Journal of Applied Fluid Mechanics, Vol. 2, No. 2, pp. 1-11, 2009.
Available online at www.jafmonline.net, ISSN 1735-3572, EISSN 1735-3645.
DOI: 10.36884/jafm.2.02.11859

Applications of Hydraulic Properties Models on Microscopic Flow in Unsaturated Porous Media

T. Bunsri[1], M. Sivakumar[2] and D. Hagare[3]

[1] *National Center of Excellence for Environmental and Hazardous Waste Management (NCE-EHWM), Department of Environmental Engineering, Faculty of Engineering, King Mongkut's University of Technology Thonburi, Bangkok 10140, Thailand*
[2] *Sustainable Water and Energy Research Group (SWERG), School of Civil, Mining and Environmental Engineering, Faculty of Engineering, University of Wollongong, NSW 2522, Australia*
[3] *Sterling College, Level 3, 770 George Street, Sydney, NSW 2000, Australia*
Email: thidarat.bun@kmutt.ac.th

(Received December 6, 2007; accepted October 29, 2008)

ABSTRACT

Several existing equations for solving the non-linear soil-hydraulic properties are introduced and validated to field and laboratory measured data. Models for non-linear hydraulic properties of unsaturated porous media arise from statistical and mathematical fit through the measured data and they can be expressed in forms of unsaturated permeability versus either pressure head or volumetric moisture content. This paper presents the difference models: Gardner, Knuze et al., Haverkamp et al., van Genuchten and Saxton et al. for calculation of hydraulic properties coefficients, typically unsaturated permeability. The accurate and computational efficiency of these five existing models are evaluated for a series of study cases simulating hydraulic properties of unsaturated porous media. The results indicate that all existing models can be applied to homogenous and heterogenous unsaturated porous media, dry and wet cycles and laboratory and field measuring data. Besides, the statistical fit model is inefficient compared to mathematical fit models. Among the mathematical fit models, van Genuchten model is the most promising model. Gardner model can be competitive with van Genuchten model and Haverkamp et al. model is less efficient than others. The mathematical fit models appear to be attractive alternatives to estimate the unsaturated permeability, although there are concerns regarding the stability behaviour of the occupied air in pores, which need to be resolved. The air movement in unsaturated porous media affected the unsaturated permeability, which gives the difference results between wet and dry cycle. Both of unsaturated permeability and volumetric water content of dry cycle were higher than ones of wet cycle. This suggests that the velocity of air-releasing during a wet process was higher than the velocity of air-entering during a dry process. The infiltration is the most important land applications. So, the wet cycle hydraulic properties test might be concerned. Moreover, most of infiltration fields locate on the mixed grain media. So too, the pore-size distribution could affect the unsaturated permeability of porous media. It was observed that the finer material, the lower unsaturated permeability.

Keywords: Hydraulic properties models, Soil-water retention curve, Unsaturated permeability, Unsaturated porous media.

NOMENCLATURE

A coefficient for Haverkamp et al. models; unitless
a coefficient for Haverkamp et al. models; unitless
B coefficient for van Genuchten models; cm^{-1}
C coefficient for Saxton et al. models; unitless
D coefficient for Saxton et al. models; unitless
e porosity; unitless
g acceleration of gravity
i interval number for Kunze et al.model; unitless
j counter number for Kunze et al. model; unitless
k_{rw} unsaturated permeability coefficient; unitless
K_S saturated permeability; cm h^{-1}
$K_S k_{rw}$ unsaturated permeability; cm h^{-1}
$(K_S)_{cal}$ calculated saturated permeability; m s^{-1}
$(K_S)_{mea}$ measured saturated permeability; m s^{-1}
m coefficient for van Genuchten models; unitless
N total number interval for Kunze et al. model; unitless
$\tilde{n}$ pore size distribution; unitless
n coefficient for van Genuchten models; unitless
S degree of saturation; unitless
T_s surface tension of water; kN m^{-1}
U_a pore-air pressure; kPa
U_w pore-water pressure; kPa
α coefficient for van Genuchten models; cm^{-1}
β coefficient for Haverkamp et al. models; unitless
γ coefficient for Haverkamp et al. models; unitless
μ_w absolute viscosity of water kN m^{-1}
θ_{10} volumetric water content at 10 kPa; cm^3 cm^{-3}
θ_r residual volumetric water content; cm^3 cm^{-3}
θ_S saturated volumetric water content; cm^3 cm^{-3}
θ volumetric water content; cm^3 cm^{-3}
ρ_w density of water; kg m^{-3}
ψ hydraulic pressure head; cm
ψ_e air entry pressure for Saxton et al. models; kPa

1. INTRODUCTION

The movements of water in unsaturated porous earth material and associated moisture content profiles are vitally important in study of global geo-hydrologic cycle. This cycle starts from infiltration of rainfall precipitated in land area, which this natural process provides the water for cultivation and ends at the groundwater reservoirs. To estimate the movement of infiltration, hydraulic permeability coefficients of unsaturated soils including relative permeability and specific storage coefficients are required. The value of relative permeability is normally much higher than the specific storage. The specific storage could be neglected in the traditional Richards equation, which was applied to calculate the unsaturated water flow (Ségol 1994). The coefficient of unsaturated permeability is better determined by direct measurement such as a rigid wall or flexible-wall permeameter. However, these direct measurement techniques are time consuming, labour intensive and tedious (Agus et al. 2003). So, the indirect measurements of these coefficients are technically undertaken by available measuring devices that determine the relative parameters involving volumetric water content and surface tension.

The measurement of volumetric water content in undisturbed soils can be made using electrical resistance blocks (Hillel 1980, Williams 1980), neutron moisture meters (Hillel 1980), gamma-ray scanners (Hillel 1980) and others new techniques that depend on the relation between water content and the dielectric constant of volume of soil, including capacitance technique (Dean et al. 1987; Bell et al. 1987) and time domain reflectometry (Topp et al. 1980; Zegelin et al. 1989; Roth et al. 1990). Dealing with a rapid progress of wireless technology, many researches are currently focusing on the way to assess and improve the information systems, especially remote sensing devices. The measurement of water content was developed by using the microwave emissivity with 21-cm wavelength, this systems could be combined with satellite, the signal can be recorded even the site was very far and in the worse conditions e.g. cloudy, moderate vegetation cover and etc. (Dingman, 1994). However, the soil moisture could be simply monitored by measuring of a surface tension forces. The tension of soil moisture can be measured using the tensiometers. The practical measurable range of tensiometer is from 0 to 800 cm, which covers mostly part of tension range observed in fine aggregate in a natural field condition (Fredlune and Rahardjo 1940; Hillel 1980). A series of tensiometers are commonly installed at the different depths to measure the vertical tension gradients. The pressure transducer attached inside the tensiometer body can be connected to the data logger, the pressure head reading can be recorded continuously (Cooper 1980). The advanced technology can function the remote sensing in the data logger. The pressure head in the field condition can be measured conveniently because there is no need for any external electrical or radiation energy, comparing to the volumetric moisture content measurement.

As measurement of these hydraulic coefficients are costly, difficult and sometimes impractical (Saxton et al. 1986). For general estimation, many statistical and mathematical models were developed to describe the volumetric water content and unsaturated permeability relationships with surface tension e.g. models of Childs and Collis-George (1950); Burdine (1953); Gardner (1958); Brooks and Corey (1964); Kunze et al. (1968); Arbhabhirama and Kridakorn (1968); Mualem (1976); Haverkamp et al. (1977); van Genuchten (1980); Saxton et al. (1986); Broadbridge and White (1988); Yeh and Harvey (1990); and Agus et al. (2003). This paper accesses and compares the estimation of hydraulic permeability of five models with different data fitting techniques: Gardner (1958); Kunze et al. (1968); Haverkamp et al. (1977); van Genuchten (1980); and Saxton et al. (1986), which were normally served hydraulic coefficients in Richards' equation. This might be the alternative way to effectively and accurately estimate the hydraulic coefficients in unsaturated porous media.

2. HYDRAULIC PROPERTIES EQUATIONS FOR UNSATURATED POROUS MEDIA

Flow of water in unsaturated porous materials that contains continuous channels occupied by air, is theoretically defined as a two-phase flow problem involving air and water. However, the unsaturated flow is generally simplified to a single-phase flow system by assuming that the pressure of air is at constant atmospheric pressure (Ségol 1994). The unsaturated permeability of porous material can be described as a function of saturation degree; S, void ratio; e and volumetric water content; θ (Fredlune and Rahardjo 1940).

$$k_{rw} = k_{rw}(S,e)\text{; or } k_{rw} = k_{rw}(e,\theta)\text{; or } k_{rw} = k_{rw}(\theta,S) \tag{1}$$

The relative permeability coefficient with respect to the water content in porous media can be simplified as a function of surface tension of unsaturated soil pore (Fredlune and Rahardjo 1940).

$$k_{rw} = \frac{\rho_w g}{\mu_w} K_S \tag{2}$$

Based on the available measuring devices, the relative permeability can be indirectly measured using the pressure head that related to the surface tension and volumetric moisture content. The relationship between the coefficient of unsaturated permeability and hydraulic pressure head was firstly proposed by Childs and Collis-George (1950). Soil was assumed to have a random distribution of pores, various pore spaces and incompressible structure. The permeability function was modified using several mathematical techniques. Thus, the equations focused in this work involved the different solving techniques, which can be applied to fit highly nonlinear pressure head and volumetric water content dependencies in the specified unsaturated permeability terms.

2.1 Gardner's equation

The unsaturated permeability coefficients were fitted using linearised exponential technique. The relative permeability depended upon the fully saturated permeability and the pore size distribution. These relationships were functioned as follows (Gardner 1958).

$$\ln(k_{rw}) = \ln(K_S) - \tilde{n}\,\psi \tag{3}$$

2.2 Kunze et al.'s equation

The unsaturated permeability function was derived based on Poiseuille's equation. The equations are presented in SI Unit and pore-water pressure instead of pressure head.

The equations are presented as follows (Kunze et al. 1968).

$$k_{rw} = \frac{(K_S)_{mea}}{(K_S)_{cal}} \frac{T_S^2 \rho_w g \theta_S^2}{2\mu_w N^2} \sum_{j=1}^{m} \left\{(2j+-2i)(U_a - U_w)_j^{-2}\right\} \quad (4)$$

$i = 1,2,...,m$ and j = a counter from "*i*" to "*m*"

2.3 Haverkamp et al.'s equations

This model was obtained from the laboratory data fitting. The analytical expression, obtained by a least square fit. The equation is given as follows (Haverkamp et al. 1977).

$$K_S k_{rw} = K_S \frac{A}{A + |\psi|^{\gamma}} \quad \text{and} \quad \theta = \frac{a(\theta_S - \theta_r)}{a + |\psi|^{\beta}} \quad (5)$$

2.4 van Genuchten's equations

This model was derived from the expansion of Brooks and Corey (1964) equation. The equation is given as follows.

$$K_S k_{rw} = K_S \frac{\left\{1 - \left(B|\psi|^{n-1}\left[1 + (\alpha|\psi|)^n\right]^{-m}\right)\right\}^2}{\left[1 + (B|\psi|)^n\right]^{m/2}} \quad \text{and}$$

$$\theta = \theta_r + \frac{\theta_S - \theta_r}{\left[1 + (\alpha|\psi|)^n\right]^m} \quad (6)$$

with $m = 1 - \frac{1}{n}$

2.5 Saxton et al.'s equations

The equations were developed for all inclusive soil texture. The experimental data were fitted using the statistical analysis. The equations are given as follows (Saxton et al. 1986).

For applied tension range: 10 to>1500 kPa

$$\psi = C\theta^D \quad (7a)$$

For applied tension range ψ_e to 10 kPa

$$\psi = 10.0 - (\theta - \theta_{10})(10.0 - \psi_e)/(\theta_S - \theta_{10}) \quad (7b)$$

For applied tension range 0.0 to ψ_e kPa

$$\theta = \theta_S \quad (7c)$$

with $C = \exp\left[\begin{matrix} -4.396 - 0.0715(\%clay) - 4.880x10^{-4}(\%sand)^2 \\ -4.285x10^{-5}(\%sand)^2(\%clay) \end{matrix}\right] 100.0$

number of samples=44, R^2=0.99, and;

$$D = -3.140 - 0.00222(\%clay)^2 - 3.484x10^{-5}(\%sand)^2(\%clay)$$

number of samples=44, R^2=0.99.

$$\theta_{10} = \exp[(2.302 - \ln C)/D]$$

$$\theta_S = 0.332 - 7.251x10^{-4}(\%sand) + 0.1276\log(\%clay)$$

$$\psi_e = 100.0[-0.108 + 0.341(\theta_S)]$$

The existing hydraulic properties equations were applied to estimate the soil-water characteristic curves presented in both of published literatures and laboratory data yielded in this work. The details of experimental setup are described in the following section.

3. Material And Methods

A laboratory scale infiltration column set up is illustrated in Fig. 1. The column was fabricated from a plexi-glass tube of 6.59 cm inside diameter and 30 cm long.

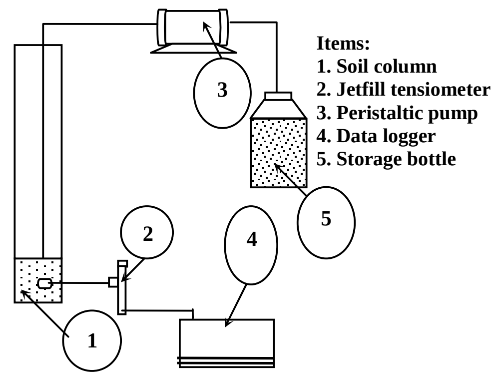


Fig. 1. Laboratory soil column test

The hydraulic properties test was carried out according to the dynamic method (Klute 1986). The homogeneous porous media utilised in this work included sand and soil. Medium grained samples of sand from river stock were sieved, with particle size ranging from 250 to 500 μm. The effective particle size of medium sand; d_{10} is 250 μm and the uniformity coefficient (d_{60}/d_{10}) is 2.00. The soil sample was collected from topsoil behind building 4-Engineering at the University of Wollongong, Australia. Soil sample was kept air dried for one week. All coarse impurities were removed and then sieved, the soil particle sizes were found to be less than 2.00 mm. A medium grain sand and topsoil samples were packed for 5 cm deep with respect to their actual field bulk densities (sand= 1.8 g/cm^3 and soil= 1.25 g/cm^3). A single tensiometer (Jet-fill tensiometer model 2100F) was inserted at the middle of soil column at the depth of 2.5 cm above the column base. The infiltration experiment was fed with Wollongong city tap water to produce varying moisture contents. All the samples of sand and soil were removed and the water content was analysed immediately. The water content was determined using the gravimetric method (AS 1289.2.1.1-1992; Rayment and Higginson 1992).

4. Applications Of Existing Hydraulic Properties Equations

4.1 Hydraulic Properties of Homogeneous and Heterogeneous Porous Media

The classical test of hydraulic properties was conducted by Yeh and Harvey (1990). The laboratory infiltration column tests were undertaken under a steady state condition to determine the relative permeability of heterogeneous sands. Three infiltration columns were packed consisting of coarse sand, medium sand and alternating layers of coarse and medium sand, respectively. The relative hydraulic permeability was determined using a technique modified from a long-column version of Klute and Dirksen's steady state flux control method. A constant hydraulic flux was applied at the column surface and a constant head was maintained at the bottom to establish a unit hydraulic gradient in the upper region. Yeh and Harvey described their experimental setup as follows: “The experimental set up (Fig. 2) includes a soil column, a tensiometer-manometer system, a multi-channel syringe pump and a recycle tank. Tensiometers with water manometers were used for coarse, medium and layered sand columns, respectively. Each tensiometer-manometer consisted of a 0.64 cm outer diameter and 2.9 cm long porous ceramic cup (high flow, 0.5 bar, Soil Moisture Corporation) into which was inserted and glued with epoxy adhesive two meters of 0.32 cm outer diameter tygon tubing. The tensiometer-manometer systems were checked for air leaks before they were installed at various heights of the upper portion of the soil columns”.

The circles presented in Yeh and Havey’s experiments are the tensiometer locations and the dimensions are in cm. The tests were conducted in both initially dry and wet conditions to estimate the hydraulic constants in dry and wet cycle, respectively. In dry cycle, soil column was initially saturated, and then column was drained until achieving a steady-state downward flow. During the draining period, the hydraulic permeabilities were analysed.

In the wet cycle, the initially dry column was fed with water uniformly, until the column achieved the fully saturation condition. The changes of hydraulic permeabilities were examined during the feeding period. The fully saturated hydraulic permeabilities of coarse and medium sand were 0.1126 and 0.0905 cm/s, respectively. The properties of packing material are given in Table 1.

Table 1 Properties of sand (Yeh and Harvey 1990)

Media	Bulk Density (g/cm^3)	Porosity
Coarse Sand	1.51	0.430
Medium Sand	1.45	0.454
Layered Sand:		
Layer 1 (Coarse)	1.46	0.449
Layer 2 (Medium)	1.46	0.449
Layer 3 (Coarse)	1.53	0.423
Layer 4 (Medium)	1.50	0.434
Layer 5 (Coarse)	1.56	0.411

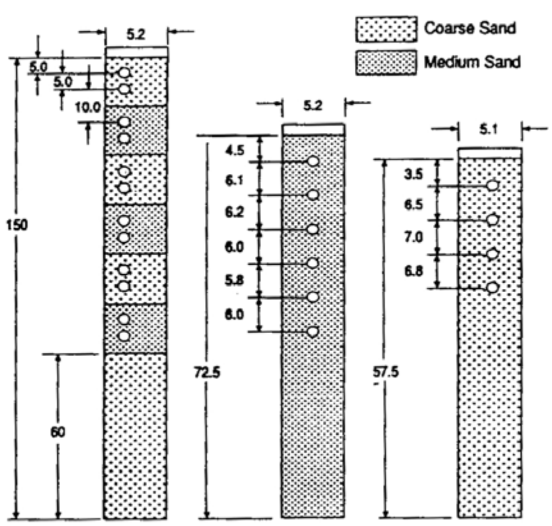


Fig. 2. Infiltration tests (Yeh and Harvey 1990)

In the original work of Yeh and Harvey, unsaturated permeability terms $(K_S k_{rw})$ and pressure head (ψ) were presented, thus the existing hydraulic properties equations can fit these data including of equations of Gardner (GD), Haverkamp et al. (HV), and van Genuchten (VG). All experimental data were cited and reported by Ségol (1994). The obtained results for hydraulic properties testing of coarse, medium and layered sand columns are presented in Fig. 3(a), (b) and (c), respectively. The parameters for hydraulic conductivity models are presented in Table 2.

Table 2 Hydraulic conductivity coefficient

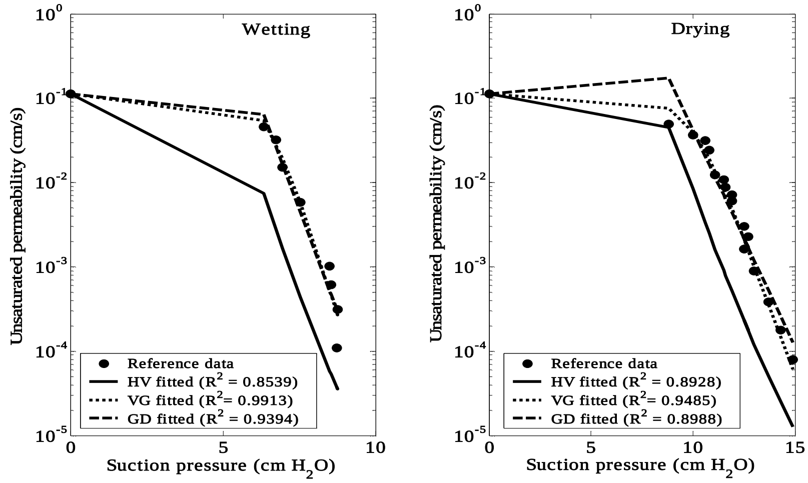
Media	HV		VG		GD	
	A	γ	B	n	ln K_S	$\tilde{n}$
Coarse Sand Wetting	1.52×10^{12}	16.648	0.143	10.16	11.21	2.206
Coarse Sand Drying	2.37×10^{15}	16.649	0.092	9.30	8.666	1.184
Medium Sand Wetting	1.07×10^{5}	6.7554	0.0913	4.27	1.202	0.5225
Medium Sand Drying	4.20×10^{6}	7.6885	0.074	4.72	1.781	0.4716
Layered Sand Wetting	3.17×10^{4}	7.7151	0.149	4.288	1.480	0.8675
Layered Sand Drying	3.52×10^{12}	13.142	0.0781	7.015	7.512	0.9293

Among these models, van Genuchten’s equations could generate the best fit for all experimental data. Gardner’s equation could also fit the experimental data well, however, the differences between fitted curve and experimental data was found when the columns nearly achieved the fully saturation. This related to the pore size distribution since pores were partly occupied with water. Haverkamp et al.’s equations can possibly fit these data. There were some significant differences between the fitted curve and experimental data, especially in the layered column. This revealed that the equation of Haverkamp et al. may not be suitably applied with the heterogeneous porous media. In addition, it was found that the higher suction pressure, the finer porous media. The values of unsaturated permeability terms obtained from dry cycle were higher than the ones yielded from wet cycle for every test.

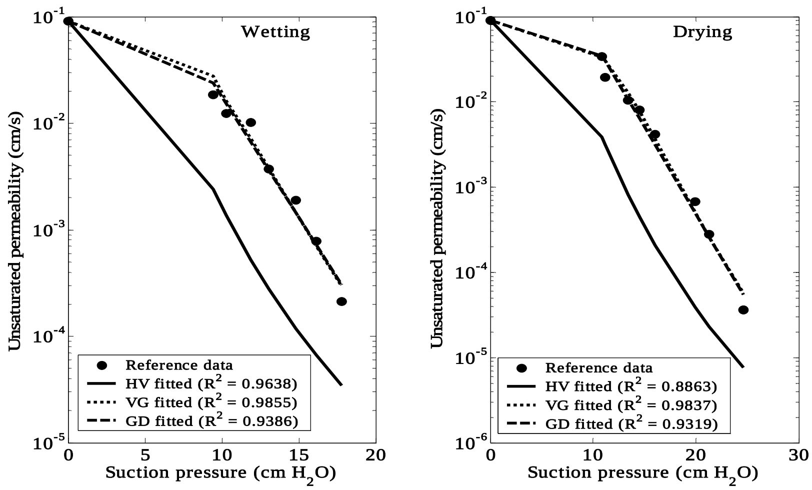
This related the movement of air through sand pores. Freudlune and Rahardjo (1940) suggested that the measurement of unsaturated permeability from either wet or dry cycle must be concerned the accumulated air inside the pores. The amount of diffused air inside the pores can be indirectly determined using the volumetric water content.

4.2 Measurement of Ideal Hydraulic Properties

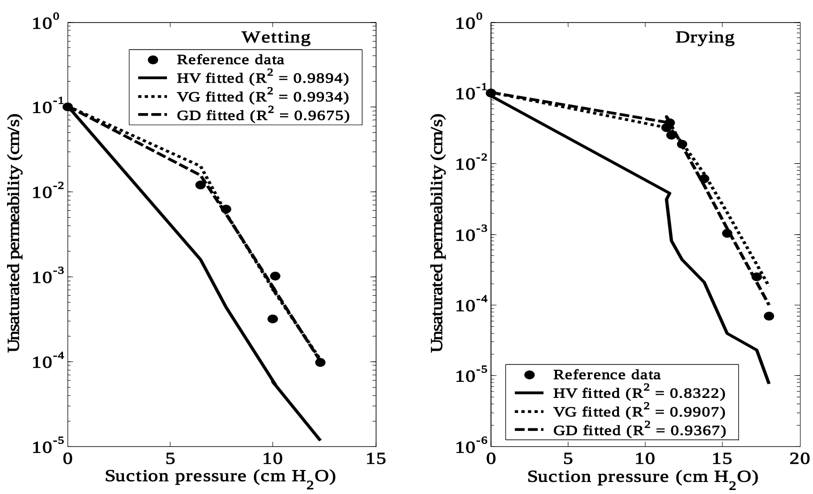
A case study presented the computation of relative permeability coefficient coupling the movement of air was reported by Fredlune and Rahardjo (1940). The plot of suction pressure versus volumetric water content is given in Fig. 4.



(a) Coarse sand



(b) Medium sand



(c) Layered sand

Fig. 3. Unsaturated permeability versus pressure head under wet and dry cycles

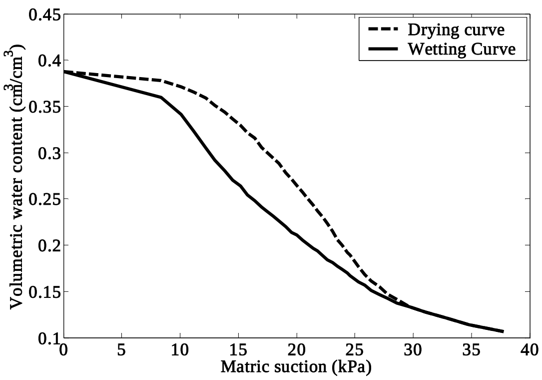


Fig. 4. Matric suction versus volumetric water content (Fredlune and Rahardjo 1940)

The saturated and residual volumetric water contents corresponded to soil-water characteristic curve of dry cycle are 0.388 and 0.102, respectively. Upon completion of the drying process, the hydraulic properties test was continued with the wetting process. The saturated and residual water contents presented in the wetting curve were same as the ones governed from the drying curve. A little difference of matric suction and volumetric water content were found in drying and wetting curve, typically in partially saturation condition. At the same volumetric water content, the matric suction presented in wetting curve was lower than one presented in drying curve. This might result from the movement of air bubbles, which entered to the soil pores during the drying process and released from soil pores during the wetting process. Air could move through the soil pore very quickly, so the matric suction changed rapidly in the drying process. On the other hand, the released air were easily trapped in the soil pores, hence the matric suction changed gradually in the wetting process. The slope of soil-water characteristic curve in a drying cycle was sharper than the one in a wetting cycle.

The authors did present only the calculated unsaturated permeability of dry cycle. The unsaturated permeability can be estimated only using Knuze et al.'s. The obtained results are presented in Fig. 5. Although, the measurement of unsaturated permeability discussed previously revealed that the different testing process gave the different unsaturated permeability, the calculated unsaturated permeability yielded from Knuze et al.'s equation in both of drying and wetting cycles were identical. The calculated unsaturated permeability might present the ideal case that there was equilibrium of entry and release of air. By comparison, the calculated unsaturated permeability governed from the original work and this present study was slightly different. The results confirmed that this empirical equation could estimate the unsaturated permeability effectively. By using Knuze et al.'s equation, unsaturated hydraulic permeability might be estimated in very short period by either dry or wet cycle. The long testing period could bring more diffusion of air in soil pore, this potentially disturb the pressure head (Fredlune and Rahardjo 1940).The authors' results demonstrated that Knuze et al.'s equation can prevent the oscillations that occurred near the saturation zone. Overall, using Knuze et al.'s equation provided significant advantages in mass conservative.

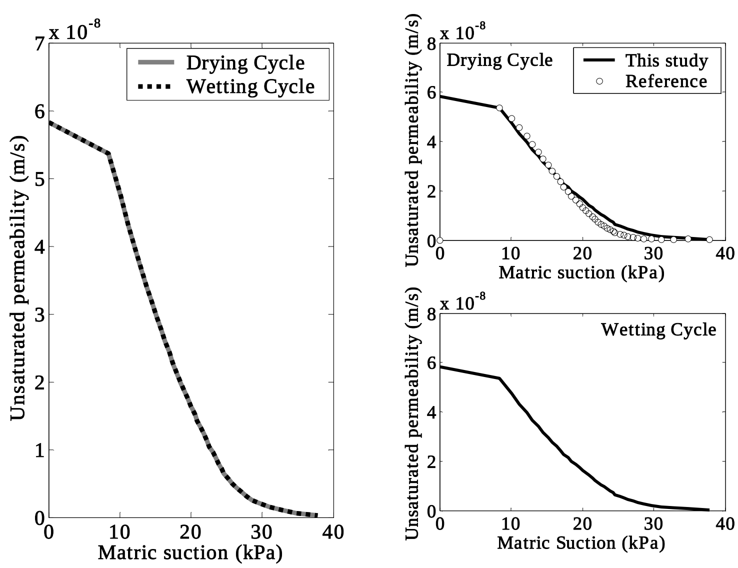


Fig. 5. Matric suction versus calculated relative permeability

4.3 Measurement of Hydraulic Properties Based on Soil Texture

Due to the limitation of measurement of air movement, there are some difficulties to obtain the accurate measurement of unsaturated permeability. Since the movement of air related to size of soil pore and diffusion, the unsaturated permeability could be estimated using the soil texture. Elzeftawy and Cartwright (1981) investigated the unsaturated permeability in a real field condition and the soil was classified as Lankland fine sand. The unsaturated permeability and volumetric water content were measured in several field depth, which were 0-0.15, 0.30-0.45 and 0.60-0.90 m. Saxton et al.'s equations were applied to estimate the unsaturated permeability for this field study. Saxton et al.'s equation could generate the possible volumetric and unsaturated permeability. From this best fit, the residual error was 2-10%, which might be in an acceptable range. The calculated volumetric water content and unsaturated permeability are presented in Fig. 6. The field data revealed that the measurement of volumetric water content and unsaturated permeability depended upon the depth of sand layer. The different depth could bring the different particle distribution. Sand sample at a deep layer might be very dense and the volumetric water content is very low. Furthermore, the weight of the top layers caused a high pressure head in a bottom layer. The unsaturated permeability of the bottom layer might be higher than the top layer.

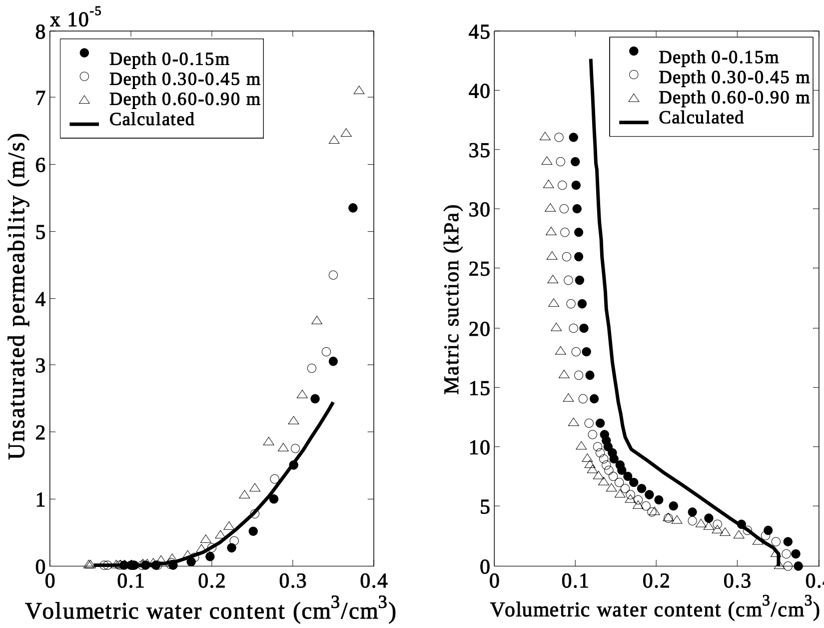


Fig. 6. Comparison between field measured and calculated hydraulic properties

4.4 Measurement of Hydraulic Properties for Land Applications

Most of researches had been determined the unsaturated hydraulic properties of sand. Based on the land applications, many applications were the drainage and infiltration fields that water penetrates from soil surface and moves through soil matrix due to the gravitational force. Furthermore, many drainage fields were located in a mixed grained soil layer that contained sand, silt and clay particles. So, the laboratory study was investigated to compare the hydraulic properties of medium grained sand and top soil. Sand could present the hydraulic properties of well-sorted material, while soil could show the hydraulic properties of mixed grained material. The physical properties of utilised sand and soil samples are presented in Table 3.

The observed hydraulic properties of these media were presented in Fig. 7. The plot of pressure head versus volumetric water content of sand was found that the water content increased rapidly, when the pressure head was higher than -50 cmH_2O. The saturated and residual water content of sand were 0.3 and 0.001 cm^3/cm^3, respectively. The soil saturated and residual water contents were 0.42 and 0.04 cm^3/cm^3, respectively. The pressure head increased slightly when volumetric water content was less than 0.12. After this point, pressure head increased dramatically and the soil reached fully saturated condition.

Table 3 Physical properties of sand and soil samples

Parameter	Media	
	Sand	**Topsoil**
Particle size analysis		
Sand (%)	100	37.51
Silt (%)	0	43.79
Clay (%)	0	18.70
Textural classification	sand	loam
K_S (cm/h)	6.466	0.662
Specific gravity	2.65	2.55
Bulk density (g/cm^3)	1.79	1.28
Void ratio	0.49	0.74
Porosity	0.33	0.43
Moisture content (%)	0.121	5.00

The unsaturated permeability term was estimated using Knuze et al.'s equation. Both columns were conducted at 23^{o}C (room temperature). Water surface tension, T_s was 7.23x10^{-5} kN/m, water density, ρ_w was 997.57 kg/m^3 and viscosity, μ_w was 9.4x10^{-4} N-s/m^2. For sand, the calculated and measured permeabilities were 4.4082 and 6.4656 cm/h, respectively. The calculated and measured permeabilities of soil were 0.6624 and 0.4756 cm/h, respectively. The plot of unsaturated permeability versus volumetric water content is presented in Fig. 8.

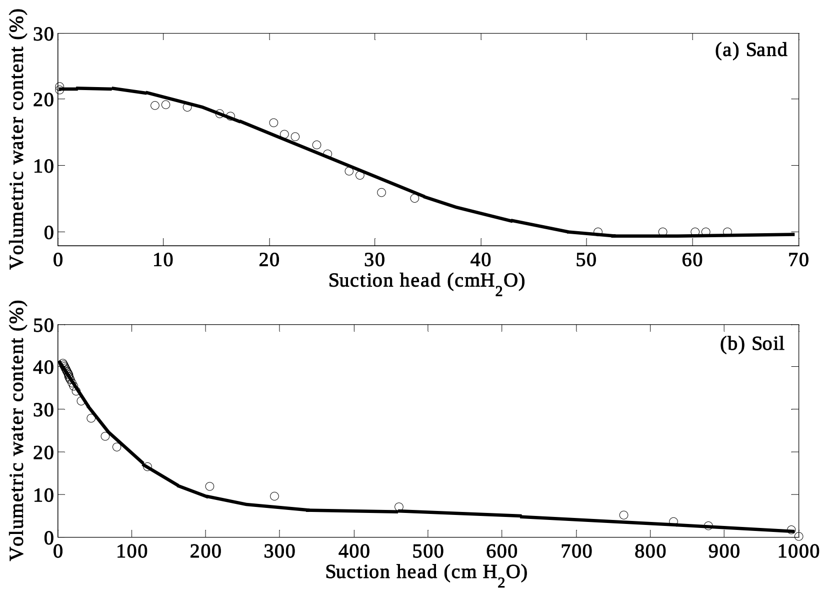


Fig. 7. Pressure head versus volumetric water content in soil and sand samples

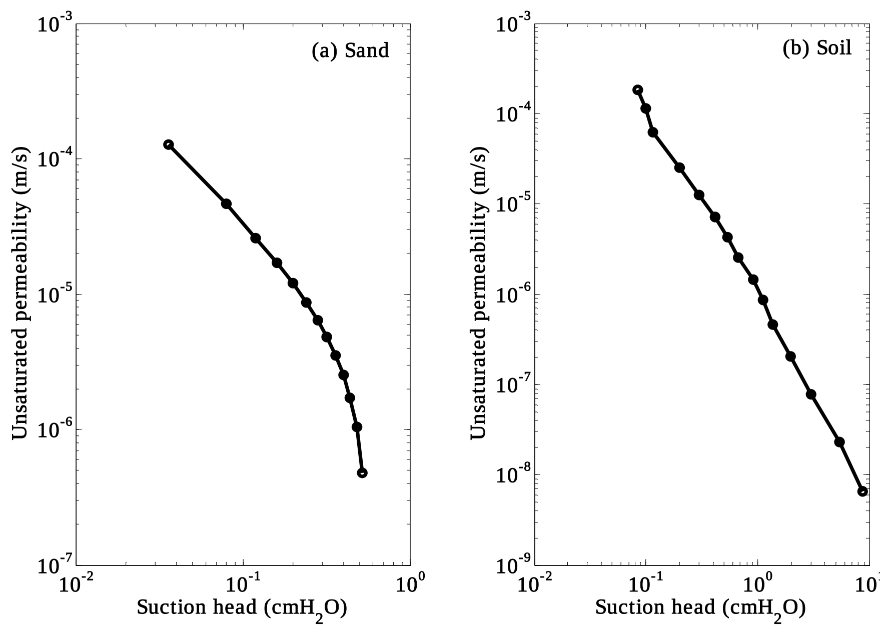


Fig. 8. Relative permeability versus pressure head in soil and sand samples

There were two models including of the van Genuchten and the Haverkamp et al. model, which could estimate the unsaturated permeability from both volumetric water content and pressure head data. The soil-water retention curve was fitted using the van Genuchten equations as presented in Fig. 9. A good fit was obtained between the observed and the calculated results of soil column. On the other hand, the equations did not well fit the hydraulic properties of sand, especially when sand was relatively dry. This error might have been generated in the measurement (Bunsri et al. 2008). The jet filled tensiometer was sensitive to presence of air bubbles. When sand was relatively dry, air bubbles could pass through a porous tip of the tensiometer. These bubbles could potentially disturb the reading signal (Fredlune and Rahardjo 1940). Ségol (1994) suggested that the hydraulic properties near saturation was very difficult to get the correct measuring data as the constant outflow rate near saturation was difficult to control, ensuring the column achieve the fully saturated condition.

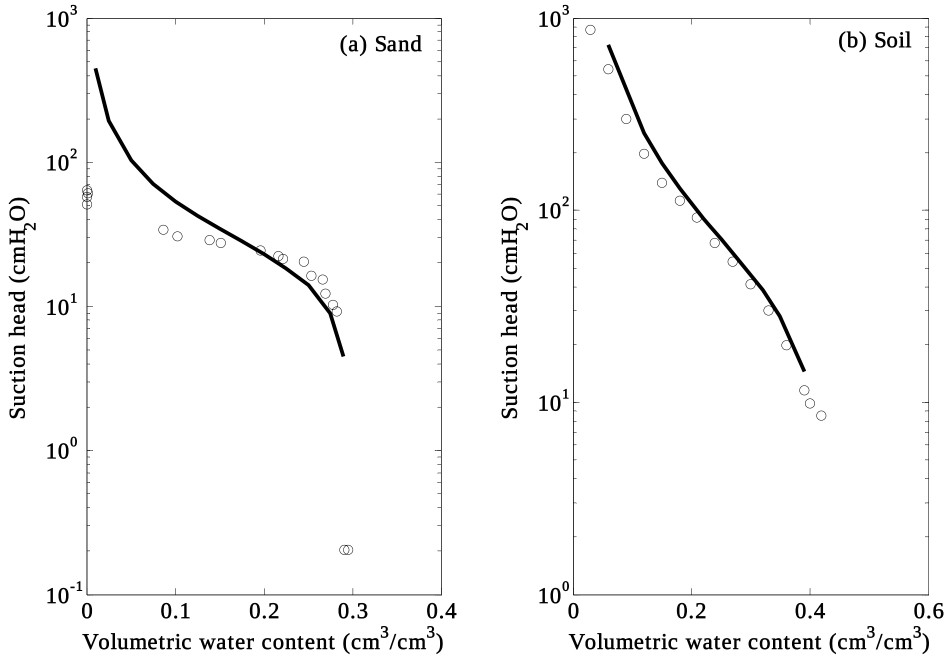


Fig. 9. Water retention curves of sand and soil sample fitted by VG equations

The soil water retention curve was also fitted using the Haverkamp et al. equations, the results are presented in Fig. 10. The data yielded from sand and soil columns were fitted well. The hydraulic properties data are given in Table 4. By comparison, the change of unsaturated permeability of sand was narrower than soil. The change of pressure head over volumetric water content in sand column was narrower than the change in soil column. The soil-water retention curve of sand presented a sharpen curve rather than the soil column did.

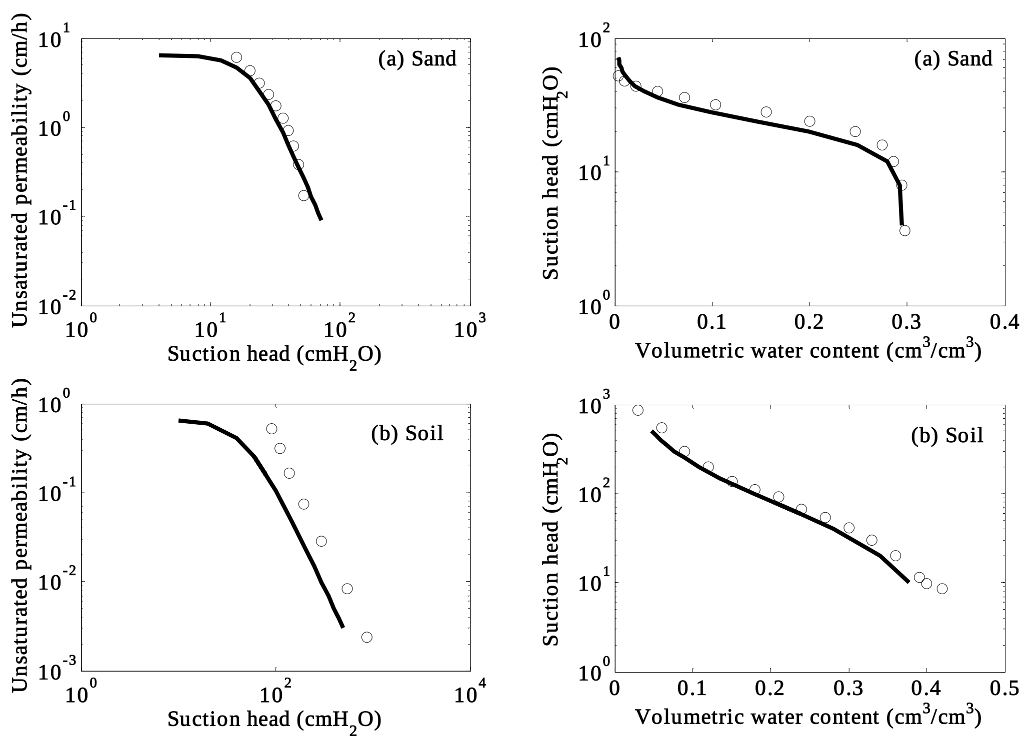


Fig. 10. Water retention curves of sand and soil sample fitted by HV equations

Table 4 Coefficients for hydraulic properties of sand and soil samples

Parameters	Sample	
	Sand	**Soil**
θ_S	0.30	0.42
θ_r	0.07	0.04
Haverkamp et al. model:		
A	$4.04x10^4$	$8.27x10^3$
a	$6.83x10^5$	$1.20x10^2$
β	4.2424	1.1045
γ	3.4765	2.3181
van Genuchten model:		
B (1/cm)	0.0446	0.0249
n	2.1636	1.6740
m	0.5378	0.4026

5. CONCLUSION

Unsaturated permeability is a major factor for estimating flow in a natural condition. Measurement of unsaturated permeability was so complicate, time consuming and costly. However, the unsaturated permeability was a function of degree of saturation, void ratio, volumetric water content and soil-pore pressure. Based on the available technical devices, the unsaturated permeability can be obtained indirectly by volumetric water content and soil-pore pressure measurements. In order to interpret the unsaturated permeability from the indirect measurement data, it is necessary to define the relations between unsaturated permeability and indirect measurement parameters. The most common approach for estimating unsaturated permeability has been to use either the statistical or mathematical. Five existing models of Gardner, Knuze et al., Haverkamp et al., van Genuchten and Saxton et al., were presented in this paper. Three case studies simulating homogeneous-heterogeneous, wet-dry cycle and pore size distribution were used to evaluate the performance of the five existing models. Accuracy and efficiency plots were produced to illustrate the behaviour of the different models over a range of accuracy levels. From the accuracy aspect, it was found that all models were also observed to be stable, except the Haverkamp et al. which produced some oscillations for one of the study cases. From the efficiency aspect, it was observed that the Knuze et al., the van Genuchten and the Haverkamp et al. models can interpret the unsaturated permeability from volumetric water content and pressure head. The van Genuchten model can also determine the unsaturated permeability, when either volumetric water content or pressure head was known. Nevertheless, the Knuze et al. and the Haverkmp et al. model can evaluate the unsaturated permeability, in case both volumetric water content and pressure head were known. So, the applications of the van Genuchten models were very wide and flexible. The Gardner model could estimate the unsaturated permeability from only pressure head. Besides, the Knuze et al. and the Saxton et al. models seem to be user friendly, they can calculate the averaged unsaturated permeability. This could be summarised that among these models, van Genuchten's model is the best in both accuracy and efficiency aspects. The laboratory soil column tests were also undertaken to simulate the unsaturated hydraulic properties of sand and soil. The results reveal that volumetric water content, pressure head and pore-size distribution affected the unsaturated permeability. The fine pore could resist the change of volumetric water content and pressure head and unsaturated permeability was very low.

ACKNOWLEDGMENT

This work was supported by the National Research Center for Environmental and Hazardous Waste Management and King Mongkut's University of Technology Thonburi, Thailand. Research facility was provided by Sustainable Water and Energy Research Group, University of Wollongong, Australia.

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