

CHAPTER 2. SOIL-WATER POTENTIAL: CONCEPTS AND MEASUREMENT

Contents:

- Transport mechanisms
- Water properties
- Definition of soil-water potential
- Measurement of soil-water potential
- Soil-water retention curve
- Components of total soil-water potential

Transport:

1. Solute molecules, dissolved in gas or liquid, move from high to low concentration
Driving force for movement is difference in concentration with distance
Transport is formulated by Fick's law of diffusion
2. Heat moves from high to low temperature
Driving force for heat transport is difference in temperature with distance
Heat transport is formulated by Fourier's law of heat conduction
3. Current (movement of electrons) is caused by electrical potential differences
Electrons move from high to low potential
Current is computed from Ohm's law
4. Water moves from high to low pressure or potential
Driving force is difference in its pressure with distance
In addition water will move by gravitational forces

In soils, water moves by pressure (or water potential) and gravitational forces

Water flow is described by DARCY's law

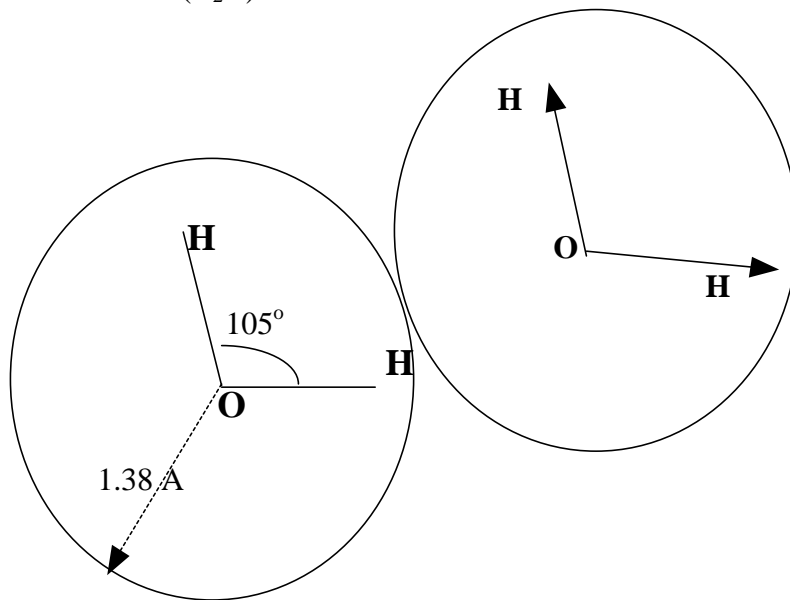
ALL TRANSPORT FOLLOWS SIMILAR MATHEMATICAL LAWS AS DARCY

Water properties:

Water is an unusual fluid and has much different physical properties than other substances with equal molecular weight

- high boiling and melting point
- low fluid density
- high heat of melting and vaporization
- high specific heat
- large dielectric constant
- good solvent

Molecular structure of water (H_2O):



H_2O molecule has no net charge (neutral), but charge distribution is asymmetrical, with the center of negative charge not coinciding with center of positive charge;

Consequently, water molecule is polar;

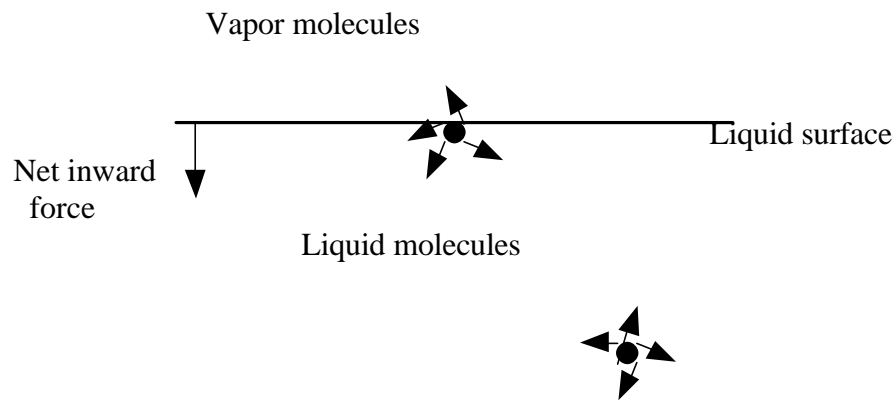
H-atoms of water molecules are hydrogen bonded with O atoms of surrounding molecules, acting as attraction forces between water molecules;

Hydrogen bonding explains the physical properties of water, and its weak crystalline structure;

★ Why does ice float on water ???

Surface tension

Molecules at fluid interface are exposed to different forces than within fluids. For example, at the water-air interface, a net inward force exists because of higher density of water molecules in water than in air. Within the water there is no net attraction in any direction. Therefore, water at interface has membrane-like properties. The extra energy of the water at the interface is called surface tension, σ , and is defined as energy per unit surface area (Nm/m^2) or force per unit length.



Surfactants (organics, detergents) concentrate at liquid-gas interface, because attraction of solute molecules to water is less than cohesive attraction forces (by hydrogen bonding) between water molecules.

Net effect is reduction of surface tension by surfactants

Surface tension of air-water = 72 dynes/cm = 0.072 N/m

★ How does surface tension depend on temperature ?

Viscosity

Resistance of fluid flow is caused by attraction forces between fluid molecules, thereby resisting motion from one laminar fluid layer to another.

Pressure forces causing fluid flow is counteracted by these drag forces.

Viscosity is defined by relation between drag force, τ , (N/m^2) and velocity gradient perpendicular to direction of flow:

$$\tau = \nu \, dv/dy \quad ,$$

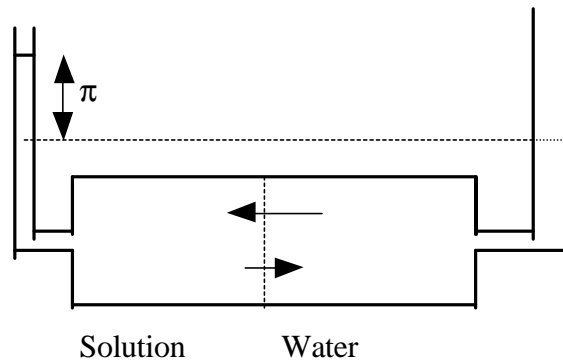
where ν is dynamic viscosity (Ns/m^2)

★ What has higher viscosity: air or water; which fluid will experience the larger drag force, and how is viscosity affected by temperature ?

Osmotic pressure:

Occurs when solutions of different concentrations are separated by a semi-permeable membrane. Random motion of water and solute molecules create a net movement of water to the compartment with higher concentration, until equilibrium is reached.

This net movement by concentration differences is called diffusion



At equilibrium, net water movement is eliminated by increase in water pressure, Π ,

$$\Pi = CRT$$

where Π is defined as osmotic pressure (N/m^2), C is solute concentration (mol/m^3), T is temperature (K), and R is universal gas constant (8.314 J/mol K).

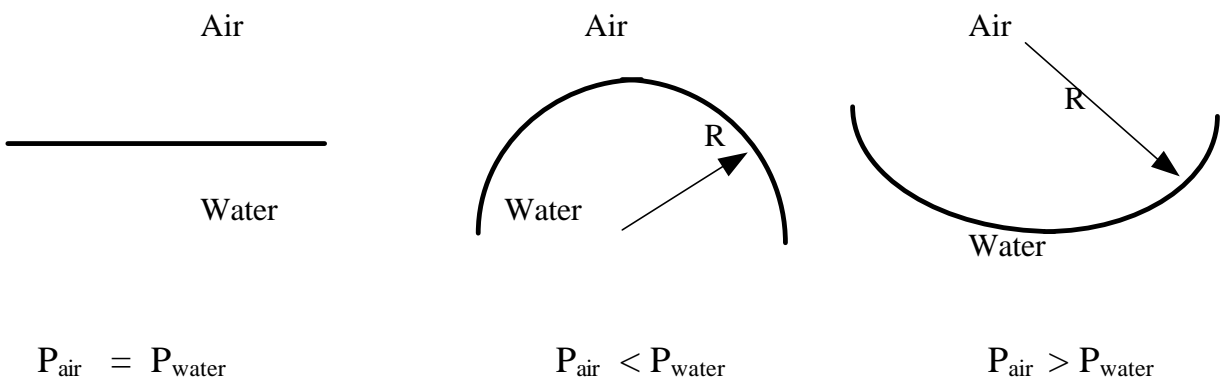
★ Salt water can be purified to drinking water by reverse osmosis. Explain.

Capillary Rise:

For a curved interface, the pressure is greater on the concave side of the air-water interface. For a hemispherical interface (with radius R), this pressure difference, ΔP , can be derived from a force balance, and is equal to

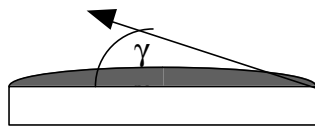
$$\Delta P = 2\sigma/R = P_{\text{air}} - P_{\text{water}}$$

That is, the surface tension force is balanced by a pressure drop across the air-water interface:

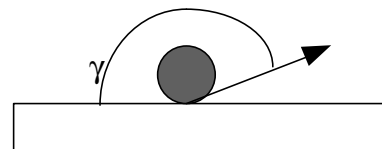


Hence, the fluid pressure is always greater on the concave side of the interface, with the difference determined by the radius of the curvature and the surface tension.

Contact angle (γ) is the angle measured from the liquid-solid interface to the liquid-air interface. For a small angle ($<90^\circ$), liquid is preferentially attracted to the solid surface (by adhesion forces), and wets the solid. If cohesion forces of liquid are stronger than the attractive force to the solid, the liquid repels from the solid surface and γ is large (mercury on glass).



Small contact angle, $< 90^\circ$
Liquid wets the solid
Hydrophilic surface



Large contact angle, $> 90^\circ$
Liquid repelled by solid
Hydrophobic surface

The contact angle adjusts to attain equilibrium between various surface tension forces. If a capillary tube is inserted in water, the water will form a concave meniscus because of net surface tension forces pulling it along the capillary wall. If diameter is small enough, the air-water interface will be curved, causing a pressure difference across the air-water

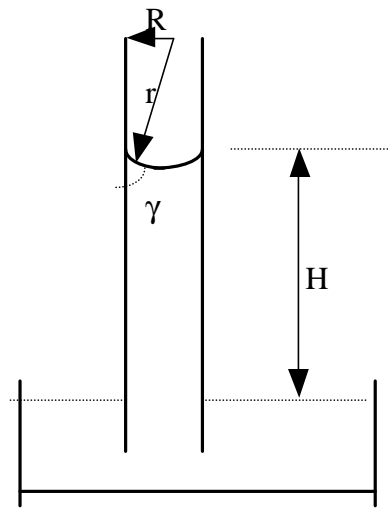
interface.

Consequently, the water in the capillary will rise. At equilibrium, the upward surface tension force is equal to the downward force by the weight of the water in the capillary.

The resulting capillary rise equation for a tube with capillary radius R is:

$$\rho_w g H = 2\sigma/r = 2\sigma \cos\gamma/R,$$

where H is the height of capillary rise and ρ_w is the water density. This is also called the La Place equation (r is radius of curvature) .



★ Where would the level of the interface be if the capillary was filled with mercury, which is repelled by the glass capillary?

Energy state of soil water:

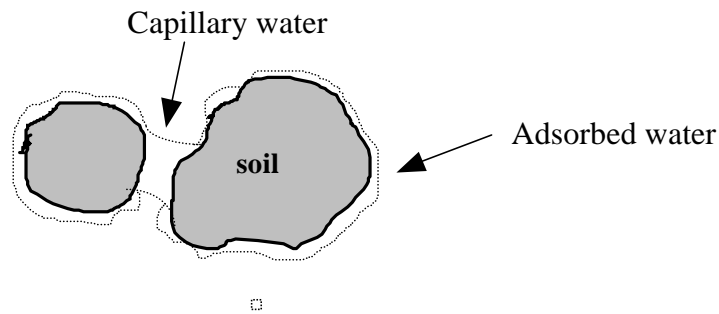
The total energy state of soil water is defined by its equivalent potential energy, as determined by the various forces acting on the water per unit quantity.

In general, flow rates of water in soils is too small to consider kinetic energy. Therefore, the energy state of soil water is defined by its equivalent potential energy, that is by virtue of its position in a force field.

Forces acting on soil water (in the vadose zone) are:

- Capillary forces
- Adsorptive forces (adhesion of water to solid soil surfaces)

Capillary and adsorptive forces together result in soil matric potential



- Gravitational forces
- Drag or shear forces (at soil surface-water interface)

Water in the soil flows from points with high soil-water potential energy to points of lower potential energy:

Driving force for flow is the change in potential energy with distance (soil-water potential gradient)

These driving forces determine:

- Direction and magnitude of water flow
- Plant water extraction rate
- Drainage volumes
- Upward water movement (or capillary rise)
- Soil temperature changes
- Solute (contaminant) transport rates

Definitions of soil-water potential:

To quantify potential energy state of soil water, a reference state is needed.

It is defined as the potential energy of pure water, with no external forces acting on it, at a reference pressure (atmospheric), reference temperature, and reference elevation. Soil-water potential is then determined as potential energy per unit quantity of water, relative to the reference potential of zero.

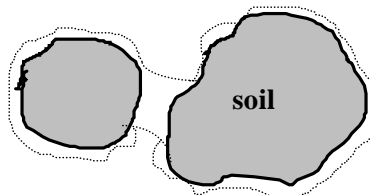
Soil water potential is measured as potential energy per unit quantity of water, relative to this reference soil water potential.

★ The soil below the groundwater table is saturated with water. Is the soil water potential below the groundwater larger or smaller than this reference potential ?

Formal definition:

Total soil water potential is defined as the amount of work per unit quantity of pure water that must be done by external forces to transfer reversibly and isothermally an infinitesimal amount of water from the standard state to the soil at the point under consideration.

Since water in soil has various forces acting upon it, potential energy usually differs from point to point, and hence its potential energy is variable as well.



★ Do we need to exert work to move water from the reference state (at atmospheric pressure) to the capillary water with the curved interface of the soil above, and hence is the soil water potential there positive or negative ?

REMEMBER: Potential = Force x Distance = $mgl = r_w Vgl$ (Nm)

Soil water potential can be expressed in three different units:

Potential per unit mass (μ) : $\mu = \text{potential/mass} = gl$ (Nm/kg)

Potential per unit volume (ψ) : $\psi = \text{potential/volume} = \rho_w Vgl / V = \rho_w gl$ (N/m²,
water pressure units)

Potential per unit weight (h) : $h = \text{potential/weight} = mgl / mg = l$ (m, head unit)
= equivalent height of water

Consequently, we do not need to compute the soil-water potential directly by computing the amount of work needed, but measure the soil-water potential indirectly from pressure or water height measurements !!!!

Total soil water potential, Ψ_T

$$\Psi_T = \Psi_p + \Psi_z + \Psi_s + \Psi_a \quad (\text{N/m}^2)$$

where Ψ_p , Ψ_z , Ψ_s , and Ψ_a are pressure, gravitational, solute (osmotic) and air pressure potentials, respectively.

Most of our discussion will only include Ψ_p and Ψ_z

$$\text{so } \Psi_T = \Psi_p + \Psi_z$$

or when potential expressed per unit weight: $H = h + z$

Ψ_p - pressure potential

Energy per unit volume of water required to transfer an infinitesimal quantity of water from a reference pool of water at the elevation of the soil to the point of interest in the soil at reference air pressure and temperature.

Pressure potential can be both negative and positive.

If soil is saturated, Ψ_p is positive, and also denoted by hydrostatic pressure potential.

If the soil is unsaturated, Ψ_p is negative, and also denoted by matric potential (Ψ_m in book).

[However, if only water column: $Y = \Psi_p$ (can be both < 0 and > 0), as opposed to water in soil matrix.]

When expressed in energy per unit weight (m) than we use h_p or simply h .

★ How is pressure potential of water (Ψ_p) in soil related to μ_p ?

$$P = \frac{F}{A} \text{ makes } F = PA$$

$$m_p = \frac{Fl}{m} = \frac{PA l}{m} = \frac{PV}{m} = \frac{P}{r_w} = \frac{y_p}{r_w}$$

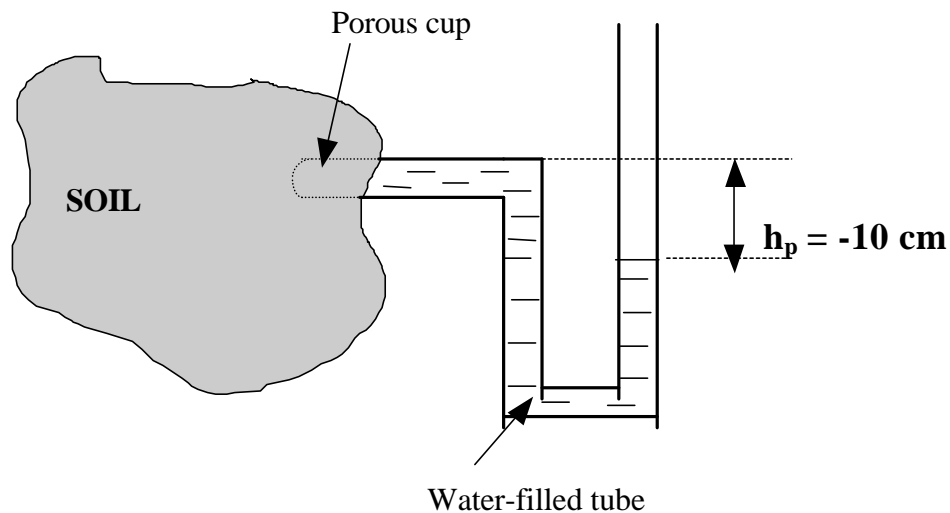
$$\text{thus } y_p = m_p r_w$$

Also, soil water pressure head is

$$h_p = h = \Psi_p / \rho_w g$$

Unless otherwise specified, we will express potential on a weight basis.

How to measure pressure potential in soil ?



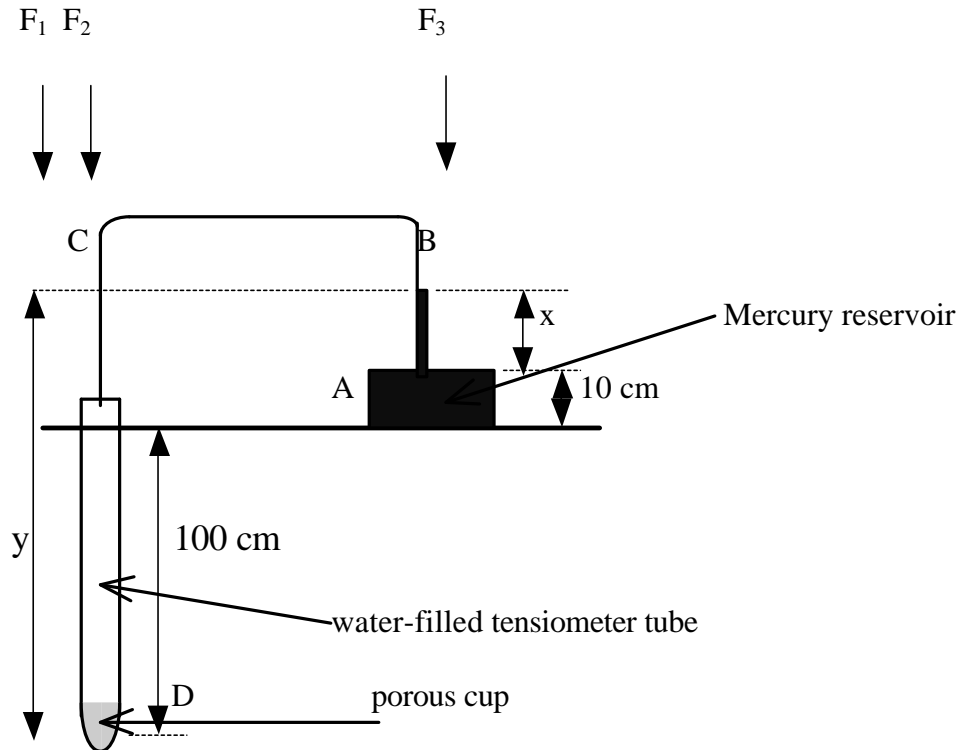
$$\Psi_p = \rho_w g h_p = \rho_w g h$$

$$\text{Then if } h = h_p = -10 \text{ cm} : \Psi_p = \rho_w g h = 1,000 \text{ (kg/m}^3\text{)} \times 9.8$$

$$\text{(m/s}^2\text{)} \times -0.10 \text{ (m)} = -980 \text{ N/m}^2 = -980 \text{ Pa} = -0.98 \text{ kPa} \quad (1\text{Pa} = 1 \text{ N/m}^2)$$

$$\text{And } \mu_p = \Psi_p / \rho_w = -980 / 1,000 = -0.98 \text{ Nm/kg}$$

How to measure h_p in a field soil? (tensiometer)



At equilibrium, all forces must balance.

The 3 forces in a tensiometer with a Hg manometer are as follows;

That is, $F_1 + F_2 = F_3$

- F_1 - force due to soil trying to pull H_2O from tensiometer
- F_2 - weight of H_2O in the tensiometer and tubing up to the level of the Hg meniscus
- F_3 - weight of mercury in tubing of height X

*Note the H_2O in the tubing above the dashed line BC (see figure) is not considered because the downward forces due to H_2O in both halves of the "U-tube" are equal.

$$F_1 + F_2 = F_3$$

The sign (+ or -) of F_1 is unknown at this stage. However, since F_2 and F_3 are acting downward, both forces are exerting a negative pull on the water located at the broken line. Thus, they are assigned negative values.

Thus: $M_1g - M_2g = -M_3g$

$$\rho_w V_1 g - \rho_w V_2 g = -\rho_{Hg} V_3 g$$

If we express this on a per unit area basis

(NOTE: $\psi_p = \rho_w g h$)

$$\rho_w g h - \rho_w g y = -13.5 \rho_w g X$$

Divide by $\rho_w g$ and rearrange to solve for h

$$\underline{\mathbf{h = y - 13.5 X}}$$

Example from tensiometer figure on previous page:

Tensiometer cup is 100 cm below soil surface

$$h = 100 + 10 + X - 13.5 X$$

If X = 20 cm,

$$h = 100 + 10 + 20 - 13.5 (20) = -140 \text{ cm}$$

a negative soil-water pressure potential (matric potential head)

If X = 5 cm,

$$h = 100 + 10 + 5 - 13.5 (5) = +47.5 \text{ cm}$$

I.e., a positive pressure potential (hydrostatic pressure head)

Thus, tensiometers can measure both + and – soil-water pressure potentials, i.e., hydrostatic pressure and matric potentials.

Alternatively, instead of force balance, one can state that at hydraulic equilibrium the total water potential at B is equal to total water potential at point D.

Then: At B: $z = 10 + X$ (soil surface is reference level)

$$h = -\rho_{\text{Hg}}/\rho_{\text{H}_2\text{O}} X = -13.5 X$$

At D: $z = -100$

$$h = h_D$$

Total water potential at B = total water potential at D, or

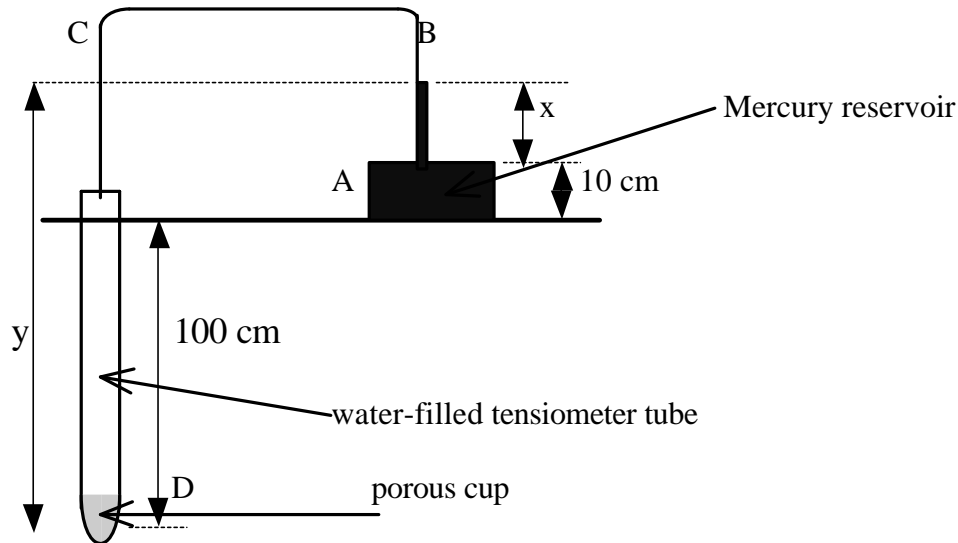
$$10 + X - 13.5X = -100 + h_D \quad \text{or} \quad h_D = 110 + X - 13.5X = Y - 12.5X$$

★ Would the rise of fluid in the reservoir (X) increase or decrease if its density would be less than mercury, for the same soil water potential at point D ?

Hence, why would one use mercury instead of a lighter fluid ?

★ What is the soil-water pressure at location D, if $x = 0$?

Let us use yet another method:



- Assume that at the time of measurement, the fluids in the tensiometer are at hydraulic equilibrium, i.e., fluid is static;
- For a static fluid (not in motion), change in pressure occurs only with a change in elevation. That is, along the horizontal plane, the pressure will be constant;
- Also, the fluid pressure changes inversely with elevation. If one travels upward in the fluid (positive z), the pressure decreases; and if one goes downward (negative z), the pressure increases; Therefore, in diagram: pressure at C = pressure at B or $\psi_C = \psi_B$

- $\psi_B = -\rho_{Hg} gX$ (hanging column of mercury)

$\psi_C = -\rho_w gY + \rho_w gh_{p,D}$ ($= -\rho_w gY + \psi_D$), where $Y = 100 + 10 + X$ and ψ_D is the pressure potential of soil water at point D, expressed by potential per unit volume (pressure units);

- Since $\rho_{Hg} = 13.5\rho_w$

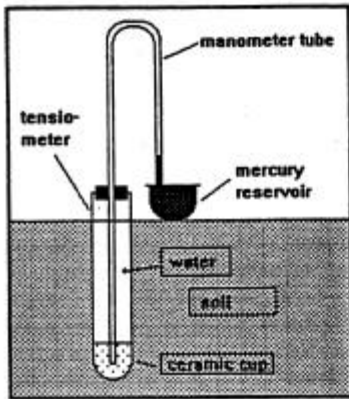
$$-13.5\rho_w gX = -\rho_w gY + \rho_w gh_{p,D} \quad \text{or} \quad \underline{h_D = Y - 13.5X}$$

Methods for measuring h_p (soil water pressure potential):

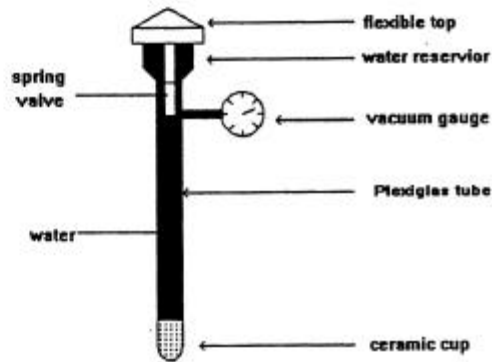
Tensiometer 0 to -80 kPa (= -0.8 bars = approximately -800 cm)

- measures water pressure relative to atmospheric pressure
- water boils if h_p in tensiometer < vapor pressure of water
- measurement range limited by air entry value of porous cup

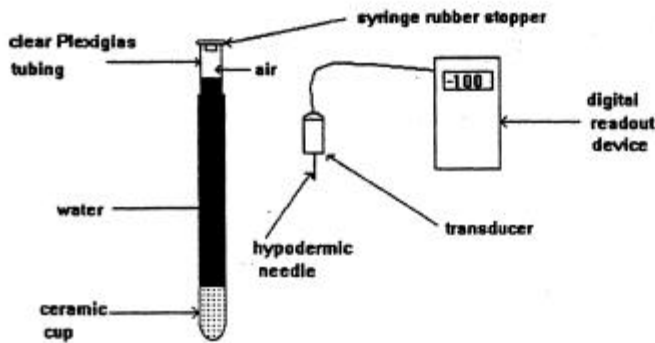
mercury types gauge types transducer types



Schematic illustration of a mercury-water manometer type tensiometer system.



Jet fill type tensiometer system.



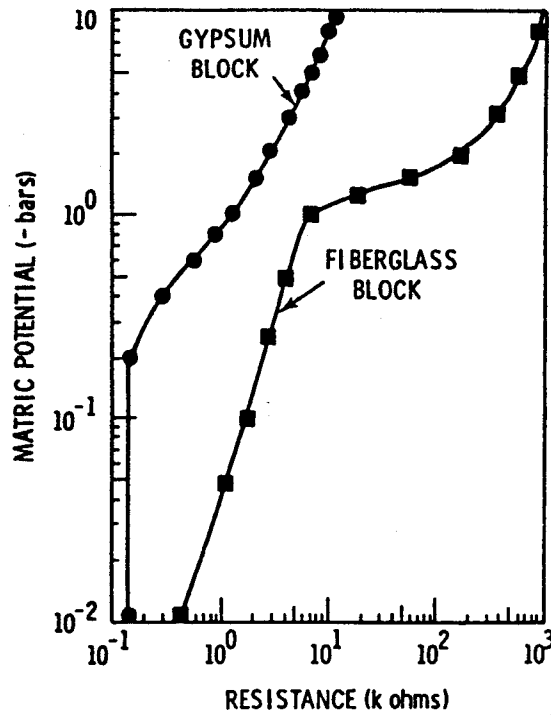
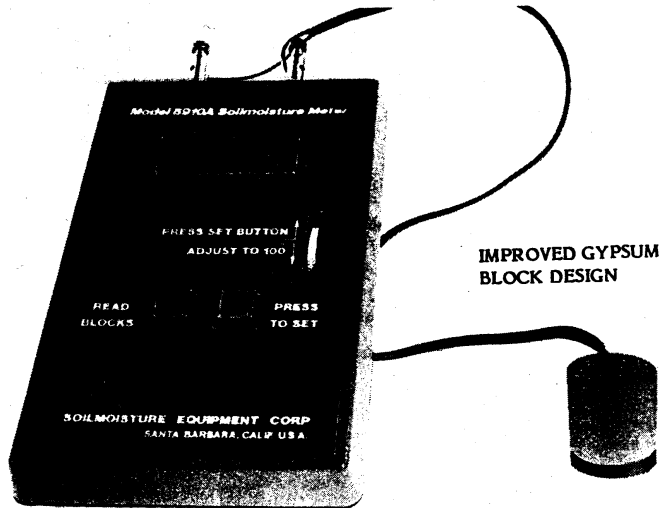
Transducer type tensiometer system.

Electrical Resistance Blocks

0 to -980 or -1,500 kPa

(0 to -10 or -15 bars)

Resistance(R) depends upon amount of H₂O in block. Must be calibrated. Requires good soil contact, and R depends on ionic concentration in block. Accurate only in dry range.



Typical calibration curves for gypsum and fiberglass block soil moisture sensors.

Thermocouple Psychrometer

-98 to -3,000 kPa

(-1 to -30 bars)

-Measures contribution of matric + osmotic potential to soil-water vapor pressure

-Measures vapor pressure of the thermocouple chamber and assumes equilibrium with the soil in the chamber

-Uses wet and dry junctions to establish vapor pressure deficit

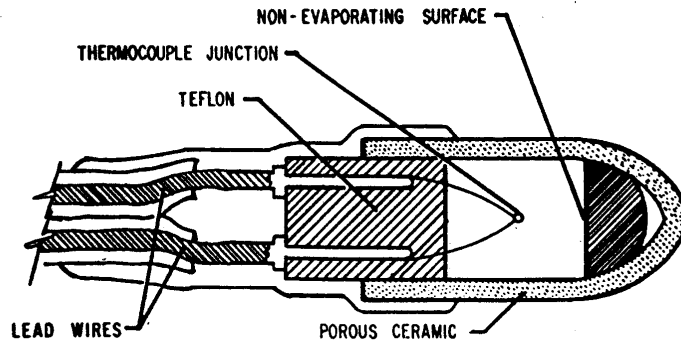


Fig. 24-7. Soil psychrometer modified to reduce error due to thermal gradients by using an additional nonevaporating surface in the chamber (Campbell, 1972).

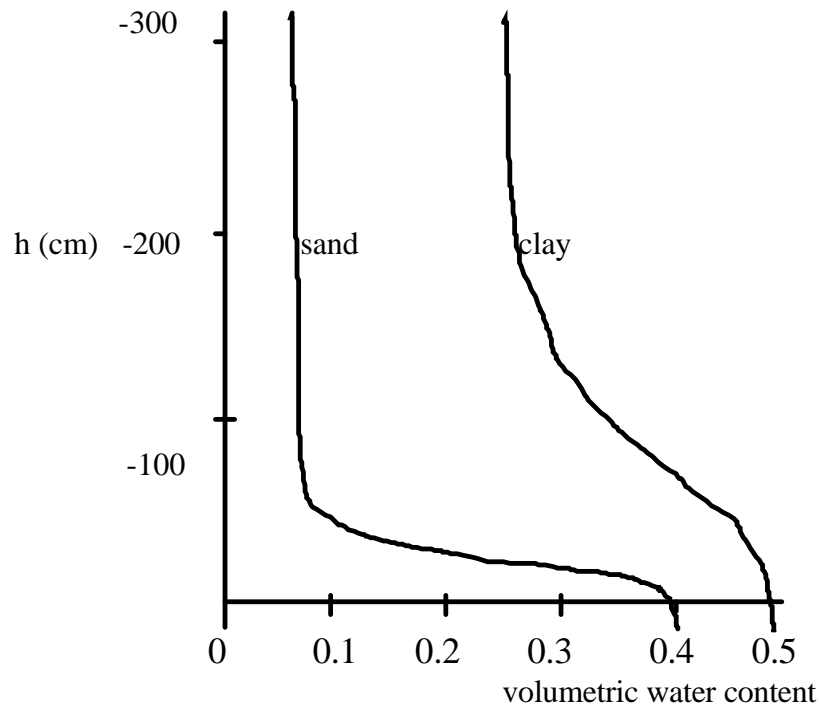
Heat Dissipation Sensor -9.8 to -100,000 kPa
 (-0.1 to -1,000 bars)

-Measures rate at which heat is conducted away from a heat source, using temperature response close to heat source (using thermocouple or thermister).

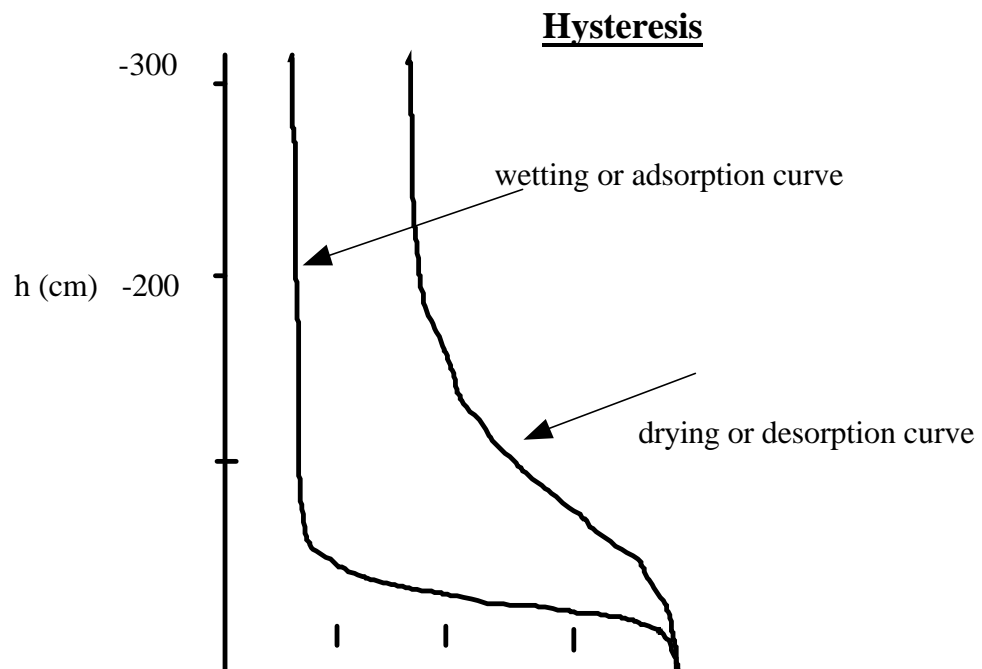
-The more water in porous matrix, the faster the heat is conducted away.

Soil-water characteristic curve (soil-water retention curve):

- Describes relationship between soil-water pressure potential and volumetric water content;
- Is determined by simultaneous measurement of water content and pressure potential;
- As soil drains, the largest soil pores empty first since the capillary forces are smallest in these pores. As the soil drains further, the maximum diameter of the water-filled pores further decreases, corresponding with pores that have decreasing values for the pressure potential (water is held by larger capillary forces);
- Soil-water retention is unique, and is a function of pore size distribution;
- At a pressure potential of zero, the soil's volumetric water content is defined as the saturated water content;
- The maximum pressure potential at which soil begins to desaturate (starting at saturation) is defined as the air entry value of the soil, and is determined by the largest pores in the soil;



- Soil available water is defined as the water content difference between field capacity ($h = -330$ cm) and permanent wilting point ($h = -15,000$ cm); Will be discussed later !!!
- ★ Would you expect the soil-water retention curve to be different if it was determined by desorption or adsorption ?

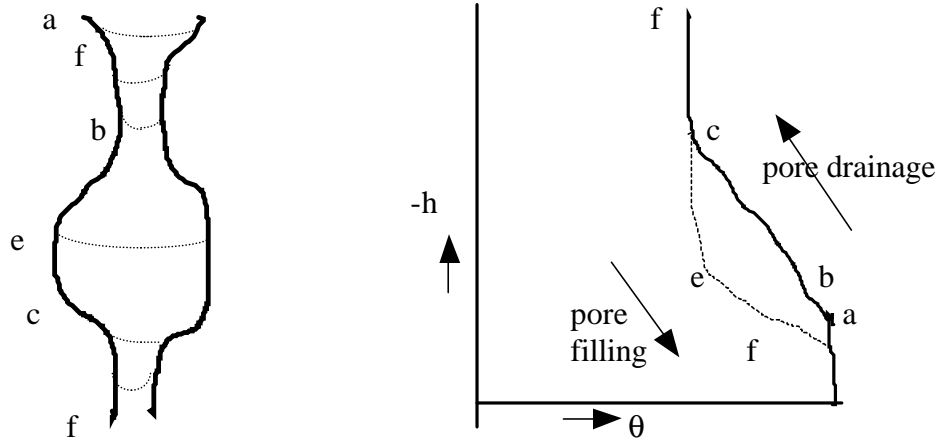




—————> volumetric water content

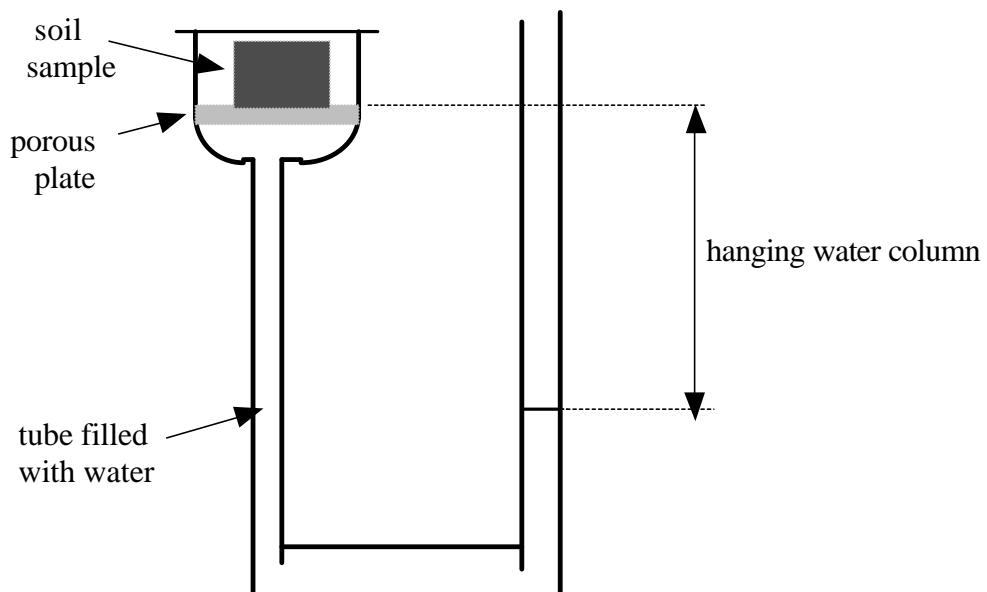
The cause of hysteresis is attributed to:

- Contact angle is larger for wetting than drying of the soil;
- Entrapment of air during soil wetting;
- “Ink bottle” effect. Pore necks (throats prevent complete drainage of soil pores)



How to measure the soil-water retention curve:

1. **Buchner funnels** can be used up to about -300 cm



★ If the length of the hanging water column is X and the system is in hydraulic equilibrium, what is the pressure potential in the soil sample ?

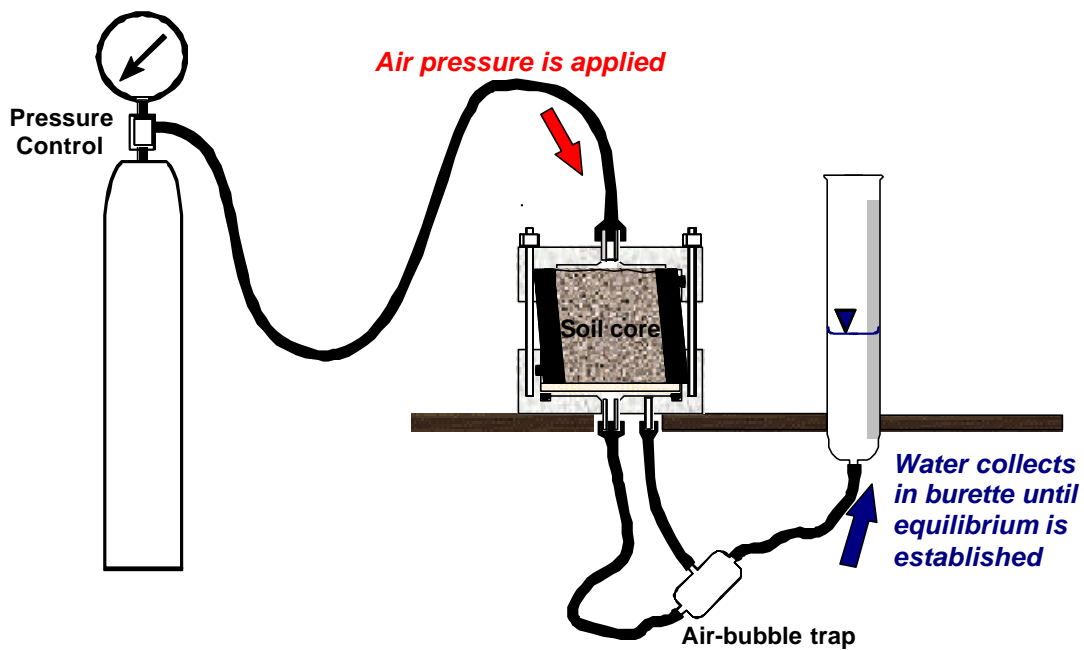
2. Pressure cell (Tempe Cell)

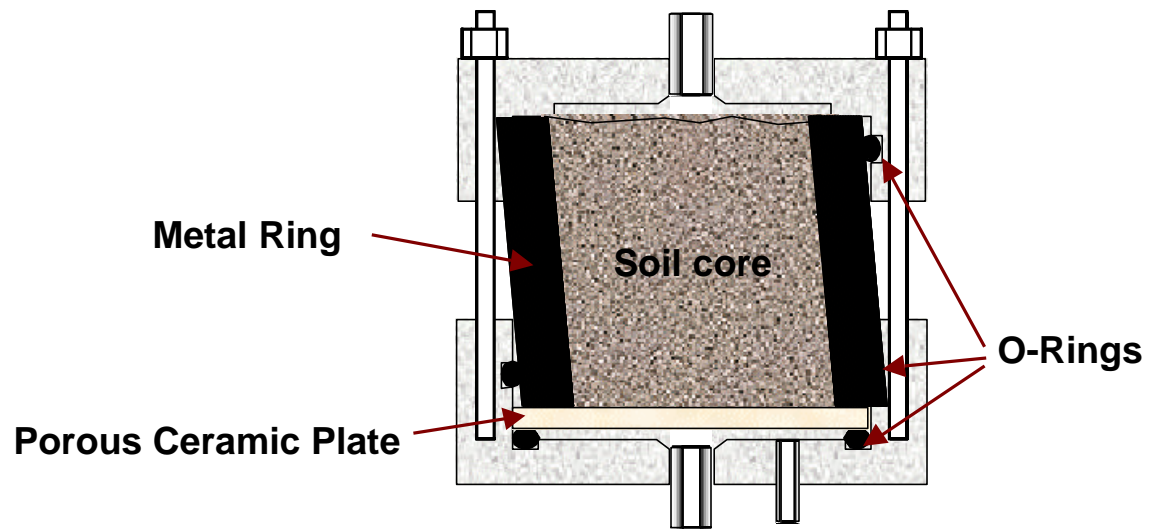
- good to -98 kPa (-1 bar)
- takes a long time to reach equilibrium in an undisturbed, full- size core
- is used by applying positive air pressure to soil core

3. Pressure plate

- good to - 1,500 kPa (-15 bar)
- not convenient for large, undisturbed cores
- soil can be disturbed because the water present in the drier range occurs in soil micropores instead of the normal pore structure
- conductivity of plate too small for wet range determination

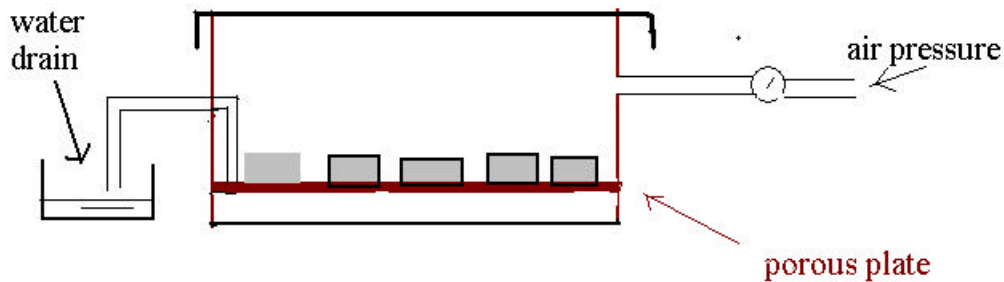
Components of the Tempe cell method





Vertical cross section of the cell

Pressure plate apparatus



★ If 1 bar gauge pressure is applied to the pressure plate apparatus, and water drainage has stopped, then what is the pressure potential of the soil water in the cores ?

Components of Total Soil-Water Potential:

Y_p – soil-water pressure potential

Remember:

Energy per unit volume of water required to transfer an infinitesimal quantity of water from a reference pool of water at the elevation of the soil to the point of interest in the soil at reference air pressure and temperature.

When expressed in energy per unit weight (m), then we simply use h (pressure head)

If the soil is unsaturated: \longrightarrow soil water matric potential ($h < 0$)

If the soil is saturated: \longrightarrow hydrostatic pressure potential ($h = p > 0$)

Use tensiometer to measure soil water pressure potential:

Total soil water potential at A
= Total water potential at B

The pressure in B is measured with a pressure transducer

As we shall see later:

From the length of the tensiometer, the pressure Potential in soil at point A can be determined (either matric or hydrostatic pressure potential).



If soil at A is saturated, then:

Pressure potential or hydrostatic water pressure is equal to the water pressure exerted by overlying unsupported saturated water at the point of interest. This is strictly positive, and is equal to the pressure equivalent of the height of water above the point of interest (h = hydrostatic pressure head, when expressed in potential per unit weight, $\text{Nm/m} = \text{m}$, sometimes also denoted by p).

If soil at A is unsaturated, then:

h = matric pressure head given by: $h = \frac{y_p}{r_w g}$ (units: m)

In short notation, we sometimes refer to h = pressure head, independent of its sign (saturated or unsaturated)

★ If the tensiometer cup at point A is located at the water table (pressure is atmospheric pressure), what is the pressure potential at point A ?

Y_z - **gravitational potential (can be + or -)**

Energy per unit volume of water required to move an infinitesimal amount of pure, free water from the reference elevation (z_0) to the soil water elevation (z_{soil}).

$$\text{Potential} = \text{Work} = \text{Force} \times \text{distance} = F(z_{\text{soil}} - z_0) = m g (z_{\text{soil}} - z_0)$$

If potential is expressed per unit volume, then gravitational potential = $(z_{\text{soil}} - z_0)$, or

$$\Psi_z = m g (z_{\text{soil}} - z_0)/V = \rho_w g (z_{\text{soil}} - z_0)$$

where z_{soil} is the height above or below an arbitrary reference level

$z_{\text{soil}} = +$, if above ref. level

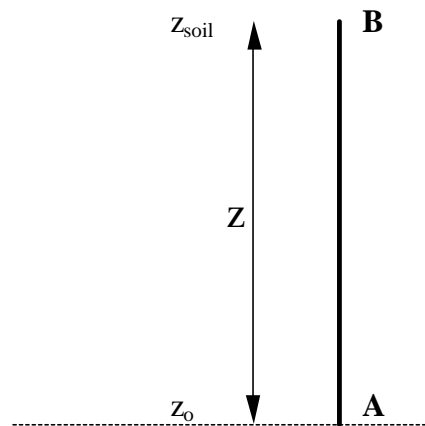
$= -$, if below ref. level

If potential is expressed per unit weight, then gravitational potential

$$z = \Psi_z / \rho_w g = (z_{\text{soil}} - z_0)$$

If one sets z_0 to 0, then gravitational potential :

$$z = (z_{\text{soil}} - z_0) = z_{\text{soil}} = z$$



Thus, z is positive, if point in consideration is above reference level (z_0), and z is negative, if point in consideration is below reference level.

One can choose z_0 anywhere, as long as one is consistent in its choice.

★ Now with this information, compute the soil water pressure potential at point A in the previous diagram with the tensiometer of length L.

Y_s - solute potential

- always negative since defined relative to pure H₂O
- due to amount of salt in soil solution
- only important if have semi-permeable membrane (plant roots) or at air-water interface (controls humidity of air phase)

s = osmotic pressure head given by: $s = \frac{y_s}{r_w g}$ (units: m)

Y_a - air pressure potential

Accounts for changes in air pressure, different than the reference pressure (atmospheric pressure). Important in pressure cells (Tempe cell) and pressure plate apparatus.

Positive, if air pressure is larger than reference pressure.

Negative, if air pressure is smaller than reference pressure

a = air pressure head given by: $a = \frac{y_a}{r_w g}$ (units: m)

Total water potential , Ψ_T

$$\Psi_T = \Psi_p + \Psi_z + \Psi_s + \Psi_a + \dots$$

(Or in head units: $H = h + z + s + a + \dots$)

Much of our discussion will only include Ψ_p (<0 or >0) and Ψ_z

so $\Psi_T = \Psi_p + \Psi_z$ or Total Head $H = h + z$

(Book Jury: sometimes uses $h = p$, if $h > 0$)

Other terminology found in the literature:

Suction = absolute value of h , if $h < 0$)

Hydraulic potential = $\Psi_p + \Psi_z$

Submergence potential = Ψ_p (+ only)

Pneumatic potential - due to air only