conductivity function overpredict the K values than the other function. However, after 200 cm ψ, the van Genuchten K continued to decline at relatively constant rate, whereas PDI predicted K values were dominating the high ψ region, which was film flow region. Table 4 shows the parameter used in the PDI conductivity function.

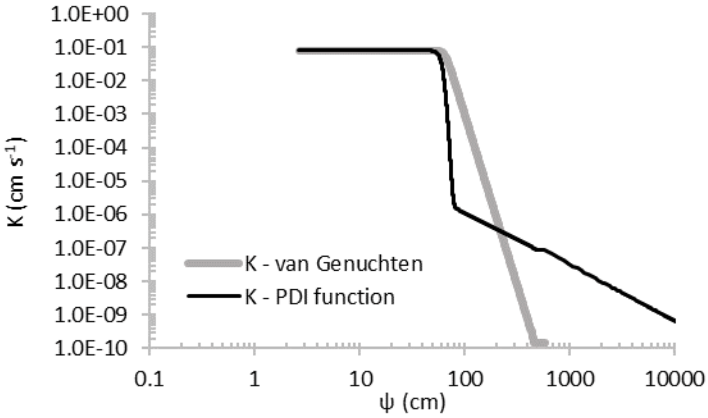

Fig. 7 - *K* curve predicted by PDI model

Table 4 - Parameters of conductivity function

Parameters	Values
ω (dimensionless)	0.0001
n (dimensionless)	18.659
ψ_o (cm)	$10^{6.8}$
ψ_a (cm)	28.936
d (dimensionless)	-1.5

4. Conclusion

The K was estimated through an experimental construct with the use of retention and function of PDI model. In addition, the van Genuchten function was included for comparison with the PDI function. The fabricated sand column allowed the measurement of the volumetric water content using the GS3 sensors. The reading showed a good match with the volumetric water content computed from the mass of measured water in column with RMSE of 0.0091. A drier soil region was not investigated in the current study. Nevertheless, the characterstic curve showed similar to that of any sandy soil. The experimental set-up is less costly than other devices, such as hyprop, which is also used for same purpose. The instrument will be useful for laboratory based measurement for K that can be used for the prediction of moisture movement in unsaturated zone.

Acknowledgement

This research was supported by Ministry of Higher Education (MOHE) through Fundamental Research Grants Scheme FRGS/1/2020/STG08/UMT/02/2.

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