Soil Water (II)

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Today’s Lecture

- **Hydraulic head**
- **Variation of soil potential with depth in the soil profile** (saturated and unsaturated soil)
- **Measuring water potential in the soil** (saturated and unsaturated)
- **Soil moisture characteristic curve** (and how it is measured)

See pages 13-24 of Notes 2.pdf

Measurement of soil water potential

Piezometer (for measuring ϕ_{ps})

In a saturated soil such as below a water table, soil water is under positive hydrostatic pressure, greater than atmospheric. The pressure potential (ϕ_{ps}) may be taken as equal to the vertical distance from a point in the soil to the surface of the free water table. Recall that we express potential in terms of length or head when potential energy is expressed per unit of weight.

The piezometer is a hollow tube placed in the soil to depths below the water table. It extends to the soil surface and is open to the atmosphere. The bottom of the piezometer is perforated to allow for soil water under positive hydrostatic pressure to enter the tube. Water enters the tube and rises to a height equal to that of the free water table.

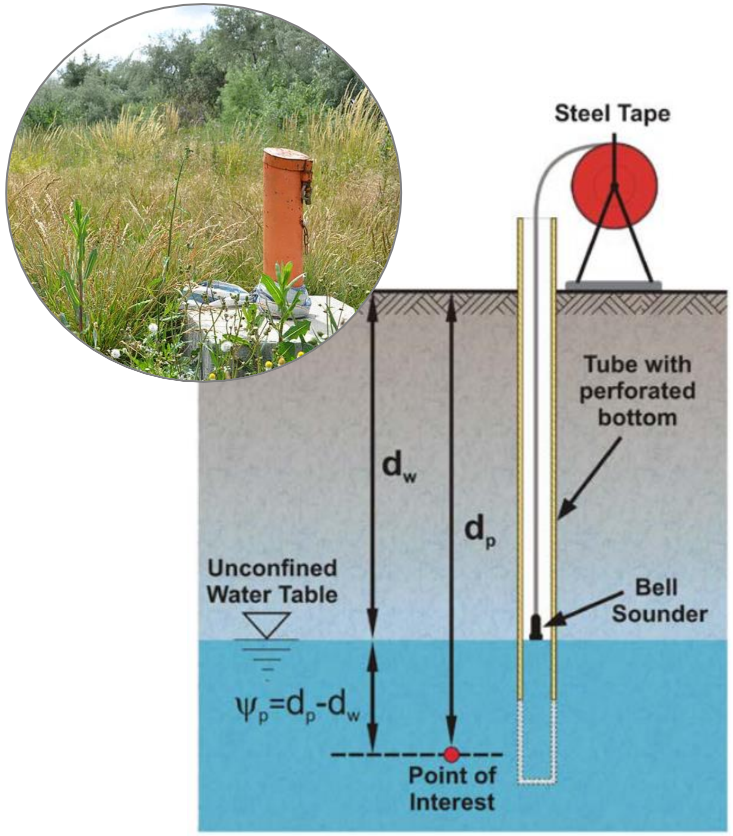
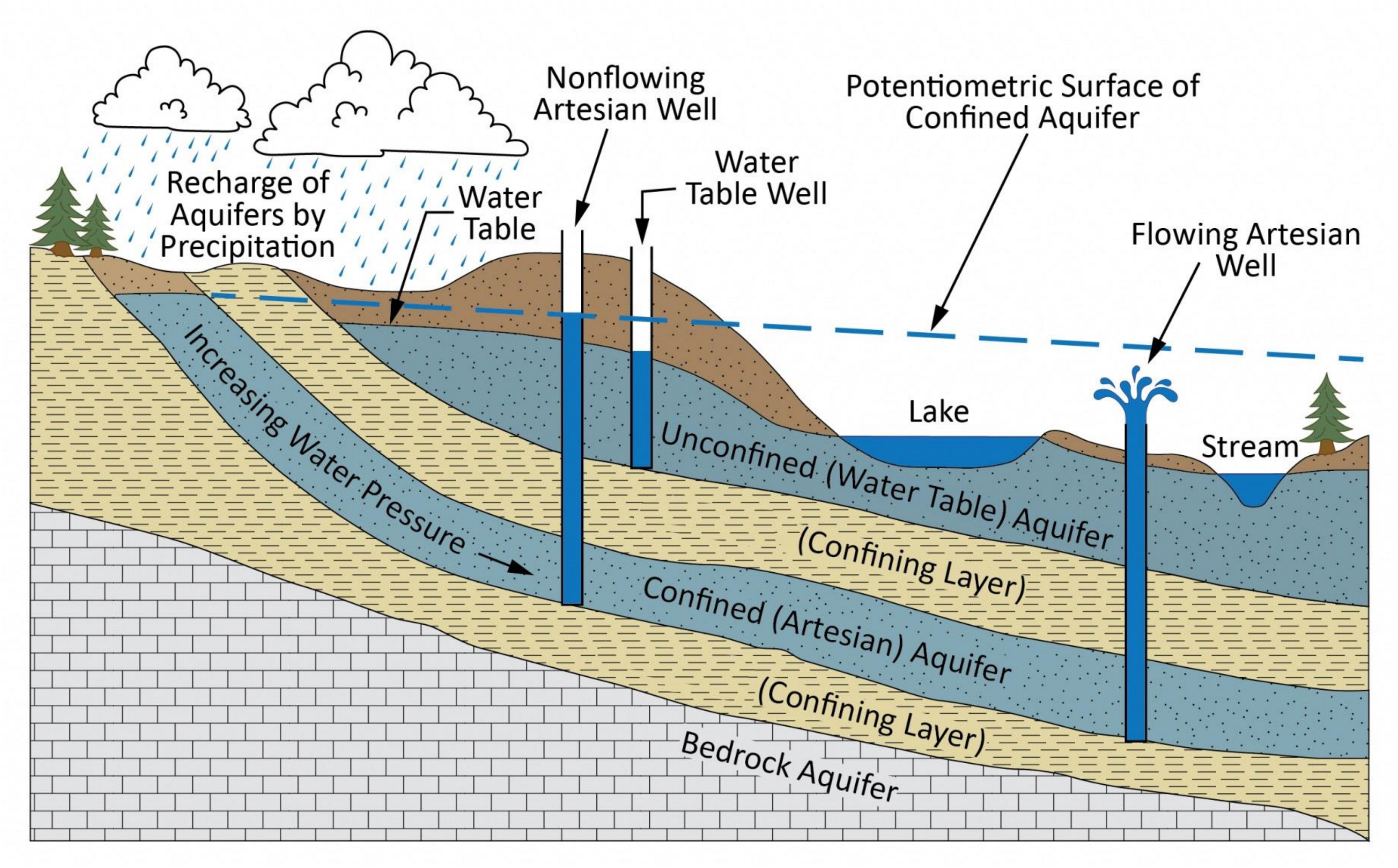


Fig.1-29: Sketch illustrating the concept of piezometer measurements

Source: Or, Tuller, & Wraith, 1994-2018

Measurement of soil water potential



[Groundwater – Planet Earth (openeducationalberta.ca)]

Measurement of soil water potential

Tensiometer (for measuring ϕ_m)

A tensiometer consists of a porous cup, usually made of ceramic and having very fine pores, connected to a vacuum gauge through a water-filled tube. The porous cup is placed in intimate contact with the bulk soil at the depth of measurement. When the matric potential of the soil is lower (more negative) than inside the tensiometer, water moves from the tensiometer along a potential energy gradient to the soil through the saturated porous cup, thereby creating suction sensed by the gauge. Water flow into the soil continues until equilibrium is reached and the suction inside the tensiometer equals the soil matric potential. When the soil is wetted, flow may occur in the reverse direction, i.e., soil water enters the tensiometer until a new equilibrium is attained.

Note: the tensiometer range is limited to suction values (negative of the matric potential) of less than -100 kPa, i.e., -1 bar or -10 m head of water.

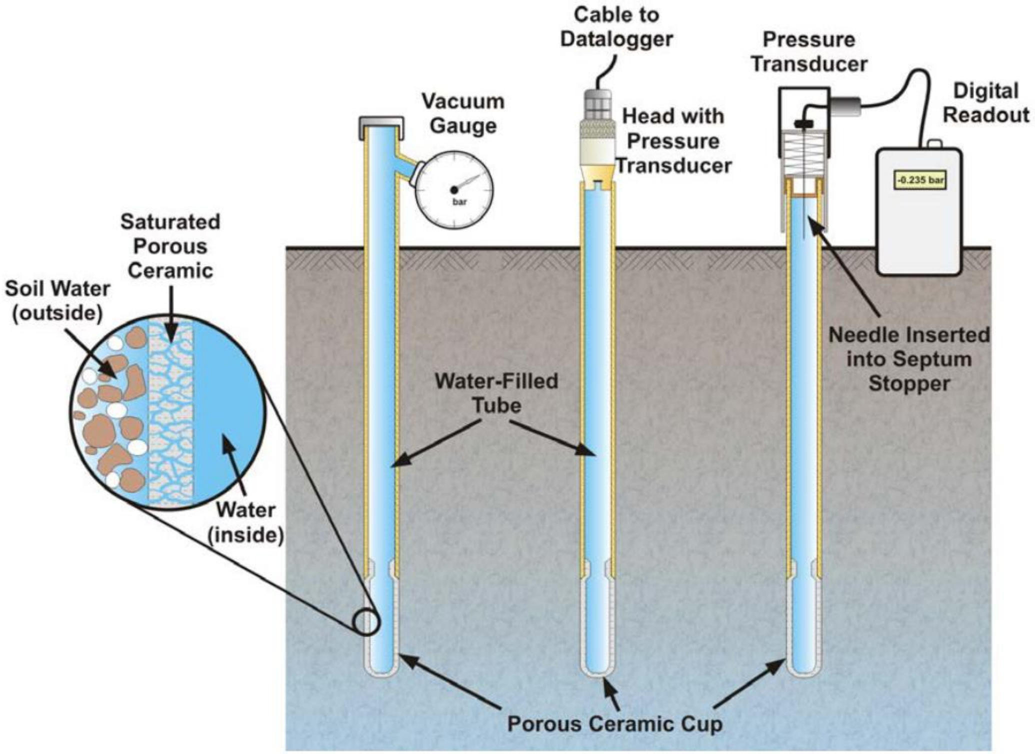
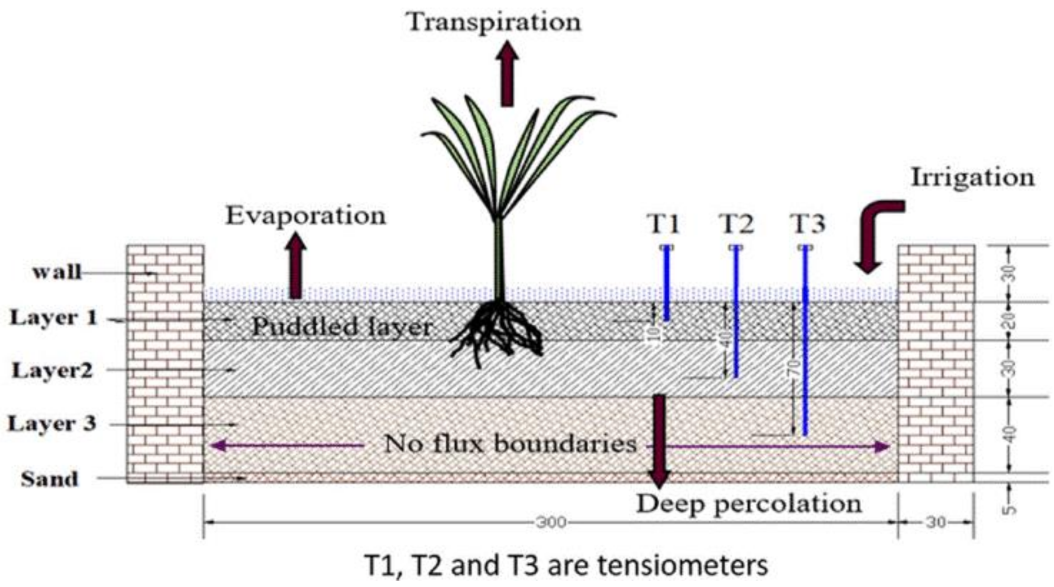


Fig.1-30: Illustration of tensiometers for matric potential measurement using vacuum gauges and electronic pressure transducers.

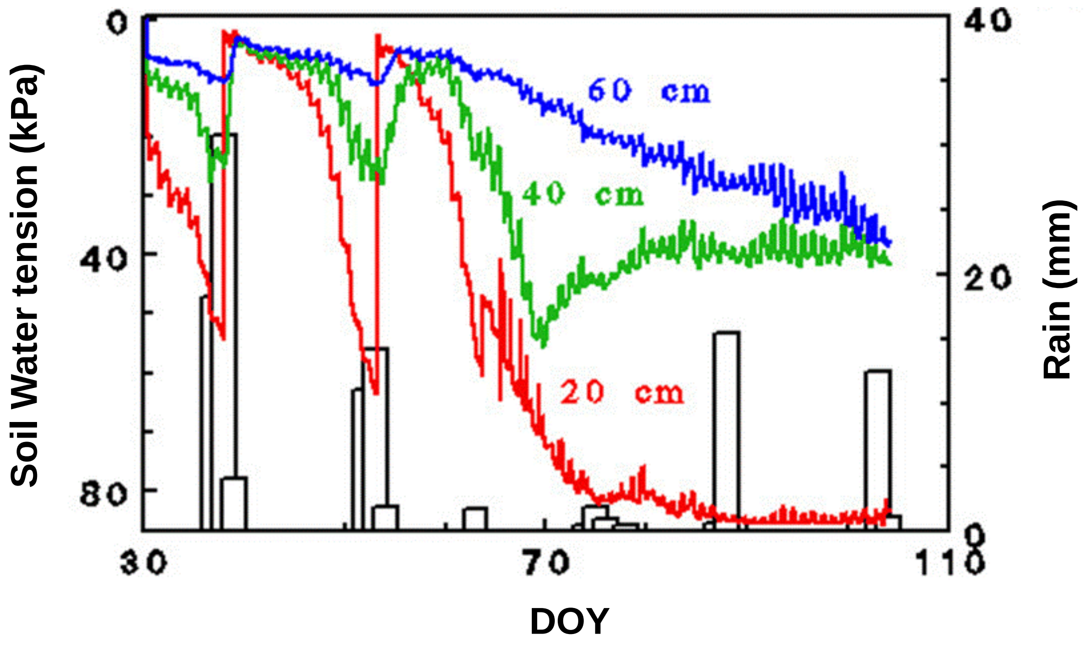
Source: Or, Tuller, & Wraith, 1994-2018

Measurement of soil water potential

Tensiometer (for measuring ϕ_m)



Shekhar et al. (2019)



Silber et al. (2019)

Measurement of soil water potential

Heat Dissipation in Rigid Porous Matrix (for measuring ϕ_m)

The rate of heat dissipation in a porous medium is dependent on the medium's specific heat capacity, thermal conductivity, and density. The heat capacity and thermal conductivity of a porous matrix is affected by its water content. Heat dissipation sensors contain heating elements in line or point source configurations embedded in a rigid porous matrix with fixed pore space.
The measurement is based on application of a heat pulse by applying a constant current through the heating element and analysis of the temperature response measured by a thermocouple placed at a certain distance from the heating source. With the heat dissipation sensor buried in the soil, changes in soil water matric potential result in a gradient between the soil and the porous ceramic matrix inducing a water flux between the two materials until a new equilibrium is established. The water flux changes the water content of the ceramic matrix which, in turn, changes the thermal conductivity and heat capacity of the sensor.

Note: typical useful matric potential range forsuch sensors is -10 kPa to -1000 kPa.

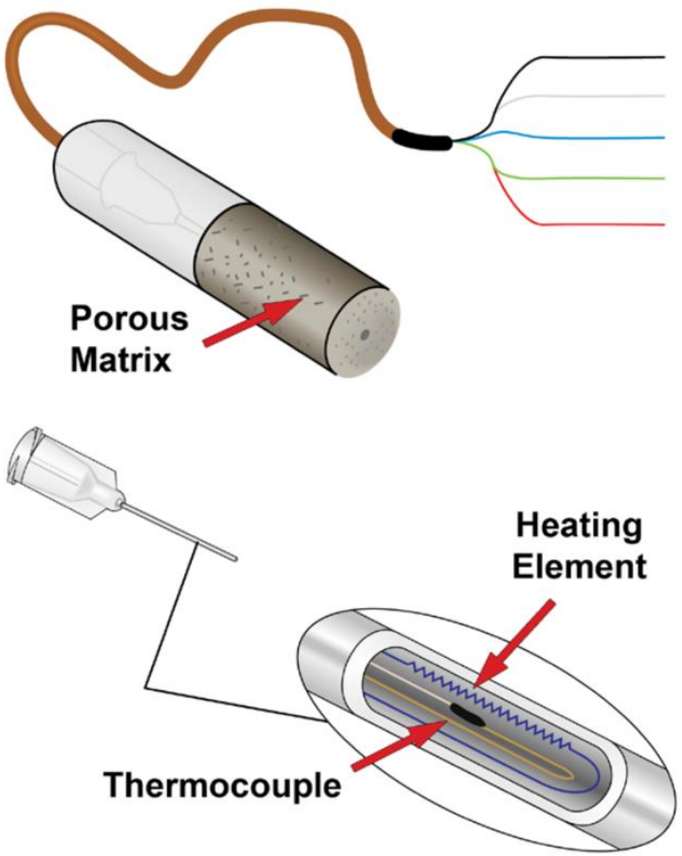


Fig.1-31: A scheme of CSI 229 heat dissipation sensor. (Source: Campbell Scientific Inc., Logan, UT).

Soil Water Content-Energy Relationship

Soil moisture characteristic curve (SCC)

Water in a saturated soil is at atmospheric pressure if it is at equilibrium with free water at the same elevation (i.e., zero hydrostatic pressure, zero suction). If a slight suction is applied, no outflow may occur until, as suction is increased, a critical value is exceeded at which the largest surface pore begins to empty and its water content is displaced by air. This critical suction is called the **air-entry suction** (threshold of desaturation).

Recalling the capillary equation ($-P = \psi = 2\sigma/R$), we can readily predict that a gradual increase in suction will result in the emptying of progressively smaller pores until, at high suction values, only the very narrow pores retain water. Increasing suction is thus associated with decreasing soil wetness. The amount of water remaining in the soil at equilibrium is a function of the sizes and volumes of the water-filled pores and of the amount of water adsorbed to the particles – i.e., it is a function of the matric suction. This function is called the **soil-moisture retention curve**, or the **soil-moisture characteristic** curve (typically measured experimentally).

Source: Or, Tuller, & Wraith, 1994-2018

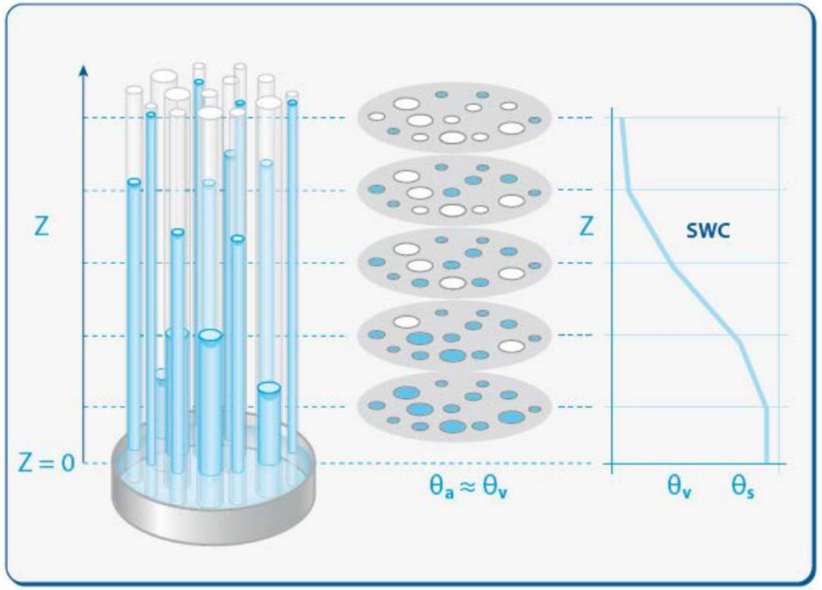


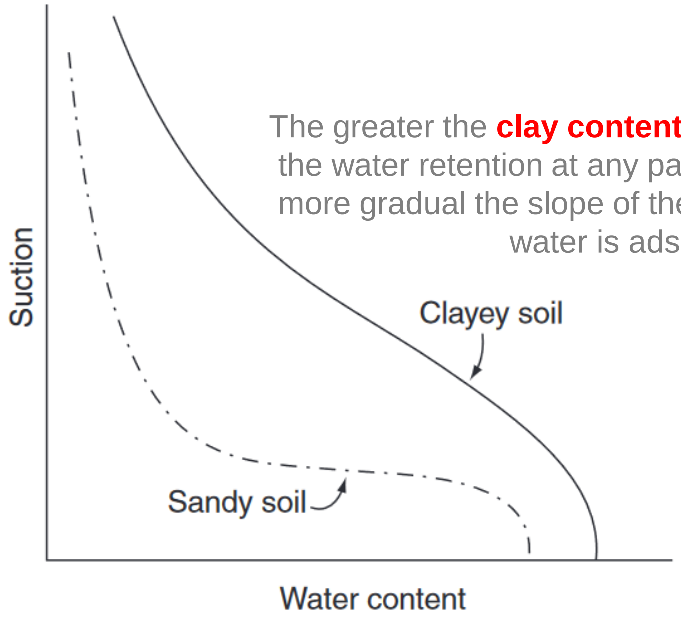
Fig.1-34: Schematic representation of the relationships between capillary size (radius), degree of saturation and matric potential (expressed as the height above a pool of water) illustrating soil water retention for pore space modeled as a bundle of cylindrical capillaries.

If you consider a soil volume as an "equivalent" bundle of capillaries dipped into a water reservoir, the relative saturation (i.e., ratio of water-filled and total cross-sectional area) decreases with height, as only capillaries with the smallest diameter are likely to be filled at high elevations.

Soil Water Content-Energy Relationship

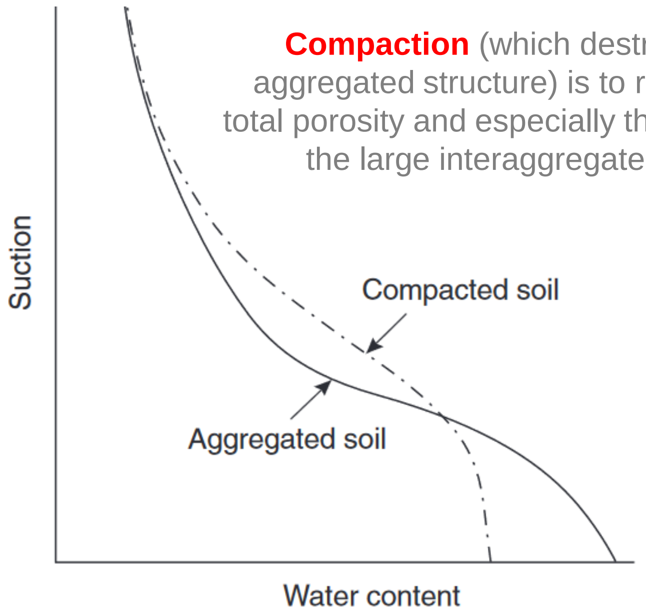
Soil moisture characteristic curve (SCC)

In a **sandy soil**, most of the pores are relatively large, and once these large pores are emptied at a given suction, only a small amount of water remains.



The greater the **clay content**, in general, the greater the water retention at any particular suction and the more gradual the slope of the curve (as more of the water is adsorbed)

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



Compaction (which destroys the aggregated structure) is to reduce the total porosity and especially the volume of the large interaggregate pores

Fig. 6.9. The effect of soil structure on soil-water retention.

Hillel (2003)

Soil moisture characteristic curve (SCC)

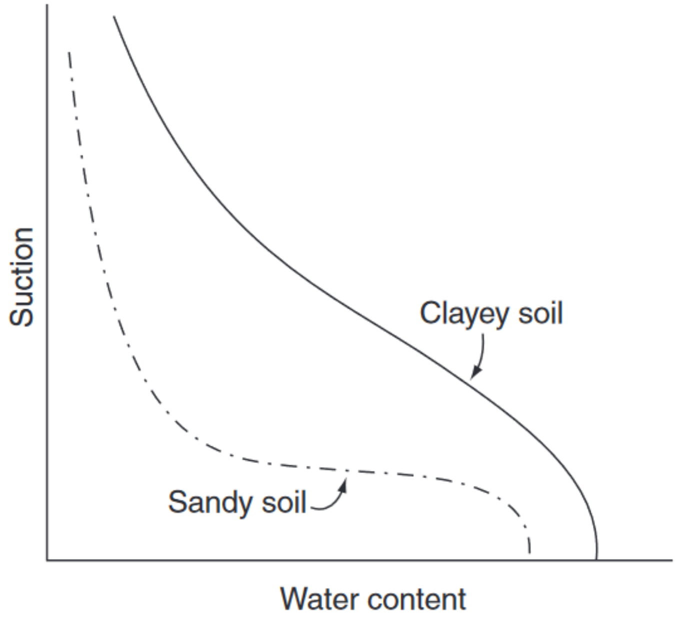


Fig. 6.8. The effect of texture on soil-water retention.

The slope of the soil-moisture characteristic curve, which is the change of water content per unit change of matric potential, is generally termed the *differential* (or *specific*) *water capacity* c_θ:

$$c_\theta = d\theta/d\phi_p \qquad \text{or} \qquad c_\theta = -d\theta/d\psi \tag{6.29}$$

The c_θ term is analogous to the well-known *differential heat capacity*, which is the change in the heat content of a body per unit change in the thermal potential (temperature). However, while the differential heat capacity is fairly constant with temperature for many materials, the differential water capacity in soils is strongly dependent on the matric potential.

Hillel (2003)

Soil Water Content-Energy Relationship

Soil moisture characteristic curve (SCC)

As yet, no universally applicable theory exists for the prediction of the matric suction versus wetness relationship from basic soil properties (i.e., texture and structure). The adsorption and pore geometry effects are generally too complex to be described by a simple model. Several empirical equations have been proposed that describe the soil-moisture characteristic for some soils and within limited suction ranges. For example:

Van Genuchten (VG) model

An effective and commonly used parametric model for relating volumetric water content, θ_v, to the matric potential, ψ_m, was proposed by van Genuchten (1980) and is denoted here as VG:

$$\Theta = \frac{\theta - \theta_r}{\theta_s - \theta_r} = \left[\frac{1}{1 + \left(\alpha \left| \psi_m \right| \right)^n} \right]^m \qquad \textbf{(39)}$$

where θ_r and θ_s are the residual and saturated water contents, respectively, and α, n, and m are parameters directly dependent on the shape of the $\theta(\psi)$ curve. Considerable simplification is gained by assuming that m=1-1/n. Thus the parameters required for estimation of the model are θ_r, θ_s, α, and n. θ_s is usually known and is easy to obtain experimentally with good accuracy, leaving only three unknown parameters (θ_r, α and n) to be estimated from the experimental data. Note that θ_r may be taken as $\theta_{-1.5\text{ MPa}}$, $\theta_{\text{air dry}}$, or a similar value, though it is often advantageous to use it as a fitting parameter.

Brooks and Corey (BC) model

Another well known parametric model was proposed by Brooks and Corey (1964) and is denoted as BC:

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

$$\Theta = 1 \qquad \psi_m \le \psi_b \qquad \textbf{(40)}$$

where ψ_b is a parameter related to the soil matric potential at air entry (b represents "bubbling pressure"), and λ is related to the soil pore size distribution. Matric potentials are expressed as positive quantities, i.e. in absolute values, in both the VG and BC parametric expressions.

Source: Or, Tuller, & Wraith, 1994-2018

Soil Water Content-Energy Relationship

VG model:

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

$$h = \frac{\left[\left(\dfrac{\theta-\theta_r}{\theta_s-\theta_r}\right)^{-\frac{1}{m}} - 1\right]^{\frac{1}{n}}}{\alpha}$$

Remember: m=1-1/n

UNSODA:

UNsaturated SOils Database, compiled by the USDA-ARS Salinity Lab

Table 1-6: 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_s	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

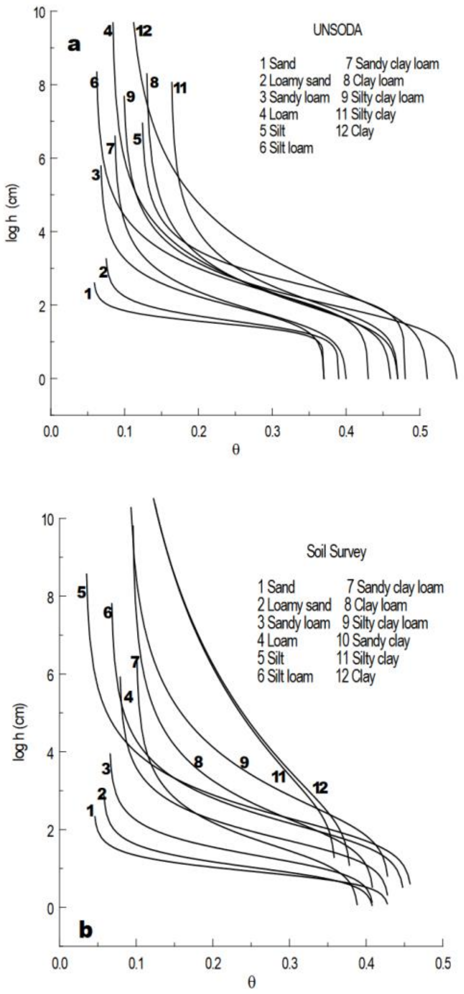
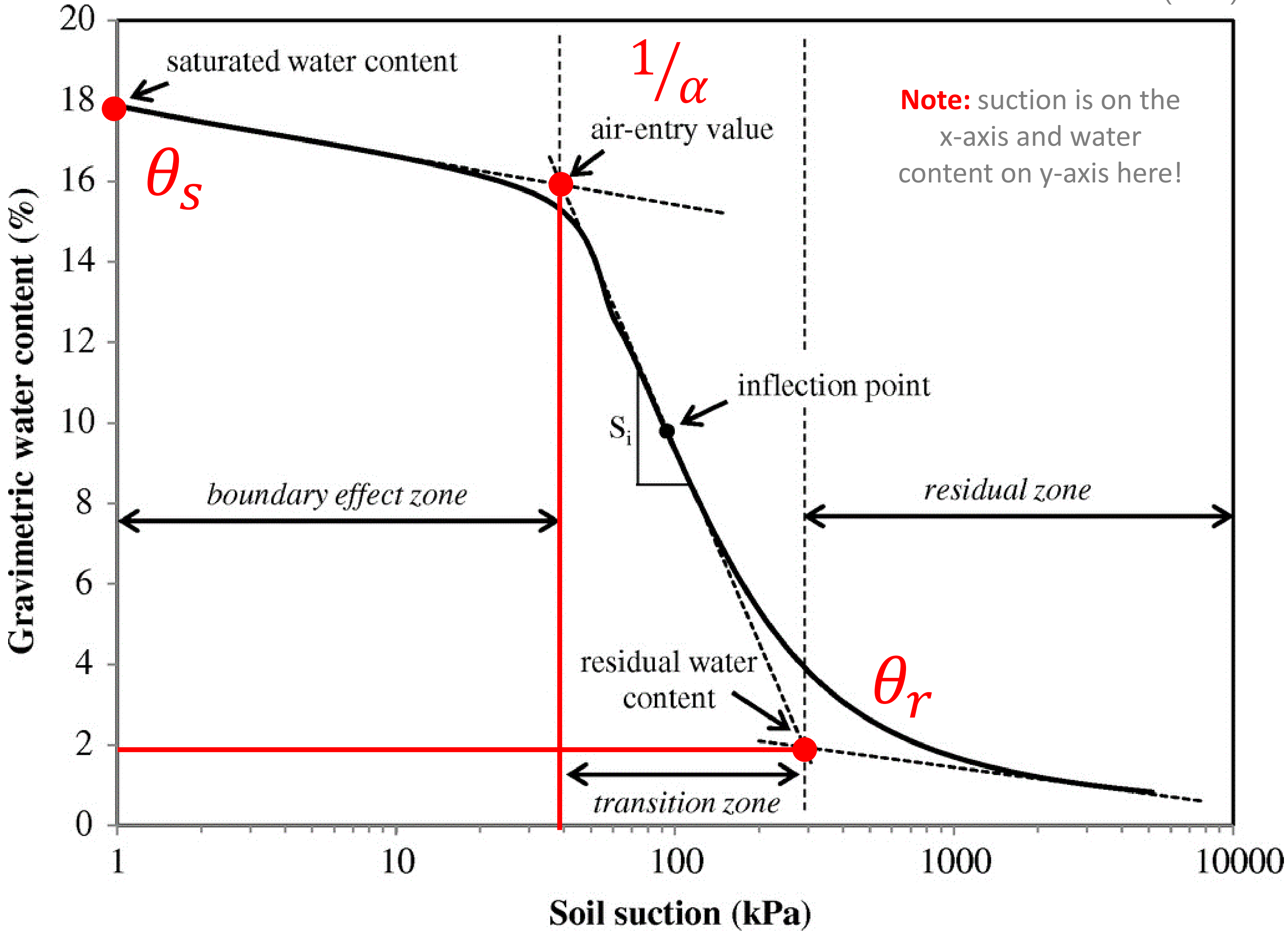


Fig.1-41: Soil water retention curves determined from textural average parameters in the VG equation, using UNSODA database and Soil Survey database (Leij et al., 1999).

Soil Water Content-Energy Relationship

Suazo et al. (2016)



Note: suction is on the x-axis and water content on y-axis here!

Soil Water Content-Energy Relationship

Note: estimation of VG or BC parameters from experimental data requires:

- sufficient data points, at least 5 to 8 ψ_m-ϑ_V pairs;
- a program for performing non-linear regression

Computer Lab: Assignment 2

Source: Or, Tuller, & Wraith, 1994-2018

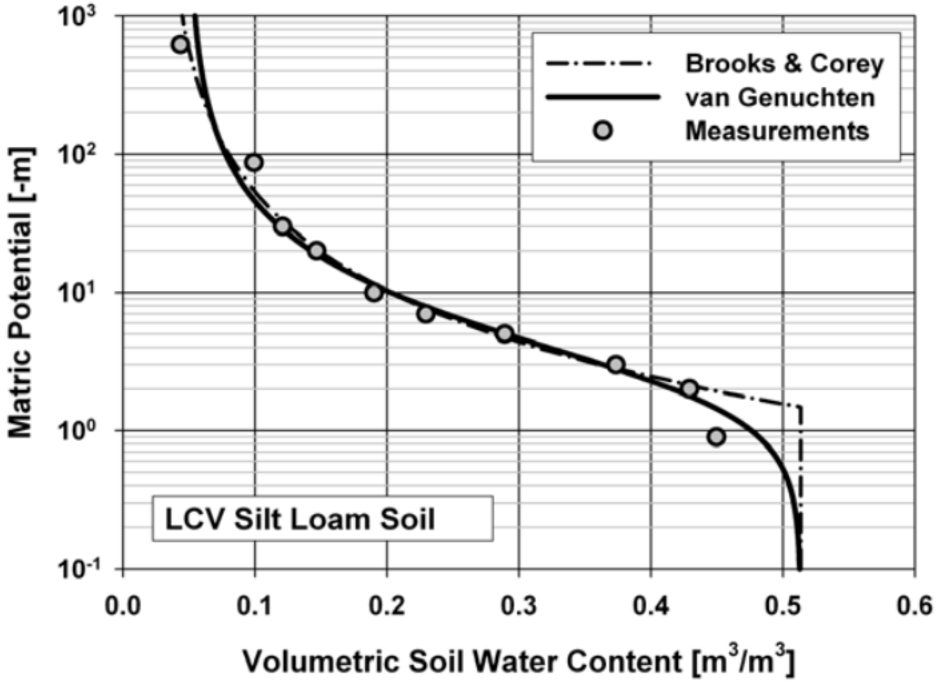


Fig.1-39: VG and BC parametric models fitted to measured silt loam SWC data from Owens Valley, CA.

Soil Water Content-Energy Relationship

Hysteresis in the Soil Water Characteristic Relation

A SCC may be obtained by applying suction to a saturated sample or gradually wetting a dry soil. These two pathways produce <u>different curves.</u> This phenomenon is called **"hysteresis"** and is defined as *"the dependence of the state of a system on its history"*.

This hysteresis could be explained by several phenomena:

- the "ink bottle“ effect (drainage is governed by the smaller pore radius r, whereas wetting is dependent on the large radius R);
- different liquid-solid contact angles for advancing and receding water menisci;
- entrapped air in a newly wetted soil;
- swelling and shrinking of the soil under wetting and drying, respectively.

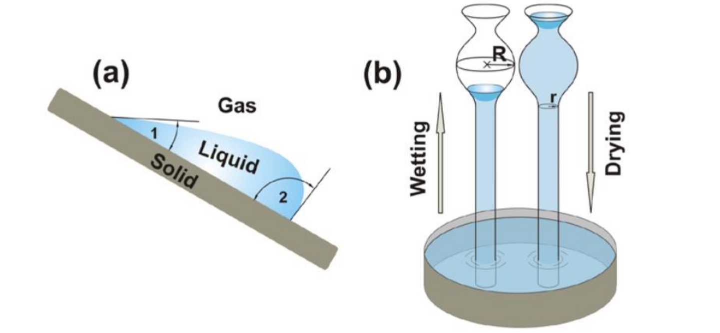


Fig.1-43: Mechanisms of hysteresis: (a) the advancing/receding contact angle effect; and (b) the "ink bottle" effect.

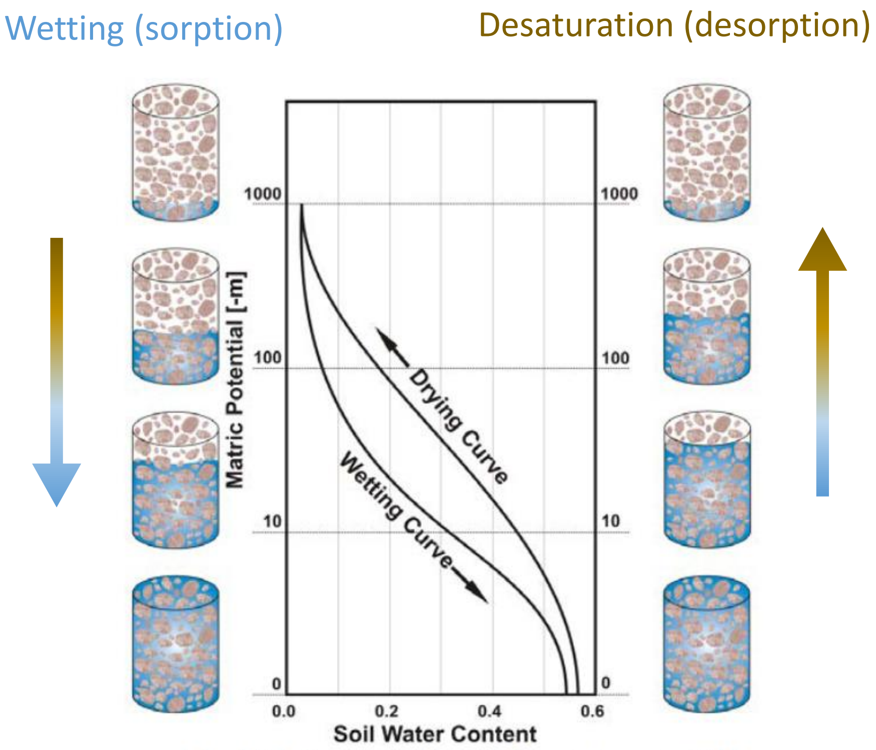


Fig.1-42: Scheme of a hysteresis loop in SWC.

Source: Or, Tuller, & Wraith, 1994-2018

Soil Water Content-Energy Relationship

Measurement of SWC Curves

- **In-situ** methods are considered the most representative techniques for determining SWCs. An effective method for obtaining simultaneous measurements of ψ_m and θ_V utilizes TDR probes installed in the soil at close proximity to transducer tensiometers
- **Laboratory** measurements with Pressure Flow Cell and Pressure Plate.

The porous plate is open to atmospheric pressure at the bottom surface, while the top surface is at the applied pressure of the chamber. Sieved soil samples are placed in retaining rubber rings in contact with the porous plate and left to saturate in water. After saturation is attained, the porous plate with the saturated soil samples is placed in the chamber and a known gas (commonly N_2 or air) pressure is applied to force water out of the soil and through the plate. Flow continues until equilibrium between the force exerted by the air pressure and the force by which soil water is being held by the soil (ψ_m) is reached. Following equilibrium between soil matric potential and the applied air pressure, the soil samples are removed from the pressure plate, weighed, and oven dried for gravimetric determination of water content.

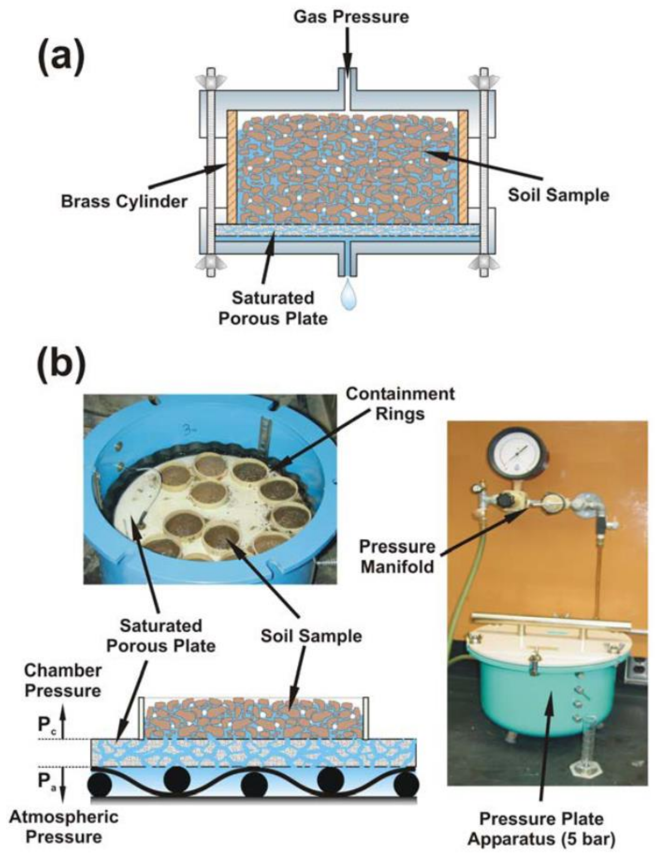


Fig.1-35: (a) Pressure and flow cell (Tempe cell); and (b) pressure plate apparatus used to desaturate soil samples to desired matric potential.

Source: Or, Tuller, & Wraith, 1994-2018

Key theoretical concepts (important!)

- Soil composition (phases) -> gas, solid, liquid -> relationships (density, moisture content, etc.) are based on mass (M) and volume (V) of each phase
- Water in soil: **quantity** (as just given above) and **total potential**
- Water **movement** depends on differences in **total potential**
- Total potential is $H = z + h$ (Hydraulic head = gravitational head + pressure head)
- $z =$ position
- Pressure head:
  - $h > 0$ (saturated zone, below the watertable)
  - $h < 0$ (unsaturated/vadose zone, above the watertable)
  - $h = 0$ at the watertable (where water pressure is 1 atmosphere)
- In the unsaturated zone, soil **suction** is $\psi = -h$, so $\psi > 0$
- Each soil is composed of a distribution of pore sizes. When water is removed from a soil, the largest pores tend to dry first, followed by smaller pores. A plot of moisture content, θ, versus suction, ψ, gives the **soil moisture characteristic curve** – this curve is unique for each soil.

This week exercises & assignments

- **Exercises** for **Weeks 3** are available in Moodle.
- **Computer Lab:** Assignment 2,
  - Water retention curves
  - Curve fitting
- **For next week:** Read up to page 14 of Notes 3.pdf