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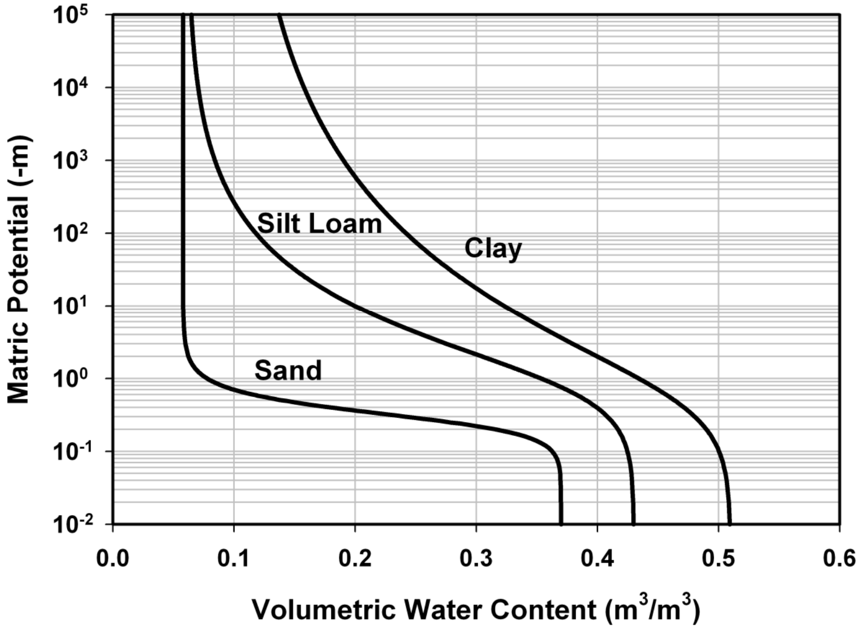
The Soil Water Characteristic - Introduction and Measurement



Editted by Muhammad Azril Hezmi

Sources:

Oschner

Fredlund Terghazi Lecture

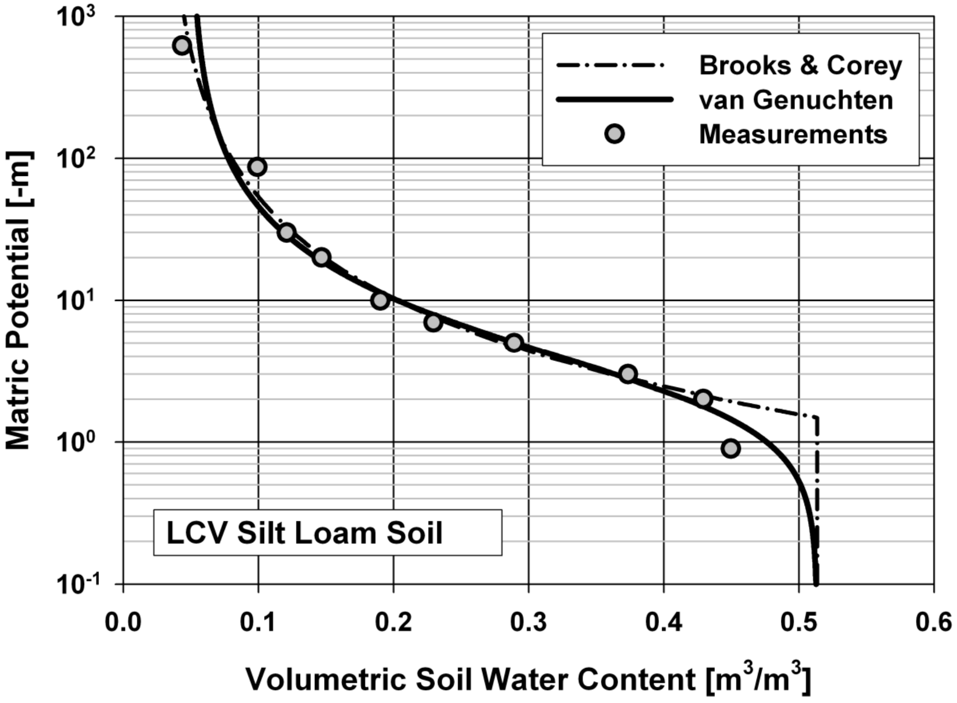
Markus Tuller and Dani Or 2002-2004

Question

- What is unsaturated soil?
- Why unsaturated soil is important?
- What is suction, degree of saturation and gravimetric water content?
- How to measure suction?
- Why SWCC is important to engineers?
- How to establish SWCC?

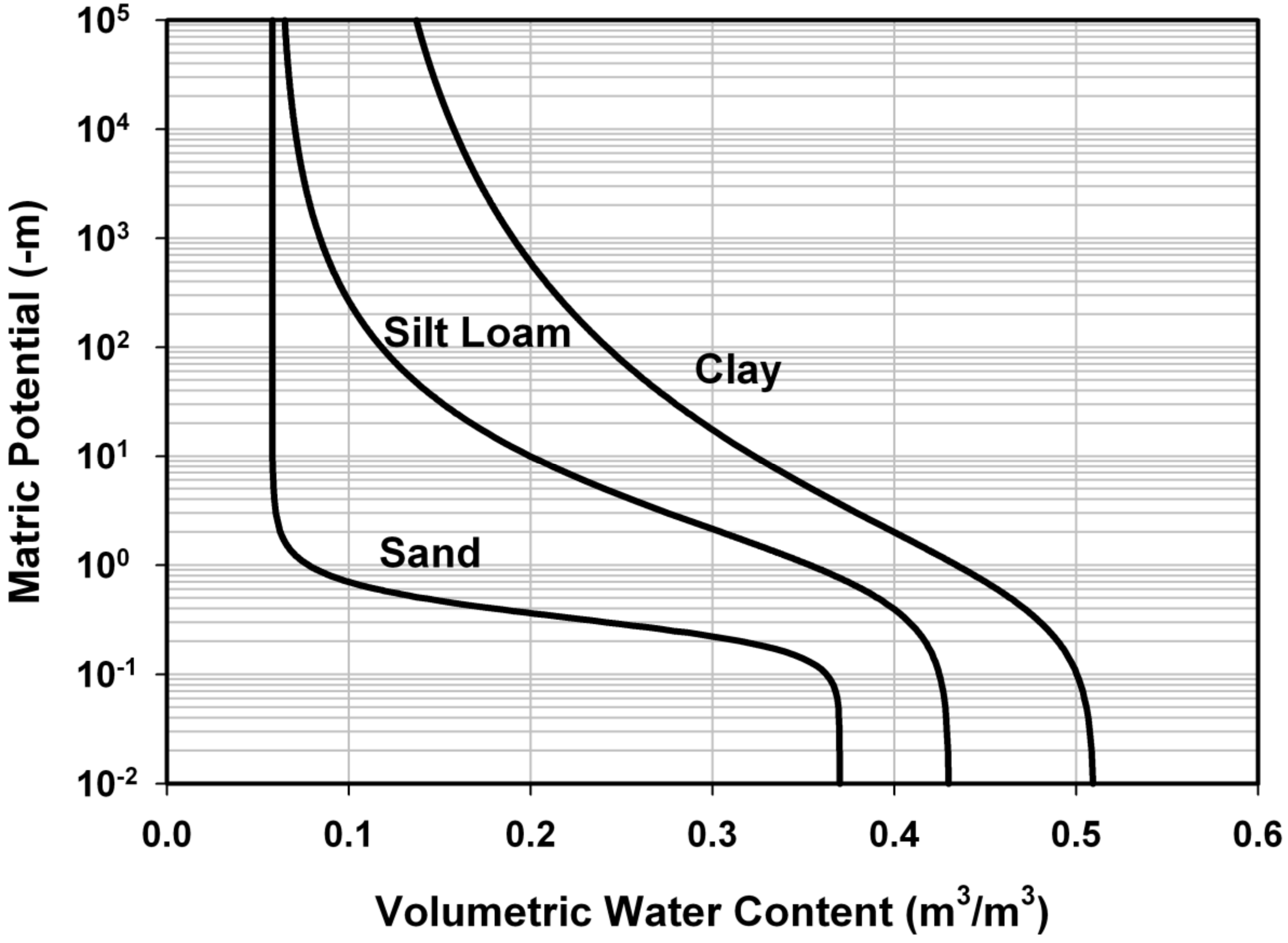
The Soil Water Characteristic Curve

- The Soil Water Characteristic (SWC) curve describes the functional relationships between soil water content (θ_v or θ_m) and matric potential under equilibrium conditions.
- The SWC is an important soil property related to pore space distribution (sizes, interconnectedness), which is strongly affected by texture and structure and related factors including organic matter.
- The SWC is a primary hydraulic property required for modeling water flow in porous materials.
- The SWC function is highly nonlinear and relatively difficult to obtain accurately.



The Soil Water Characteristic Curve

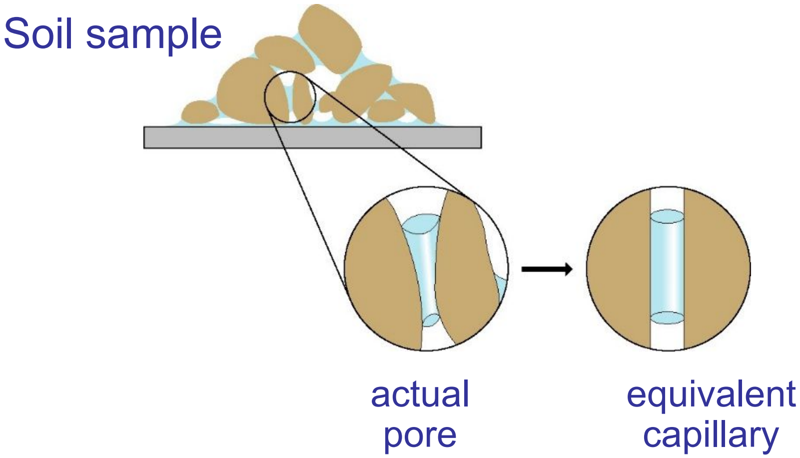
Typical soil water characteristic curves for soils of different texture

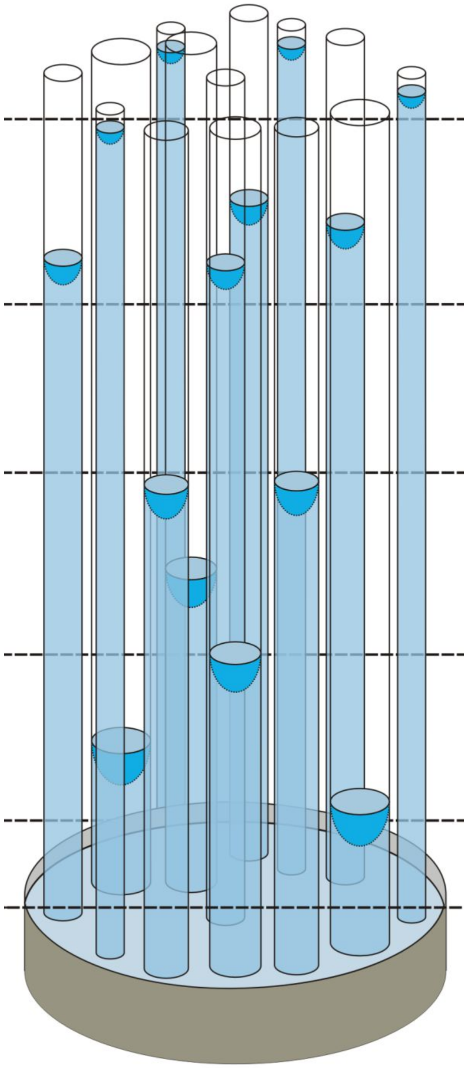


The Soil Water Characteristic Curve

Early conceptual models for SWC curve were based on the "bundle of cylindrical capillaries" (BCC) representation of pore space geometry (Millington and Quirk, 1961).

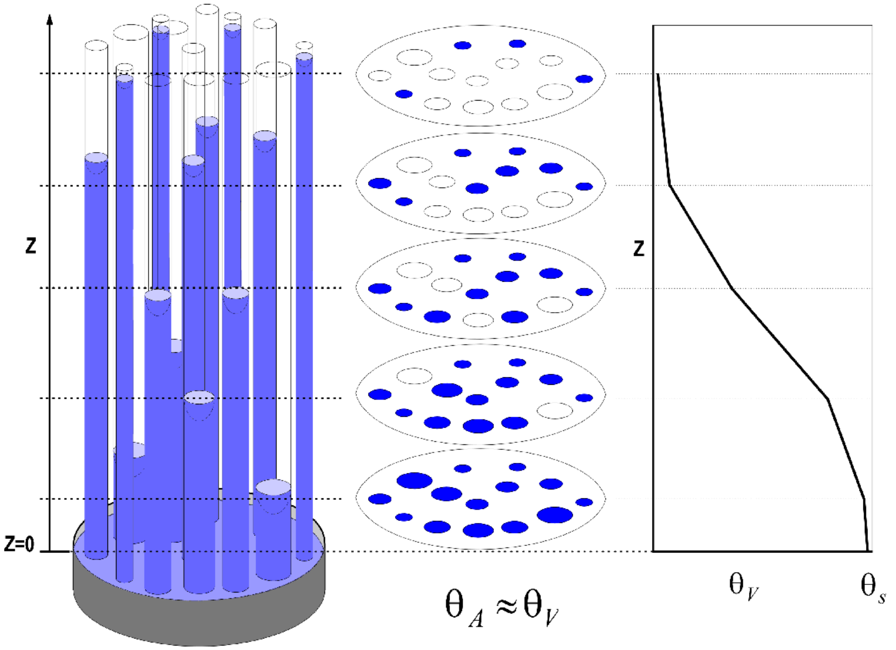
The BCC representation postulates that at a given matric potential a portion of interconnected cylindrical pores is completely liquid filled, whereas larger pores are completely empty.





The Soil Water Characteristic Curve

This convenient idealization of soil pore space enables a linkage between the soil pore size distribution and the SWC based on capillary rise equation



$$h_i = \frac{2\sigma \cos\gamma}{\rho_w g r_i}$$

$$A_i = r_i^2 \pi n_i$$

BCC Model - Example

A bundle of cylindrical capillaries having the following diameters and numbers was vertically dipped into a water reservoir.

# of capillaries	300	400	325	250	150	90	50	10	5	2
Diameter [mm]	0.001	0.005	0.01	0.02	0.05	0.1	0.2	0.5	1	2

Compute and plot the relative saturation of the capillaries at different elevations above the free water surface :

The first step is to calculate the capillary rise for various capillary diameters:

$$\boxed{h = \frac{2\sigma \cos\gamma}{\rho_w g r}}$$

For each elevation we then calculate the cross-sectional area of all filled capillaries:

$$\boxed{A = \frac{d^2 \pi}{4} n}$$

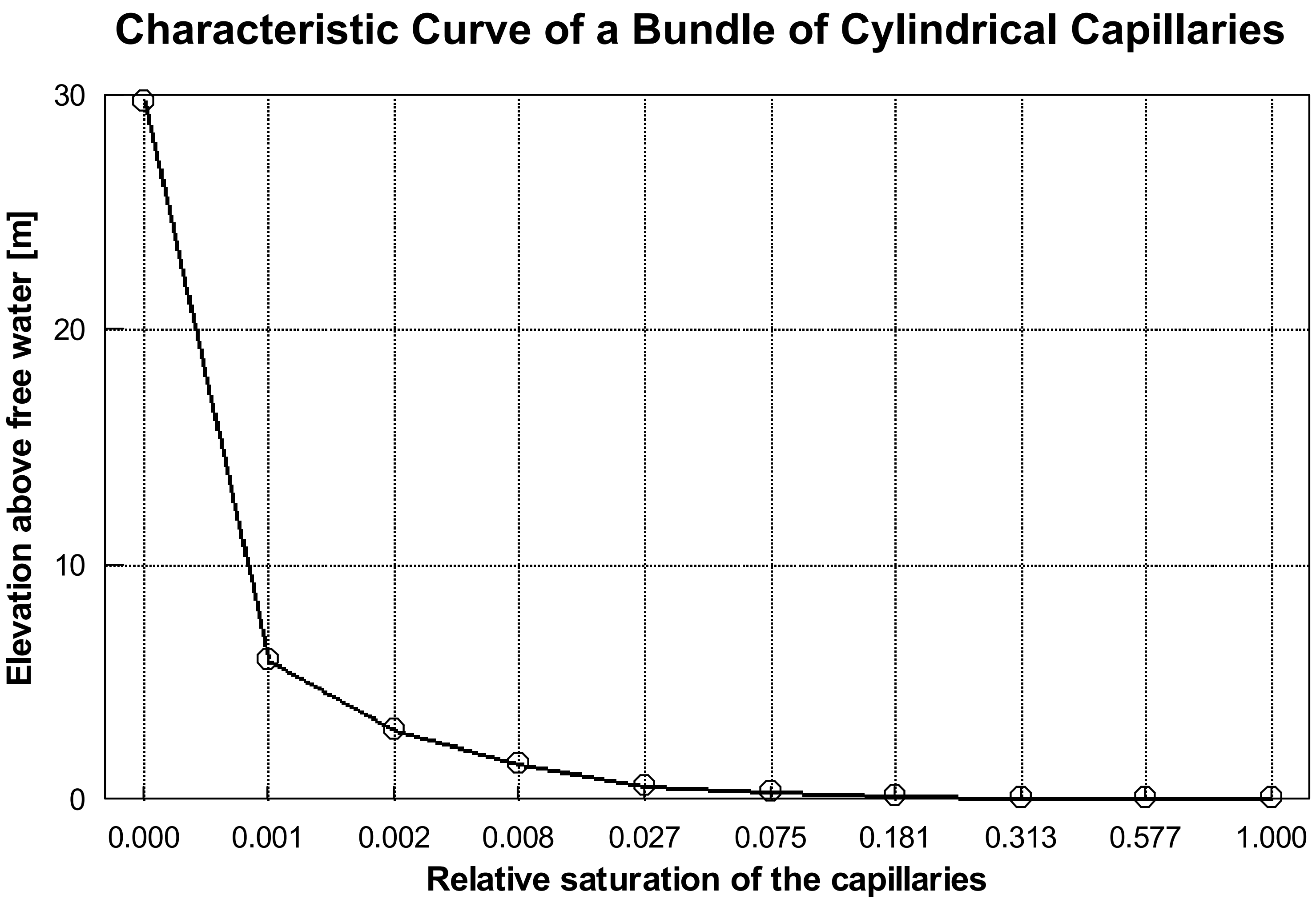
We start with the highest elevation where only capillaries with the smallest diameter are likely to be filled. Then we gradually move down to the lowest elevation where all capillaries are expected to be filled. At each elevation increment we add the water filled cross-sectional areas of capillaries with smaller diameters.

BCC Model - Example

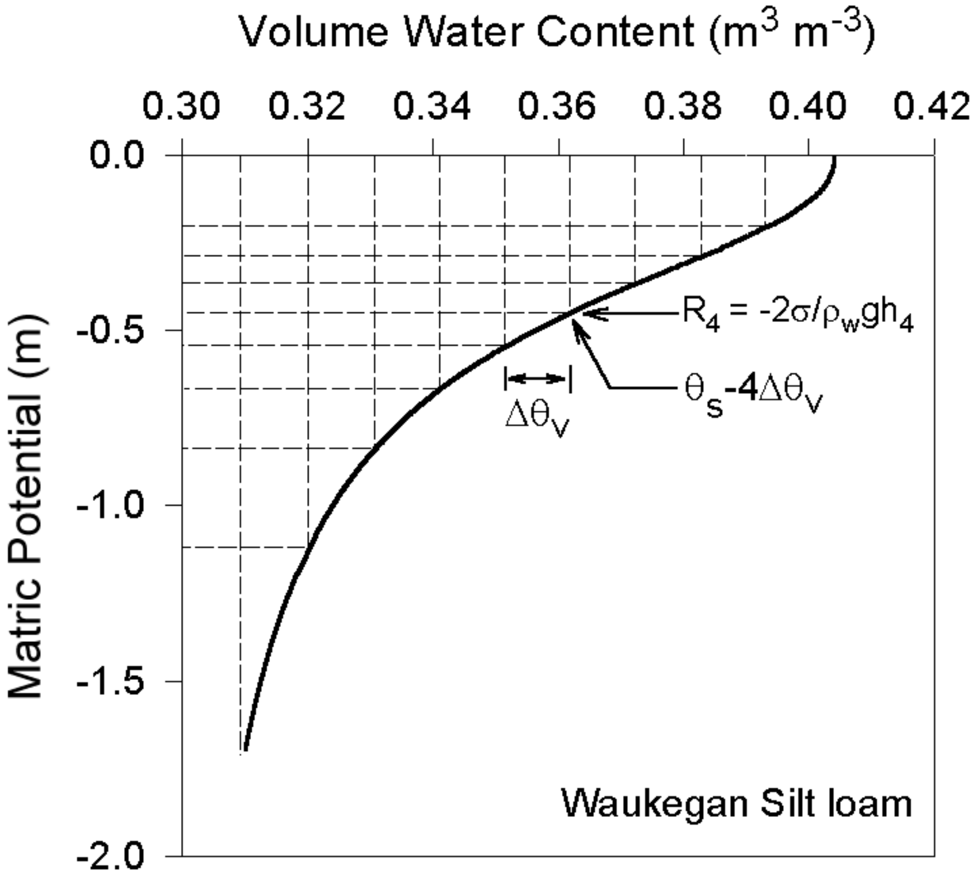
Finally we calculate the relative saturation at each elevation as the ratio of water-filled cross-sectional area at a certain elevation and the total cross-sectional area.

#	**Diameter** [m]	**h** [m]	**A** [m^2]	θ_{vrel}
300	1E-06	29.74	2.36E-10	0.000016
400	5E-06	5.95	8.09E-09	0.000544
325	1E-05	2.97	3.36E-08	0.002262
250	2E-05	1.49	1.12E-07	0.007548
150	5E-05	0.59	4.07E-07	0.027371
90	1E-04	0.30	1.11E-06	0.074945
50	2E-04	0.15	2.68E-06	0.180666
10	5E-04	0.06	4.65E-06	0.312817
5	1E-03	0.03	8.58E-06	0.577118
2	2E-03	0.01	1.49E-05	1.000000

BCC Model - Example



Using SWC to determine pore size distribution

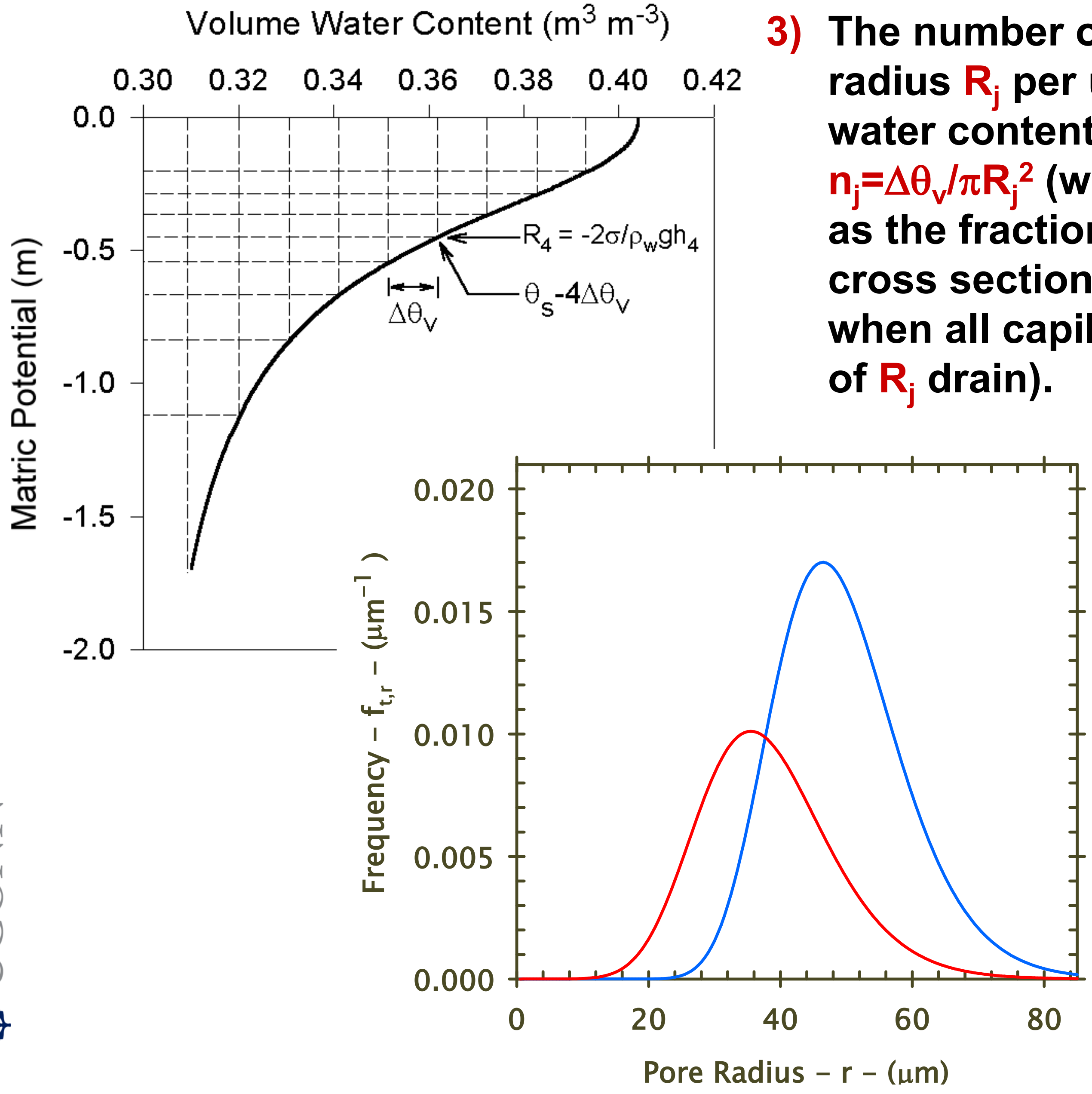


1) The total saturation water contend θ_s is divided into a certain number **M** of equal increments $\Delta\theta_v$ where the matric potential h_j corresponds to a water content of $\theta_s - j \times \Delta\theta_v$

2) We assume that all tubes with radii greater than R_j have drained at matric potential h_j

$$r > R_j = \frac{-2\sigma}{\rho_w g h_j}$$

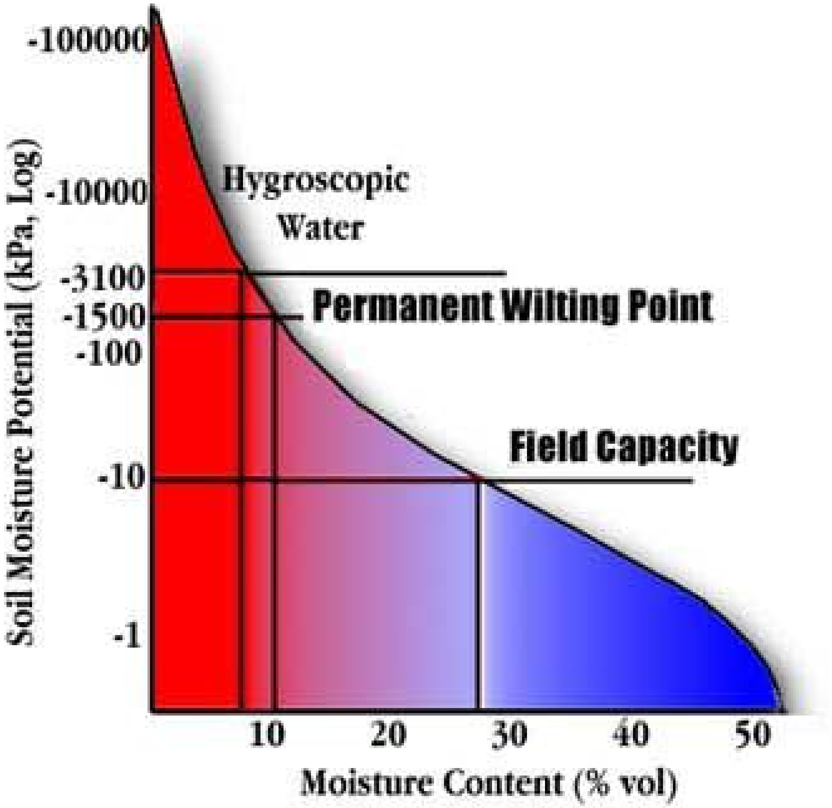
Using SWC to determine pore size distribution



3) The number of capillaries having a radius R_j per unit area in each water content interval is: $n_j=\Delta\theta_v/\pi R_j^2$ (where $\Delta\theta_v$ is interpreted as the fraction of the water-filled cross sectional area that is reduced when all capillaries having a radius of R_j drain).

SWC and Plant Available Soil Revisited

- The concept of Field Capacity and Wilting Point discussed in the previous section on water content have a more quantitative definition in terms of potentials and SWC.
- Field Capacity - water content @ 1/3 bar (for sandy soils 0.1 bar)
- Wilting Point – water content @ -15 bars



Factors influencing soil water retention

- Soil structure (ρ_b, aggregate size distribution)
  a) important at low suctions, 0 to 50 kPa
  b) Capillary effects

- Clay content
  a) Positively related to surface area of soil particles
  b) Positively related to water adsorption
  c) Dominant factors at high suctions

Effect of texture on SWCC

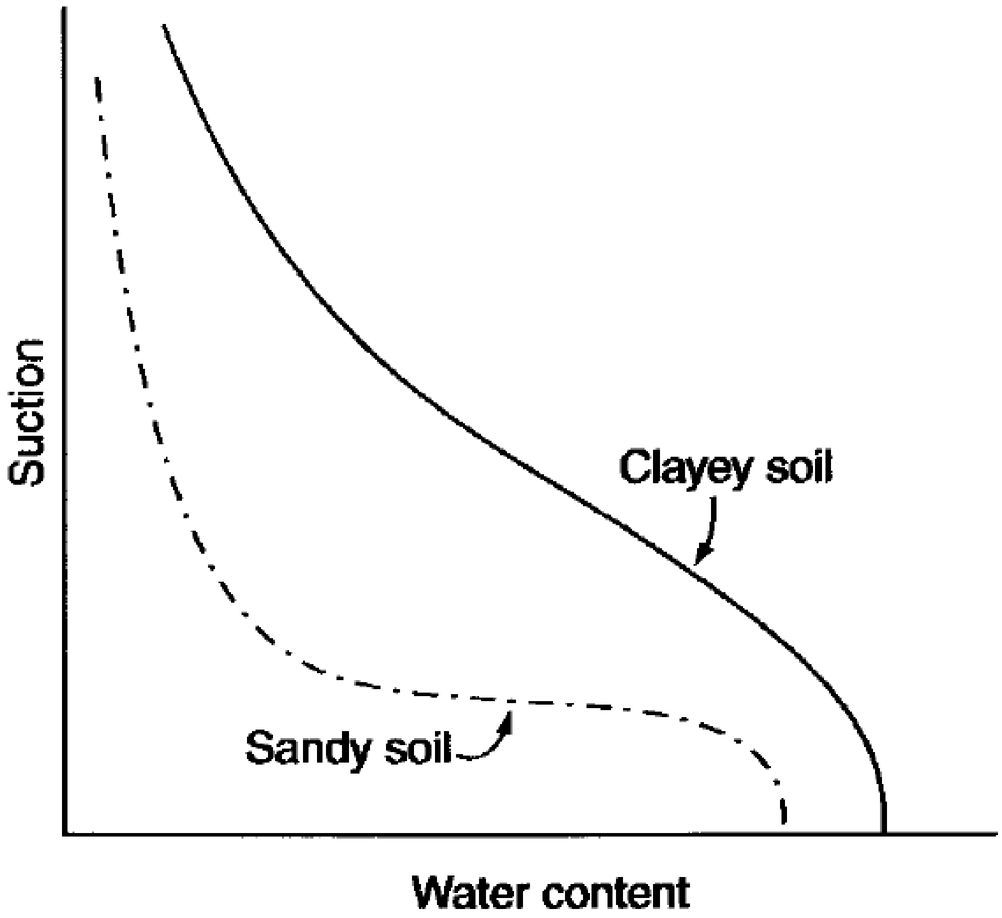


Fig. 6.8. The effect of texture on soil-water retention.

Factors influencing soil water retention

- Soil structure (ρ_b, aggregate size distribution)
  a) important at low suctions, 0 to 50 kPa
  b) Capillary effects

- Clay content
  a) Positively related to surface area of soil particles
  b) Positively related to water adsorption
  c) Dominant factors at high suctions

- Soil organic matter
  a) Reduces ρ_b
  b) Increases water retention at low suctions

Measurement Methods for SWC

The basic requirement is to find pairs of water content θ and matric potential ψ_m over the wetness range of interest.

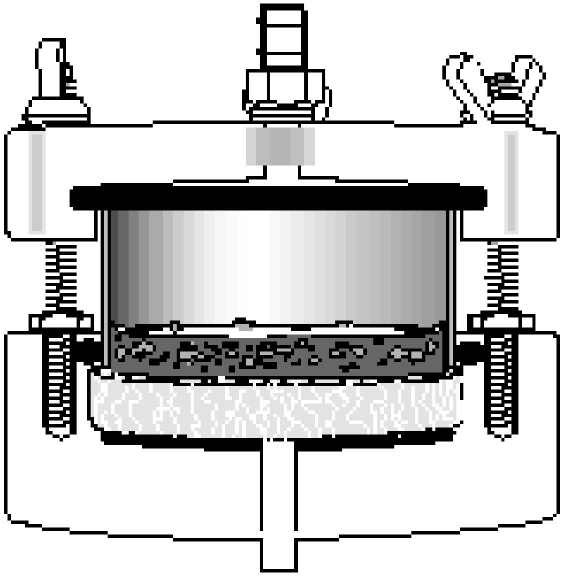
Experimental Difficulties:

- The limited functional range (-10 m) of tensiometers used for in-situ measurements.
- Difficulty to obtain undisturbed samples for laboratory determination.
- Very long equilibration times for low matric potential values associated with dry soils

Measuring soil water retention curves

- Hanging water column
- Tempe cells
- Pressure plates

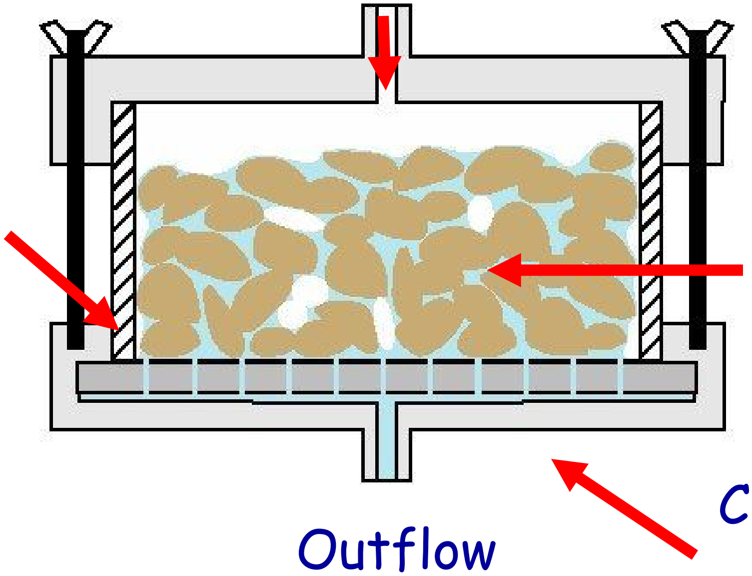
http://web.ku.edu/~soil/Facilities_files/IMG_0141.jpg



http://www.ictinternational.com.au/images/extractor1400-2.gif

Tempe Cell

The pressure flow cell (Tempe cell) is usually applied for the pressure (matric potential) range from 0 to -10 m.



Gas Pressure

Brass Ring

Soil Sample

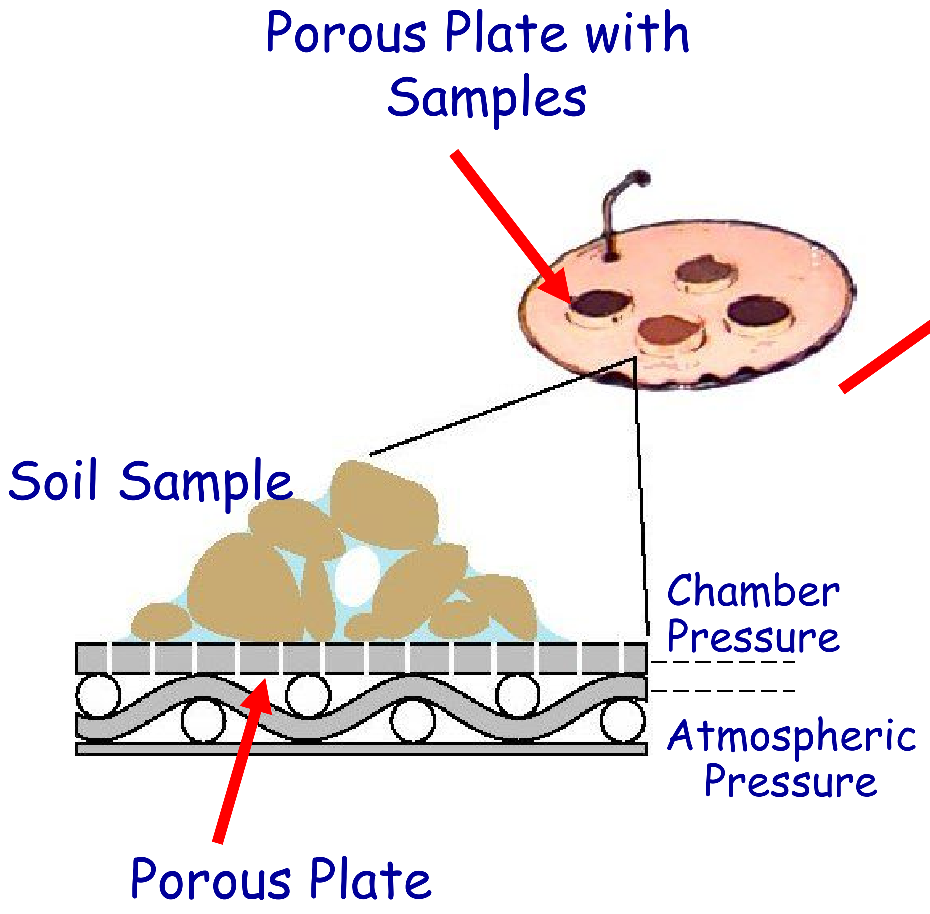
Ceramic Plate

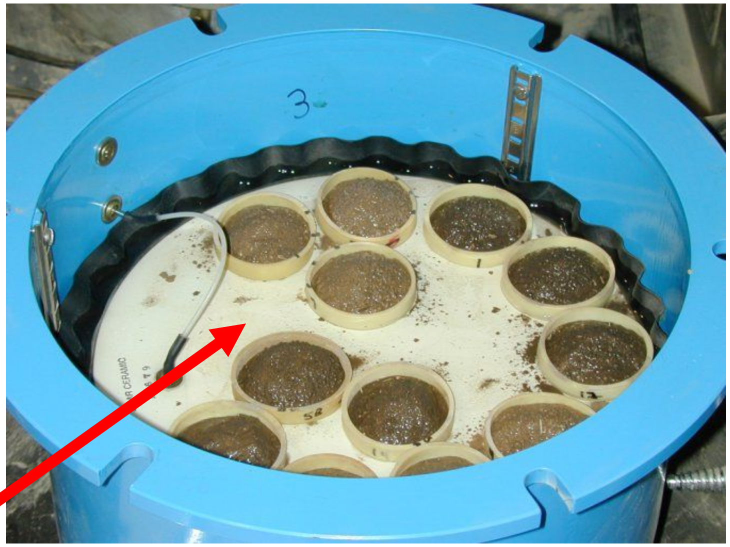
Outflow

Close to saturation soil water retention is strongly influenced by soil structure and the natural pore size distribution. Therefore undisturbed core samples are preferred over repacked samples.

Pressure Plate Apparatus

The pressure plate apparatus is applied for the pressure (matric potential) range from -10 to -50 m.

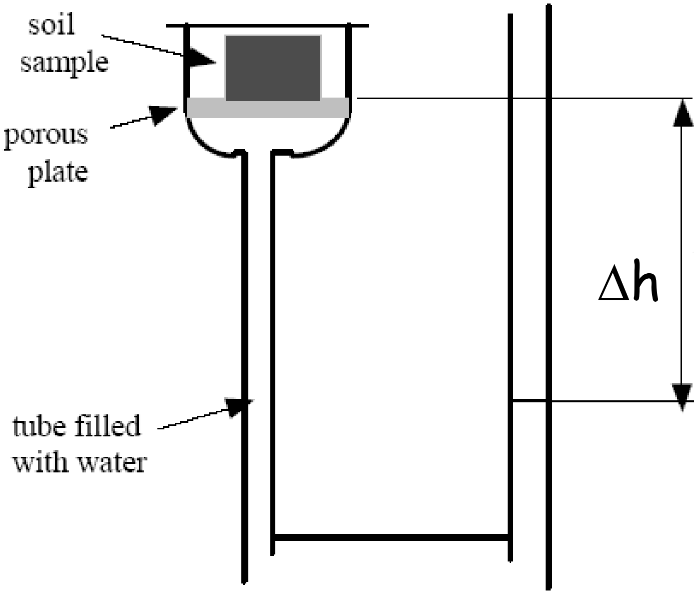


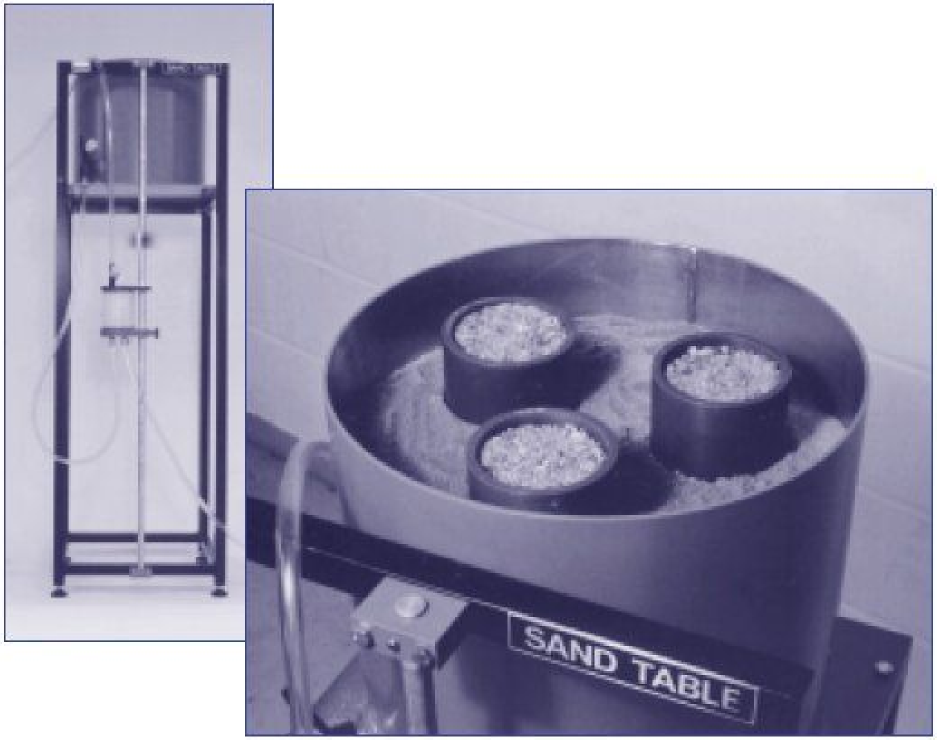


Pressure Plate Apparatus

Hanging water column and suction table

- **Measurements at very low pressure ranges of 0 to 2 m.**
- **Useful for coarse soils due to precise pressure application.**
- **Wetting and drying cycles of the SWC (reversible flow into the sample).**





Vapor Pressure-Based Methods

A procedure inferring water potential using thermocouple psychrometers that is commonly used in newer instruments is called **DEWPOINT METHOD**

In this method one surface is brought to dew point temperature and kept at exactly this temperature using a monitoring system and electronic circuitry.

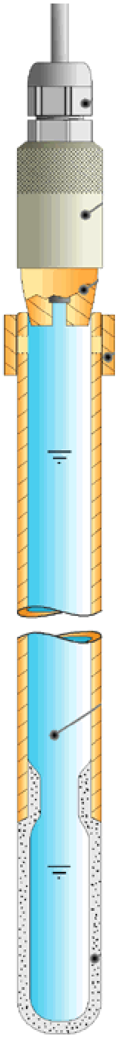
State of the art equipment (e.g., WP4 Potentiameter) uses chilled mirror dewpoint technique combined with a photoelectric detection system to keep the surface of a mirror at dewpoint temperature. Ambient temperature at the sample surface is measured with an infrared thermometer.

WP4 Potentiameter

In-situ measurement methods - Sensor Pairing

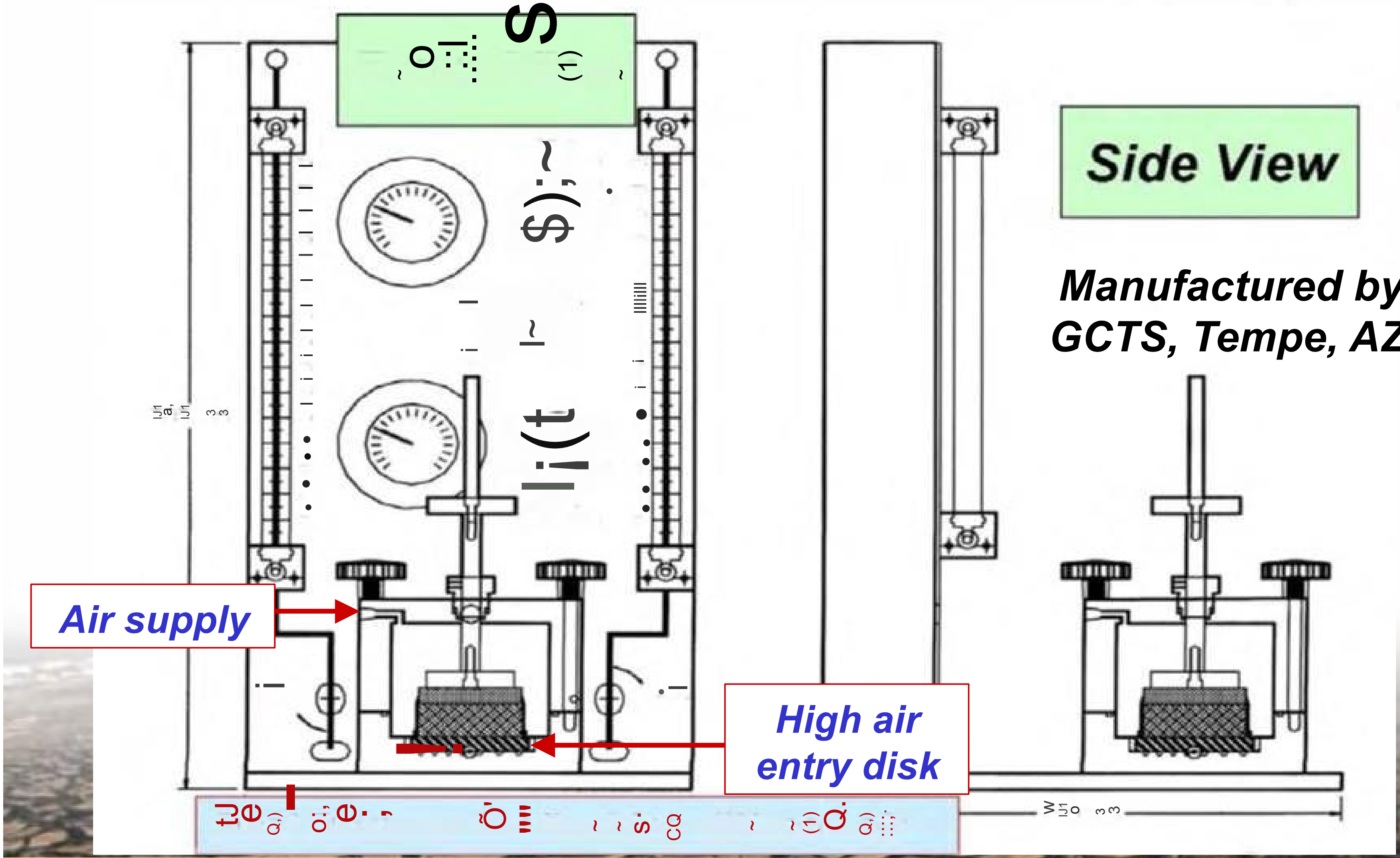
SENSOR PAIRING: (TDR, Neutron Probe, Tensiometer, Heat Dissipation, etc)

Example - TDR Probes installed in close proximity to transducer-equipped tensiometers are commonly used for automated recording of changes of water content and matric potential with time.



IN-SITU MEASUREMENTS ARE CONSIDERED MOST REPRESENTATIVE.

Pressure Plate Apparatus to Measure Void Ratio and Water Content While Applying Total Stress and Matric Suction



Manufactured by GCTS, Tempe, AZ

Fifteen bar Pressure Plate equipment manufactured by GCTS, U.S.A.

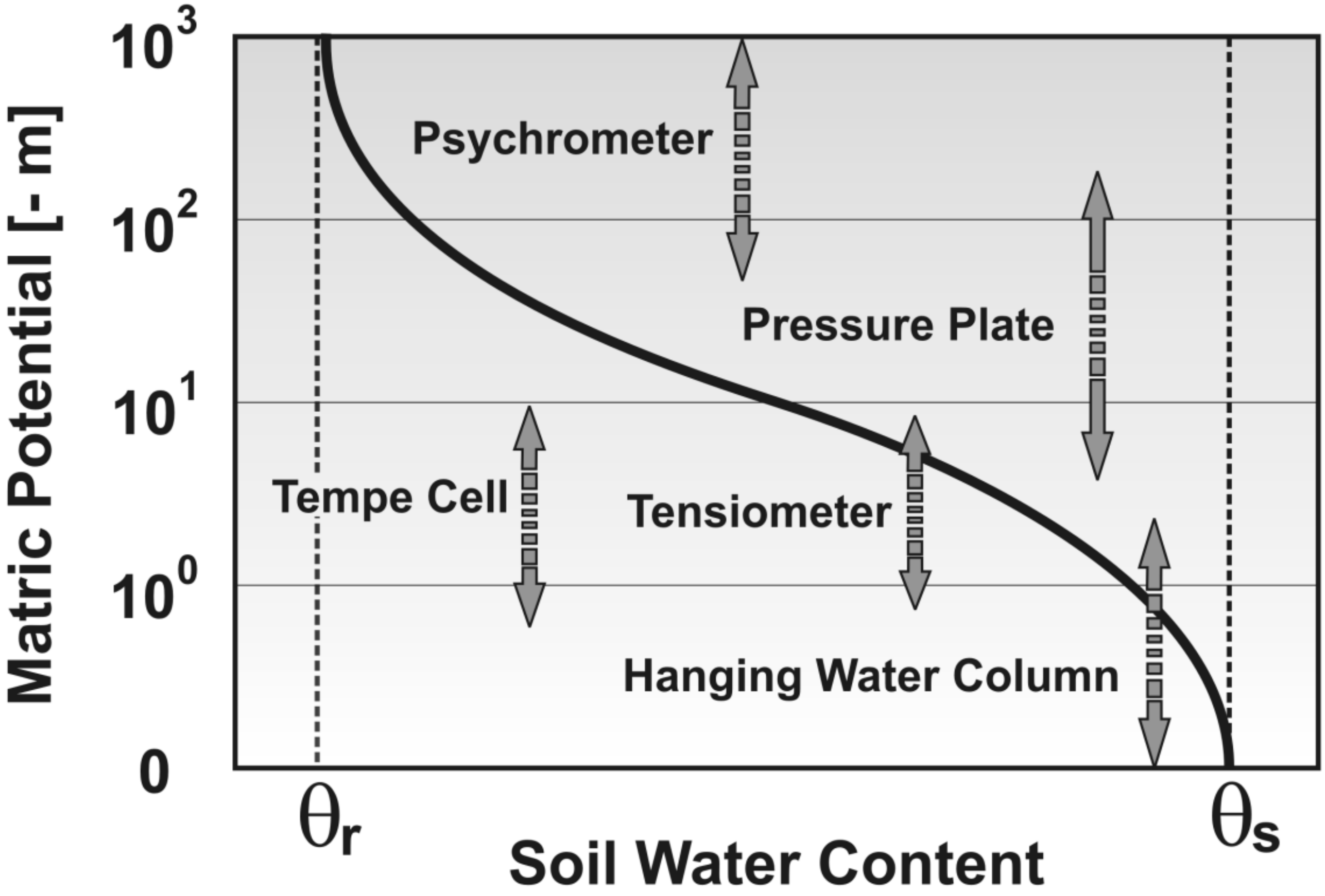
- ***Wide range of applied suctions***
- ***Applies total stresses***
- ***Measures water and total volume change***
- ***Measure diffused air***
- ***Test individual specimens***
- ***Null-type initial suction***
- ***Drying and wetting modes***

Field Measurement Methods - Sensor Pairing

Limitations:

- **Differences in the soil volumes sampled by each sensor, e.g. large volume averaging by a neutron probe vs. a small volume sensed by heat dissipation sensor or psychrometer**
- **In-situ water content measurement methods are instantaneous, matric potential sensors require time for equilibrium; hence the two measurements may not be indicative of the same wetness level**
- **Limited ranges and deteriorating accuracy of different sensor pairs; this often results in limited overlap in retention information and problems with measurement errors within the range of overlap.**

SWC measurement ranges



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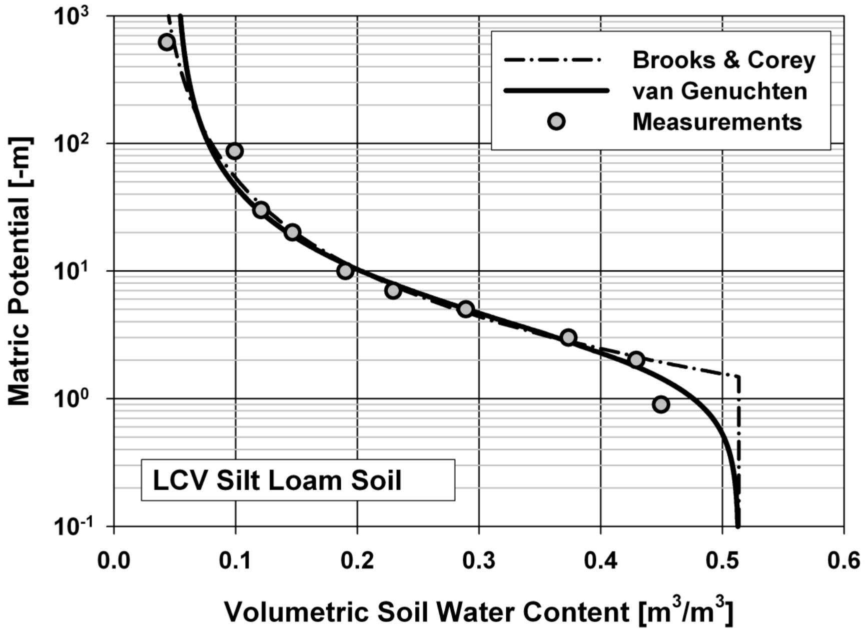
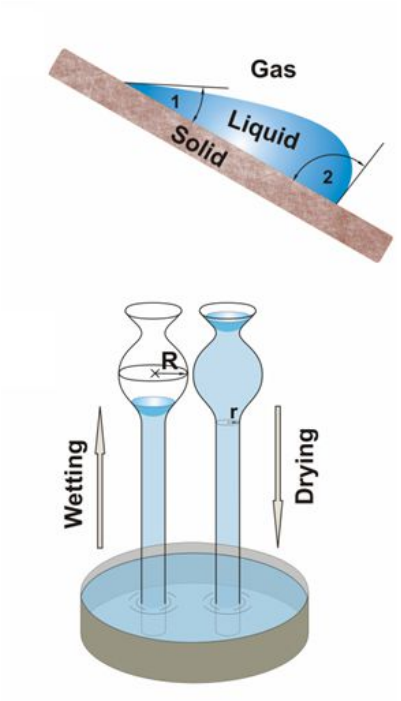
The Soil Water Characteristic - Parametric Models and Hysteresis





Parametric SWC Models

Measuring a SWC is laborious and time consuming. Usually there are only a few data pairs available from measurements.

For modeling and analysis (characterization and comparison of different soils) it is beneficial to represent the SWC relationship as continues parametric function.

Commonly used parametric models are the van Genuchten and Brooks & Corey relationships.

θ_s .... **Water Content at Saturation**
θ_r .... **Residual Water Content**
ψ_m... **Matric Potential**
α..... **Shape Parameter**
m .... **Shape Parameter**
n ..... **Shape Parameter**

Van Genuchten Model (1980):

$$\Theta = \frac{\theta - \theta_r}{\theta_s - \theta_r} = \left[\frac{1}{1 + \left(\alpha \left| \psi_m \right| \right)^n} \right]^m$$

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

The unknown parameters (free parameters) α, n, and θ_r can be obtained by fitting the model to a few (at least 5-8) measured data pairs (Nonlinear regression with $0 \leq m \leq 1$, and $\theta_r \geq 0$).

Parametric SWC Models

Brooks and Corey Model (1964):

$$\Theta = \frac{\theta - \theta_r}{\theta_s - \theta_r} = \left[\frac{\psi_b}{\psi_m}\right]^{\lambda} \qquad \psi_m > \psi_b$$

$$\Theta = 1 \qquad \psi_m \leq \psi_b$$

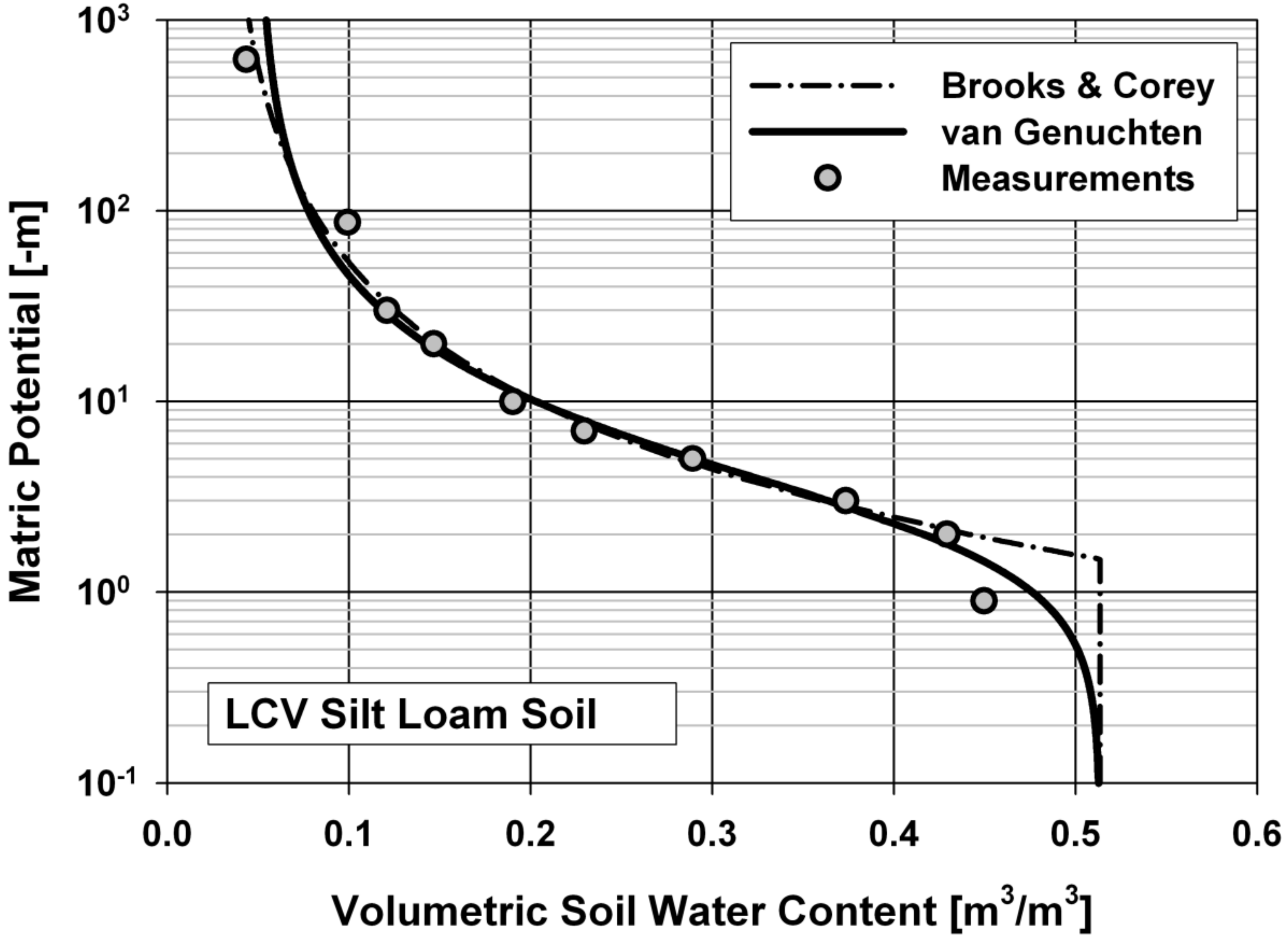
θ_s .... **Water Content at Saturation**
θ_r .... **Residual Water Content**
ψ_m... **Matric Potential**
ψ_b ... **Bubbling Pressure (Air Entry Value)**
λ ..... **Parameter Related to the Shape of the Pore Size Distribution**

The unknown parameters (free parameters) ψ_b, θ_r, and λ can be obtained by fitting the model to measured data pairs

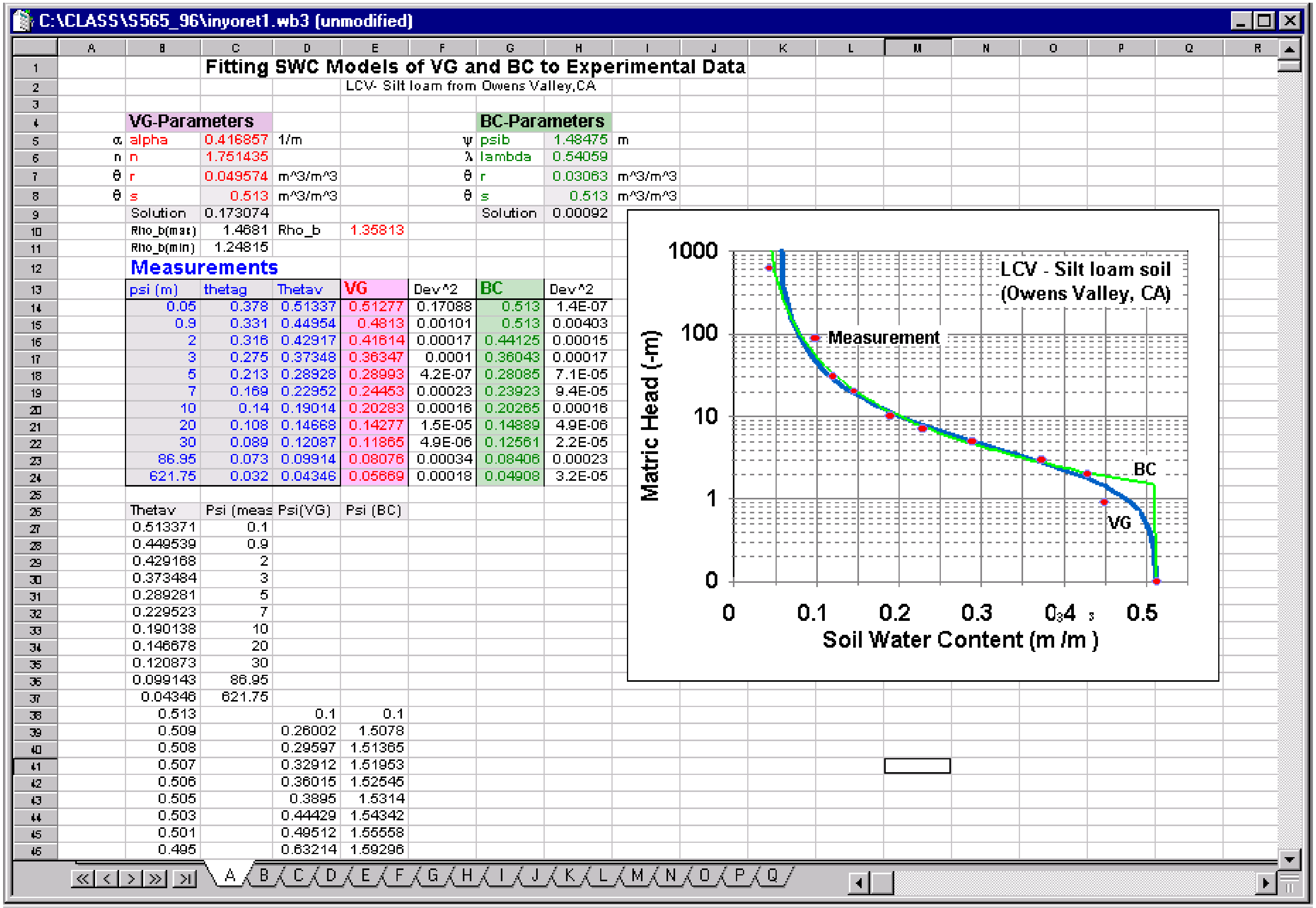
In both models MATRIC POTENTIALS are expressed as positive (absolute) quantities.

There are various computer codes available (e.g., RETC) for estimation of free model parameters. A simple procedure is the application of solver tools that are part of most spreadsheet software packages.

Van Genuchten and Brooks & Corey Models



Fitting SWC models



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Fitting SWC Models of VG and BC to Experimental Data

LCV- Silt loam from Owens Valley,CA

	VG-Parameters					**BC-Parameters**		
α	alpha	0.416857	1/m		ψ	psib	1.48475	m
n	n	1.751435			λ	lambda	0.54059	
θ	r	0.049574	m^3/m^3		θ	r	0.03063	m^3/m^3
θ	s	0.513	m^3/m^3		θ	s	0.513	m^3/m^3
	Solution	0.173074				Solution	0.00092	
	Rho_b(max)	1.4681	Rho_b	1.35813				
	Rho_b(min)	1.24815						

Measurements

psi (m)	thetag	Thetav	VG	Dev^2	BC	Dev^2
0.05	0.378	0.51337	0.51277	0.17088	0.513	1.4E-07
0.9	0.331	0.44954	0.4813	0.00101	0.513	0.00403
2	0.316	0.42917	0.41614	0.00017	0.44125	0.00015
3	0.275	0.37348	0.36347	0.0001	0.36043	0.00017
5	0.213	0.28928	0.28993	4.2E-07	0.28085	7.1E-05
7	0.169	0.22952	0.24453	0.00023	0.23923	9.4E-05
10	0.14	0.19014	0.20283	0.00016	0.20265	0.00016
20	0.108	0.14668	0.14277	1.5E-05	0.14889	4.9E-06
30	0.089	0.12087	0.11865	4.9E-06	0.12561	2.2E-05
86.95	0.073	0.09914	0.08076	0.00034	0.08406	0.00023
621.75	0.032	0.04346	0.05669	0.00018	0.04908	3.2E-05

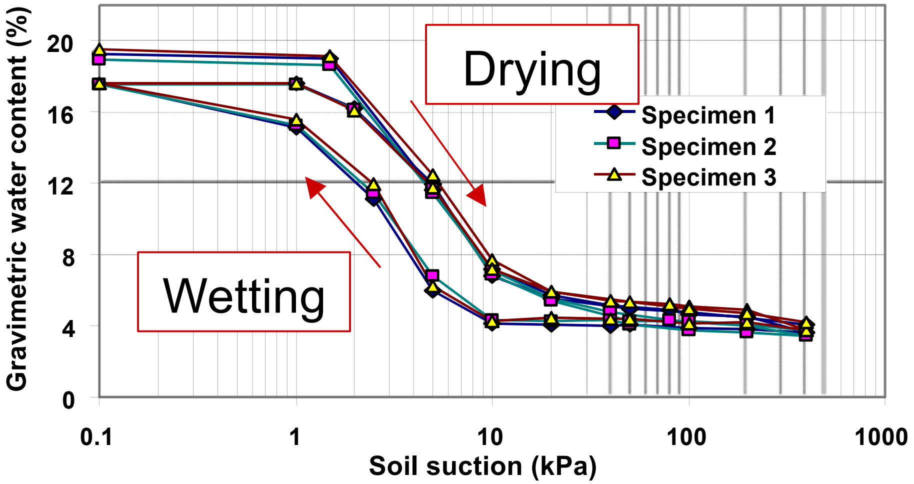
Thetav	Psi (meas	Psi(VG)	Psi (BC)
0.513371	0.1		
0.449539	0.9		
0.429168	2		
0.373484	3		
0.289281	5		
0.229523	7		
0.190138	10		
0.146678	20		
0.120873	30		
0.099143	86.95		
0.04346	621.75		
0.513		0.1	0.1
0.509		0.26002	1.5078
0.508		0.29597	1.51365
0.507		0.32912	1.51953
0.506		0.36015	1.52545
0.505		0.3895	1.5314
0.503		0.44429	1.54342
0.501		0.49512	1.55558
0.495		0.63214	1.59296

Typical "van Genuchten" Model Parameters

Table1: Typical van Genuchten model parameters (α, n) including residual (θ_r) and saturated (θ_s) water contents compiled from the UNSODA database (Leij et al., 1996). N indicates the number of soils or samples of a given textural class from which the mean values are compiled.

Textural Class	N	θ_r [cm^3/cm^3]	θ_s [cm^3/cm^3]	α [1/cm]	n
Sand	126	0.058	0.37	0.035	3.19
Loamy Sand	51	0.074	0.39	0.035	2.39
Sandy Loam	78	0.067	0.37	0.021	1.61
Loam	61	0.083	0.46	0.025	1.31
Silt	3	0.123	0.48	0.006	1.53
Silt Loam	101	0.061	0.43	0.012	1.39
Sandy Clay Loam	37	0.086	0.40	0.033	1.49
Clay Loam	23	0.129	0.47	0.030	1.37
Silty Clay Loam	20	0.098	0.55	0.027	1.41
Silty Clay	12	0.163	0.47	0.023	1.39
Clay	25	0.102	0.51	0.021	1.20

Equations to Best-Fit SWCC Data



Numerous equations have been proposed:

-Brooks & Corey (1964)

- van Guenuchten (1980)

$$w(\psi) = C(\psi) \times \frac{w_s}{\{\ln[e + (\psi/a_f)^{n_f}]\}^{m_f}}$$

Asymmetry Variable

Rate of desaturation

Air entry value

Correction Factor

$$C(\psi) = 1 - \frac{\ln(1 + \psi/\psi_r)}{\ln[1 + (1000000/\psi_r)]}$$

ψ = Soil suction

Fredlund and Xing (1994)

Databases for Soil Hydraulic Properties

Table 1-1: Textural Averages of Hydraulic Parameters Based on UNSODA Unsaturated Hydraulic Properties Database and NRCS Soil Survey Database (Leij, et al., 1999).

	Water Retention					Saturated Hydraulic conductivity	
Textural Class	N†	θ_r	θ_r	α [1/cm]	n	N†	K_s [cm/d]
			UNSODA				
Sand	126	0.058	0.37	0.035	3.19	74	505.8
Loamy Sand	51	0.074	0.39	0.035	2.39	31	226.5
Sandy Loam	78	0.067	0.37	0.021	1.61	50	41.6
Loam	61	0.083	0.46	0.025	1.31	31	38.3
Silt	3	0.123	0.48	0.006	1.53	2	55.7
Silt Loam	101	0.061	0.43	0.012	1.39	62	30.5
Sandy Clay Loam	37	0.086	0.40	0.033	1.49	19	9.69
Clay Loam	23	0.129	0.47	0.030	1.37	8	1.84
Silty Clay Loam	20	0.098	0.55	0.027	1.41	10	7.41
Silty Clay	12	0.163	0.47	0.023	1.39	6	8.40
Clay	25	0.102	0.51	0.021	1.20	23	26.0
			SOIL SURVEY				
Sand	246	0.045	0.43	0.145	2.68	246	712.18
Loamy Sand	315	0.057	0.41	0.124	2.28	315	350.2
Sandy Loam	1183	0.065	0.41	0.075	1.89	1183	106.1
Loam	735	0.078	0.43	0.036	1.56	735	25.0
Silt	82	0.034	0.46	0.016	1.37	88	60.0
Silt Loam	1093	0.067	0.45	0.020	1.41	1093	10.8
Sandy Clay Loam	214	0.100	0.39	0.059	1.48	214	31.4
Clay Loam	364	0.095	0.41	0.019	1.31	345	6.24
Silty Clay Loam	641	0.089	0.43	0.010	1.23	592	1.68
Sandy Clay	46	0.100	0.38	0.027	1.23	46	2.88
Silty Clay	374	0.070	0.36	0.005	1.09	126	0.48
Clay	400	0.068	0.38	0.008	1.09	114	4.80

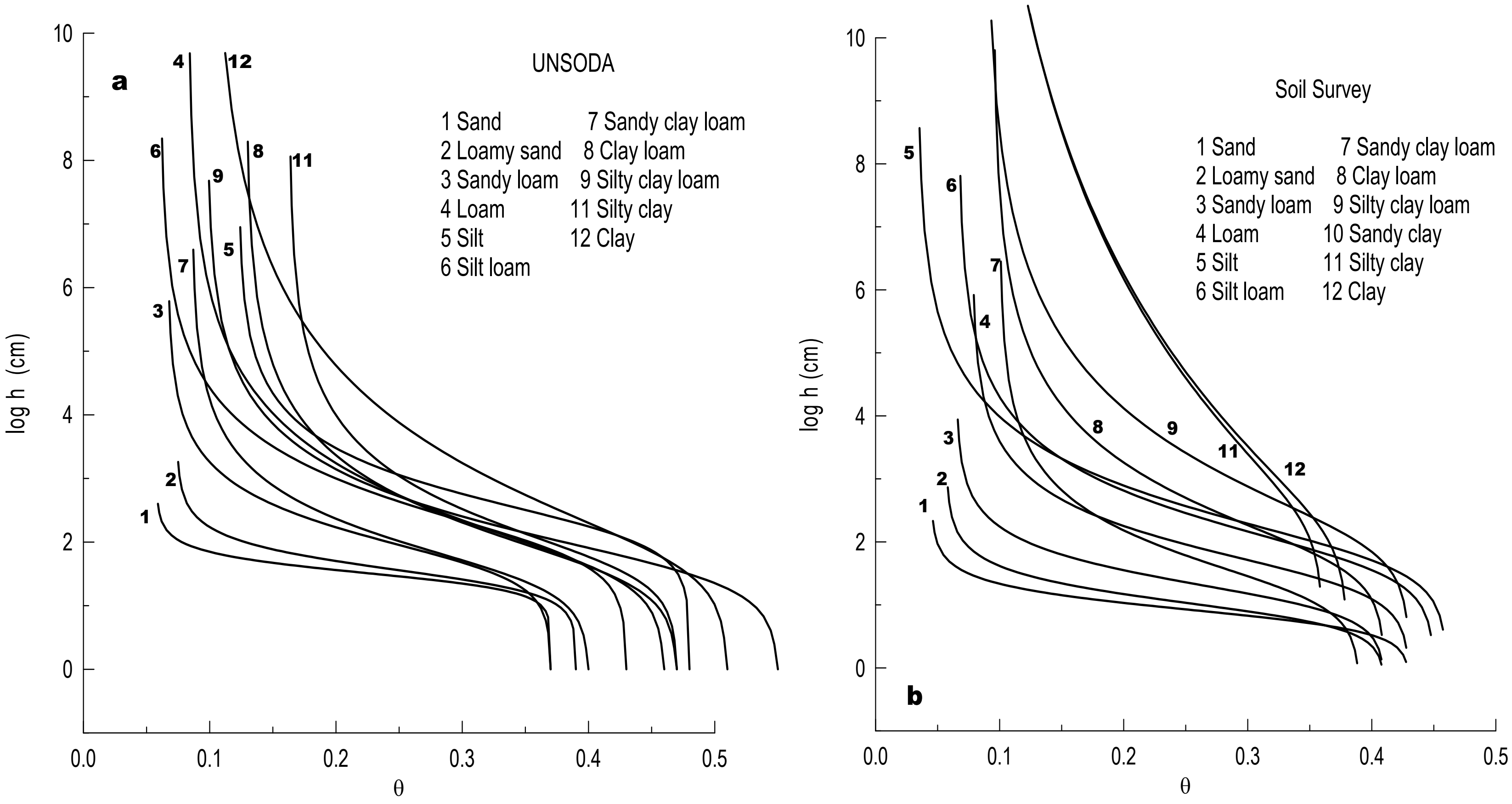
† Approximate sample size for Soil Survey database

Databases for hydraulic soil properties have been compiled by several agencies.

These data are good estimates for various soil textural classes and may be used as initial guesses for optimization of measured data.

Databases for Soil Hydraulic Properties

Graphical representation of various SWC curves contained in the UNSODA and NRCS databases.



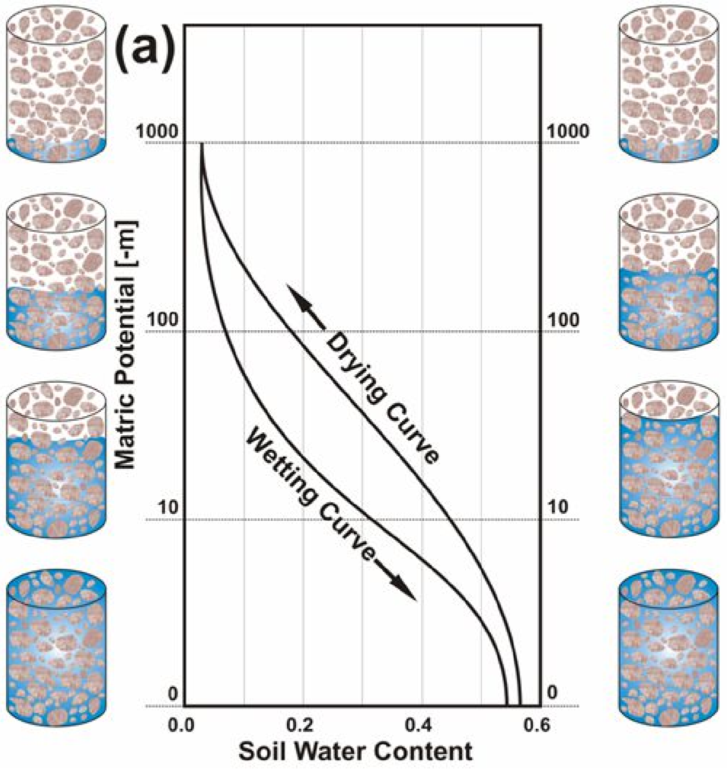
Hysteretic behavior of SWC

Soil Water Content and **Matric Potential** are not uniquely related and depend on the path of saturation or desaturation.

SWC can be either obtained by desaturation of an initially saturated sample by applying suction or pressure **(DRYING CURVE)**, or by gradually wetting of an initially oven-dry sample **(WETTING CURVE)**.

The two procedures often produce different SWC curves - the water content of the drying branch is typically higher than water content of a wetting curve at the same potential.

This phenomenon is known as **HYSTERESIS**



Hysteresis in SWC

The Hysteresis in the SWC relationship depends on several micro- and meso-scale phenomenon:

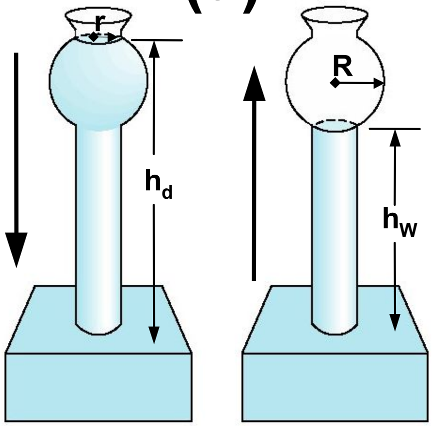
"INK BOTTLE" EFFECT resulting from non-uniformity in shape and size of interconnected pores:

Drainage is governed by the smaller pore radius, whereas wetting is governed by the larger radius. (Large pores drain first but fill up last)

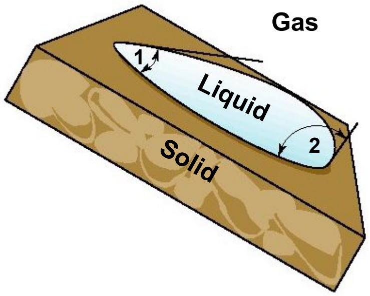
Different LIQUID-SOLID CONTACT ANGLES for advancing and receding liquid. ENTRAPPED AIR in newly wetted soil

SWELLING AND SHRINKING of soil under wetting and drying

(a)



(b)

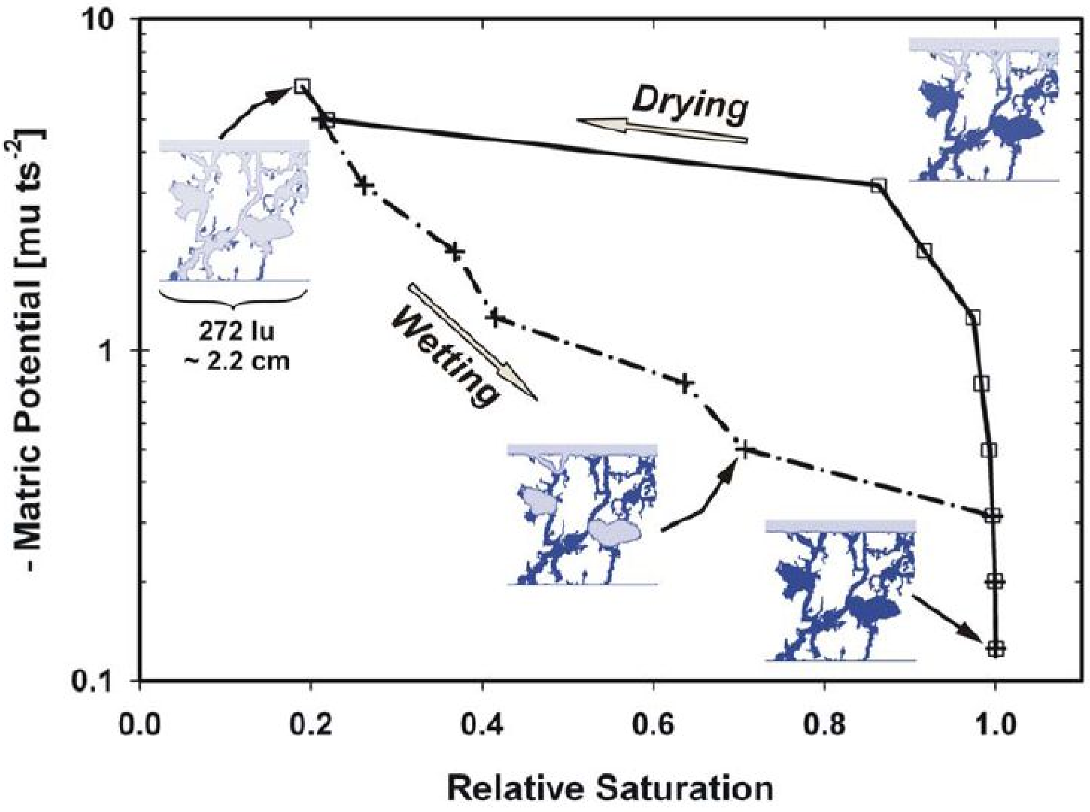


The role of individual factors remains unclear and is subject of ongoing research.

Hysteresis in SWC – meso-scale

Meso-scale manifestation of hysteresis through Lattice Boltzmann simulation of liquid configuration in complex pore spaces.

Entrapment of liquid in pore clusters

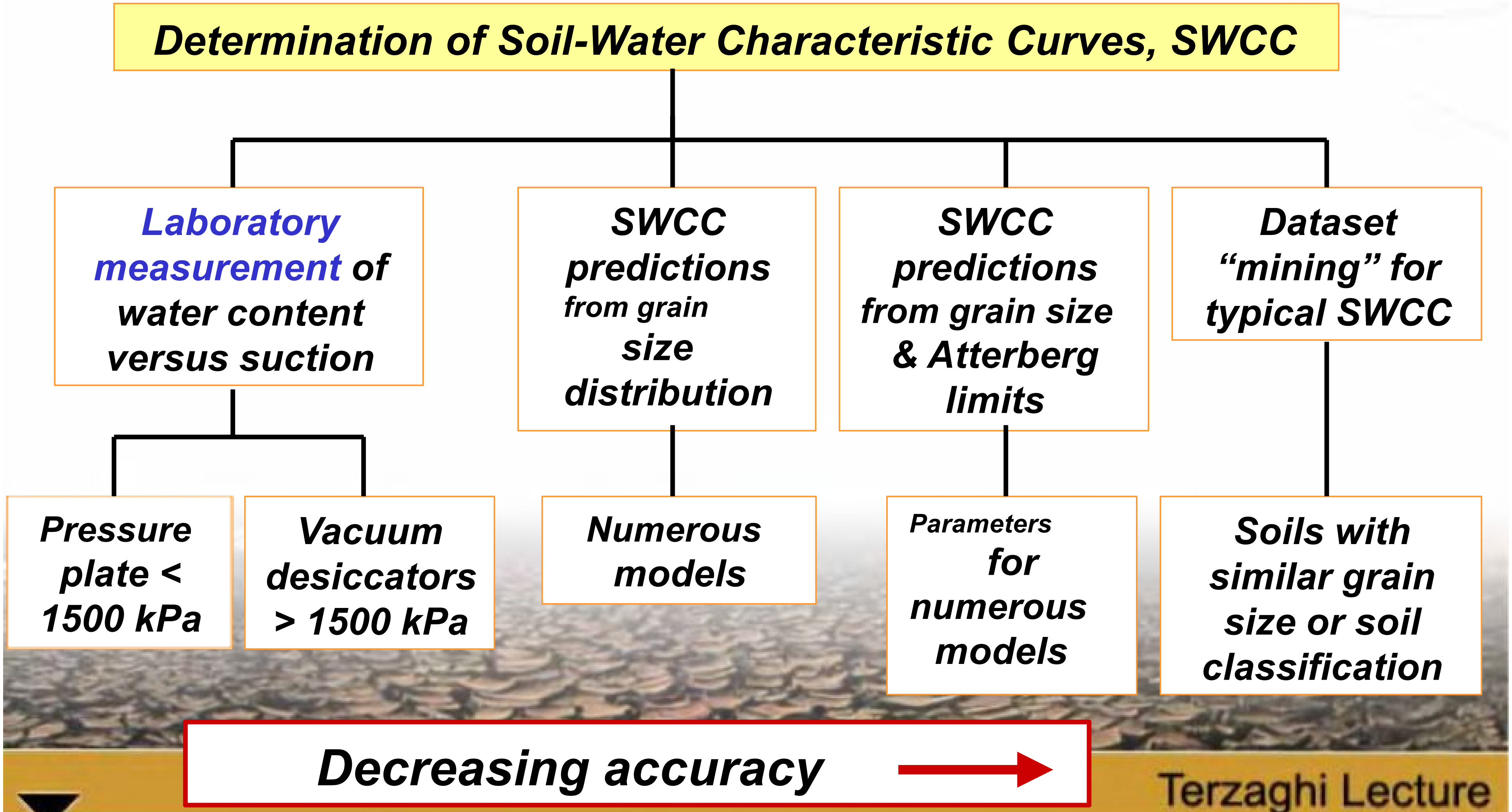


Hysteresis in the Soil-Water Characteristic Curve

- Hysteretic SWCC Models will eventually be available for geotechnical usage
- Presently, the Geotechnical Engineer must decide which curve to use:
  - Select wetting curve or drying curve based on process being simulated
- Hysteresis loop shift at point of inflection:
  - Sands: 0.15 to 0.35 Log cycle
    - Average: 0.25 Log cycle
  - Loam soils: 0.35 to 0.60 Log cycle
    - Average: 0.50 Log cycle

Estimation Values

Approaches that can be used to obtain the Soil–Water Characteristic curves



Determination of Soil-Water Characteristic Curves, SWCC

Laboratory measurement of water content versus suction

Pressure plate < 1500 kPa

Vacuum desiccators > 1500 kPa

SWCC predictions from grain size distribution

Numerous models

SWCC predictions from grain size & Atterberg limits

Parameters for numerous models

Dataset "mining" for typical SWCC

Soils with similar grain size or soil classification

Decreasing accuracy →