J. Agric. Sci. Mansoura Univ., 32 (10): 8777 - 8794, 2007

A NEW EQUATION FOR SIMULATING SOIL WATER CHARACTERISTIC CURVE

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ABSTRACT

Several mathematical equations have been proposed to simulate soil water characteristic curve (SWCC). All the equations show reasonable fit with measured data through a specified range of suction and in a specific soil texture, but this is not the case for suction less than air entry and close to residual water content.

The present work is aiming to introduce an applicable equation can simulate the SWCC and achieve good fit to measured data through the entire range of soil suction for variety of soil textures.

Following different sequence than that has been followed by many authors who focus on the physical meaning of the equation parameters, we attempted to create a new equation depending on the features of the SWCC. This idea helped in avoiding the difficulty of mathematical processes and non-accuracy of graphical solutions and also not include any soil properties except soil suction and water content. Such equation could be easily calculated using any non-linear fitting computer program.

The performed statistical analysis and obtained fit with measured data, revealed that the proposed equation successfully simulated SWCC for entire range of suction (i.e. 0 : 10^6 kPa).

The results also reveal that the presented equation was constantly the best equation in its fit to measured data among 16 SWCC studied equations. It could be concluded that the proposed equation is applicable accurate and flexible and can successfully employed as a predictive equation for the total SWCC. The research also suggest further studies to find out average values to different soil texture types to predict SWCC for Egyptian soils. Another needed studies are using the equation in calculating grain size distribution and hydraulic conductivity for unsaturated soils, since the equation give the common sigmoidal curve.

Keywords: Soil water characteristic curve – mathematical equations – nonlinear regression

INTRODUCTION

Soil water characteristic curve (SWCC) is one of the most important soil properties. The experimental determination of the entire SWCC is difficult in both laboratory and field. For that reason many models have been proposed to simulate the SWCC. Up tell now there does not appear to be generally accepted complete theory describing the total SWCC. So, finding a physical meaning of soil parameters and obtaining good fit is not available in addition to the difficulties of graphical estimation and mathematical derivations.

Following different sequence than that has been followed by many authors who focus on the physical meaning of the equation parameters, we attempted to create a new equation depending on the general shape of SWCC which is sigmoidal or what called S-curve. The equation parameters were be free or not related to soil properties but related to shape features of the SWCC.

Leong and Rahardjo (1997) stated most of SWCC models provide a reasonable fit of SWCC data, only, in the low and intermediate suction ranges.

Moreover, the fit is also conditional on soil texture. Therefore, the model validation is limited by applicability regarding to suction range and soil texture. So, if our concern is the accurate estimating, regarding less theoretical base, then the challenge of any provided equation should be its fit through the entire range of suction (i.e. from 0 to 10^6 kPa) and the tremendous challenge should be the flexibility or fit satisfaction at different soil textures.

The objectives of the study are:

1- reviewing SWCC equations and evaluating their fit to measured data through the entire range of soil suction.

2- Introducing new equation with parameters related to the shape features of SWCC for the purpose of achieving the best possible fit for wide range of soil varieties and to overcome the difficulty of graphical and numerical solutions.

3- Comparing the proposed equation with the equations which show best fit to measured data.

COMMON SWCC MATHEMATICAL EQUATIONS AND PROPOSED EQUATION

1- DEFINITIONS

The following terms and symbols will be used in the paper which need some clarifications. These clarifications are illustrated from Fredlund and Xing (1994), Leong and Rahardjo (1997), James *et al.* (1997) and Sillers and Fredlund (2001).

The soil-water characteristic curve is a relationship between the amount of water in the soil and soil suction. The amount of water in the soil is generally quantified in terms of gravimetric water content w, or volumetric water content θ, dimensionless water content Θ_d ($\Theta_d = \frac{\theta}{\theta_s}$) and effective water content or normalized water content Θ_n ($\Theta_n = \frac{\theta - \theta_r}{\theta_s - \theta_r}$). Where θ_s and θr are volumetic water content at saturation and residual water content respectively. The residual water content is the water content where a large suction change is required to remove additional water from the soil or the water content when soil hydraulic conductivity reached zero. More specific definition of θr which is “the water content corresponding to the asymptote of the SWCC at the low degrees of saturation”.

The common SWCC curve usually has two bending or inflection points (some curves have one point or more than two points). First one is associated with the suction at bubbling pressure or what called air entry value (ψ_e) which is referring to the soil matric suction where air starts to enter the largest soil pores. The second inflection point is at soil matric suction associated with residual water content (ψ_r). Fredlund and Xing (1994) and Leong and Rahardjo (1997) mentioned that the total suction corresponding to zero water content appears to be essentially the same for all types of soils (i.e. 10^6 kPa). Fig. 1 points up SWCC and important scientific terms.

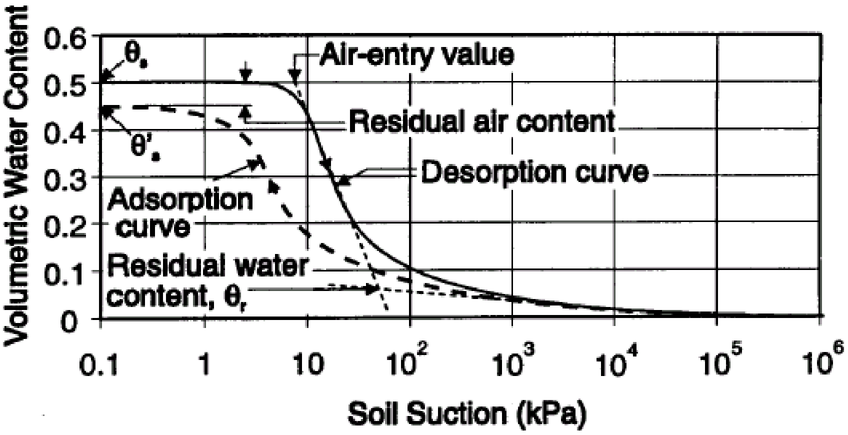

Fig. 1: Definitions of terms of typical SWCC (from Fredlund *et al.*, 1994).

2- REVIEW AND DISCUSSION

Several mathematical equations have been proposed to describe the soil-water characteristic curve (Sillers and Fredlund, 2001; Jr Gilson and Fredlund, 2004). The equation of Gardner (1958) was originally proposed for defining the unsaturated hydraulic conductivity and its application to the soil-water characteristic curve is inferred. Campbell (1974) tried to reduce the number of the fitting parameters in Gardner (1958) by letting the parameter a equal to soil suction at air entry. Such approximation found to be reduces the capability of the equation in fitting the data in addition to the non-accuracy resulting from graphical estimation of ψ_r. However, Campbell (1974) equation is considered a special case of Gardner (1958) and not included because its fit is less than Gardner (1958).

In this respect, it is important to stress that the smaller the number of equation parameters that must be estimated from the data, the less the accuracy and the flexibility of the equation. So, complex equations are fine if required and if they were able to be calculated someway.

The mathematical equations proposed by Burdine (1953), Brutsaert (1966) and Maulem (1976) are two-parameter equations that become special cases of the more general three-parameter equation proposed by van

Genuchten, 1980. Fredlund and Xing, 1994) mentioned that this condition (i.e. m=1/(1-n)) reduce the flexibility of the equation and suggested leaving m and n with no fixed relationship to obtain more accurate results. In addition to that Zhou and Yu (2005) modified van Genuchten (1980) by applying another fitting parameter. So three expressions of van Genuchten (1980) (with and without the condition that m=1/(1-n) in addition to Zhou and Yu (2005)) were included in the comparison to show how the number of equation parameters can affect the flexibility and accuracy of the equation.

Also, the equations associated with specified range of soil suction, such as Assouline *et al.* (1998) equation which calculate soil suction from saturation up to wilting point, and the equations which depending on particle size distribution such as Saxton *et al.* (1986) or measuring specific soil properties such as Kosugi (1994) equation which required a calculation of what he called the mode of particle size distribution and complementary error function, are not included.

Also, the equations of Farrel and Larson (1972), Willams *et al.*, (1983), Mckee and Bumb (1984) and Mckee and Bumb (1987) are not included because they did not converge with estimation process for available data and considered out of comparison. In this respect Leong and Rahardjo (1997) found in comparative study of SWCC equations that Farrel and Larson (1972), Willams *et al.*, (1983), Mckee and Bumb (1984) do not give the sigmoid curve. They also found that Mckee and Bumb (1987) do not give satisfactory fit to the data.

From the discussion above only the pore size distribution based equations are concerned in this study and only the best fit 7 equations among 16 equations are chosen after avoid special case equations (e.g. general forms are chosen) and poor fit equations as mentioned above, for reasonable comparison.

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3- EQUATIONS EXPRESSIONS AND CALCULATION PROCEDURE

For generalization and ignoring mentioning saturation value in the equations, soil water content of the all studied equations were converted to the dimensionless form. Such dimentionless form was taken as dependent variable (since the water content is following applied suction in desorption curve determination which is usually followed). All the necessary mathematical changes are performed.

Also an approximation was applied only to Haverkamp *et al.* (1977) equation, which is considering Θn equal to Θd by assuming is equal zero because it can not be estimated when full curve is not available and to avoid the non accuracy in the graphical determination.

This assumption has been accepted by van Genuchten *et al.* (1991) and James *et al.* (1997).

To pass up involving in complicated deferential and integral procedures and keep away from graphical errors and difficulty in calculating equations parameters, the unknown parameters for all studied equations, were calculated statistically through the user define loss-function in the commercial computer program STATISTICA (ver. 7). Same procedure could be done using any commercial statistical computer program such as SPSS or SAS or wetting up specific non-linear fitting computer program for each equation. In this respect, Fredlund and Xing (1994) stated that: the graphical estimation only gives approximate values for the parameters. Fredlund *et al.* (1994) added that when the number of measurements exceeds the number of fitting parameters, a curve fitting procedure can be applied to determine the fitting parameters. This approach allows a closed-form analytical solution.

The value of the soil parameter ψ_e in the Brooks and Corey (1964) equation was taken as a free soil parameter to improve the obtained fit of the equation. Especially it was found that the calculated value is usually close to the graphical estimation. Also, it is important to say that the equation fitting curve could be improved if the data of suction less than air entry are cancelled. This is may be due to that the equation was developed based on a condition that $\psi \geq \psi_e$. Such action did not performed because our concern is the full curve determination and also to compare the equations based on constant conditions.

Van Genuchten (1980)* will be referring to Van Genuchten (1980) with three free parameters (e.g. a, n, and m) as suggested by Fredlund and Xing (1994) is consider equation No. 5 for subsequently use.

The mathematical SWCC equations and their soil parameter symbols are presented in table 1.

3-1 SUGGESTED EQUATION

Siller and Fredlund (2001) Stated that the SWCC can be viewed as the continuous sigmoidal function describing the water storage capacity of a soil as it is subjected to various soil suctions. Gitirana and Fredlund (2004) stated appropriate equations to mathematically represent SWCC are required for both graphical presentations and for numerical modeling. Difficulties in the application of the available equations exist because the parameters of these equations are not individually related to shape features of the SWCC. They also said the lack of physical meaning for the fitting parameters is also undesirable.

So, if our concern in this research is focusing in accurate estimation of SWCC rather than finding a theoretical base of physical relations between equation parameters and soil properties, then the highest correlated equation should be the best in this respect. So, if we can somehow proposed an equation can successfully simulate the common sigmoidal shape (S-curve) of SWCC and to be flexible enough to fit variety of SWCC measured data, then we can employ such equation in estimating SWCC. For this purpose we first tried to use logistic function or pearl curve function. This is because this function is already built in all the commercial computer programs and represents similar shape of SWCC. Unfortunately, the function did not fit with the data at all. The only option was to propose self equation representing S-curve and fit with the variety of data for the entire range of soil suction and do not require special measurements of soil properties but only soil suction and water content and in addition to this it should be able to be calculated using non-linear fitting programs.

Table 1: The mathematical SWCC equations under consideration

	Author(s)	Equation	Soil parameters
1	Gardner (1958)	$\Theta_d = \dfrac{1}{1+\left(\dfrac{\psi}{a_1}\right)^{b_1}}$	a_1; b_1
2	Brooks and Corey (1964)	$\Theta_d = \left(\dfrac{a_2}{\psi}\right)^{b_2}$	$a_2 = \psi_e$; b_2
3	Haverkamp *et al.* (1977)	$\Theta_d = \dfrac{a_3}{a_3 + \lvert\psi\rvert^{b_3}}$	a_3; b_3
4	Van Genuchten (1980)	$\Theta_d = \left[\dfrac{1}{1+(a_4\psi)^{b_4}}\right]^{c_4}$	a_4, b_4, c_4 $where: \mathrm{c}_4 = \dfrac{1}{1\text{-}\mathrm{b}_4}$
5	Van Genuchten (1980) *	$\Theta_d = \left[\dfrac{1}{1+(a_5\psi)^{b_5}}\right]^{c_5}$	a_5, b_5, c_5
6	Fredlund and Xing (1994)	$\Theta_d = \dfrac{1}{\left[\ln\left(e+\left(\dfrac{\psi}{a_6}\right)^{b_6}\right)\right]^{c_6}}$	a_6; b_6;c_6
7	Zhou and Yu (2005)	$\Theta_d = \dfrac{1}{\left[a_7 + (b_7\psi)^{c_7}\right]^{d_7}}$	a_7; b_7; c_7; d_7

The proposed equation is essentially empirical (e.g. somewhat as same as many of earlier models). The equation is asymptotic to horizontal lines in the low soil suction range and a suction beyond residual conditions. The following expression is suggested by the authors:

$$\Theta_d = \frac{1-a}{\left\{1+a\left[b+\left(\dfrac{\psi}{c}\right)^{d}\right]\right\}^{(d-c)}} \qquad (8)$$

Where a, b, c, d are soil parameters.

As shown, the equation did not require previous determination of air entry suction or residual soil water content which are somewhat difficult and not accurate as mentioned previously. The equation parameters were calculated using the commercial program STATISTICA as same as other studied equations for easier and realistic comparison.

STATISTICAL ANALYSIS AND FITTING CURVES

After creating the equation, the next step should be validating it through fitting it with measured data and comparing it with the chosen best fit SWCC common equations.

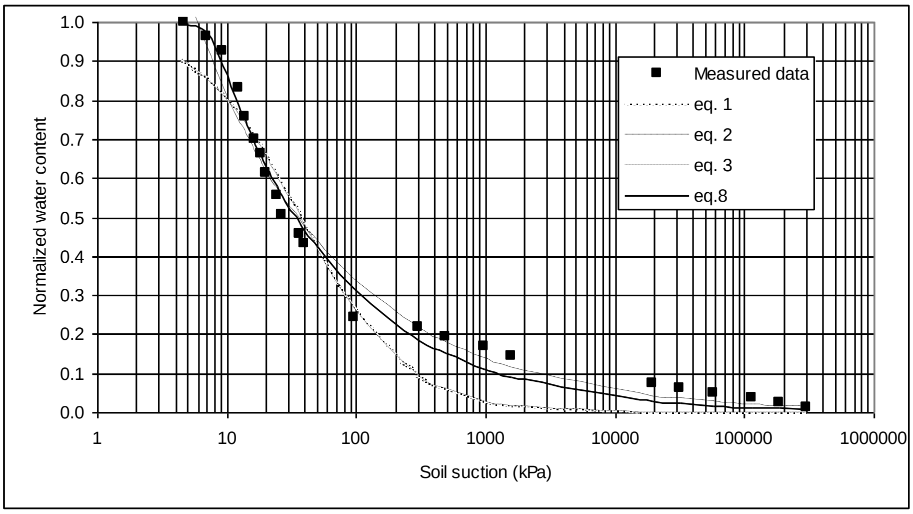
Since most of the experimental SWCC data are in the pressure membrane range (i.e. 1500 kPa maximum), then we did our best to find out complete curves or wider range of suction through interconnected experiments of both pressure membrane and vapor equilibrium of one study no-matter of the soil type or place or date of performing such experiments.

Figures 2 through 8 show the fit of the different studied equations and the presented equation with different seven measured data collected from literature. Table 2 shows the equations fitting parameters for the figures 2 through 8. Such parameters are useful in predicting SWCC for the soils which have reasonable similarity in texture.

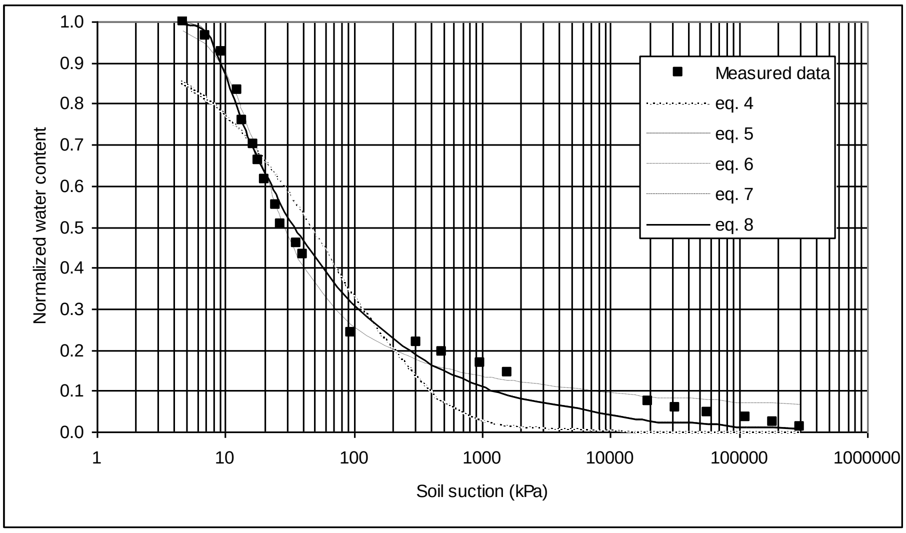
Table 3 shows the loss function final values and correlation coefficients of the equations under consideration and the proposed equation for figures 2 through 8.

Table 2: Fitted parameters for data subsets shown in figures 2:8 of the equations under consideration

Equations Parameters		1	2	3	4	5	6	7	8
Fig. 2	**a**	37.36	5.950	47.57	0.0028	0.1384	13.284	0.1382	0.1949
	b	1.067	0.3883	1.0670	0.6834	10.32	2.495	1.172	-5.088
	c					0.0434	0.8461	11.44	9.982
	d							0.0392	10.03
Fig. 3	**a**		11.91	24.260	0.0005	0.0762	37.45	0.0113	0.0643
	b		0.2446	0.5528	0.4569	14.85	1.154	0.2514	-15.16
	c					0.0171	0.8892	0.1413	14.03
	d							2.139	14.04
Fig. 4	**a**	12.53	1.197	825	0.0010	0.1459	8.33	0.146	0.4934
	b	2.656	0.324	2.656	0.9823	18.54	6.22	1.134	-2.02
	c					0.0731	0.8752	20.49	10.71
	d							0.0661	10.84
Fig. 5	**a**	35.93	0.4372	40.47	0.0029	0.1494	12.944	0.1509	0.225
	b	1.033	0.1742	1.033	0.7351	8.553	2.37	3.158	-4.412
	c					0.0545	0.8952	19.07	10.02
	d							0.0242	10.06
Fig. 6	**a**	18.19	0.1684	6.088	0.0091	0.4004	4.958	0.4003	0.3098
	b	0.6227	0.1851	0.6227	0.4828	9.363	2.945	1.000	-3.210
	c					0.041	0.7023	12.02	5.266
	d							0.032	5.338
Fig. 7	**a**	3E-5	3.671	109.7	5E-5	0.0634	17.62	0.0727	0.0081
	b	-0.071	0.2247	1.169	0.1075	1.995	2.024	1.241	22.68
	c					0.2755	0.7779	3.059	2.890
	d							0.1685	3.059
Fig. 8	**a**	1380	5.269	47.7	0.0001	0.0113	315.9	0.0138	0.0008
	b	0.5346	0.1388	0.5346	0.4488	1.31	0.7334	1.217	182.6
	c					0.2261	1.45	2.191	1.751
	d							0.13	1.902

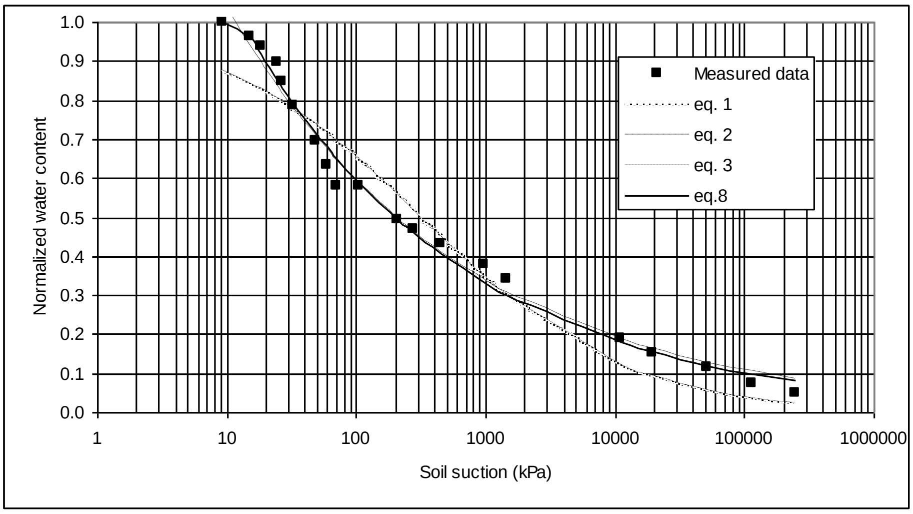


a- Equations 1, 2 and 3 versus proposed equation (8) and measured data



b- Equations 4, 5,6 and 7 versus presented equation (8) and measured data

Fig 2: Comparison of the equations fit (data from Jackson *et al.* 1965)



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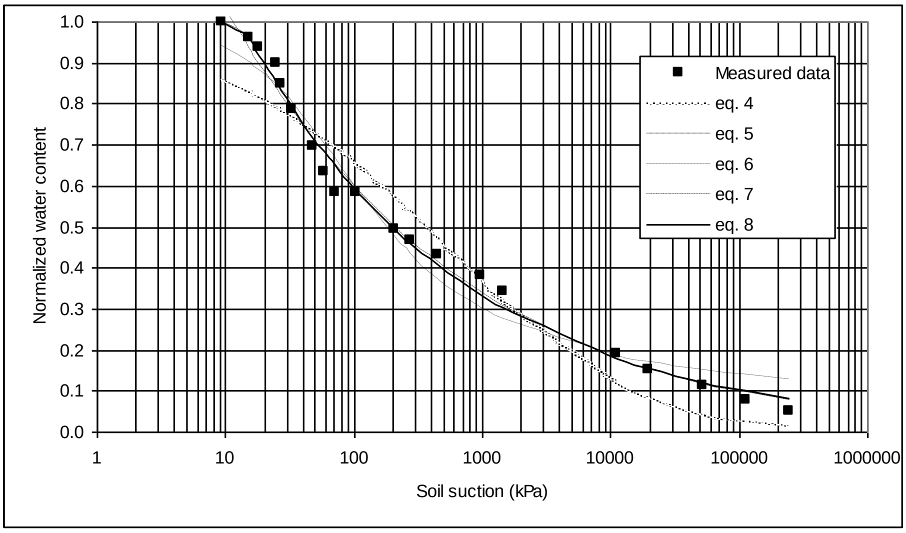
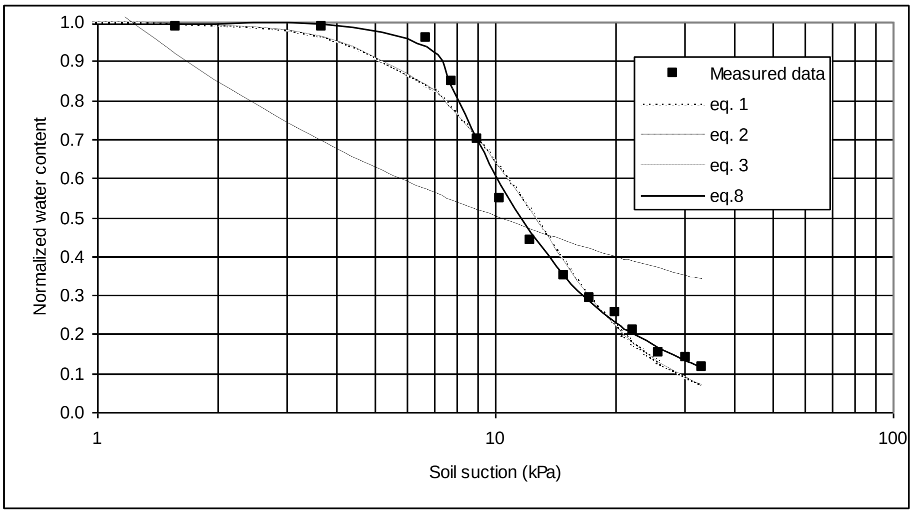
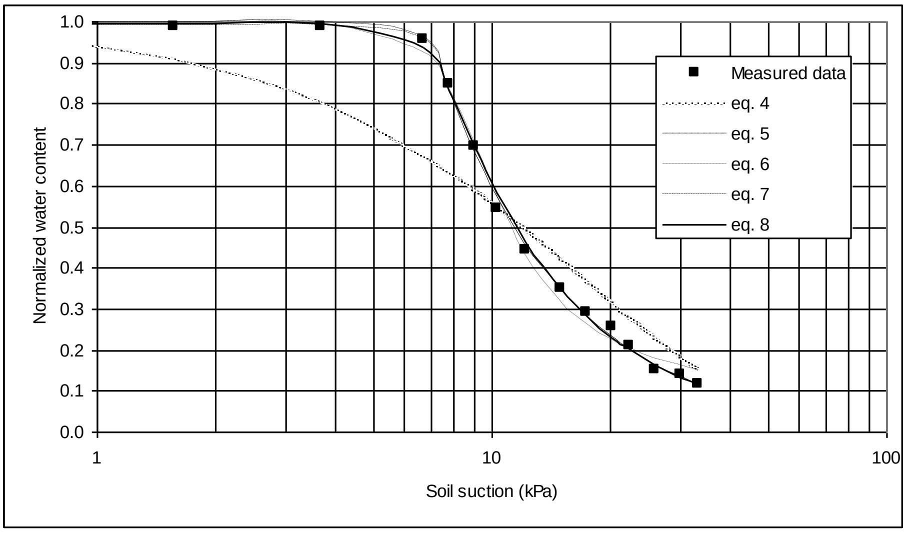


b- Equations 4, 5,6 and 7 versus presented equation (8) and measured data

Fig 3: Comparison of the equations fit (data from Jackson *et al.* 1965)

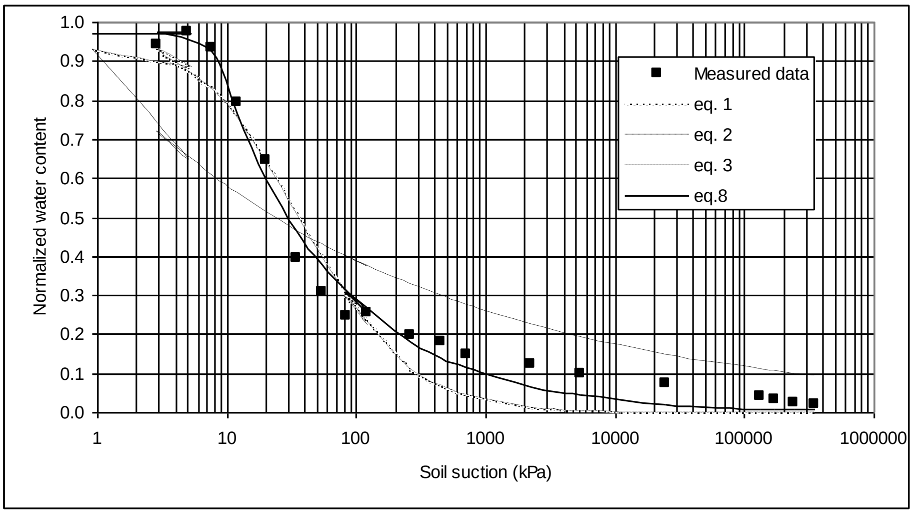


a- Equations 1,2 and 3 versus proposed equation (8) and measured data

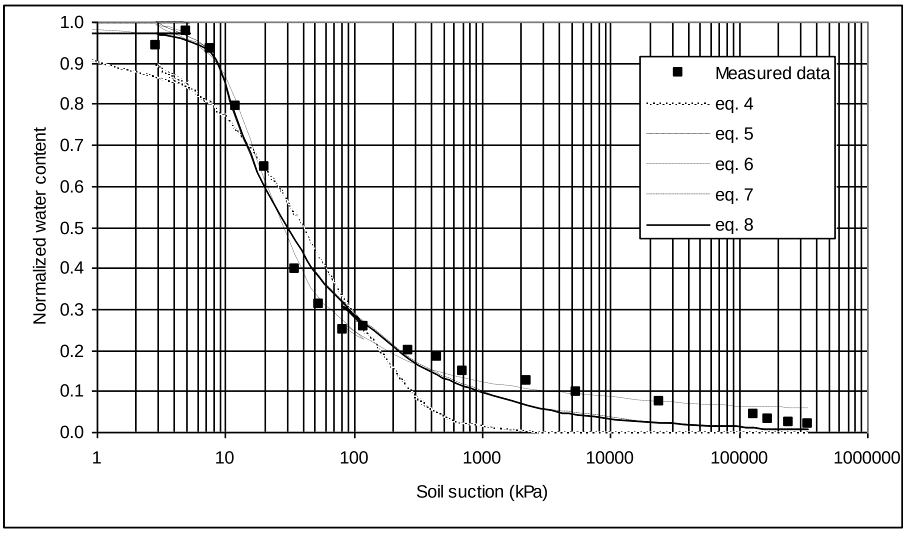


b- Equations 4, 5,6 and 7 versus presented equation (8) and measured data

Fig 4: Comparison of the equations fit (data from Leong and Rahardjo 1997)

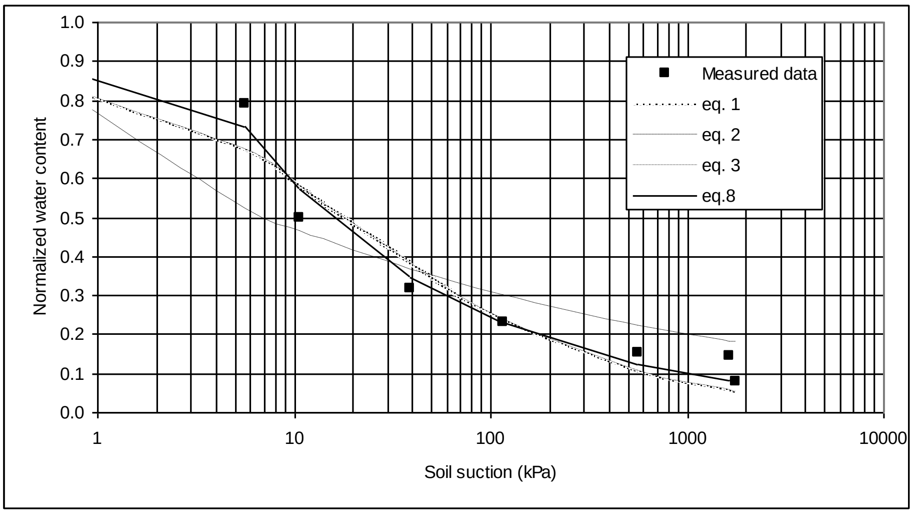


a- Equations 1,2 and 3 versus proposed equation (8) and measured data

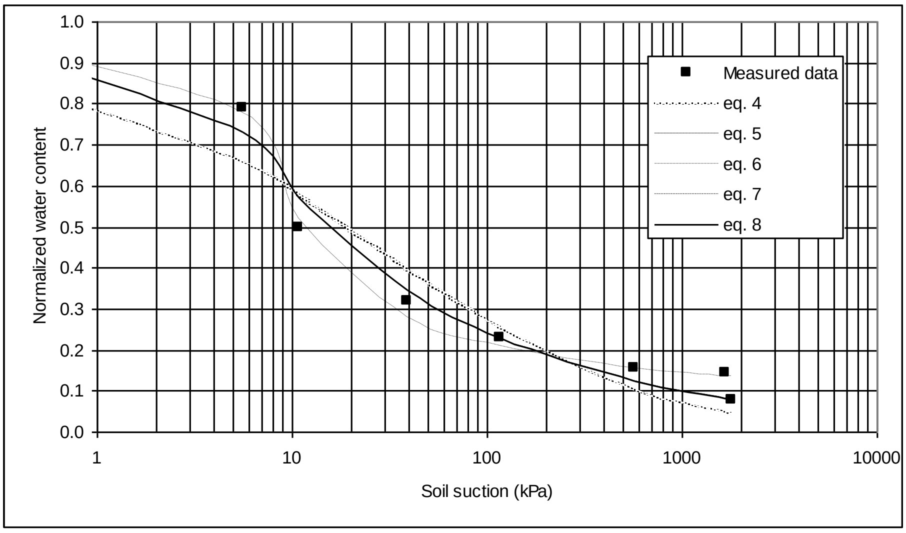


b- Equations 4, 5,6 and 7 versus presented equation (8) and measured data

Fig 5: Comparison of the equations fit (data from Sillers and Fredlund, 2001)

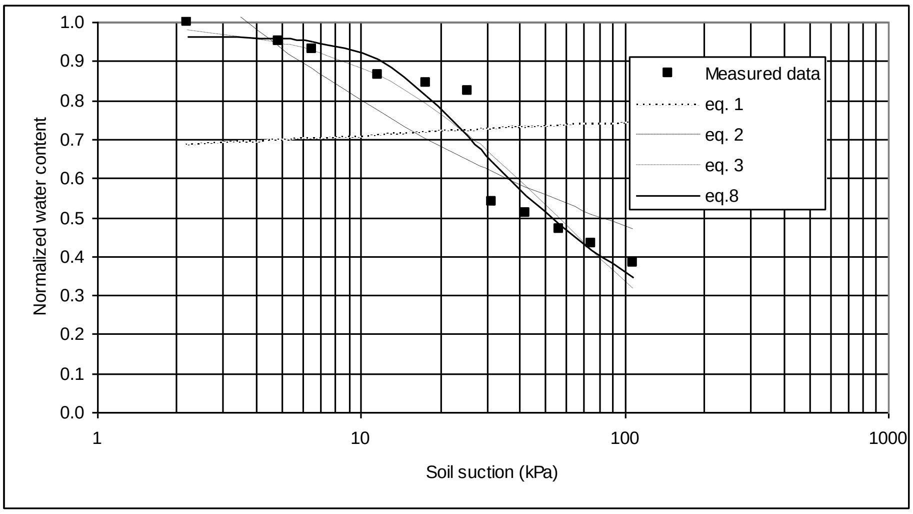


a- Equations 1,2 and 3 versus proposed equation (8) and measured data

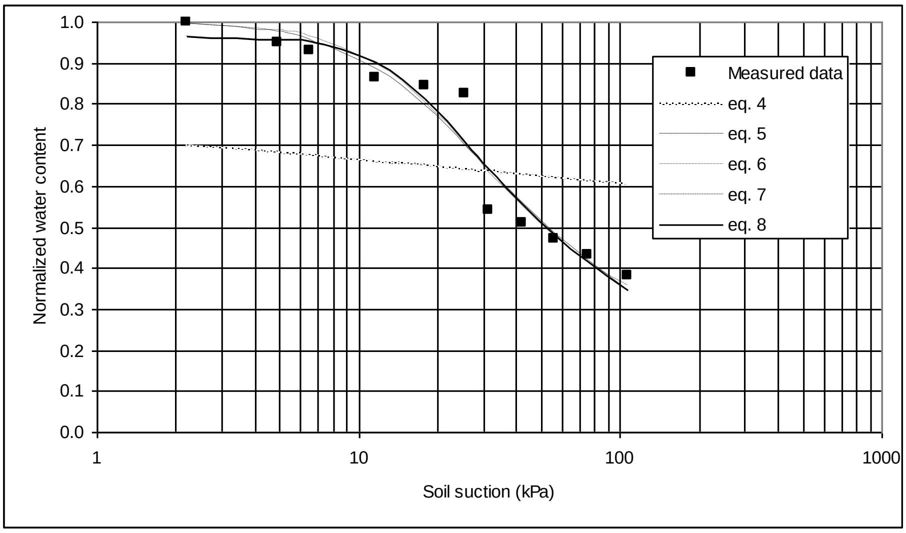


b- Equations 4, 5,6 and 7 versus presented equation (8) and measured data

Fig 6: Comparison of the equations fit (data from Sillers and Fredlund, 2001)

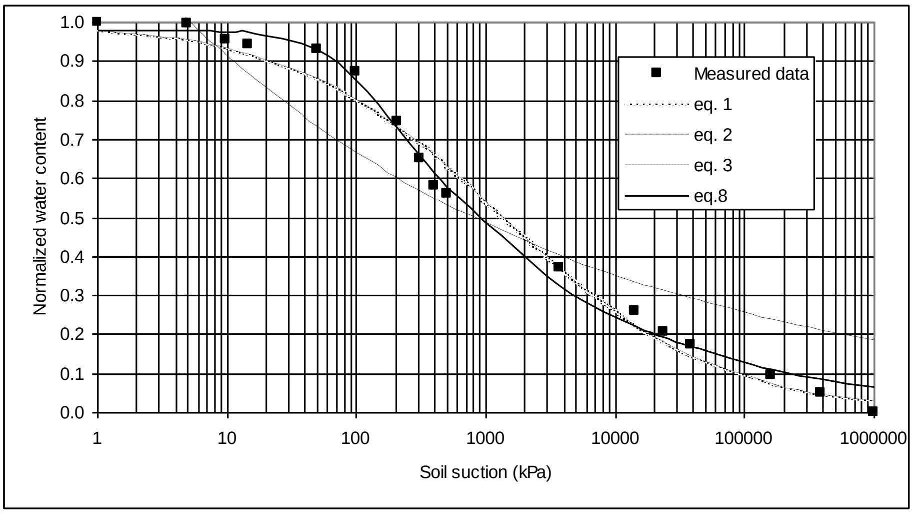


a- Equations 1,2 and 3 versus proposed equation (8) and measured data

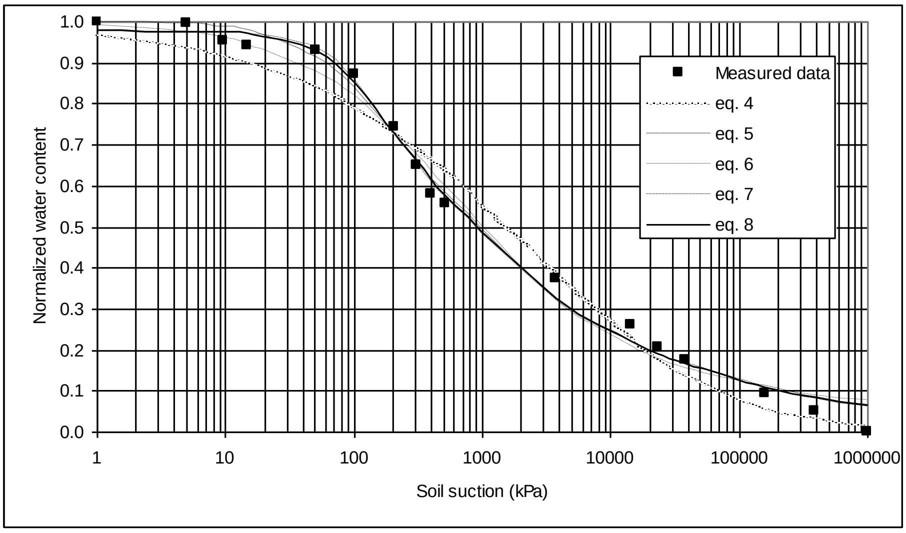


b- Equations 4, 5,6 and 7 versus presented equation (8) and measured data

Fig 7: Comparison of the equations fit (data from Sillers and Fredlund, 2001)



a- Equations 1, 2 and 3 versus proposed equation (8) and measured data



b- Equations 4, 5,6 and 7 versus presented equation (8) and measured data

Fig 8: Comparison of the equations fit (data from Ghorbel and Leroureil 2006)

Table 3: Least square and correlation coefficient of the equations under consideration and proposed equation

Equations Statistics		1	2	3	4	5	6	7	8
Fig. 2	**Loss***	0.137	0.046	0.137	0.191	0.028	0.018	0.028	0.028
	R**	0.972	0.991	0.972	0.961	0.994	0.996	0.994	0.994
Fig. 3	**Loss***	0.102	0.022	0.102	0.125	0.016	0.054	0.021	0.016
	R**	0.972	0.994	0.972	0.966	0.996	0.985	0.994	0.996
Fig. 4	**Loss***	0.040	0.650	0.040	0.212	0.003	0.008	0.002	0.004
	R**	0.988	0.786	0.988	0.935	0.999	0.998	0.999	0.999
Fig. 5	**Loss***	0.105	0.566	0.105	0.151	0.035	0.013	0.032	0.032
	R**	0.979	0.879	0.979	0.969	0.993	0.997	0.994	0.994
Fig. 6	**Loss***	0.036	0.101	0.036	0.046	0.014	0.006	0.014	0.014
	R**	0.977	0.934	0.977	0.970	0.991	0.996	0.991	0.991
Fig. 7	**Loss***	0.639	0.106	0.040	0.465	0.034	0.031	0.032	0.032
	R**	----	0.900	0.963	0.404	0.969	0.972	0.971	0.971
Fig. 8	**Loss***	0.031	0.299	0.031	0.041	0.016	0.026	0.014	0.014
	R**	0.993	0.928	0.993	0.991	0.996	0.994	0.997	0.997
Mean	**Loss***	**0.1557**	**0.2557**	**0.0701**	**0.1759**	**0.0209**	**0.0223**	**0.0204**	**0.0200**
	R**	**----**	**0.9160**	**0.9777**	**0.8851**	**0.9911**	**0.9911**	**0.9914**	**0.9917**

*** Loss function = (observed – predicted)^2**
**** R = correlation coefficient**

Fig 2 and 3 revealed that equations Gardner (1958), Brooks and Corey (1964), and Van Genuchten (1980) performs poorly at both low and high suction ranges while, the other equations showed satisfied fit. Also, the proposed equation and the equation of Zhou and Yu (2005) showed identical fitting curves. Fig 4 showed that Brooks and Corey (1964) and Van Genuchten (1980) failed to fit the measured data. The other equations showed satisfied fit. Fig 5 indicted that both equations of Brooks and Corey (1964) and Van Genuchten (1980) did not fit the data for the entire range of suction same as fig 2. Only fig 6 showed comparative fit for all the equations this was because that the measured data are scattered away and did not directly follow applied suction which allowed all the regretted lines to run somehow through the data points. Fig 7 revealed that both of Gardner (1958) and Van Genuchten (1980) completely failed to fit the data to fit the measured data and Brooks and Corey (1964) showed poor fit. Fig 8 showed that all equations satisfied the fit to measured data except Brooks and Corey (1964).

Going over the main points of figures 2 through 8 and the average values (calculated to nearest 4 digits number for sensitive comparison) of loss function and correlation coefficients, presented in table 3, we can say that:

1-All of equations van Genuchten (1980)*, Fredlund and Xing (1994), Zhou and Yu (2005) and the proposed equation showed very close fit to measured data.

2-The proposed equation showed the best fit at all followed by Zhou and Yu (2005) then van Genuchten (1980)* then Fredlund and Xing (1994), with very small increments between them, and Haverkamp *et al.* (1977) equation and the other equations considered out of comparison.

3-The equation of Haverkamp *et al.* (1977) was superior over Gardner (1958), Brooks and Corey (1964) and Van Genuchten (1980).

4-The equations of Gardner (1958), Brooks and Corey (1964), and Van Genuchten (1980) do not showed good fit especially in the case of entire range of suction and they were highly dependable on data.

5-Increasing the number of equation fitting parameters increase the accuracy and flexibility of the equation which were very clear with the obtained fitting and loss and R values of similar form equation (i.e. Van Genuchten (1980), 2 parameters, Van Genuchten (1980)*, 3 parameters, and Zhou and Yu (2005), 4 parameters).

CONCLUSION

The study successfully proposed an equation with 4 free parameters related to the shape features of the SWCC can simulate the entire range of soil suction. The equation parameters could be easily calculated using any non-linear fitting computer program.

The proposed equation was constantly the best-fit equation to measured data among 16 SWCC studied equations (the best 7 of them were discussed in details and the others mentioned in reviewing discussion). This result insures the equation capability and accuracy. Therefore, determining average values of the equation fitting parameters for different texture soils will allow reliable simulation of SWCC for similar Egyptian soils. Consistent with that the equation can simulate the S-shape-curve, further studies are suggested to employ this equation in predicting grain size distribution curve and unsaturated hydraulic conductivity.

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استحداث معادلة لحساب المنحني الرطوبة المميز للتربة

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هناك العديد من المعادلات الرياضية التي اقترحت بغرض حساب المنحني الرطوبي المميز للتربة، كل هذه المعادلات تظهر تطابق مقبول مع البيانات المقدرة عمليا خلال مدي معين من الشد الرطوبي وفي قوام معين للأرض، بخلاف الحال عند محاولة استخدامها للحساب عند شد أقل من جهد دخول الهواء للمسام وعند المستويات العالية من الشد الرطوبي.

يهدف البحث إلي استحداث معادلة تطبيقية يمكن من خلالها تمثيل منحني الشد الرطوبي بدقة عالية للمدى الكامل للشد الرطوبي وتكون صالحة لمدي واسع من الأراضي، هذه المعادلة بنيت علي أساس الشكل النهائي لمنحني الشد الرطوبي وليس علي أساس خواص الأرض بخلاف الاتجاه السائد لمعظم الأبحاث السابقة، وذلك لزيادة دقة و مرونة المعادلة فضلا عن سهولة الحساب بحيث لا تتطلب عمليات رياضية معقدة أو حلول بيانية تقريبية، مما يمكن من حسابها مباشرة عن طريق البرامج الإحصائية للانحدار غير الخطي.

وقد أظهرت النتائج نجاح هذه المعادلة في حساب المنحني الكامل للشد الرطوبي مع جميع البيانات المستخدمة، وكانت دائما أفضل معادلة في التطابق مع البيانات المقاسة بالمقارنة مع ستة عشر معادلة أخري لحساب منحني الشد الرطوبي المميز.

ويوصي البحث بعمل دراسات مستقبلية لمعرفة القيم المتوسطة لمجاهيل المعادلة في أنواع من الأراضي مختلفة القوام، و ذلك بغرض استخدامها مباشرة في حساب المنحني الرطوبي المميز (في المدى الكامل للشد الرطوبي) للأراضي المصرية المشابهة في القوام. و نظرا لنجاح المعادلة في تمثيل الشكل العام للمنحني (S-curve) بكفاءة علية فان البحث يوصي كذلك باختبار مدي إمكانية استخدام المعادلة في التنبؤ بمنحني التوزيع الحجمي لحبيبات التربة والتوصيل الهيدروليكي للأرض غير المشبعة.