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Comparative study of soil water characteristic curve prediction methods

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ABSTRACT: The soil-water characteristic curve (SWCC), which defines the relation between soil suction and water content, plays a key role in geotechnical studies of the unsaturated soils. Some researchers such as Brooks & Corey (1968), Van Genuchten (1982) and Fredlund& Xing (1994) have proposed curve fitting equations for SWCC. Fitting equations to the laboratory test data obtained from direct measurement of water content versus changes in matric suction is the most reliable method, but it is expensive and time consuming. Alternatively, there are indirect approaches, which estimate SWCC based on the particle size distribution (PSD) in granular soils and plasticity index in fine grained soils. In this research, we are presenting the drying SWCC of five different soils obtained from laboratory pressure plate and hanging column tests (according to ASTM D 6836, methods A & C), together with application of (1) curve-fitting methods, and (2) SWCC estimation methods based on particle size distribution and plasticity index, proposed in the literature. The materials used in this study are a sand specimen, a specimen of silt and three specimens of clay. We compare different curve-fitting methods and predicted SWCCs with the laboratory data. We found that except Gardner (1958), curve-fitting methods can successfully model the SWCC. We also concluded that any of Fredlund& Wilson (1997), Scheinost (1996), Vereecken (1989) and Arya& Paris (1981) pedo-transfer functions (PTFs) can predict the SWCC somewhat better than the rest of the prediction methods in any of the five soils and none of them is the single best for all these soils.

1 INTRODUCTION

One of the major reasons that partially saturated soils have not yet received high level of implementation in practice is the difficulties in measuring unsaturated soil properties. SWCC, as one of the most fundamental unsaturated soil properties, is a curve with a similar shape to soil gradation curve and represents water content values of the soil corresponding to different suctions. SWCC along with the saturated soil properties has proven to provide a satisfactory basis for estimating the hydraulic conductivity and shear strength functions for an unsaturated soil. Researchers quite often fit equations to this curve in order to incorporate it into their calculations more easily.

Test procedures for obtaining SWCC are expensive, very sensitive and time consuming. This has made researchers try to find a shortcut to estimate it using some more common properties of the soils such as particle size distribution (PSD) and dry density. These estimations are referred to as Pedo-Transfer Functions (PTF) and there exists a large number of PTFs that have been proposed in the literature by different researchers.

The objectives of this study are to; (1) evaluate the performance of seven well-known fitting methods such as Fredlund and Xing (1993), bimodal (Fredlund, 1980), Van Genuchten (1980) and its two updates, Brooks and Corey (1964) and Gardner (1958) for best-fitting SWCC to experimental data, and, (2) compare SWCC predictions from PSD by seven commonly used PTFs; namely, Abertine et al. (1998), Fredlund& Wilson (1997), Scheinost (1997), Vereecken et al. (1989), Tyler &Wheatcraft (1989), Rawls &Brakensiek (1985) and Arya& Paris (1981).

2 BACKGROUND

2.1 Definition of Terms

Pedo-transfer function (PTF) (Bouma 1989) is a function that uses basic soil data, such as the grain-size distribution or porosity, and yields a soil property function, such as SWCC.
SWCC simply defines the relation between water content and suction in a soil.

2.2 Representation of SWCC by Fitting Formulas

The SWCC of a soil can be obtained by carrying out laboratory tests such as pressure plate or hanging column, or other methods as summarized by ASTM D 6836. The output of a laboratory test to obtain SWCC is a number of points in the water content vs. suction plane. It is common to fit a predefined equation to these data points, where the constants in equation are obtained from minimum root mean square error method. The result is the SWCC, expressed in function form. Most prominent curve-fitting formulas for the SWCC are known as Brooks & Corey (1964), Van Genuchten (1980) and Fredlund& Xing (1993). In 1964, Brooks and Corey (1964) presented a power-law relationship which was the first attempt to use an equation to describe the SWCC. Later Van Genuchten (1980) presented a three parameter equation with the flexibility to fit to a wide range of soils. The parameters of the equation were typically found using a least-squares algorithm. Later this equation was updated two times by the impact from Burdine (1953) and Mualem (1976) and became more convenient to use. Another equation was proposed by Fredlund& Xing (1993), which was more flexible to fit to a wide range of soils by introduction of bimodal SWCC fitting approach. It was also modified to provide increased accuracy in the high suction range. There is also an old equation by Gardner (1958) which was originally proposed to describe the coefficient of permeability function for an unsaturated soil. Gardner (1958) proposed a one-parameter equation for the SWCC which provides an indication of the rate of de-saturation of a soil but assumes that de-saturation commences as soon as suction is applied. This form of Gardner (1958)'s equation has not found wide acceptance in geotechnical engineering because of its basic limitations.

2.3 SWCC Estimation Methods

SWCC mainly depends on the pore size distribution of the soil, which is primarily controlled by the particle size and secondarily the density. Therefore, the PSD and density of the soil may reasonably be correlated to SWCC. Here, different approaches of most well-known SWCC estimation methods have been summarized. Since different soil properties are used by different researchers for estimation of SWCC, their successes may vary.

1. *Point regression method*

In this approach, PSD parameters are correlated with water content at various suction levels of SWCC. Gupta & Larson (1979) method is an example work based on this approach.

2. *Functional Parameter Regression Method*

This method assumes that functional parameters of the final equation can be correlated to basic properties of the soil. For instance, Rawls &Brakensiek (1985) presented some regression equations to estimate parameters of Brooks & Corey (1964) formula. Although the estimation of the air-entry value for most soils was quite reasonable, the de-saturation rate appears to be overestimated for most soils. This is likely due to the sharp initial slope inherent in the Brooks and Corey equation. In another study, Vereecken et al. (1989) used a dataset of forty soils to fit to Van Genuchten (1980). Then using a sensitivity analysis and factorial analysis they concluded that by having PSD, dry density and organic carbon content, SWCC is predictable.

3. Physical Model Method

Arya& Paris (1981)PTF is the first method proposed to estimate SWCC using physio-empirical approach. It estimates pore sizes from the PSD and converts pore radii to equivalent soil suction through capillary theory. Then the volumetric water content, θ_i, is obtained by summing the water-filled pore volumes. This method requires a reasonably well defined grain size distribution.

The Fredlund& Wilson (1997) is another prominent PTF based on physio-empirical approach which assumes that a soil is composed of a series of uniform, homogeneous particles, each leading to a unique SWCC. The general shape of the SWCC for pure sand, pure silt, and pure clay was assumed to be known. Using a best-fit analysis for the Fredlund& Xing (1994) equation, three parameters were computed for each soil type. These parameters are assumed to be associated with a dominant particle size on the grain-size plot. It is hypothesized that as a soil tends towards being uniform in size, the values of the fitting parameters show a trend towards a particular value. The fitting parameters for particle sizes falling between pure clays, pure silts, and pure sands are approximated. The particle-size distribution curve can be divided into small divisions with uniform soil particles. The analysis starts from the smallest particle sizes. A packing porosity is estimated for each soil division. The divisional SWCCs are then summed starting with the smallest particle sizes and continuing until the volume of the pore spaces are equal to that of the entire heterogeneous soil. The result is a theoretically estimated SWCC.

The Scheinost et al. (1997) PTF uses a linear regression analysis to estimate the parameters for a Van Genuchten (1980) type equation. The Scheinost et al. (1997) PTF was developed to account for extreme variations in the soil parameters, with textures varying from gravels to clays, organic contents varying over a wide range, and bulk densities from 0.80 to 1.85 Mg/m^3. The PTF was trained using a soil data set from near Munich, Germany.

Tyler &Wheatcraft (1989) uses a fractal dimension to estimate the Arya& Paris (1981) α input parameter. The fractal dimension is calculated through the use of a linear regression analysis for particles associated with the grain-size fractions. The method does not appear to improve on the performance of the Arya& Paris (1981) estimation.

Aubertin (1998) has done some modifications on original version of the Kovács (1981) model, which makes a distinction between water retention due to capillary forces and retention by adhesion. This model has complementary relationships developed for specific applications on granular materials and on plastic/cohesive (clayey) soils.

3 METHODOLOGY

3.1 Material Properties

The materials used in this study are fine grained and coarse grained soils from different regions of Turkey. Summary of their properties is listed in Table 1. Figure 1 presents particle size distribution curves for these soils.

3.2 Testing methods

To obtain the SWCC in the laboratory, standard ASTM D 6836 was referred and methods A and C were used. Method A, hanging column method, is suitable for measuring suctions in the range of 0 to80 kPa. Method C, pressure chamber with gravimetric measurement, is suitable for suctions in the range of 50 to 1500 kPa. The main difference between these two, other than the material that can be tested in each, is the method to apply the suction.In method A, the matric suction is applied by reducing the pore water pressure while maintaining the pore gas pressure at the atmospheric condition, while in method C water pressure is maintained atatmospheric pressure, and the pore gas pressure is raised to apply the suction via the axis translation principle.

Required setups for both of these methods were manufactured in the soil mechanics laboratory of Middle East Technical University in Ankara. In these setups 1, 3, and 15 bar porous ceramic disks were used. The maximum suction capacities of the systems were restricted to 8.5 bar (850 kPa) and 60 kPa for pressure chamber and hanging column setups, respectively.

Table 1. Material properties

Name of soil	Index properties				PSD indexes				Atterberg limits		
		g/cm³	*%*		*mm*	*mm*	*mm*	*mm*	*%*	*%*	*%*
	G_s	$\gamma_{d\ max}$	W_{opt}	USCS	D_{10}	D_{30}	D_{50}	D_{60}	LL	PL	PI
Tailing	2.96	1.85	15.1	CL-ML	0.0016	0.008	0.02	0.28	24	20	4
Topsoil-1	2.80	1.801	15.2	GC	0.0011	0.1	3	5	48	23	25
Topsoil-2	2.77	1.78	15.7	GM	0.006	3	8	10	35	24	11
Iz Clay	2.70	-	-	CL-ML	0.002	0.017	0.11	0.26	55	34	21
Iz Sand	2.68	-	-	SM	0.11	0.26	0.49	0.6	N.P.	N.P.	N.P.

In order to obtain SWCC, several soil samples were placed in both setups in stainless steel rings of 32 mm diameter and 10 mmheight. For the cohesive material with high dry density, the samples were prepared outside the setup but sandy material and low consistency cohesive specimens were prepared mostly on the porous ceramic disks. For preparation of samples either inside or outside the setup, container rings are placed on a horizontal surface.A mass of sample,which corresponds to the desired density within the volume of the retaining ring, is tamped into the rings in three layers. Afterthe application of suction and its consequent stabilization, soil water content of the samples were measured.

Five different soils were tested, including two CL-ML soils and one from each of GC, GM and SM. Using appropriate setups, seven soil water-suction datasets were produced (for two of the soils different SWCCs obtained in two different dry densities).

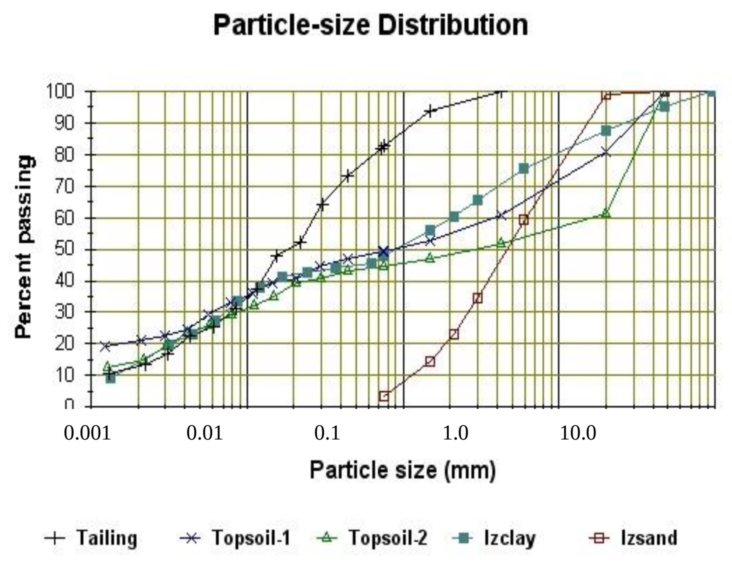


Figure 1. Particle size distribution of the soils used in this study. (Curves represent the PSD of the samples as they are used in SWCC lab tests, because the very large pieces were removed).

3.3 Data Analysis

All the curve fittings and estimations were performed by using the software Soil Vision. This software makes it possible to compare any estimation of SWCC with experimental and either best fitted curves. Also it’s possible to compare SWCC of any soil with that of others in the database.

Using SoilVision software package, appropriate SWCC equations were fitted to the test data. Error values (R^2), air entry value (AEV) and fitted curve max slope at inflection (i.e. de-saturation rate) were compared for different fitting methods. In addition, SWCC estimation from PSD is carried out by different methods. To do so, the particle size distributions (PSD) of the soils were entered into SoilVision along with some other soil properties such as dry density and plasticity indexes (Table 2).

Table 2. Dry density and water content of the samples as they are placed in testing setups

Sample Name	Soil class	Dry density	Initial water content
		g/cm^3	*%*
	USCS	$\gamma_{d\ max}$	w_{opt}
Tailing	CL-ML	1.8	14.8
Topsoil-1	GC	1.8	18.6
Topsoil-2	GM	1.8	19.4
Izclay-1.35	CL-ML	1.35	15
Izclay-1.55	CL-ML	1.55	15
Izsand-1.35	SM	1.35	5
Izsand-1.7	SM	1.7	5

4 EXPERIMENTAL RESULTS & BEST FITS

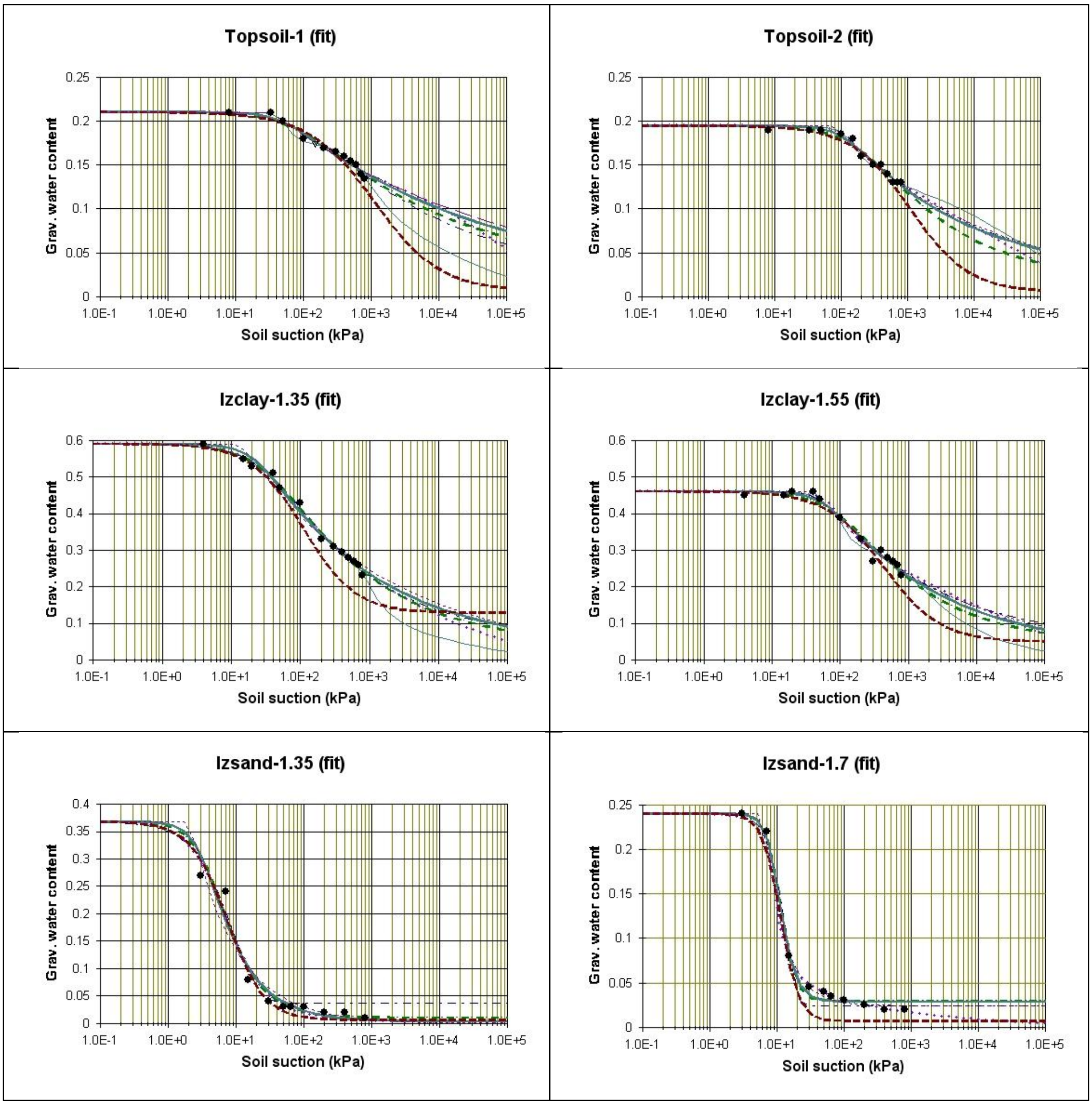
SoilVision only does nonlinear regression over the experimental data and fits them to any of the predefined SWCC formulas. Here, all fitted curves have been shown in one plot for a soil specimen along with its experimental data points. To determine the successes of the curve fitting methods, coefficient of determination (R^2) was used as a comparison criterion. Figure 2, which shows the experimental data and fitted curves, indicate that for Tailing, Topsoil-1 and Topsoil-2 data sets, Fredlund Bimodal fit gives the best fitted curve. In addition, Gardner (1958) fit shows greater differences from both experimental and best fitted curves.

As for the two specimens of Izclay soil, the only difference between Izclay-1.35 and Izclay-1.55 was the packing porosity in sample preparation. Referring to Figure 2, it is obvious that Fredlund& Xing (FX) and Fredlund Bimodal (FB) are overall best fits for these datasets. Gardner (1958) fit also does not have high error in fitting to the points with low suction while it deviates from the test data at higher suctions. Another noteworthy observation is that the residual water content predicted by Gardner (1958) method probably is the most sensitive to the sample dry density, since 10% difference in water content is obvious between low and high dry density specimens. In the residual suction range, unlike Izclay samples, there is experimental data for Izsand. It is quite clear from Figure 2 that Gardner (1958) formula does not fit the residual data points in dense specimens even in sandy soil.According to Figure 2 almost all of the fitting formulas have been fitted to the experimental data while some of them like FX and Van Genuchten&Burdine have shown the least error with R^2=0.9980.

5 ESTIMATION OF SWCCs

After entering required inputs, such as PSD and dry density, SoilVision can estimate SWCC for the soil using any of the estimation methods described in section 2. For all of the soils tested in this work, estimations for the curve by different methods are presented in Figure 3. It must be noted that despite using a 15 bar pressure plates, our air compression system was unable to apply more than 9 bars (approximately 900 kPa). So applied matric suctions are limited to 800 kPa.

Referring to the literature, success in estimation can be evaluated by various criteria, such as coefficient of determination (R^2), absolute error in air-entry values (AEV), and differences between the measured and estimated maximum slopes of the SWCC.For Tailing specimen Aria & Paris (AP) method estimated best fitted SWCC and its clear from its value of R^2=0.85. When we compare AEV and inclination s, also AP and Vereecken both has done well. It must be noted that compared to the lab data, almost all of the estimation methods are unable to predict the SWCC accurately, or even approximately. For example, for the Tailing soil specimen estimations by Aubertin, Rawls &Brakensiek (RB) and Tyler &Wheatcraft (TW) are off by more than an order of magnitude of suction. For Topsoils, Fredlund& Wilson (FW) and Vereecken have done barely schematically similar estimations. In Izclay datasets, Vereecken PTF, regardless of the dry density of the specimens, has done a better estimation. Plot of the estimations for Izsand also shows that Scheinostmostly predicts the SWCC correctly in almost the entire suction range of test data. It can be seen in figure 3 that many of the PTF's were able to predict the inclination of SWCC correctly, although none could predict the whole SWCC accurately.



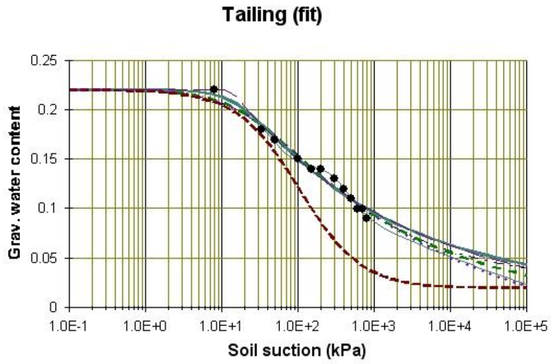
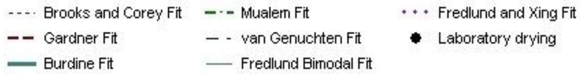
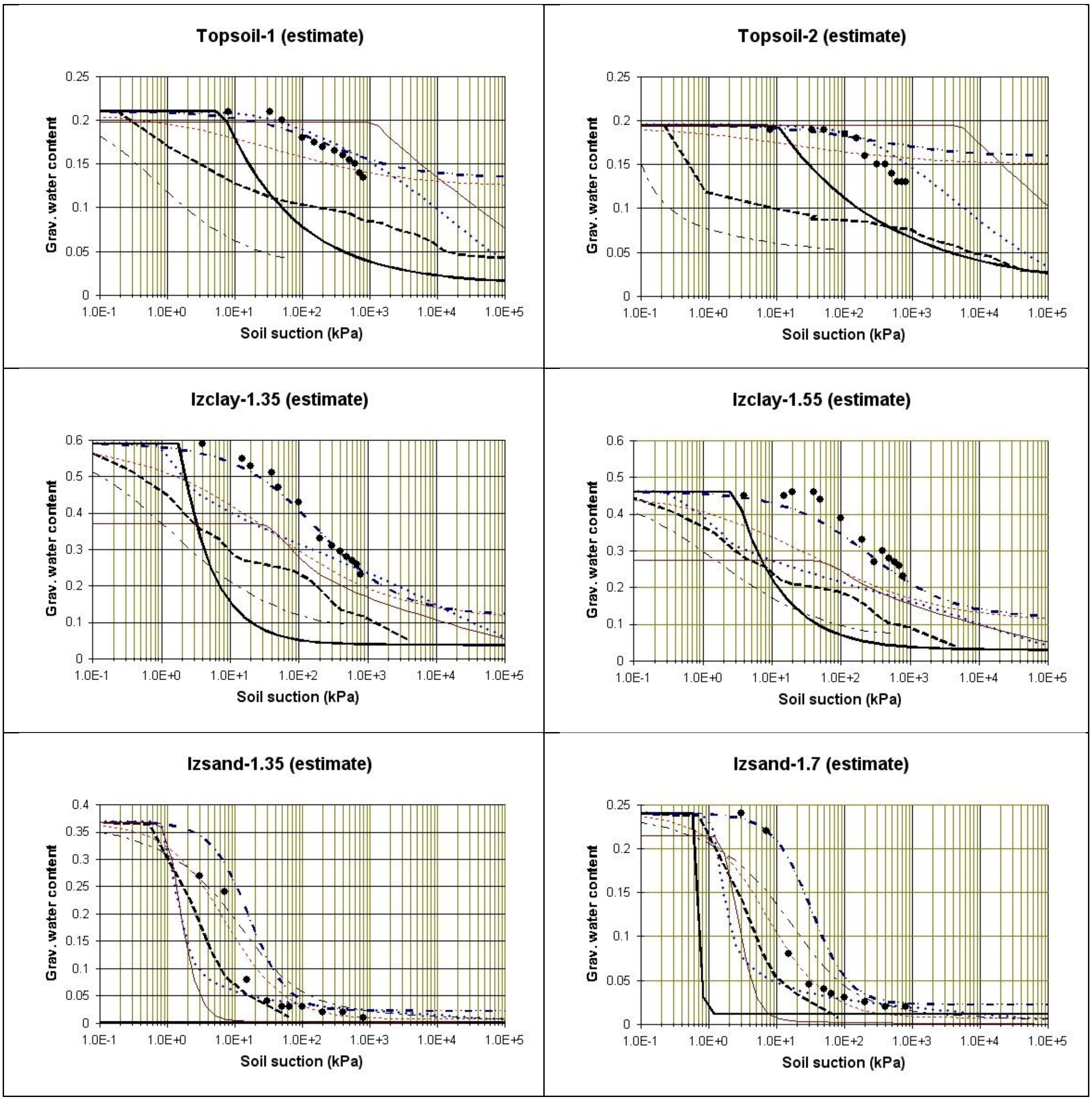


Figure 2. Experimental data of gravimetric water content and soil suction together with fitted curves, for the soils used in this study



Consequently, summary of results including best fitted formulas, best SWCC estimations and corresponding R^2, AEV and inclination rates have been presented in Table 3.



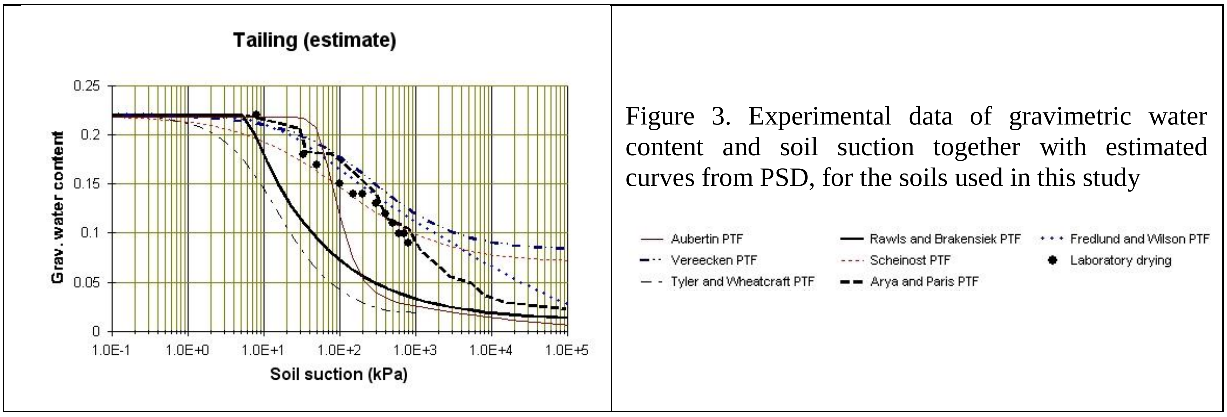


Figure 3. Experimental data of gravimetric water content and soil suction together with estimated curves from PSD, for the soils used in this study

Table 3- Comparison of the successes of the fitted curves and estimations of SWCC from PSD

Specimen	Fitted formula	R^2	Estimation method	R^2	AEV	Desaturation. max. slope
Tailing	FB	0.9948	AP	0.8671	12 kPa	0.32
Topsoil-1	FB	0.9964	FW	0.7944	40 kPa	0.26
Topsoil-2	FB	0.9841	FW	0.5441	100 kPa	0.35
Izclay-1.35	FB	0.9934	Vereecken	0.9782	15 kPa	0.36
Izclay-1.55	FX	0.9801	Vereecken	0.8095	40 kPa	0.4
Izsand-1.35	Gardner	0.9605	Tyler	0.7637	2 kPa	0.91
Izsand-1.7	FX	0.9993	Tyler	0.8	6 kPa	2.05

7 CONCLUSIONS AND REMARKS

- Almost all of SWCC curve fitting formulas fitted well to the experimental water content-suction datasets obtained in the laboratory, as indicated by high R^2 values. Furthermore, Fredlund bimodal was concluded as the best fit for soils with higher fine content, while Fredlund& Xing (1993) fitted better to the SWCC of sandy specimens.
- Not a single prediction method from PSD was found to successfully estimate the SWCC for all soils in this study. However, Fredlund&Wilson (1997) and Vereecken et al. (1998) estimation methods show higher capability to estimate SWCC for different categories of soils. Further studies are needed to study the accuracy of estimation methods.
- More tests are needed for determining the effect of density on SWCC estimation.

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