A dissertation report on

"PREDICTION OF SOIL PERMEABILITY USING SOIL WATER CHARACTERISTIC CURVE"

Submitted in Partial Fulfillment of the Requirement for the Award of the Degree of

MASTER OF TECHNOLOGY

In

CIVIL ENGINEERING

(*With specialization in Geotechnical Engineering***)**

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By

MAUSOM KALITA

Roll No. PG/C/23/08

ASTU Reg No. 230620062006

Under the guidance of

Dr. MALAYA CHETIA

PROFESSOR

DEPARTMENT OF CIVIL ENGINEERING
ASSAM ENGINEERING COLLEGE
JALUKBARI, GUWAHATI

CERTIFICATE OF SUPERVISION

This is to certify that the work presented in this report entitled **— "PREDICTION OF SOIL PERMEABILITY USING SOIL WATER CHARACTERISTIC CURVE"** is carried out by Mausom Kalita, Roll No: PG/C/23/08, a student of M.Tech 3rd semester, Department of Civil Engineering, Assam Engineering College, under my guidance and supervision and submitted in the partial fulfillment of the requirement for the award of the Degree of Master of Technology in Civil Engineering with specialization in Geotechnical Engineering under Assam Science and Technology University.

Date:

Place:

Dr. MALAYA CHETIA

Professor, Department of Civil Engineering,

Assam Engineering College,

Jalukbari, Guwahati-781013

CERTIFICATE FROM HEAD OF THE DEPARTMENT

This is to certify that the mini project report entitled **"PREDICTION OF SOIL PERMEABILITY USING SOIL WATER CHARACTERISTIC CURVE"** has been submitted by Mausom Kalita, Roll No: PG/C/23/08, a student of M.Tech 3rd Semester, Geotechnical Engineering (Civil Engineering), Assam Engineering College, in partial fulfillment of the requirements for the award of the degree of Master of Technology in Geotechnical Engineering of Assam Science & Technology University.

Date :

Place :

DR. JAYANTA PATHAK

Professor and Head of Department

Department of Civil Engineering

Assam Engineering College, Guwahati – 781013

DECLARATION

I hereby declare that the mini project "**PREDICTION OF SOIL PERMEABILITY USING SOIL WATER CHARACTERISTIC CURVE**" in partial fulfillment of the requirement for the award of the degree of " MASTER OF TECHNOLOGY" in Civil Engineering (With specialization in Geotechnical Engineering), submitted in the Department of Civil Engineering, Assam Engineering College, Jalukbari, Guwahati-13 under Assam Science & Technology University, is a real record of the work carried out in the said college for six months under the supervision of Dr, Malaya Chetia, Professor, Department of Civil Engineering, Assam Engineering College, Jalukbari, Guwahati-13. Do hereby declare that this project report is solemnly done by me and is my effort and that no part of it has been plagiarized without citation.

Date : MAUSOM KALITA

This is to certify that the above statement made by the candidate is correct to the best of my knowledge.

Date: Dr. MALAYA CHETIA

Professor, Department of Civil Engineering

Assam Engineering College, Jalukbari, Ghy-13

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Date: MAUSOM KALITA

Place: M.Tech, 3rd Semester

Geotechnical Engineering

Department of Civil Engineering

Assam Engineering College, Jalukbari, Ghy-13

Abstract

Soil water characteristic curve is mandatory for studying the behaviour of unsaturated soil. The soil water characteristic curve is widely used in the design and evaluate the geotechnical and geoenvironmental engineering aspects such as slope stability under influence of environmental factors. Soil water characteristics curve can be used to calculate unsaturated permeability of the soil which is used for analysis of transient seepage used for prediction of landslide, contaminant transport etc.. In this study, relationship between soil texture, bulk density, wilting point and field capacity of the soil and soil water characteristic curve and soil unsaturated permeability is investigated. The softwares used are studied and their way of use are highlighted. Relation between suction and permeability in different water content is shown.

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Chapter 1

Introduction

1.1. General:

Unsaturated soil or partially saturated soil comes under the scope of interest of soil water interaction problem. Soil water characteristic curve (SWCC) is curve showing the relation between metric suction of the soil and water content. This curve (which is also known as water retention curve) provides an understanding between water content (gravimetric or volumetric) and energy state of the water phase (metric suction). Soil water characteristics curve is a key aspect of unsaturated soil mechanics problems. The classical soil mechanics deals with two phase problem (i.e. soil solid and water) thus producing conservative analysis and design. But in real life problems this assumption will not be true, since many real life situations, where soil is three phase or multi phase problem. In these situations soil is mostly unsaturated and metric suction is positive. The study of unsaturated soil behavior is dependent on relationship between suction and water content, which is presented by soil water characteristic curve. The applications of unsaturated soil mechanics are extensive, affecting various aspects of geotechnical engineering. Key areas where this knowledge is applied includes foundation design, slope stability analysis and environmental engineering.

This study attempts to show the work done on prediction of soil permeability from soil water characteristic curve. Soil water characteristic curve or water retention curve is divided in different zones based on three points which are air entry point, inflection point, residual point. Air entry point is the point at which the water air meniscus breaks and air start filling the void of soil. From saturation point to air entry point the curve is effectively horizontal showing little decrease in water the curve is effectively horizontal showing little decrease in water content. Inflection point is the point at which the change of slope of the curve changes sign, i.e. change of slope start to decrease from increase in case of wetting to drying or from increase to decrease in case of drying to wetting. The residual point on the water retention curve marks the transition where the soil retains an equilibrium amount of water despite increasing suction. Water content does not have substantial decrease beyond this point for a very large range of suction.

Different soil water retention models are developed to predict the soil water characteristics curve. Various models are Brooks and Corey model, Van Genuchten model (Van Genuchten (1980)), Gardner model , Kosugi model, Fre. Among them Brooks and Corey model and Van Genuchten model is used in this analysis. These models are combined with pore water distribution models of soil by Mualem[1976] and Burdine[1953] to predict the associated permeability at that suction and predict the associated permeability at that suction and water content.

Many softwares has been developed to employ these mathematical models for prediction of soil water characteristic curve and unsaturated hydraulic conductivity. In this study. Two of such softwares has been used, namely SPAW (soil, plant, atmosphere and water) and RETC. Both of these two softwares has been in use for soil suction, SWCC and unsaturated hydraulic conductivity measument worldwide.

1.2. Motivation and Objective:

Soil water characteristic curve(SWCC) is a key aspect of analysis for geotechnical behaviour of unsaturated soi. SWCC can be used to predict many characteristics of unsaturated soil such as permeability or hydraulic conductivity. In many vadose zone problems knowledge of unsaturated hydraulic conductivity must be known. The knowledge of hydraulic conductivity and diffusivity is directly related to the contaminant transport through soil. Unsaturated hydraulic conductivity also plays crucial role in controlling transient seepage, which used to analyse landslide, contaminant transport etc.

In this study an attempt is made to determine the effect of soil texture, bulk density, wilting point and field capacity to SWCC and soil permeability behaviour with soil suction and water content of the soil.

1.3. Overview of soil water characteristics curve:

Soil water characteristics curve is the plot between soil suction and water content (gravimetric or volumetric). This plot is also known as water retention characteristic curve (WRCC).SWCC obtained by drying and wetting the sample is called desaturation(desorption) and saturation(adsorption) curve respectively. Atypical drying and wetting SWCC is continuous ‘S’ shaped relation and is hysteretic. Due to hysteresis, drying curve shows higher suction at same water content than wetting curve. Below is the figure of an idealized SWCC with key points and hysteresis shown,

Here, Ψ is the suction in kPa
Θ is the volumetric water content
Θ_s is the saturation water
Θ_r is residual water content
Ψ_a is air entry value
Ψ_r is residual suction

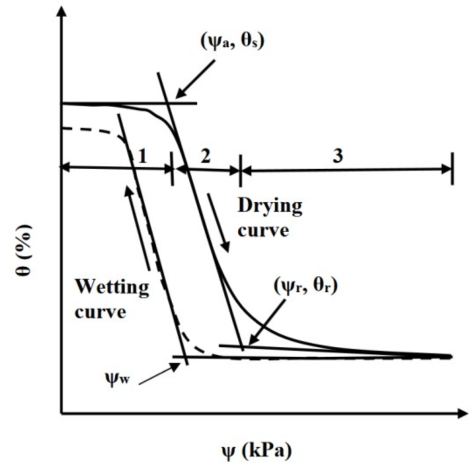
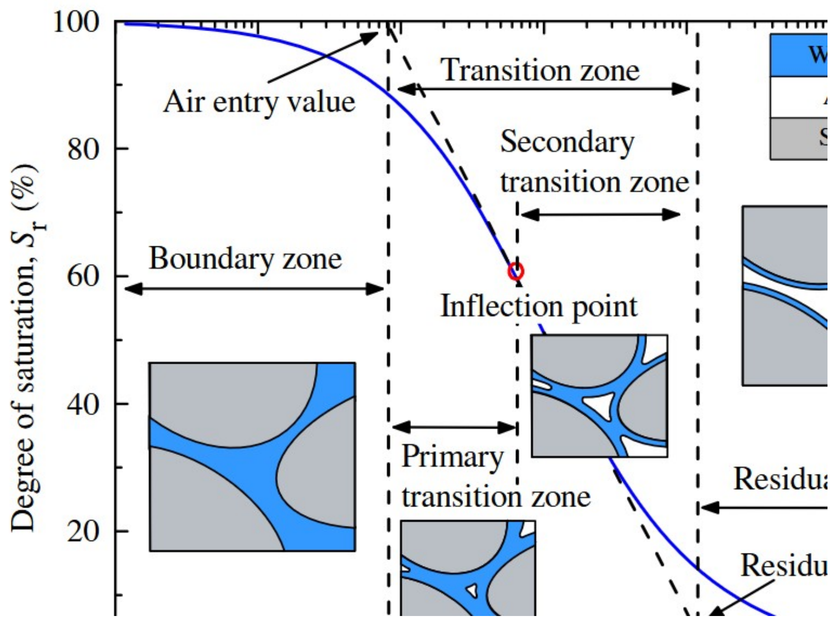


Figure 1: Ideal SWCC (image source: GeoEnv-EnvGeo-NPTEL Course book)

For SWCC, air entry value is the point in which water breaks the meniscus and gets inside the pores of the soil while drying, residual point is the point after which no significant decrease in water content occurs while drying process. SWCC is divided in three zones, which are boundary zone, transition zone and residual zone.

Boundary effect zone is the zone of saturation in which all pores are filled with water relative change of water content is very small than change in suction, it is due to the water tension form a meniscus which is not easy to break. At air entry value(AEV), this meniscus breaks and air gets inside which starts transition zone. In transition zone, water content rapidly decreases when soil suction increases, due to capillary action of the soil. Hence this zone is also known as capillary zone. In the transition zone there is a point of inflection at which rate of decrease of water content starts slowing down. The transition zone is divided in two sub-zones, which are primary transition zone and secondary transition zone(Gao et al. (2019)). After the residual point, starts the residual zone at which no capillary water is left. Due to only hydroscopic water present, process of drying does not change water content relative to increase in suction that makes the SWCC flat.



Here, degree of saturation, $S_r = \frac{\theta}{\theta s}$

Figure 2: SWCC with different zones shown (image source: Modified from Vanapalli 2010, source Gao et al. (2019))

The residual water content specifies the maximum amount of water in a soil that will not contribute to liquid flow because of blockage from the flow paths or strong adsorption onto the solid phase. Θ_s is the maximum volumetric water content in the soil. But, due to presence of entrapped air, Θ_s is found to be 5 to 10 percent less than porosity.(RETC code, Genuchten et al)

1.4. Soil texture data by USDA recommendation:

Due to all the available research and softwares on SWCC and soil permeability are based on USDA(United States Department of Agriculture) recommended soil classification, soil classification used in this study is also USDA recommendation. Different from IS classification, USDA classification is as given below,

Soil particle sizes	US standards	IS standard
Gravel	>2 mm	>4.75 mm
Sand	0.05 – 2 mm	0.075 – 4.75 mm
Silt	2 – 50 micron	2 – 75 micron
Clay	Less than 2 micron	Less than 2 micron

Table 1: Soil particle sizes for USDA and Indian standards.

There are 12 textural classes of soil depending on the percentage of sand, silt, clay present in the soil. These are as follows, sand, loamy sand, sandy loam, sandy clay loam, loam, silt loam, silt, silty clay loam, clay, clay loam, sandy clay and silty clay. Each texture class has a distinctive characteristic(s) which can be estimated in the field by trained personnel. Based on the known percentage of sand, silt and clay (SSC) soil texture also can be determined by soil texture triangle provided in USDA recommendation.

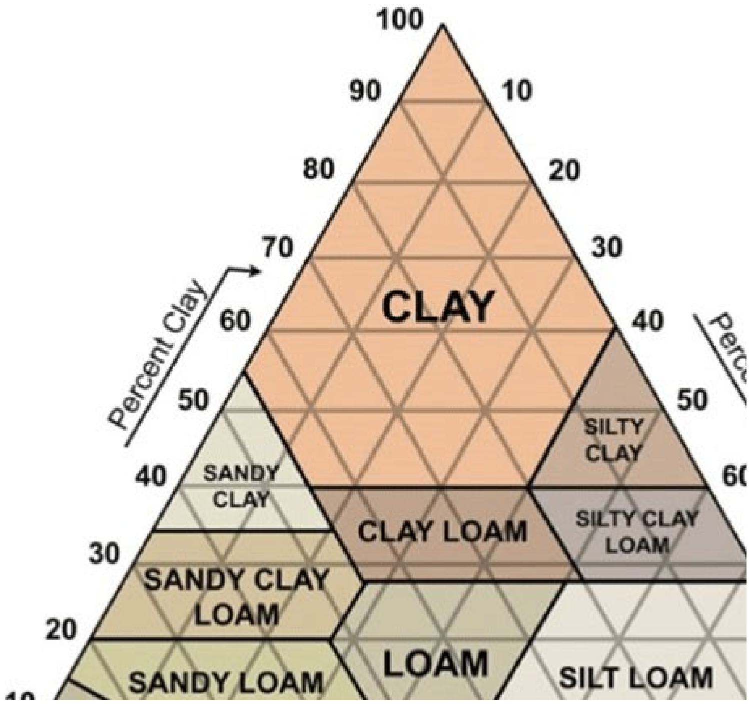


Figure 3: Soil texture triangle (source: https://www.researchgate.net/profile/Shabbir-Shahid/publication/329240675/figure/fig1/AS:699746301779976@1543843927568/USDA-soil-textural-classes.ppm

To look up the soil texture class, the respective angles given in the triangle side must be followed for each particle range along the given percentage of SSC.

Wilting point and field capacity of soil:

The permanent wilting point is the point when there is no water available to the plant. The permanent wilting point depends on plant variety, but it is usually around 1500 kPa (15 bars). At this stage, the soil still contains some water, but it is difficult for the roots to extract from the soil. Nearly 15 bars of tension is required to extract water by the plants. At this limit, if no additional water is supplied to the soil, most of the plants die.(Rai et al. (2017)). The water content at this suction in SWCC is the wilting point of soil, which is denoted by Θ_{1500}.

Soil suction at field capacity is a critical measurement in determining how much moisture soil can retain after excess water has drained away. It reflects the tension within the soil's water, which affects the availability of water for plants. The soil suction at field capacity refers to the matric potential, typically defined at a suction of approximately 33 kPa. The water content at this suction on SWCC is the field capacity of the soil, which is denoted as Θ_{33}

Chapter 2

Literature Review

N. T. Burdine (1953)	• Developed pore water distribution model based on statistical analysis of entry pore size, pore volume, tortuosity, porosity.
Brooks and Corey (1964)	• Compared large number of experimental data to conclude a parametric equation for soil water charactistics curve.
Campbell (1974)	• One of the simplest sets of equations for describing soil hydraulic properties was developed. This included retention function and hydraulic conductivity function.
Mualem (1976)	• Developed pore water distribution model to predict relative hydraulic conductivity of soil.
Gupta and Larson (1979)	• Used multiple linear regression equations to predict soil water content of 12 given soil water potential.
Van Genuchten (1980)	• Developed water retention model based on an empirically based power law equation describing the relationship between pressure head, h, and moisture content, θ, with the Mualem (1976) predictive pore-size

	distribution model for the unsaturated hydraulic conductivity.
Carsel and Parrish (1988)	• A method was presented for developing probability density functions for several water retention characteristics for 12 soil texture classifications using joint multivariate distribution.
Rawls et al. (1982)	• Reported a multiple linear regression analysis of soil-water content at 12 soil-water potentials with soil attributes using a very extensive data set
Schaap and Leij (2000)	• Showed that hierarchical approach was not possible for unsaturated hydraulic conductivity due to poor relation between tortuasity and conductivity with texture and bulk density. • Conductivity could be estimated from fitted water retention data. • Developed pedotransfer functions as predictor for soil hydraulic properties.
Saxton and Rawls (2006)	• This study developed new soil water characteristic equations from the USDA soil database, combining variables like texture and organic matter. These equations form a predictive system for agricultural water management and hydrologic analyses, available for easy application.
Malaya and Sreedeep (2012)	Deal with parameters that needs critical assessment and addresses factors inflencing SWCC.

Pham et al. (2021)	• This study uses three advanced machine learning algorithms, artificial neural network (ANN), support vector machine (SVM), and random forest (RF), to predict soil permeability coefficient. • Results show RF model is more efficient than ANN and SVM, indicating its potential for accurate soil permeability coefficient estimation in construction projects.
Solangi et al. (2024)	This study explores soil hydraulic conductivity in loam and clay soils using constant head and falling head methods. Results show sandy loam soils have higher Ksat values, suggesting the falling head method for cost-effective and simple determination.

2. Soil water retention models:

Different analytical models for empirical describe the soil water characteristic curve has been developed, each suggesting different functions to empirically describe the soil water retention curve.

2.1. Brook's and Corey model:

Brooks and Corey model also refers as BC equation is,

$$S_e = \frac{1}{(\alpha h)^{\lambda}} \qquad \text{when } h > \alpha$$

$$S_e = 1, \qquad \text{when } h < \alpha$$

$$\text{And } S_e = \frac{\Theta - \Theta_r}{\Theta_s - \Theta_s}$$

Where h is the suction, α is the inverse of air entry value, S_e is reduced pressure head or effective degree of saturation (RETC code, Genuchten et al), this equation gives the simple SWCC curve, which can be analysied in the form $y = \frac{1}{x^{\lambda}}$, here λ is a pore size distribution parameter, which affects the slope of the retention function. Simple analysis of this curve shows that when λ is increase the curve gets steeper. On logarithmic plot this equation generates two curve which intersects at air entry value.

The main drawback of this function is the presence of non differentiability at air entry value. This is why a continuous 'S' curve is not by this curve. But still BC equation can be used for simple analysis of soil suction.

2.2. Van Genuchten model:

Van Genuchten model or simply refered to as VG equation is,

$$S_e = \frac{1}{(1 + (\alpha h)^n)^m}$$

Here α, m and n are empirical constants. This curve can produce a continuous 'S' curve and is differentiable at all points. The term αh is refered as reduced pressure head.

2.3. Analysis of VG equation:

When plots are made between S_r and αh, equation simplifies to, $y = \frac{1}{(1+x^n)^m}$
Actual value of h can be found by dividing x by α in linear graph or shifting the logarithmic scale by log(a). Below are the plots of above equation with varing m, n values are shown.

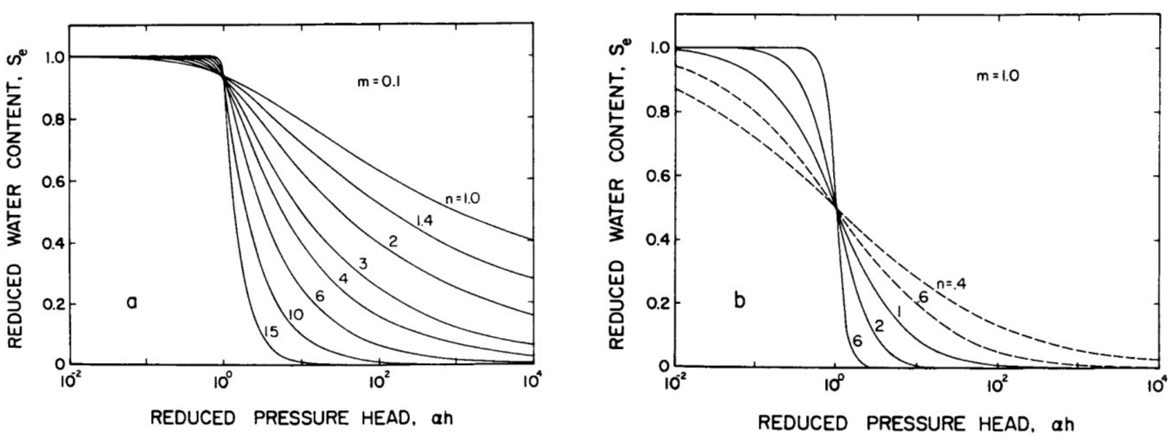


figure 4: reduced pressure head vs reduced water content, m fixed at 0.1 and 1.0. (source: RETC code, Genuchten et al)

By comparing the two sets of curves, it can be inferred that increase in m shifts the intersection point down for varing n in the curve. The parameter n is directly related to the slope of SWCC. Increase of n should and increases the slope of the curve.

In the plots below, the product mn was kept constant at an arbitrary value of 0.4. This last feature causes all curves to approach a limiting curve at low values of the relative saturation, S_e.

This limiting curve follows from VG equation by removing the factor 1 from the denominator, and is equivalent to the Brooks and Corey equation with λ = mn (RETC code, Genuchten et al)

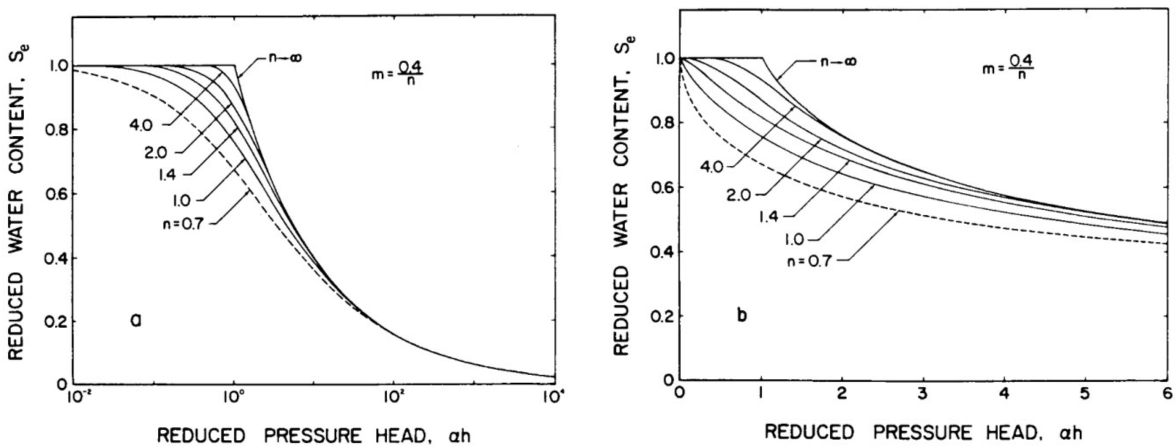


Figure 5: semi-logarithmic (left) and regular(right) plots of VG equation with mn = 0.4 (source: RETC code, Genuchten et al)

2.4. Burdines pore conductivity model (1953):

Burdine developed a pore water distribution model beased on pore sizes and tortuosity of the soil for determining the unsaturated hydraulic conductivity of the soil. The equation of unsaturated hydraulic conductivity is

$K(S_e) = K_s S_e^{l} \frac{g(S}{g(}$ in which $g(S_e) = \int_0^{S_e} \frac{1}{[h(x)]^2}$ (RETC code, Van Genuchten et al)

In this model, Burdine assumed the exponential component, l to be 2. By assuming $m = 1 - \frac{2}{n}$ in SWCC, this equation can be simplified to VG closed form equation for hydraulic conductivity (Van Genuchten, 1980).

2.5. Mualems pore conductivity model:

The Mualems pore water conductivity model establishes relation between pore structure of the soil and the hydraulic conductivity based on Burdines model (1953). The equation is

$K_r(S_e) = S_e^{l} \left[\frac{f(S}{f(1} \right.$ where, $f(S_e) = \int_0^{S_e} \left(\frac{S_e^{1/m}}{1 - S^{1/m}} \right)^{1}$ (Neto et al. (2011))

In this model, the exponential component, l suggested by Mualem is 0.5, By assuming $m = 1 - 1/n$, this equation can be simplified to VG closed form equation for hydraulic conductivity (Van Genuchten, 1980).

Closed form equation of hydraulic conductivity(Van Genuchten, 1980):

The closed form equation of hydraulic conductivity by Van Genuchten, 1980 is given by,

$$K(S_e) = K_s S_e^{l} [1 -(1 -S_e^{1/}$$

In case of Mualem based restriction, $m = 1 - \frac{1}{n}$ and $l = 0.5$

relative hydraulic conductivity is given by, $$K(h) = \frac{K_s\{1 -(\alpha h)^{mn}[1 +(\alpha}{[1 +(\alpha h)^n]^{ml}}$$

and diffusivity is given by, $$D(S_e) = \frac{(1 -m)K_s S_e^{l-1/m}}{\alpha m(\theta - \theta)}\left[(1 - S_e^{1/m})^{-m} + (1 -\right.$$

In case of Burdine based restriction, $m = 1 - \frac{2}{n}$ and $l = 2.0$

relative hydraulic conductivity is given by $$K(h) = \frac{1 -(\alpha h)^{n-2}[1 +(\alpha}{[1 +(\alpha h)^n]^{m}}$$

and diffusivity is given by, $$D(S_e) = \frac{(1 -m)K_s S_e^{l-(m+1)/2m}}{2\alpha m(\theta - \theta)}\left[(1 - S_e^{1/m})^{-(m+1)/2} - (1 -\right.$$

Chapter 3

Methodology and software used for the research:

3.1 SPAW:

The software SPAW (soil plant atmosphere and water) can be used for determining soil suction and hydraulic conductivity at specific moisture content. The SPAW model is authored by Dr. Keith E. Saxton and Mr. Patrick H. Willey. This is a computer model that simulates the daily hydrologic water budgets of agricultural landscapes by two connected routines, one for farm fields and a second for impoundments such as wetland ponds, lagoons or reservoirs. The sub program available with SPAW, 'soil water characteristics' can estimate soil suction and hydraulic conductivity with given inputs, that are (i) Percentage of clay, (ii) Percentage of Sand, (iii) Percentage of organic matter, (iv) Salinity in dS/m, (v) Percentage of Gravel, (vi) compaction (which can be used to change the density of the soil) and (vii) moisture content (by percentage of volume). Below is a screen shot of main page of the software.

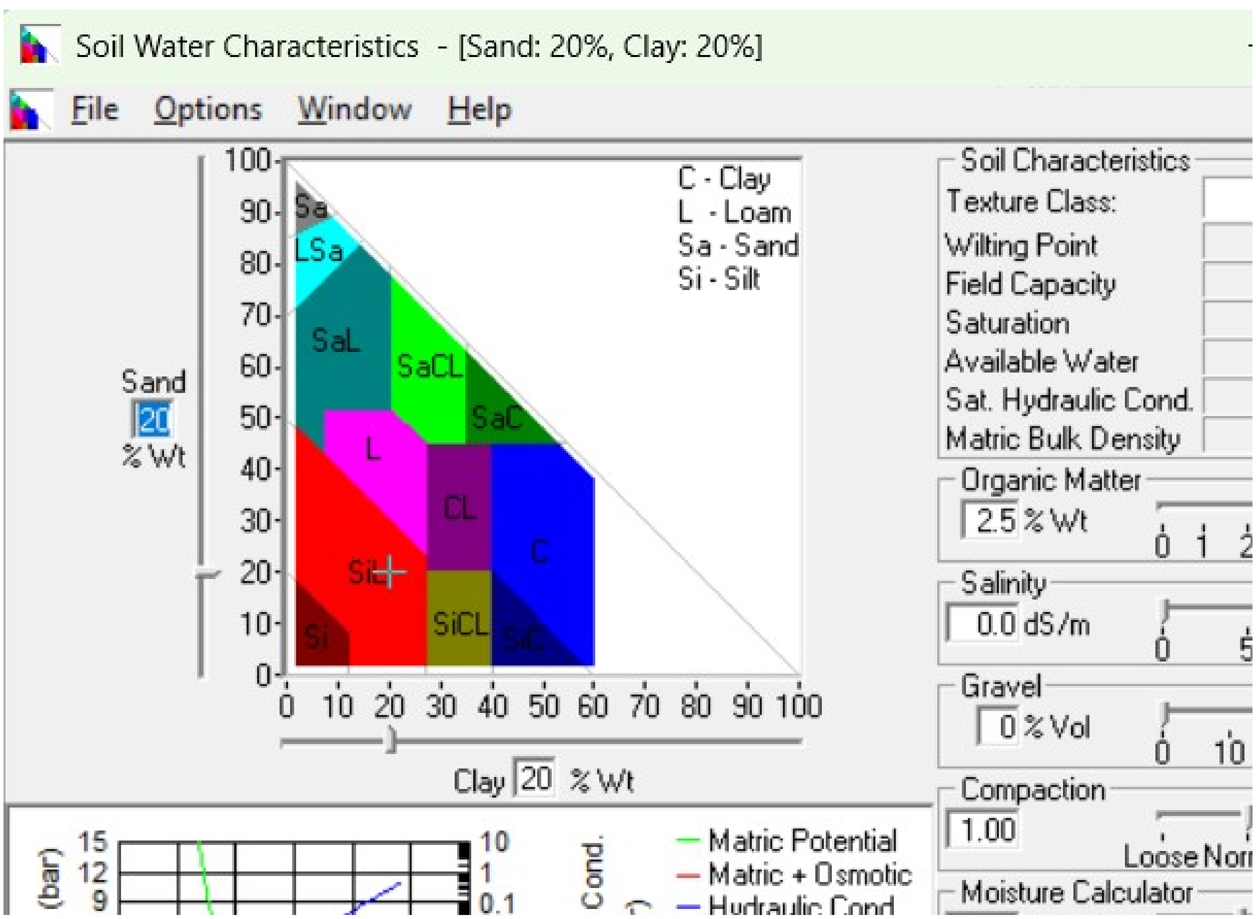


figure 6: Home page of the soil water characteristics software.

This software is modeled based on the research paper Saxton et al. (1986) and Saxton and Rawls (2006), which uses mathematical regression model of Gupta and Larsen(1979), Brook's and Corey model, Campbell hydraulic conductivity model to estimate soil suction and permeability (Campbell (1974)). This software is downloaded from https://www.nrcs.usda.gov/resources/tech-tools/spaw-version-602.

3.2. RETC software:

The RETC parameter optimization program or RETC software rovides several options for describing or predicting the hydraulic properties of unsaturated soils. These properties involve the soil water retention curve, Θ(h), the hydraulic conductivity function, K(h) or K(Θ), and the soil water diffusivity function, D(Θ) in either graphical or text based output file. Below are screenshots of RECT software.

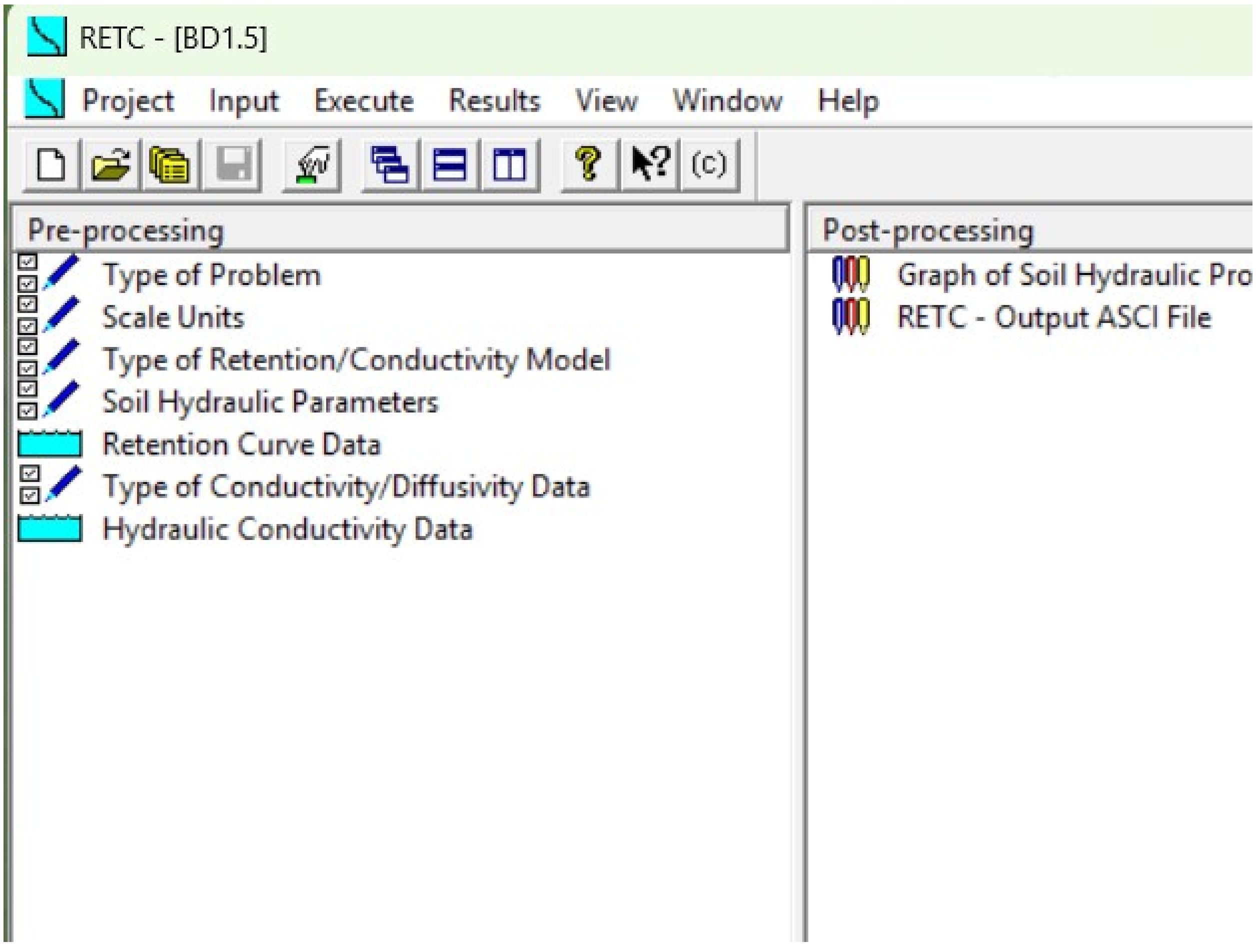


Figure 7: Homepage of the RETC software.

RETC uses neural network to predict 5 different variables used by VG equation to plot SWCC from soil texture data. This artificial neural network is Rosetta, developed by Marcel G. Schaap, Feike J. Leij, Martinus Th. van Genuchten in 2001 (Schaap et al. (2001)). This program which implements 5 hierarchical pedotransfer functions (PTFs) for the estimation of water retention, and the saturated and unsaturated hydraulic conductivity. The hierarchy in PTFs allows the estimation of van Genuchten water retention parameters and the saturated hydraulic conductivity using limited &textural classes only) to more extended &texture, bulk density, and one or two water retention points) input data. rosetta is based on neural network analyses combined with the bootstrap method, thus allowing the program to provide uncertainty estimates of the predicted hydraulic parameters (Schaap et al. (2001)).

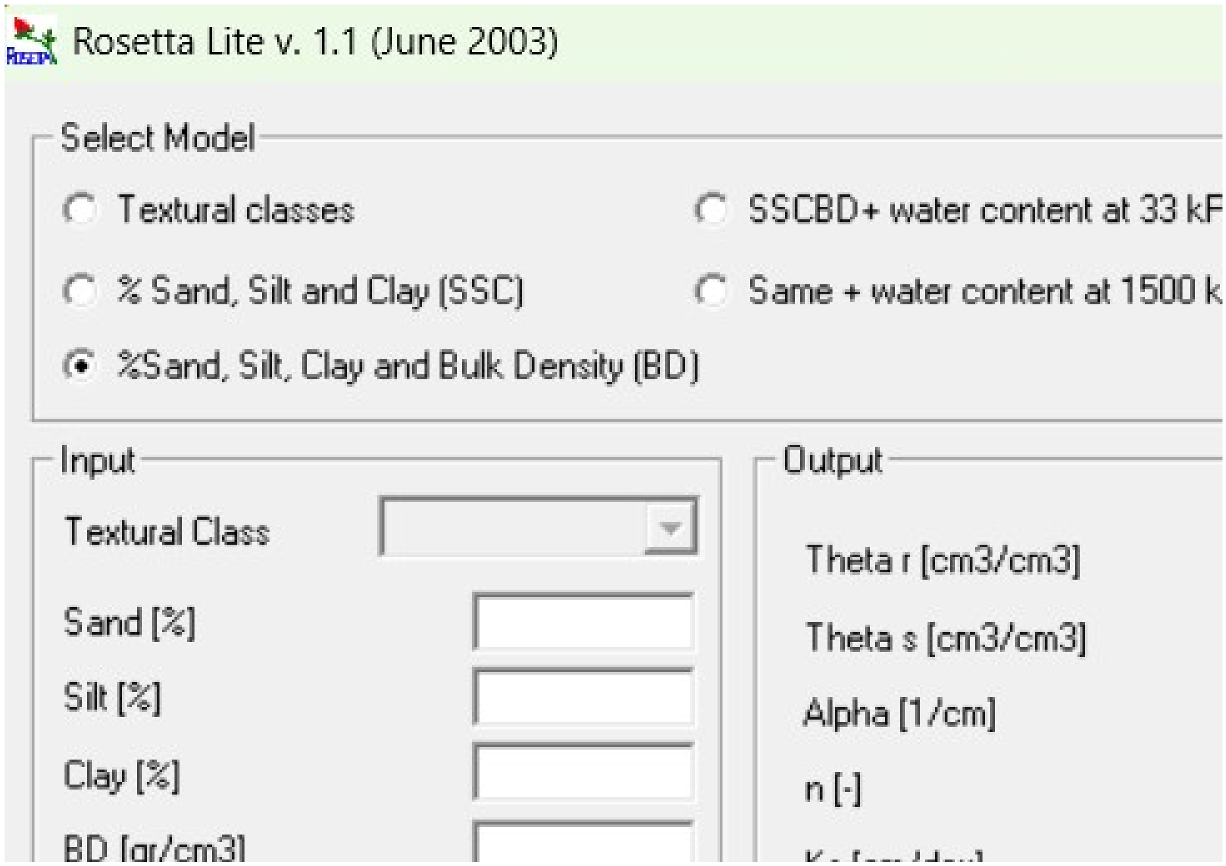


figure 8: Rosetta that is incorporated in RETC software.

3.3. Output of RETC:

RETC produces graphical output of the fitted curve or text based result of the regression analysis. When input is and incompatible data, fitted curve s not generated in graphical output which result only input points being plotted and output points are not calculated in text based result. This result can be used as text analyser program simply copy paste the soil hydraulic data in excel of generate the graph. Note, the soil hydraulic data is available in the form of table with columns WC, P, logP, K, logK, D, logD which are water content, head, log of head, hydraulic conductivity, log of hydraulic conductivity, diffusivity, log of diffusivity.

3.4. **Methodology:**

Since, this study is mainly done using softwares, data input and output is also software dependent. Both of the two softwares employs different approach to calculate, data collection will be error prone with data is shifted between softwares, without prior consideration of where those data fits. Soil water characteristics program of SPAW estimates soil suction and hydraulic conductivity from multiple linear regression analysis of given soil texture. As the result of this analysis, an estimate of Θ_{1500}, Θ_{33}, Θ_s, saturated hydraulic conductivity (K_s) is calculated. We can adjust the slider on compaction data to get desired bulk density of the soil.

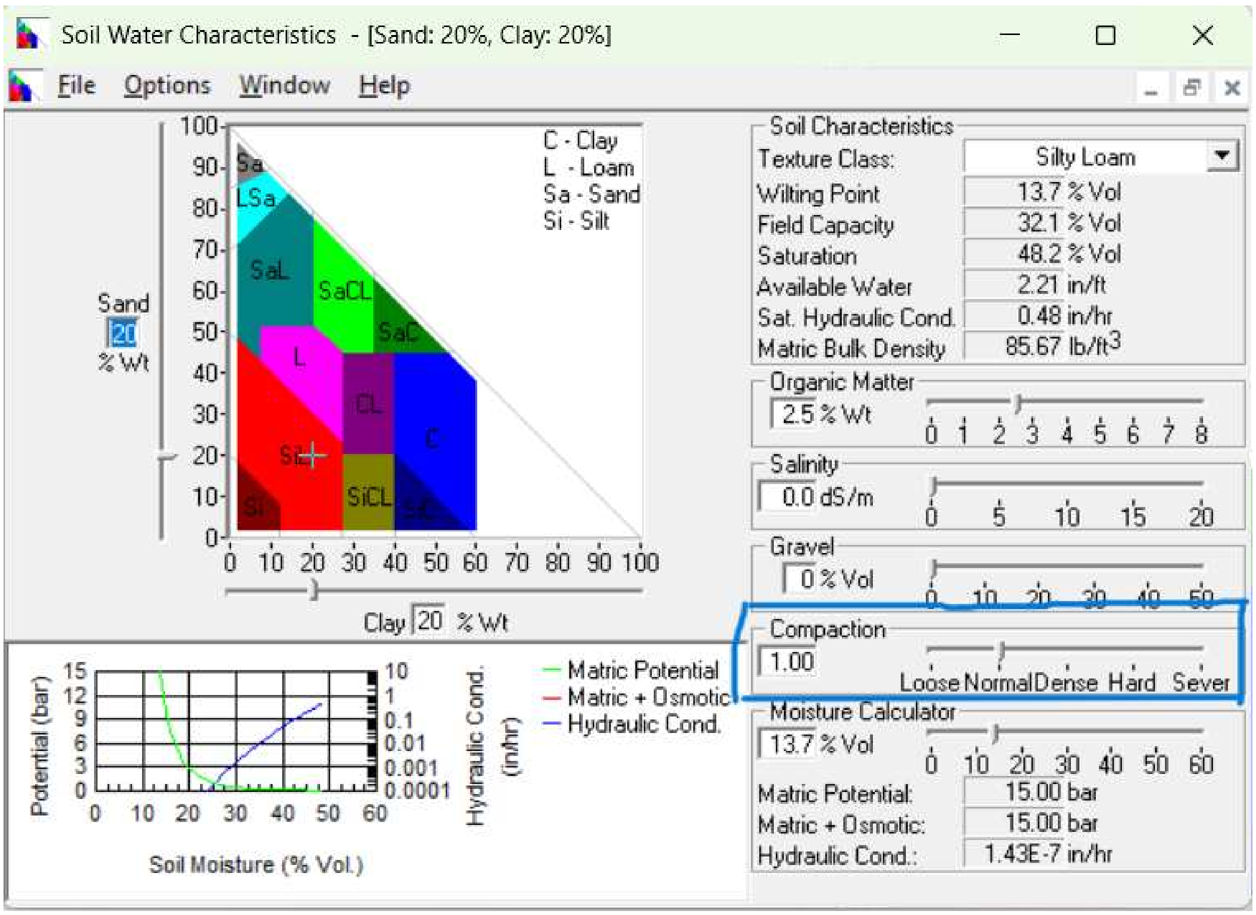


figure 9: slider on compaction soil water characteristics software.

The water content (V/V %) can be adjusted by moisture calculator slider below the compaction slider. This changes the Matric potential, Matric + Osmotic potential and Hydraulic Conductivity values. If there is zero salinity as an input, by definition the osmotic potential will be zero, which makes matric potential same as the total potential. This program does not present the air entry value of the soil not it shows the pore size distribution parameter λ.

Rosetta in RETC calculates 5 parameters as output, Θ_r, Θ_s, α, n and K_s. These 5 parameters are sufficient for calculation of SWCC and soil permeability based on Van Genuchten (1980) equations of both SWCC and hydraulic conductivity. There are 5 predictor models of rosetta based on the input level at which the program estimates the output. These are,

(i) H1 model, General soil texture class is the input.
(ii) H2 model, SSC percentages are the input.
(iii) H3 model, SSC and bulk density are the input.
(iv) H4 model, SSC, bulk density(BD) and $\Theta_{33}$are input parameters
(v) H5 model, SSC, BD, Θ_{33} and Θ_{1500} are the nput parameters.

Based on the output of rosetta, RETC program fits the SWCC and soil permeability curve for the selected unsaturated soil. RETC program output can be fitted or non fitted. In case of fitted outside points are necessary on which the curve is fitted, but if the points are incompatible i.e. the points have error or initial texture points are too different etc fitting will not be done. In case of non fitted, using rosetta 5 parameter outputs are calculated which is used to calculate the curves for the soil.

Based on the above information a few workflow can be devised.
(i) In soil water characteristics of SPA software fix soil texture, BD, organic matter (OM), salinity and use the moisture slider to get different values of soil suction and hydraulic conductivity. Note the Θ_{33} and Θ_{1500} for that soil texture and BD.

(ii) Use the no fitting option and input the SSC, BD, Θ_{33} and Θ_{1500} in rosetta to estimate the PTF output Θ_r, Θ_s, α, n and K_s. Use that to directly plot the SWCC and soil permeability functions.
Or, Use the both retention and conductivity data in fitting option to input the recorded the values of soil suction and hydraulic conductivity from soil water characteristics and fit the curve. For compatible inputs this have really good fitting. But it does show ouput in case of incompatible input.

Engineering notation used in this report is 1.0E+2 style notation which denotes 100.

Chapter 4

Results and discussion

First set of result:

15 soil textures, different BDs organic matter and salinity 0. SSC, Bulk density (zero water content, i.e. dry density), Th33 and Th1500 in input data in rosetta. Compaction is kept at 1.0. SPAW data in input in RETC and plot is drawn.

Sand%	Silt %	Clay %	BD g/cc	AEV (cm)	Θr (V/V %)	Θs (V/V %)	Ks (cm/day)
35	60	5	1.67	63.4	0.031	0.311	17.21
40	55	5	1.66	53.2	0.030	0.310	17.26
45	50	5	1.66	42.5	0.029	0.310	18.46
50	45	5	1.65	35.0	0.029	0.314	20.96
55	40	5	1.64	29.2	0.029	0.320	24.62
35	55	10	1.65	82.0	0.038	0.323	11.62
40	50	10	1.65	66.5	0.037	0.321	11.45
45	45	10	1.65	52.9	0.036	0.323	12.59
50	40	10	1.64	43.2	0.036	0.328	14.88
55	35	10	1.64	35.0	0.036	0.333	17.40
35	50	15	1.62	96.5	0.047	0.339	8.28
40	45	15	1.63	76.5	0.045	0.338	8.03
45	40	15	1.63	61.0	0.045	0.340	9.18
50	35	15	1.63	49.0	0.045	0.345	10.90
55	30	15	1.63	40.4	0.045	0.349	13.13

Table 2: Comparision table for change in sand content at 5, 10, 15% clay on AEV, Θ_s, Θ_r, K_s.

From above table we can infer the following,

- As sand content increases for fixed clay content, AEV is decreasing and saturated permeability is increasing.
- BD decreasing slightly and saturated water content has slight increase. But water content at retention is more or less the same.
- Increase in clay content shows sharp increase in AEV and sharp decrease in saturated water content.

We can conclude that increase in sand content increases pore size which decreases AEV and increases saturated permeability. Similarly, increase in clay content decrease pore size and increase AEV and saturated permeability.

Second sets of result:

Values for minimum silt content: fixed at 2% (which is minimum silt content selectable in SPAW software)

Clay content at 38%, 35% and 30%. Soil texture class sandy clay loam. Values are recorded from SPAW and used as input data in RETC.

Clay (%)	Sand (%)	Silt (%)	BD (g/cc)	Θ_s (%)	K_s (cm/day)
38	60	2	1.57	40.6	3.19
35	63	2	1.59	39.8	5.4
30	68	2	1.62	38.8	12.048

Table 3: Soil hydraulic properties for minimum silt content 2% for clay content 38%, 35%, 30% in SPAW.

Following are the recorded data points table found by varying water content in soil characteristics of SPAW for above soil texture.

Water content (v/v%)	suction, -h (kpa)	suction, -h (cm)	Permeability (mm/hr)	Permeability (cm/day)	Water content (w/w%)
22.8	1500	15300	9.48E-07	2.28E-06	14.52
24.3	743	7578.6	4.70E-06	1.13E-05	15.48
25.7	408	4161.6	1.85E-05	4.44E-05	16.37
27.2	206	2101.2	8.81E-05	2.11E-04	17.32
28.7	125	1275	2.73E-04	6.55E-04	18.28
30.2	73	744.6	9.47E-04	2.27E-03	19.24
31.7	43	438.6	3.09E-03	7.42E-03	20.19
32.5	33	336.6	5.68E-03	1.36E-02	20.70
34	28	285.6	1.71E-02	4.10E-02	21.66
35.5	22	224.4	4.90E-02	1.18E-01	22.61
37	16	163.2	1.34E-01	3.22E-01	23.57
38.5	11	112.2	3.55E-01	8.52E-01	24.52
40	5	51	9.01E-01	2.16E+00	25.48
40.6	3	30.6	1.30E+00	3.12E+00	25.86

Table 4: SPAW data points for soil clay 38%, sand 60%.

Water content (v/v%)	suction, -h (kpa)	suction, -h (cm)	Permeability (mm/hr)	Permeability (cm/day)	Water content (w/w%)
21	1500	15300	4.26E-07	1.02E-06	13.21
22.5	707	7211.4	2.37E-06	5.69E-06	14.15
24	358	3651.6	1.12E-05	2.69E-05	15.09

25.5	189	1927.8	4.84E-05	1.16E-04	16.04
27	103	1050.6	1.92E-04	4.61E-04	16.98
28.5	59	601.8	7.04E-04	1.69E-03	17.92
30	34	346.8	2.42E-03	5.81E-03	18.87
30.1	33	336.6	2.62E-03	6.29E-03	18.93
31.5	29	295.8	7.84E-03	1.88E-02	19.81
33	24	244.8	2.40E-02	5.76E-02	20.75
34.5	19	193.8	7.01E-02	1.68E-01	21.70
36	15	153	1.95E-01	4.68E-01	22.64
37.5	10	102	5.23E-01	1.26E+00	23.58
39	5	51	1.34E+00	3.22E+00	24.53
39.8	3	30.6	2.25E+00	5.40E+00	25.03

Table 5: SPAW data points for soil clay 35%, sand 63%.

Water content (v/v%)	suction, -h (kpa)	suction, -h (cm)	Permeability (mm/hr)	Permeability (cm/day)	Water content (w/w%)
17.9	1500	15300	6.28E-08	1.51E-07	11.05
19.5	627	6395.4	4.64E-07	1.11E-06	12.04
21.1	279	2845.8	2.97E-06	7.13E-06	13.02
22.7	132	1346.4	1.65E-05	3.96E-05	14.01
24.3	66	673.2	8.21E-05	1.97E-04	15.00
25.5	40	408	2.55E-04	6.12E-04	15.74
26	33	336.6	4.03E-04	9.67E-04	16.05
27.6	29	295.8	1.64E-03	3.94E-03	17.04
29.2	25	255	6.18E-03	1.48E-02	18.02
30.8	22	224.4	2.17E-02	5.21E-02	19.01
32.4	18	183.6	7.13E-02	1.71E-01	20.00
34	14	142.8	2.21E-01	5.30E-01	20.99
35.6	10	102	6.53E-01	1.57E+00	21.98
37.2	6	61.2	1.84E+00	4.42E+00	22.96
38.8	2	20.4	5.02E+00	1.20E+01	23.95

Table 6: SPAW data points for soil clay 30%, sand 68%.

These input data are fitted to the RETC, and the output curves are as follows,

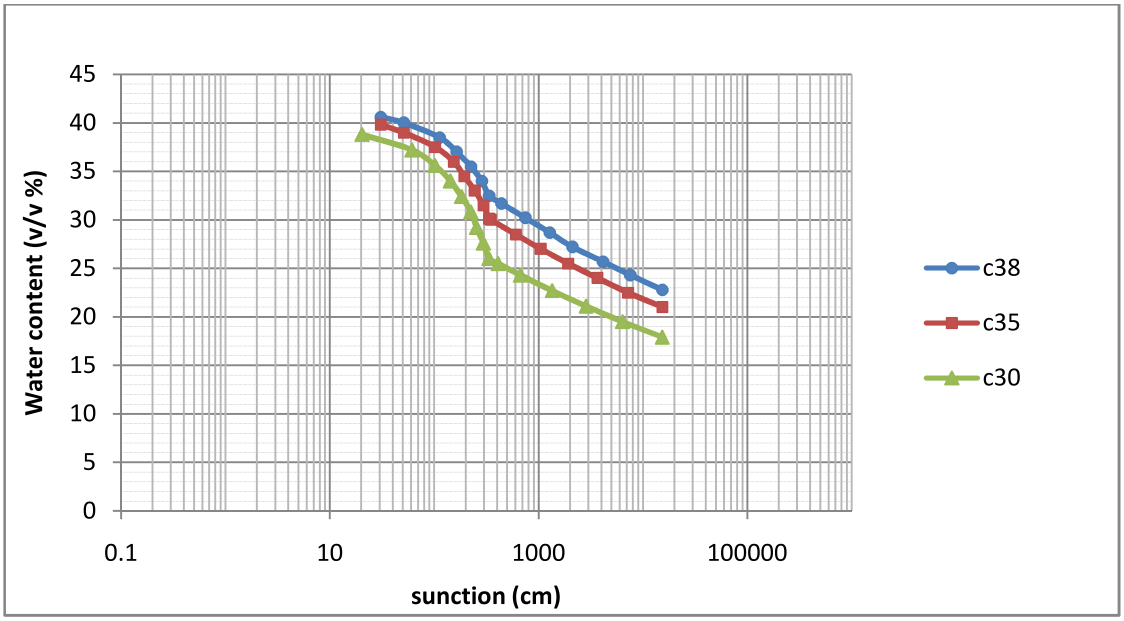


Figure 10: Plot for suction and water content in soil water characteristics for SPAW data points for soil clay 30%, sand 68%..

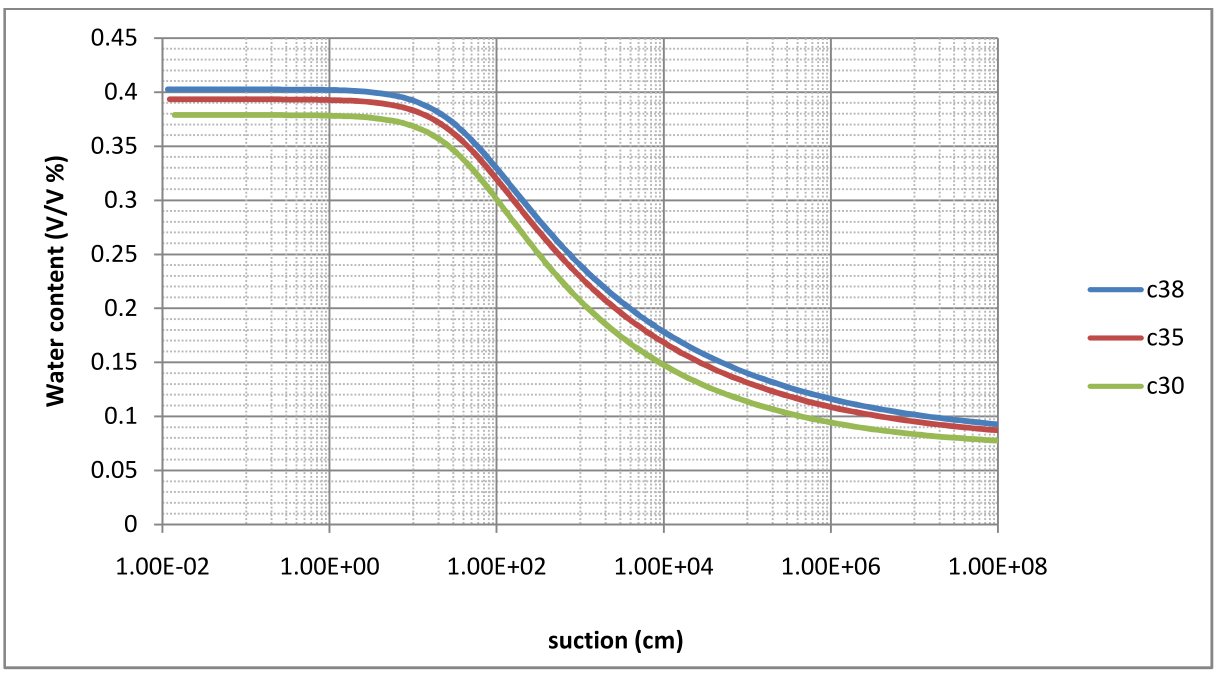


Figure 11: SWCC by RETC for soil texture C38, C35, C30, amount of silt fixed at 2%.

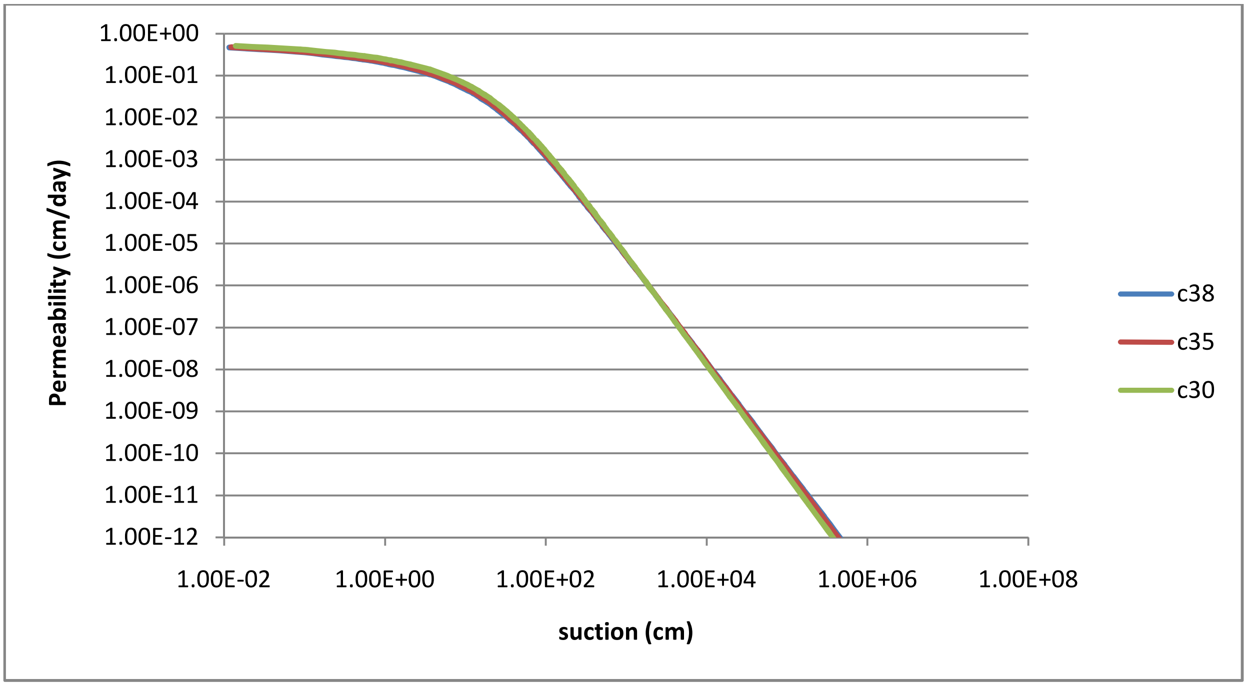


Figure 12: Suction vs Permeability curve by RETC for soil texture C38, C35, C30, amount of silt fixed at 2%.

Third set of result:

Fixed soil texture, varying dry density (BD since it is used as in RETC and SPAW)

Texture sand = 65%, silt = 25%, clay = 10%, class: Sandy loam.

Organic matter and salinity fixed at zero.

Soil water characteristics result:

Bulk density (g/cc)	Saturated permeability, K_s (cm/day)	Percentage of saturation, Θ_s (%)
1.5	140	43.3
1.65	85	37.8
1.8	45.6	32.2

Table 7: Soil hydraulic inputs estimated by SPAW for soil texture sand 65%, silt 25%, clay 10%

For bulk density = 1.5 g/cc, soil water characteristic output table

Suction (kPa)	Wc V/V (%)	Permeability. (mm/hr)	Suction (cm)	Permeability (cm/day)
1	43.3	5.82E+01	10.197	1.40E+02
4	40.8	3.04E+01	40.788	7.30E+01
7	38.3	1.53E+01	71.379	3.67E+01
9	35.8	7.40E+00	91.773	1.78E+01
12	33.3	3.39E+00	122.364	8.14E+00
15	30.8	1.46E+00	152.955	3.50E+00
18	28.3	5.85E-01	183.546	1.40E+00
21	25.8	2.15E-01	214.137	5.16E-01
24	23.3	7.16E-02	244.728	1.72E-01
27	20.8	2.10E-02	275.319	5.04E-02
30	18.3	5.28E-03	305.91	1.27E-02
33	15.5	8.79E-04	336.501	2.11E-03
65	13	1.32E-04	662.805	3.17E-04
149	10.5	1.31E-05	1519.353	3.14E-05
431	8	6.95E-07	4394.907	1.67E-06
1053	6.4	5.88E-08	10737.44	1.41E-07
1500	5.8	2.20E-08	15295.5	5.28E-08

Table 8: Soil hydraulic properties recorded by SPAW by varying moisture content for soil texture sand 65%, silt 25%, clay 10% bulk density 1.5 g/cc

For bulk density 1.65 g/cc, soil water characteristic output table:

Suction (kPa)	Wc V/V (%)	Permeability (mm/hr)	Suction (cm)	Permeability (cm/day)
2	37.8	3.54E+01	20.394	8.50E+01
5	35.7	1.81E+01	50.985	4.34E+01
8	33.6	9.07E+00	81.576	2.18E+01
11	31.5	4.34E+00	112.167	1.04E+01
13	29.4	1.97E+00	132.561	4.73E+00
16	27.3	8.44E-01	163.152	2.03E+00
19	25.2	3.38E-01	193.743	8.11E-01
22	23.1	1.25E-01	224.334	3.00E-01
24	21	4.20E-02	244.728	1.01E-01
27	18.9	1.26E-02	275.319	3.02E-02
30	16.8	3.28E-03	305.91	7.87E-03
33	14.7	7.12E-04	336.501	1.71E-03
57	12.6	1.22E-04	581.229	2.93E-04
124	10.5	1.52E-05	1264.428	3.65E-05
317	8.4	1.18E-06	3232.449	2.83E-06
541	7.4	2.78E-07	5516.577	6.67E-07
727	6.9	1.25E-07	7413.219	3.00E-07
1142	6.2	3.67E-08	11644.97	8.81E-08
1500	5.8	1.75E-08	15295.5	4.20E-08

Table 9: Soil hydraulic properties recorded by SPAW by varying moisture content for soil texture sand 65%, silt 25%, clay 10% bulk density 1.65 g/cc

For bulk density 1.8 g/cc, soil water characteristic output table:

Suction (kPa)	Wc V/V (%)	Hydr. Cond. (mm/hr)	Suction (cm)	Hydr. Cond (cm/day)
4	32.2	1.90E+01	40.788	4.56E+01
7	30.2	8.52E+00	71.379	2.04E+01
10	28.2	3.67E+00	101.97	8.81E+00
13	26.2	1.49E+00	132.561	3.58E+00
16	24.2	5.62E-01	163.152	1.35E+00
19	22.2	1.95E-01	193.743	4.68E-01
22	20.2	6.12E-02	224.334	1.47E-01
26	18.2	1.70E-02	265.122	4.08E-02
29	16.2	4.08E-03	295.713	9.79E-03
32	14.2	8.11E-04	326.304	1.95E-03
33	13.2	3.31E-04	336.501	7.94E-04
48	12.2	1.26E-04	489.456	3.02E-04
72	11.2	4.41E-05	734.184	1.06E-04

178	9.2	3.94E-06	1815.066	9.46E-06
304	8.2	9.61E-07	3099.888	2.31E-06
556	7.2	1.95E-07	5669.532	4.68E-07
1111	6.2	3.11E-08	11328.87	7.46E-08
1500	5.8	1.40E-08	15295.5	3.36E-08

Table 10: Soil hydraulic properties recorded by SPAW by varying moisture content for soil texture sand 65%, silt 25%, clay 10% bulk density 1.8 g/cc

Plot for suction vs water content:

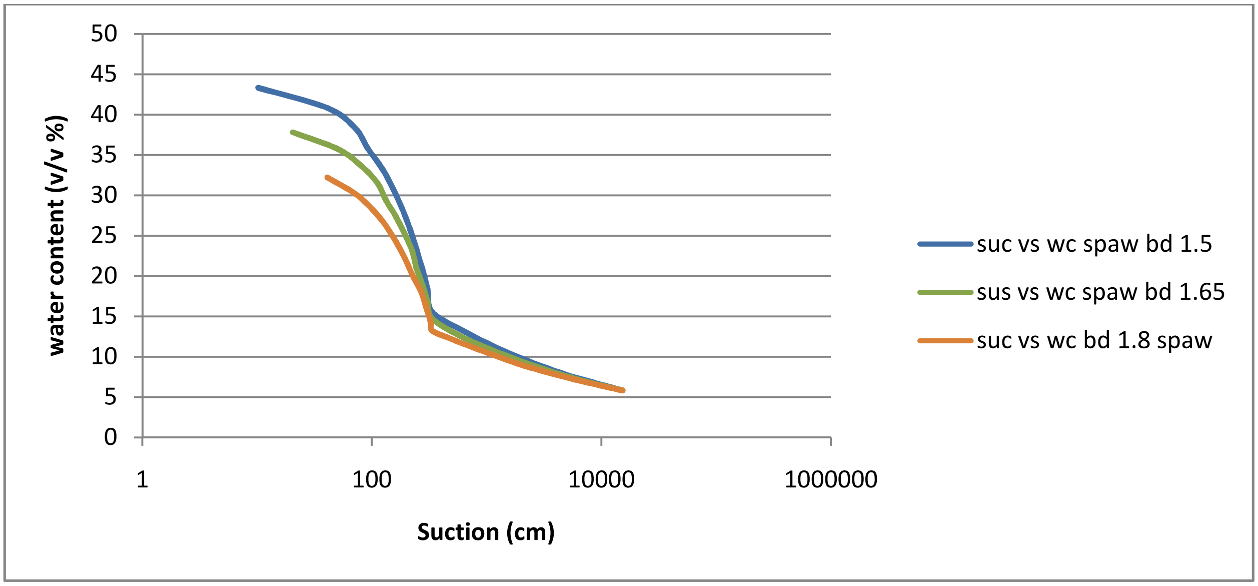


Figure 13: Plot for suction vs water content for BD1.5, 1.65, 1.8 g/cc recorded in SPAW.

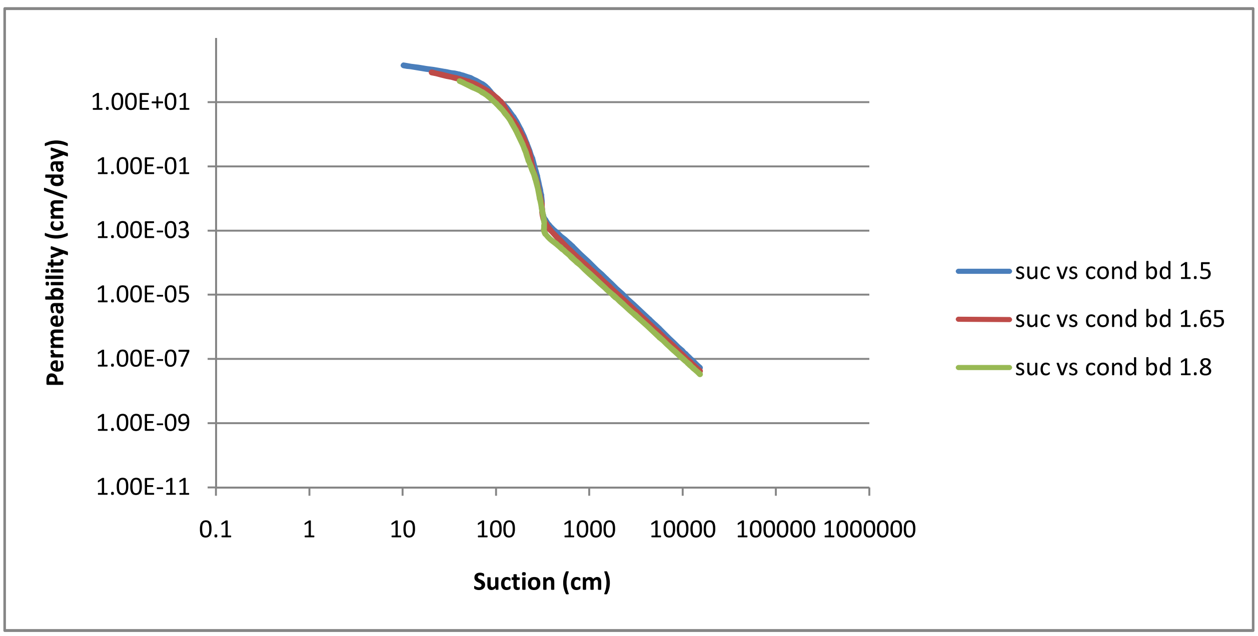


Figure 14: Suction vs permeability plot for texture sand 65%, silt 25%, clay 10% varying BD plotted from recorded data of SPAW.

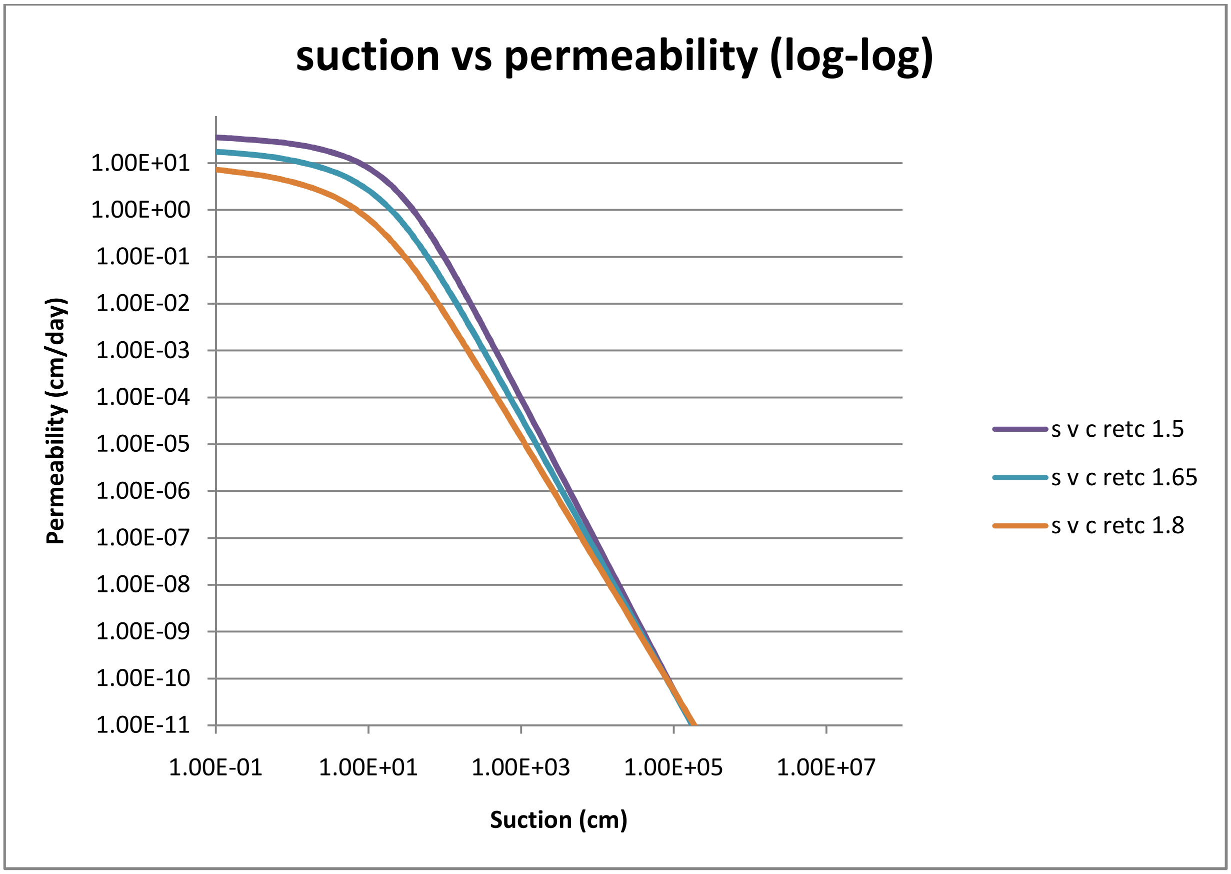


Figure 15: Plot for suction vs permeability based on RETC fitted from SPAW recorded data.

It can be observed from the plot that suction vs permeability curve starts showing a linear trend for suction higher than 10 cm (0.98 kPa) in log-log plot and decreases with the increase in suction. At low suction (less than 1cm i.e. 0.01 kPa) hydraulic conductivity remains nearly same and decreases with increase in density of the soil.

Observation using rosetta, RETC:

Varying bulk density at 1.5, 1.65, 1.8 for soil texture sand 65%, silt 25%, clay 10%.

BD (g/cc)	Θ_r (%)	Θ_s (%)	Alpha, α (cm^{-1})	N	K_s (cm/day)
1.5	0.0255	36.81	0.0354	1.368	59.02
1.65	0.0267	33.14	0.0377	1.372	38.79
1.8	0.0274	29.71	0.0411	1.365	25.48

Table 11: Soil hydraulic output parameter from rosetta varying bulk density at 1.5, 1.65, 1.8 for soil texture sand 65%, silt 25%, clay 10%.

Following are the curves got from fitting above data.

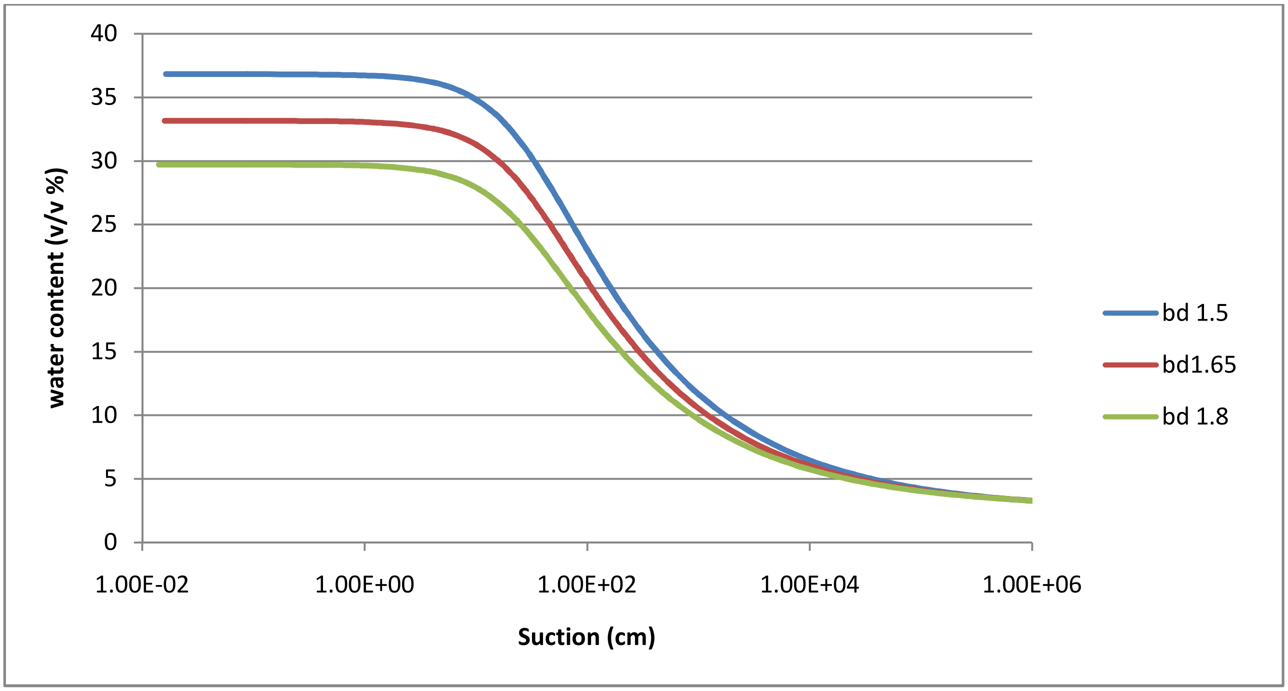


Figure 16: SWCC for varying bulk density at 1.5, 1.65, 1.8 for soil texture sand 65%, silt 25%, clay 10% from rosetta prediction.

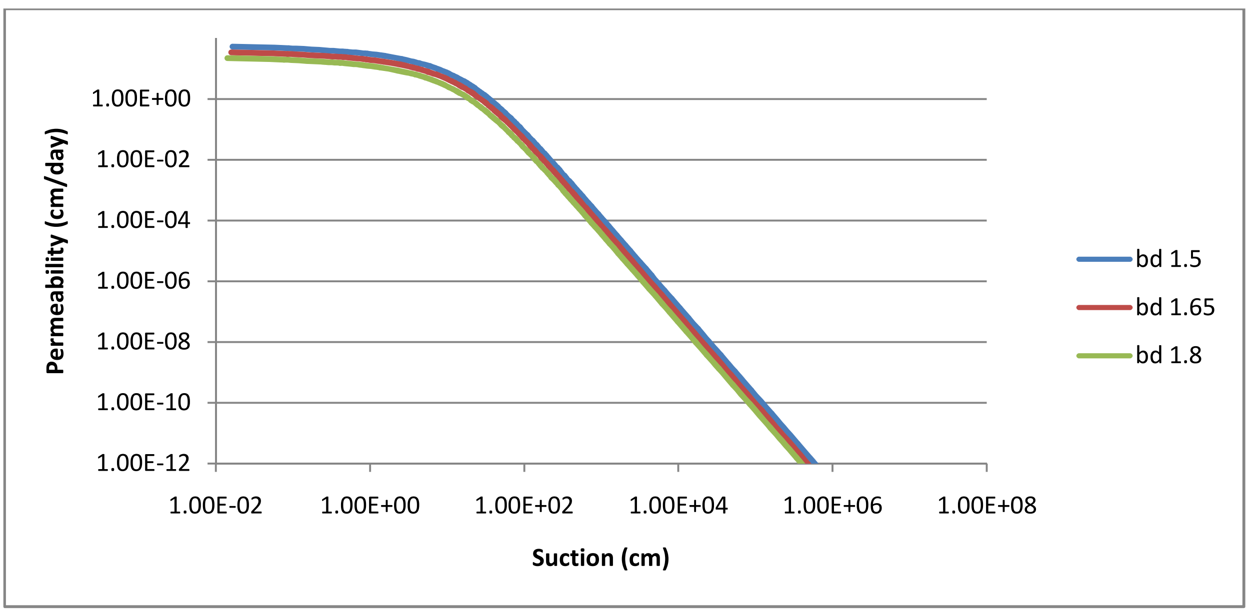


Figure 17: Plot for suction vs hydraulic conductivity permeability curve for varying BD at 1.5, 1.65, 1.8 for soil texture sand 65%, silt 25%, clay 10% from rosetta prediction.

There is a slight variation on the permeability curve. Shape is remaining the same but increase in BD showing slight decrease in permeability. The value of alpha is found to be increasing while increase of BD. And as expected K_s is decreasing with increase in BD.

Fourth set of result:

Soil texture sand 65%, silt 25%, clay 10% BD fixed at 1.5 g/ cc. Organic matter varying at 0%, 2%, 4%. The values of wilting point(Θ_{1500}) and field capacity(Θ_{33}) is recorded and as input in rosetta. RETC predicted curves are as follows.

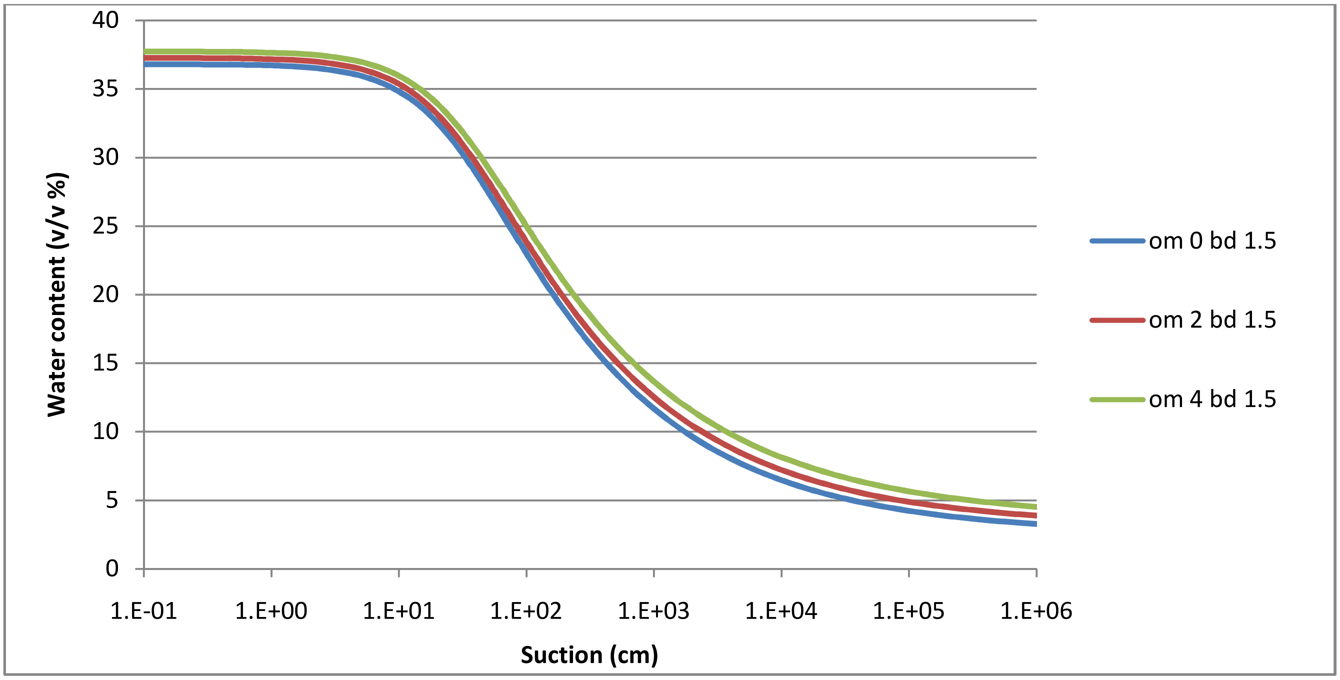


Figure 18: SWCC for fixed BD at 1.5, 1.65, 1.8 g/cc and varying OM 0, 2, 4% for soil texture sand 65%, silt 25%, clay 10% from rosetta prediction

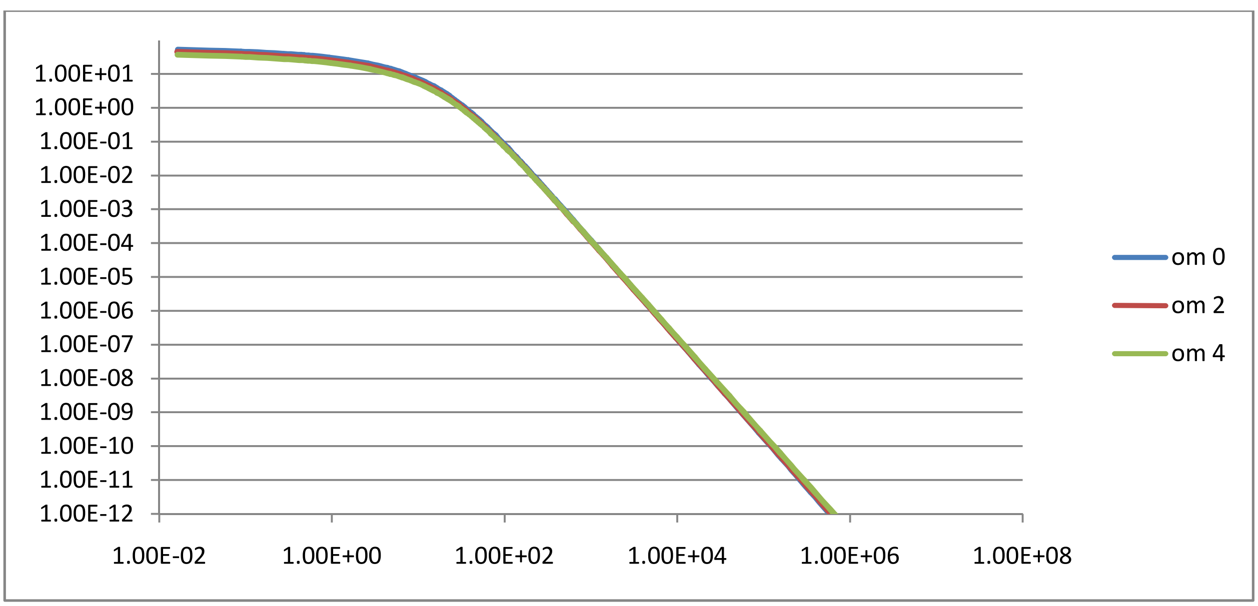


Figure 19: Suction vs permeability curve for fixed BD at 1.5, 1.65, 1.8 g/cc and varying OM 0, 2, 4% for soil texture sand 65%, silt 25%, clay 10% from rosetta prediction

From above plot we can observe that variation due to organic matter is negligible on suction vs permeability curve for this soil.

Fifth set of result:

Soil texture: sand 65%, silt 25%, clay 10%, BD fixed at 1.5 g/cc. Salinity varying at 0, 5, 10 dS/m.

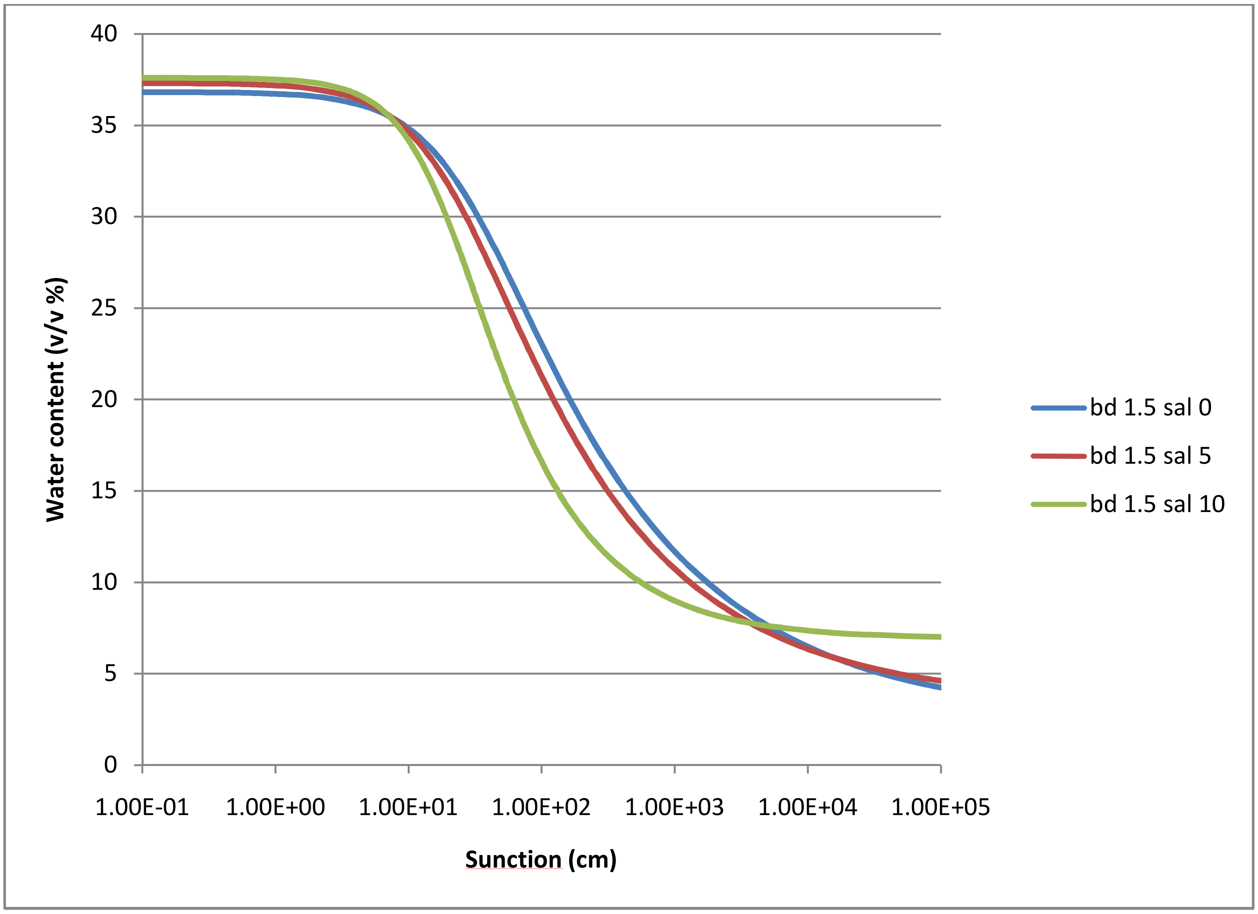


Figure 20: SWCC for soil texture sand 65% clay 10% for Salinity varying at 0, 5, 10 dS/m (mmho/cm)

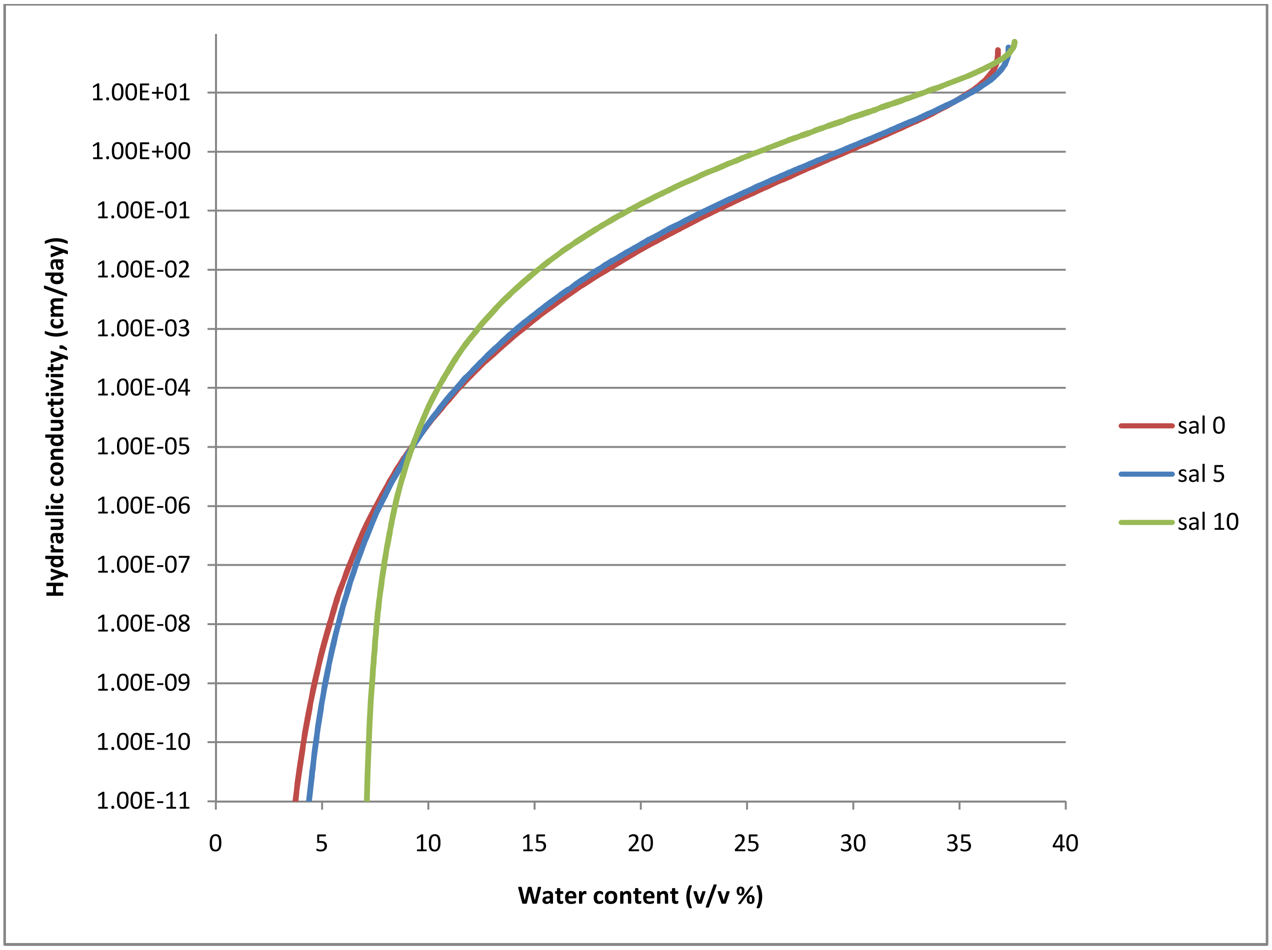


Figure 21: Plot for volumetric water content and hydraulic conductivity for soil texture sand 65% clay 10% for Salinity varying at 0, 5, 10 dS/m (mmho/cm)

Sixth set of result:

Comparison of values found in Rosetta for the soil texture sand 65% clay 10%:

AEV of SWCC is given by $AEV = 1/\alpha$.

OM = 0%

BD (gm/cc)	Θ33	Θ1500	model (H)	Θr	Θs	α (cm-1)	n	Ks cm/day	aev (cm)
1.5	0.154	0.058	5	0.026	0.368	0.036	1.369	59.776	27.743
1.6	0.147	0.058	5	0.026	0.343	0.037	1.372	44.544	27.230
1.7	0.139	0.058	5	0.027	0.320	0.039	1.372	33.794	25.772
1.8	0.132	0.058	5	0.027	0.297	0.041	1.365	25.478	24.342
1.9	0.124	0.058	5	0.028	0.275	0.045	1.358	20.038	22.337
2	0.117	0.058	5	0.028	0.255	0.049	1.346	15.173	20.594
2.1	0.109	0.058	2	0.042	0.386	0.030	1.404	40.014	32.795

OM=1%

BD (gm/cc)	Θ33	Θ1500	model (H)	Θr	Θs	α (cm-1)	n	Ks cm/day	aev (cm)
1.5	0.163	0.067	5	0.028	0.370	0.035	1.364	55.198	28.297
1.6	0.155	0.067	5	0.029	0.346	0.037	1.367	40.842	27.265
1.7	0.148	0.067	5	0.029	0.322	0.038	1.364	29.879	26.172
1.8	0.141	0.067	5	0.030	0.299	0.041	1.356	21.970	24.682
1.9	0.133	0.067	5	0.030	0.277	0.044	1.347	16.821	22.626
2	0.125	0.067	5	0.030	0.257	0.049	1.338	12.711	20.597

OM=2%

BD (gm/cc)	Θ33	Θ1500	model (H)	Θr	Θs	α (cm-1)	n	Ks cm/day	aev (cm)
1.4	0.179	0.076	5	0.030	0.398	0.035	1.354	72.248	28.875
1.5	0.172	0.076	5	0.031	0.373	0.035	1.359	50.984	28.834
1.6	0.164	0.076	5	0.032	0.348	0.036	1.361	36.894	27.719
1.7	0.157	0.076	5	0.032	0.324	0.038	1.356	26.435	26.561
1.8	0.149	0.076	5	0.032	0.301	0.041	1.349	19.354	24.639
1.9	0.141	0.076	5	0.032	0.279	0.044	1.340	14.442	22.598

OM = 3%

BD (gm/cc)	Θ33	Θ1500	model (H)	Θr	Θs	α (cm-1)	n	Ks cm/day	aev (cm)
1.3	0.196	0.085	5	0.031	0.427	0.034	1.340	99.234	29.410
1.4	0.188	0.085	5	0.033	0.401	0.034	1.350	68.320	29.451
1.5	0.181	0.085	5	0.033	0.375	0.034	1.354	47.138	29.348
1.6	0.173	0.085	5	0.034	0.350	0.036	1.354	33.368	28.153
1.7	0.166	0.085	5	0.034	0.326	0.037	1.347	23.424	26.936
1.8	0.158	0.085	5	0.034	0.303	0.040	1.339	16.748	24.960

Table 12: Soil water characteristics for soil texture sand 65%, clay 10% varying BD and OM.

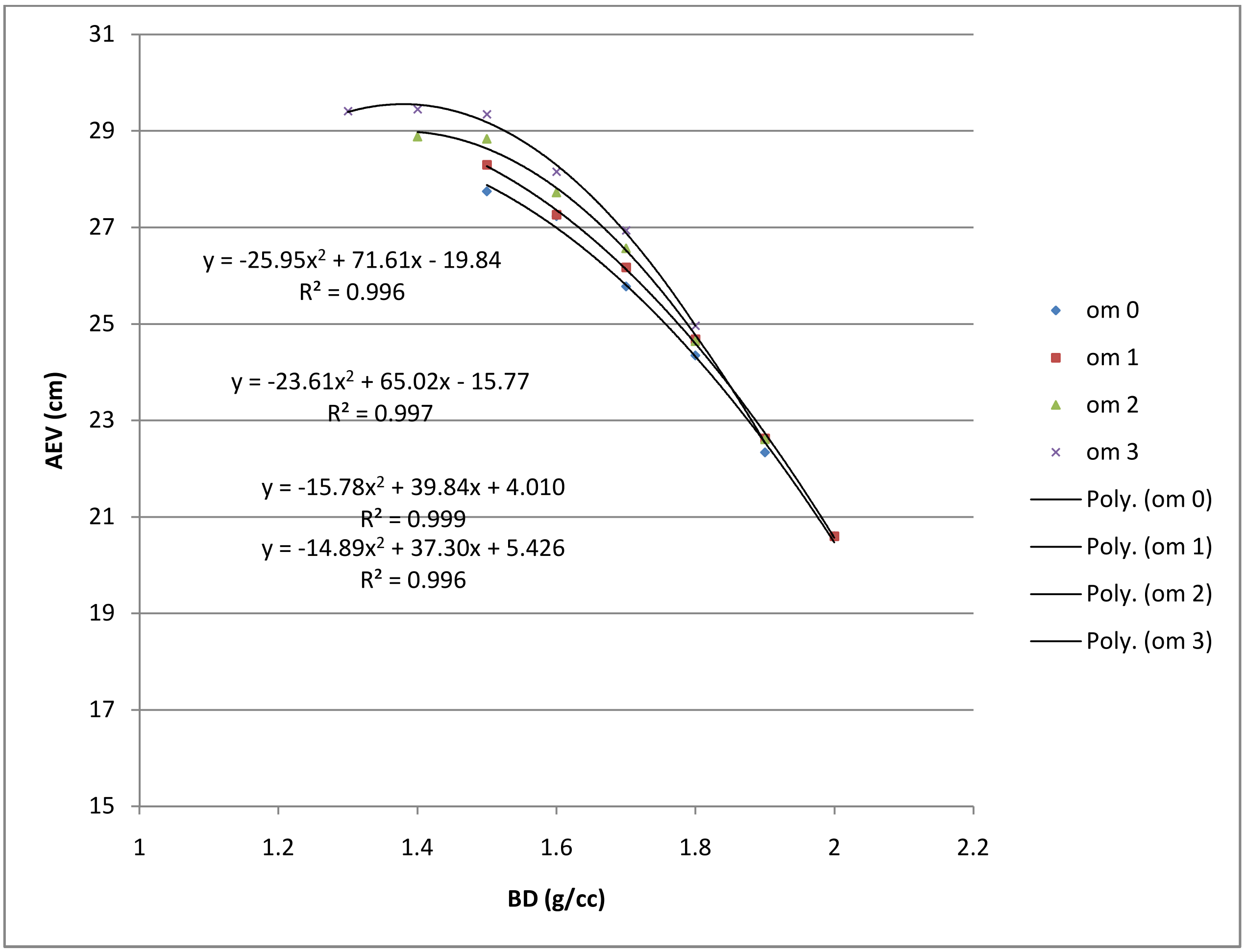


Figure 22: Plot for AEV vs BD for sand 65% clay 10% keeping the BD fixed at 1.5 g/cc and OM varying 0, 2, 4% as predicted by rosetta from input values of SPAW.

It is found that the AEV value has quadratic relation with BD.

Seventh set of resuly:

Observation in case of sandy soil:

Percentage of sand = 80%, clay= 10%, loamy sand

(i) OM = 0, silt=10%, BD = 1.5 g/cc

Soil water characteristics:

wc %	P (kPa)	K (mm/hr)	wc (frac)	P (cm)	K (cm/days)
43.3	0	7.51E+01	0.433	0	1.80E+02
41.3	2	4.07E+01	0.413	20.4	9.77E+01
39.3	4	2.16E+01	0.393	40.8	5.18E+01
37.3	7	1.11E+01	0.373	71.4	2.66E+01
35.3	9	5.47E+00	0.353	91.8	1.31E+01
33.3	11	2.60E+00	0.333	112.2	6.24E+00
31.3	13	1.18E+00	0.313	132.6	2.83E+00
29.3	15	5.07E-01	0.293	153	1.22E+00
27.3	17	2.05E-01	0.273	173.4	4.92E-01
25.3	19	7.77E-02	0.253	193.8	1.86E-01
23.3	21	2.71E-02	0.233	214.2	6.50E-02
21.3	23	8.63E-02	0.213	234.6	2.07E-01
19.3	26	2.45E-03	0.193	265.2	5.88E-03
17.3	28	6.05E-03	0.173	285.6	1.45E-02
15.3	30	1.26E-04	0.153	306	3.02E-04
13.3	32	2.10E-05	0.133	326.4	5.04E-05
12.1	33	6.28E-06	0.121	336.6	1.51E-05
10.1	78	6.25E-07	0.101	795.6	1.50E-06
8.1	230	3.73E-08	0.081	2346	8.95E-08
6.1	918	9.96E-10	0.061	9363.6	2.39E-09
5.5	1500	2.76E-10	0.055	15300	6.62E-10

Table 13: Soil water characteristics for soil texture sand 80% and clay 10%, BD 1.5g/cc, OM 0

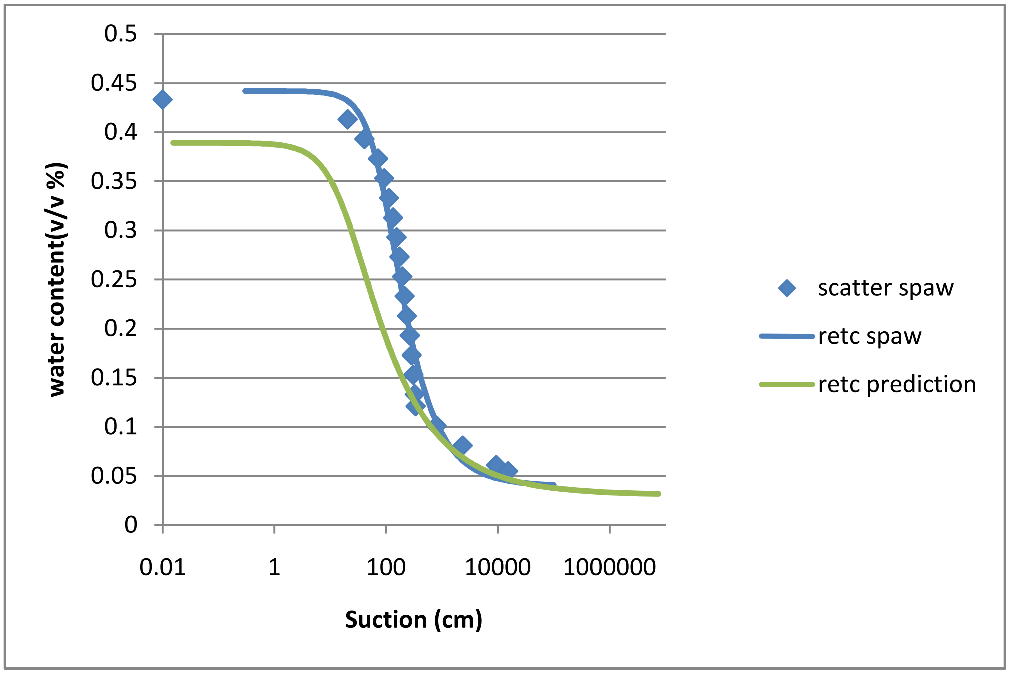


Figure 23: SWCC comparing results of RETC prediction and RETC fit using recorded data of SPAW for soil texture sand 65%, clay 10%, OM 0%.

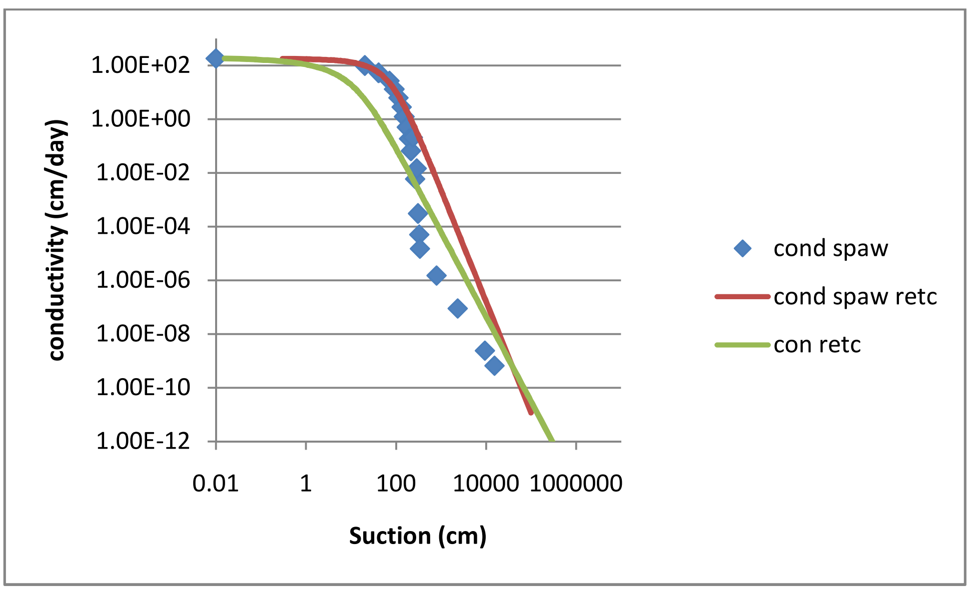


Figure 24: Suction vs permeability curve comparing results of RETC prediction and RETC fit using recorded data of SPAW for soil texture sand 65%, clay 10%, OM 0%.

Increase OM by 1%:

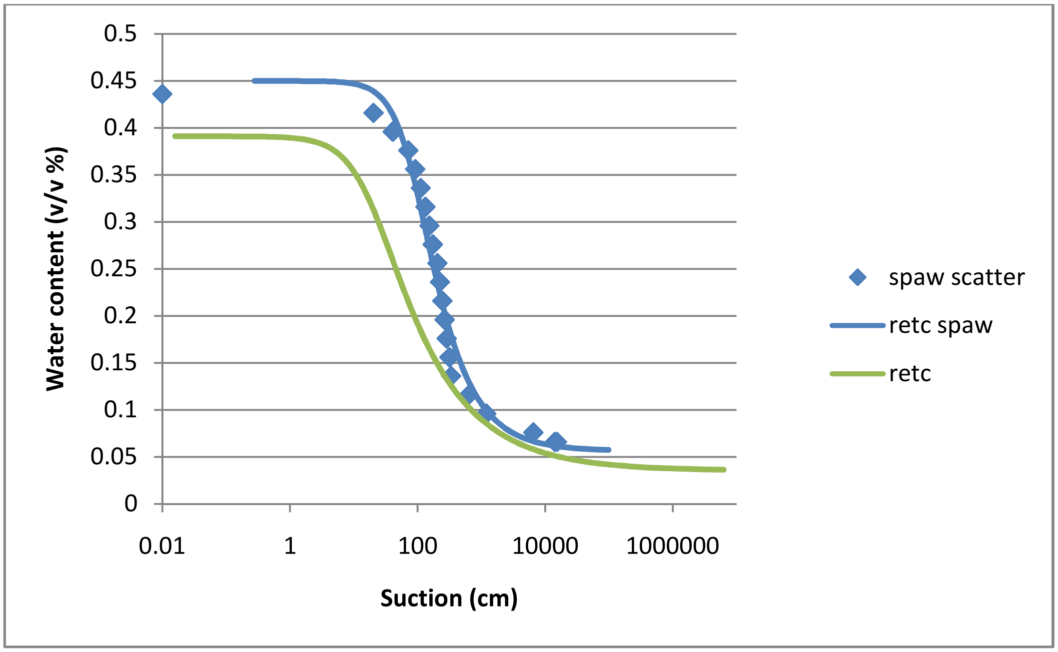


Figure 25: SWCC comparing results of RETC prediction and RETC fit using recorded data of SPAW for soil texture sand 65%, clay 10%, OM 1%.

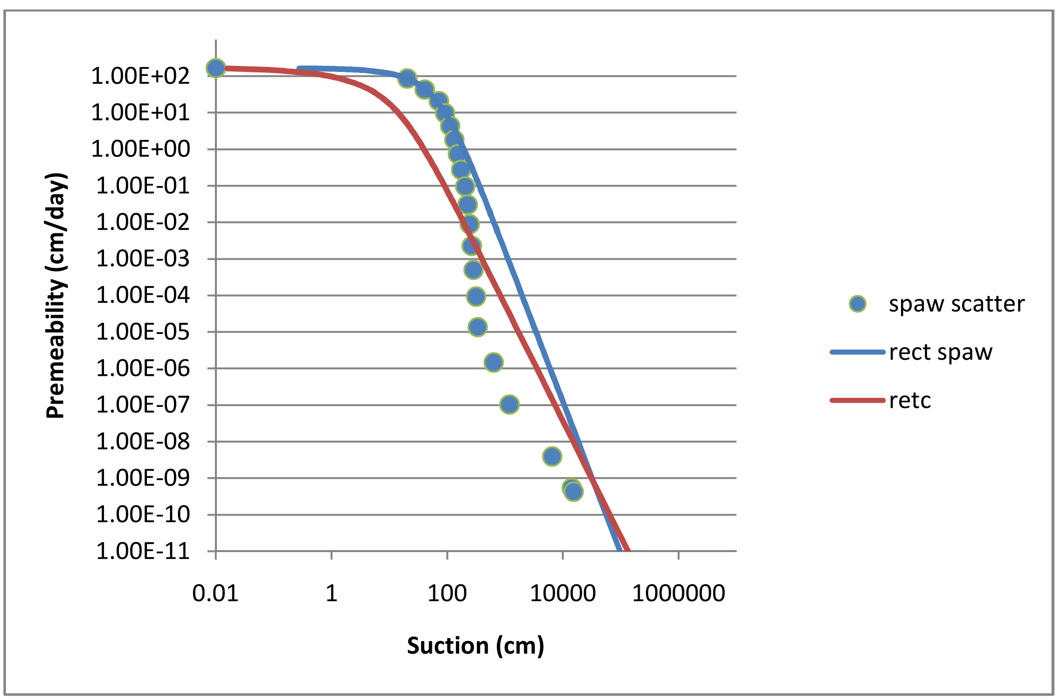


Figure 26: Suction vs permeability curve comparing results of RETC prediction and RETC fit using recorded data of SPAW for soil texture sand 65%, clay 10%, OM 1%.

Increase OM by 1%

OM=2%

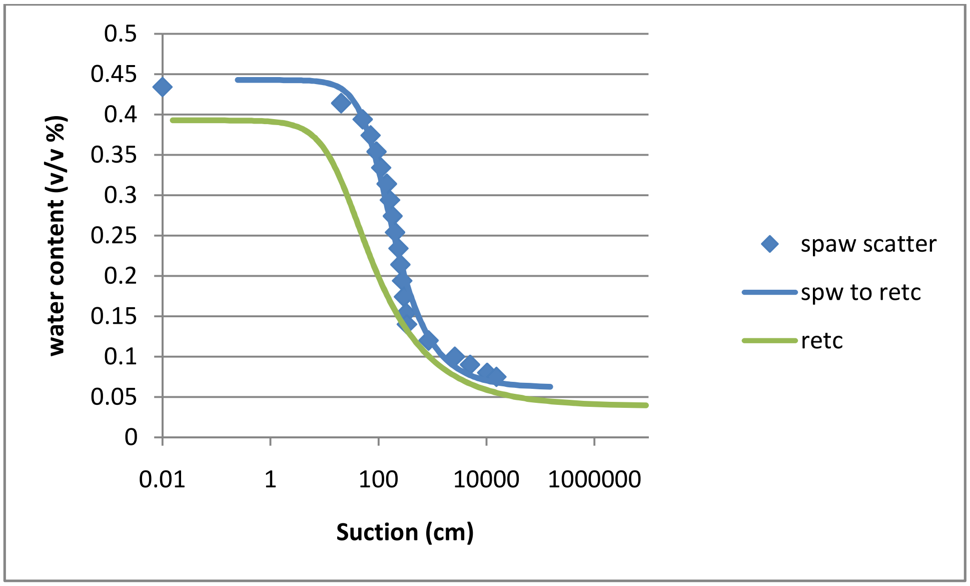


Figure 27: SWCC comparing results of RETC prediction and RETC fit using recorded data of SPAW for soil texture sand 65%, clay 10%, OM 2%.

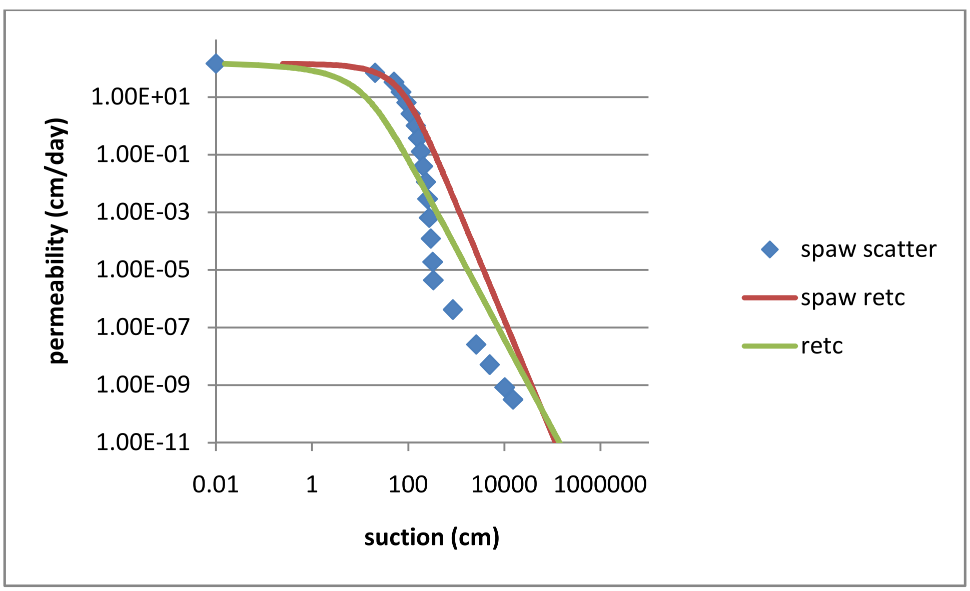


Figure 28: Suction vs permeability curve comparing results of RETC prediction and RETC fit using recorded data of SPAW for soil texture sand 65%, clay 10%, OM 2%.

Chapter 5

Conclusion

In this study both soil water characteristic and RETC is used for different soil texture, bulk density and organic matter. Both no fitted and fitted point are compared.

To find unsaturated soil permeability, soil water characteristics of SPAW and RETC with rosetta is used. Both of those softwares uses different models to estimate SWCC and hydraulic conductivity. That is why careful considerations needs to be taken for investigating using these software.

Bulk density decrease the water holding capacity of the soil, which decrease the saturated water content. That is why SWCC starts to shift down and starts lower water content for same sunction. Further study needs to be done to quanitify this behaviour.

RETC nofitting curve and fitted curves are starting at different water content for SWCC. For RETC, Θ_s is less. For the permeability curve RETC is showing less slope than fitted curve. But at higher suction both of the curve are merging together.

Analysis of curves shown above we can see that at low suction the permeability stays nearly same. For sandy loamy soils the curves shows linear decrease with suction increase in log-log curve. The threshold suction is found about 1 kPa.

Future works suggested:

Investigation on difference in values predicted by different models is suggested as future work. We can see that there is difference in values using different approach using RETC and SPAW.

Changes on soil hydraulic parameter due to large changes in textures can be investigated. Soil texture values from experimental data can be used to attempt to generate SWCC for a particular site, can be used to calculate the permeability for that site.

Verification of K_{sat} estimation using real sample can be done. Detailed investigation of difference in rosetta and soil water characteristics models can be documented. An attempt can be made to create a code for calculation for efficient prediction of hydraulic conductivity using soil texture and SWCC data.

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