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Part 1: Soil Water Potential
Part 2: Tensiometer
Part 3: Soil Water Content
Part 4: Soil Water Retention Properties

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PART I : SOIL WATER POTENTIAL

PART II : TENSIOMETER

PART III : SOIL WATER CONTENT

PART IV : SOIL WATER RETENTION PROPERTIES

I . SOIL WATER POTENTIAL

1. Introduction.

Soil water content is not sufficient to specify the entire status of water in soil. For example, if soils with a same water content but with different particle size distribution are placed in contact with each other, water will flow from a coarse textured soil to a fine textured soil.

One needs to define a property that will help to explain this observation.

Perhaps the following analogy will help. Heat content (analogous to soil water content) is a property of a material that is useful for many purposes. It will not, however, tell us directly whether heat will flow. Therefore a heat intensity term, temperature, has been defined which permits to determine the direction of heat flow. The soil water term that is analogous to temperature (i.e. the intensity with which the water is in the soil) is called the soil water potential. Water potential is a much more complicated property than temperature.

2. Energy state of soil water.

Soil water, like other bodies in nature, can contain energy in different quantities and forms. Classical physics recognizes two principal forms of energy, kinetic and potential. Since the movement of water in the soil is quite slow, its kinetic energy, which is proportional to the velocity squared, is generally considered to be negligible. On the other hand, the potential energy, which is due to position or internal condition, is of primary importance in determining the state and movement of water in the soil.

The potential energy of soil water varies over a very wide range. Differences in potential energy of water between one point and another give rise to the tendency of water to flow within the soil. The spontaneous and universal tendency of all matter in nature is to move from where the potential energy is higher to where it is lower and to equilibrate with its surroundings. In the soil, water moves constantly in the direction of decreasing potential energy until equilibrium, definable as a condition of uniform potential energy throughout, is reached.

The rate of decrease of potential energy with distance is in fact the moving force causing flow. A knowledge of the relative potential energy state of soil water at each point within the soil can allow us to evaluate the forces acting on soil water in all directions, and to determine how far the water in a soil system is from equilibrium. This is analogous to the well-known fact that an object will tend to fall spontaneously from a higher to a lower elevation, but that lifting it requires work. Since potential energy is a measure to the amount of work a body can perform by virtue of the energy stored in it, knowing the potential energy state of water in the soil and in the plant growing in that soil can help us to estimate how much work the plant must expend to extract a unit amount of water.

Clearly, it is not the absolute amount of potential energy "contained" in the water which is important in itself, but rather the relative level of that energy in different regions within the soil. The concept of soil-water potential is a criterion, for this energy. It expresses the specific potential energy (= per unit mass) of soil water relative to that of water in a standard reference state. The standard state generally used is that of a hypothetical reservoir of pure free water (i.e. water not influenced by the solid phase), at atmospheric pressure, at the same temperature as that of soil water (or at any other specified temperature) and at a given and constant elevation.

It is the convention to assign to free and pure liquid water a potential value of zero.

Since the elevation of this hypothetical reservoir can be set at will, it follows that the potential which is determined by comparison with this standard is not absolute, but by employing even so arbitrary a criterion we can determine the relative magnitude of the specific potential energy of water at different locations or times within the soil.

The concept of soil water potential is of great fundamental importance. This concept replaces the arbitrary categorizations which prevailed in the early stages of the development of soil physics and which purported to recognize and classify different forms of soil water: e.g. gravitational water, capillary water, hygroscopic water.

New definition by the soil physics terminology committee of the International Soil Science Society provided more clarity in what used to be a rather complicated theoretical set of criteria. The total potential of soil water was defined as follows: "the amount of work that must be done per unit quantity (mass, volume or weight) of pure free water in order to tranport reversibly and isothermally an infinitesimal quantity of water from a pool of pure water at a specified elevation at atmospheric pressure (standard reference state) to the soil water at the point under consideration in the soil-plant-atmosphere-system (figure 1).

If work is required the potential is positive, but if water in the reference state can accomplish work in moving into the soil the potential is negative.

Soil water is subjected to a number of force field which cause its potential to differ from that of pure free water. Such forces result from the attraction of the solid matrix for water, as well as from the presence of dissolved salts and the action of the local pressure in the soil gas phase and the action of the gravitational field. Accordingly the total potential (ψ_t) of soil water relative to a chosen standard rate can be thought of as the sum of the separate contributions of the various components as follows:

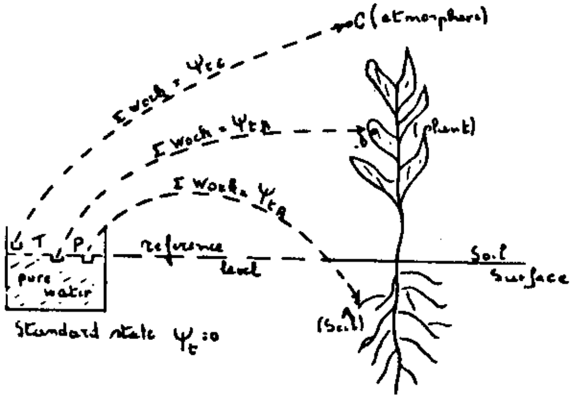


Figure 1. Potential of soil water, water in plant cell and water in the atmosphere.

$$\psi_t = \psi_g + \psi_o + \psi_m + \psi_{e.p} + \dots$$

where: ψ_t = total soil water potential
ψ_g = gravitational potential
ψ_o = osmotic potential
ψ_m = matric potential
$\psi_{e.p}$ = external gas pressure potential

The dots signify that additional terms are theoretically possible.

The main advantage of the total potential concept is that it provides a unified measure by which the state of water can be evaluated at any time and every where within the soil-plant-atmosphere system.

3. Quantitative expression of soil water potential.

The dimensions of the soil water potential are those of energy per unit quantity of water and the units depend on the way the quantity is specified. Common alternatives used are:

a. Energy per unit mass of water.

Joule kg^{-1}

This method of expression is not widely used.

b. Energy per unit volume of water (pressure).

This is the most common method of expressing potential and can be written with units of either Pascal or bar or atmosphere

Joule m^{-3} or $N\ m^{-2}$ (Pa)

c. Energy per unit weight of water (head).

This method of expressing potential is also common and has units of length.

Joule N^{-1} = $Nm\ N^{-1}$ = m

For conversion from one unit to another knows that:

- 1 bar corresponds to 100 J kg^{-1}
- 1 bar = 10^5 Pa
- 1 bar corresponds to 10 m water head

4. Gravitational potential.

Every body on the earth's surface is attracted towards the center of the earth by a gravitational force equal to the weight of the body, that weight being the product of the body's mass by the gravitational acceleration. To rise a body against this attraction, work must be expended and this work is stored by the rised body in the form of gravitational potential energy. The amount of this energy depends on the body's position in the gravitational force field.

Conversion table for units of soil water potential (*)

Specific potential units	Volumetric potential units				Weight potential units
Joule/kg	bar	millibar	Pa	atmosphere	m
-0.0001	-0.000001	-0.001	-0.1	-0.000000987	-0.001017×10^{-2}
-1	-0.01	-10	-10^{3}	-0.00987	-10.17×10^{-2}
-100	-1	-1000	-10^{5}	-0.987	-10.17
-0.1	-0.001	-1	-10^{2}	-0.000987	-1.017×10^{-2}
-101.3	-1.013	-1013	-1.013×10^{5}	-1	-10.30
-0.09833	-0.0009833	-0.9833	-98.33	-0.0009703	-10^{-2}

(*) The density of water was taken as 1.000 g/cm^3. This holds only at 4 °C but is approximately correct at other temperatures.

The gravitational potential of soil water at each point is determined by the elevation of the point relative to some arbitrary reference level. If the point in question is above the reference, ψ_g is positive; if the point in question is below the reference, ψ_g is negative. Thus the gravitational potential is independent of soil properties. It depends only on the vertical distance between the reference and the point in question.

At a height z below a reference level (e.g. the soil surface) the gravitational potential of a mass M of water, occupying a volume V is:

$$- M g z = - \rho_w V gz$$

where ρ_w is the density of water and g the acceleration of gravity.

Gravitational potential can be expressed:

- per unit mass: $\psi_g = - gz \quad (J\ kg^{-1})$
- per unit volume: $\psi_{gv} = \psi_g \cdot \rho_w = - \rho_w g z$ (Pa)
- per unit weight: $\psi_{gw} = \psi_g 1/g = - z$ (m)

5. Osmotic potential.

The osmotic potential is attributable to the presence of solutes in the soil water. The solutes lower the potential energy of the soil water. Indeed, the fact that water molecules move through a semi-permeable membrane from the pure free water into a solution (osmosis) indicates that the presence of solutes reduces the potential energy of the water on the solution side (figure 2). At equilibrium sufficient water has passed through the membrane to bring about significant difference in the heights of liquid. The difference (z) in the levels represents the osmotic potential.

Since the osmotic potential of pure free water is zero the osmotic potential of a solution at the same temperature of free water is negative (water flow occurs from point of high potential to one with lower potential).

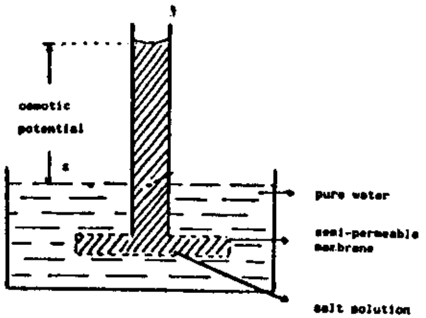


Figure 2. Schematic presentation of osmosis.

Differences in osmotic potential only play a role in causing movement of water when there is an effective barrier for salt movement between the two locations at which the difference in ψ_o was observed. Otherwise, the concentration of salts will become the same throughout the profiles by the process of diffusion and the difference in ψ_0 will no longer exist. Therefore osmotic potential does not act as a driving force in water flux. This potential is of importance in water movement into and through plant roots, in which there are layers of cells which exhibit different permeabilities to solvent and solute.

6. Matric potential (*).

Matric potential results from forces associated with the colloidal matric and includes forces associated with adsorption and capillarity. These forces attract and bind water in the soil and lower its potential energy below that of bulk water. The capillarity results from the surface tension of water and its contact angle with the solid particles. In an unsaturated (three-phase) soil system, curved menisci form which obey the equation of capillarity

$$P_a - P_i = \Delta P = \gamma \left(\frac{1}{R_1} + \frac{1}{R_2}\right)$$

(*) Matric potential and the former term matric suction are numerically equal - when expressed in the same units - but except for the sign.

where P_a is the atmospheric pressure, conventionally taken as zero; ΔP_i the pressure of soil water, which can be smaller than atmospheric; ΔP is the pressure deficit; γ the surface tension of water and R_1 and R_2 are the principal radii of curvature of a point on the meniscus, and taken as negative when the meniscus is concave.

As we assume the soil pores to have a cylindrical shape (figure 3) the meniscus has the same curvature in all directions and equation above becomes:

$$- P_i = \Delta P = \frac{-2\gamma}{R}$$

since:

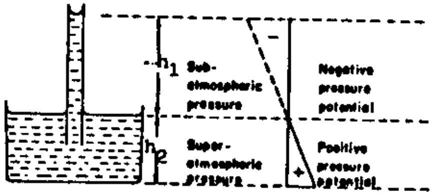
$$R = \frac{r}{\cos\alpha} \quad (\alpha = 0; \text{ angle of contact between water and the soil particle surface})$$

$$- P_i = \Delta P = \frac{-2\gamma}{r}$$

where: h = height of capillary rise
ρ_a = density of water
g = acceleration of gravity

If the soil were like a simple bundle of capillary tubes, the equations of capillarity might be themselves suffice to describe the relation of the negative pressure potential or matric potential to the radii of the soil pores in which the menisci are contained. However, in addition to the capillary phenomenon, the soil also exhibits adsorption, which forms hydration envelopes, over the particle surfaces. These two mechanisms of soil water interaction are illustrated in figure 4.

The presence of water in films as well as under concave menisci is most important in clayey soil and at high suctions or low potential, and it is influenced by the electric double layer and the exchangeable cations present. In sandy soils adsorption is relatively unimportant and the capillary effect predominates.



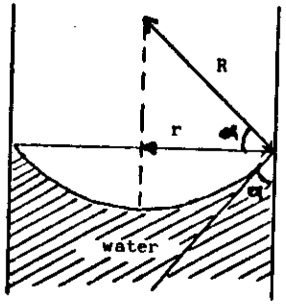


Figure 3 : Capillary rise of water into a capillary tube.

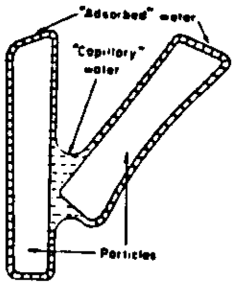


Figure 4 : Water in an unsaturated soil is subject to capillarity and adsorption, which combine to produce a matric potential

In general, however, the matric potential results from the combined effect of the two mechanisms, which cannot easily be separated since the capillary "wedges" are at a state of internal equilibrium with the adsorption "films" and the ones cannot be changed without affecting the others. Hence matric potential denotes the total effect resulting from the affinity of the water of the whole matric of the soil, including its pores and particle surfaces together.

The matric potential can be expressed:

- per unit mass:

$$\psi_m = g\,h = -\frac{2\gamma}{\rho r} \qquad (\mathrm{J\ kg^{-1}})$$

- per unit volume:

$$\psi_m\,\rho_w = -\rho\,g\,h = -P = \frac{-2\gamma}{r} \qquad (\mathrm{Pa})$$

- per unit weight:

$$\psi_m\,\frac{1}{g} = -h = \frac{-2\gamma}{\rho\,g\,r} \qquad (\mathrm{m})$$

The matric potential is a dynamic property of the soil.

In saturated soil (below the ground water level) the liquid phase is at hydrostatic pressure greater than atmospheric and thus its pressure potential is considered positive (figure 3). Thus water under a free water surface is at a positive pressure potential (hydrostatic pressure potential ψ_h), while water at such a surface is at zero pressure potential (assuming atmospheric pressure in the soil) and water which has risen in a capillary tube above that surface is characterized by a negative pressure or matric potential.

Since soil water may exhibit either of the two potentials, but not both simultaneously, the matric and the hydrostatic pressure potential are referred to as the pressure potential (ψ_p).

Nevertheless it is an advantage in unifying the matric potential and hydrostatic pressure potential in that this unified concept allows one to consider the entire profile in the field in terms of a single continuous potential, extending from the saturated zone into the unsaturated zone, below and above the water table.

7. External gas pressure potential.

A factor which may affect the pressure of soil water is a possible change in the pressure of the ambient air. In general this effect is negligible in the field as the atmospheric pressure remains nearly constant small barometric pressure fluctuations notwithstanding. However, in the laboratory the application of excess air pressure to change the soil water pressure is a common practice resulting into the so called external gas pressure of pneumatic potential (See determination of the soil water characteristis curve by the pressure plate extraction apparatus).

FINAL REMARK.

The effect of an external gas pressure different from the atmospheric (reference) pressure is generally also included in the pressure potential so that:

$$\psi_p = \psi_m + \psi_h + \psi_{e.p}$$

Accordingly the total potential being:

$$\psi_t = \psi_g + \psi_o + \psi_p$$

characterizes fully the state of water in soil under the prevailing conditions; the gradients of these three parameters are the basis for transport theory.

8. Hydraulic head.

The total potential is obtained by combining the relevant component potentials:

$$\psi_t = \psi_g + \psi_o + \psi_p$$

Equilibrium, which is defined as the situation where mass transfer of water in the liquid phase is absent, is obtained when the value of the total potential at different points in the system is constant. Usually, sufficient condition is that the sum of the component potentials, ψ_o being ignored, is constant. The equilibrium condition states then that:

$$\psi_g + \psi_p = \text{constant} = \psi_H$$

called hydraulic potential.

As already stated, the external gas pressure or pneumatic potential in the field may be assumed to be zero. Also the soil water within a profile may exhibit either matric or hydrostatic pressure potential (figure 3) but not simultaneously. Therefore it is an advantage in unifying both in a single continuous potential extending from the saturated region into the unsaturated region below and above the water table.

As it is often usual to designate the potential in terms of head, equation (1) becomes:

$$H = h + z$$

where: h = the soil water pressure head (m)
> 0 under the water table (saturated zone)
< 0 above the water table (unsaturated zone)
z = the gravitational head (m)
H = the hydraulic head(m)

The definition is very important because the hydraulic gradient between two points under consideration in a soil is the driving force for water movement.

In figure 5 the condition is applied to a vertical soil column in equilibrium with a water table. No water movement occurs in the column. The water table is taken as the reference level for the gravitational potential.

Under the water table matric potential equals zero, but a pressure potential called hydrostatic pressure potential occurs which can also be presented by a value of h but with always a positive sign.

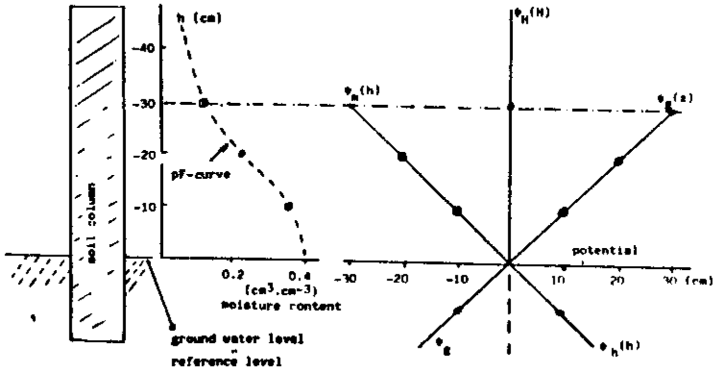


Figure 5. Equilibrium condition in a soil column.

height(cm)	ψ_g (z,cm)	ψ_m (h,cm)	ψ_h (h,cm)	ψ_H (H,cm)
30	30	- 30	0	0
20	20	- 20	0	0
10	10	- 10	0	0
0 reference level	0	0	0	0
- 10	- 10	0	10	0
- 20	- 20	0	20	0

II. TENSIOMETER

1. Hydrostatic pressure potential - Piezometer.

As discussed earlier the hydrostatic (positive) pressure potential ψ_h under field conditions applies to saturated soils and is measured with a piezometer (figure 6).

A piezometer is a tube of a few cm inner diameter, open at both ends, which is installed in a soil profile. If the lower end is below the groundwater table, a piezometer is partially filled with water. By determining the height of the water level in a piezometer it is possible to calculate the (positive) hydrostatic pressure potential of the soil water at the lower end of the tube. The diameter of piezometers is chosen large enough that capillary rise and resistance to water flow are negligible. As a result, any variation in hydraulic potential that may arise inside the piezometer, is instantaneously equalized. Thus, even if the hydrostatic pressure potential at the lower end is changing rapidly, the water inside a piezometer goes through a series of static equilibria and at any moment it can be assumed that the hydraulic head is uniform and equal to the hydraulic head of the soil water at the open lower end. There exchange of water takes place such that the pressure is always locally uniform. The static hydraulic head in piezometers can be determined by measuring the depth of the water level, since at the flat air-water interface the pressure potential is zero.

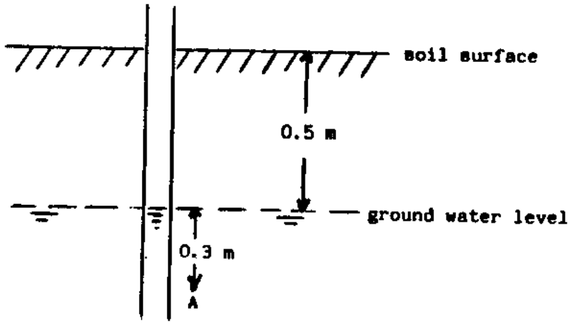


Figure 6. A piezometer in a soil profile.

Figure 6 shows a piezometer in a soil profile in which the water is at static equilibrium. The reference point z = 0 is taken at the soil surface. In the piezometer at the water level $H = h + z = 0 - 0{,}5\ m = -0{,}5\ m$. Thus at point A, H must also be $-0{,}5\ m$ ($H = h + z = 0{,}30\ m - 0{,}80\ m = -0{,}50\ m$).

The hydrostatic pressure potential expressed per unit weight of water at any point in the soil under the water table is the distance between the point and the water level in the piezometer tube.

The water level in a piezometer tube is at the level of the groundwater table in a situation of static equilibrium, independent of the depth of the lower end.

2. Matric potential - Tensiometer.

Piezometers cannot be used to measure negative pressure potentials because in unsaturated conditions, water flows out of the tube into the soil leaving the tube dry. The negative pressure or matric potential can be measured with the so-called tensiometer.

The tensiometer consists of a liquid filled porous cup, mostly of ceramic material and connected to a pressure measuring device such as a mercury manometer or vacuum gauge via a liquid-filled tube (Figure 7).

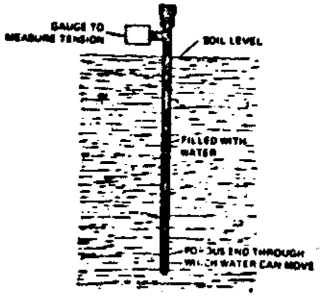


Figure 7. Tensiometers with a vacuum gauge.

If the ceramic cup is embedded in soil, the soil solution can flow into or out of the tensiometer through the very small pores in the ceramic cup. Analogously to the situation discussed for piezometer, this flow continues until the (negative) pressure potential of the liquid in the cup has become equal to the (negative) pressure potential of the soil water around the cup. Thus the (negative) pressure potential called matric potential ψ_m of soil water can be measured with a tensiometer, and is therefore also often called tensiometer pressure potential.

3. Principle of the tensiometer.

When the cup is placed in a water reservoir (figure 8), the water inside the cup comes into hydraulic contact with the water in the reservoir through the water-filled small pores in the ceramic walls. The water level in the tube will indicate the level of the water in the reservoir.

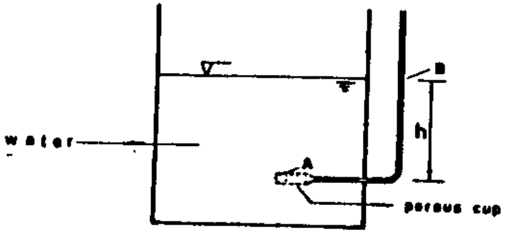


Figure 8. Porous cup connected with a piezometer tube for measuring pressure potentials under the water table.

The pressure is given by the height h of the water level above the middle of the porous cup and the pressure P_A equals:

$$P_A = \rho_w\, g\, h$$

where: ρ_w = density of water
g = acceleration due to gravity

If we place now the porous cup, connected with a U-shape water filled tube in a soil than the bulk water inside the cup will come in hydraulic contact with the liquid phase in the soil. When initially placed in the soil, the water in the tensiometer is at atmospheric pressure. Soil water in unsaturated soil has a negative pressure and therefore exercices a suction which drawn out a certain amount of water from the rigid and air-tight tensiometer, causing a drop in the water level at the open end of the U-tube (figure 9).

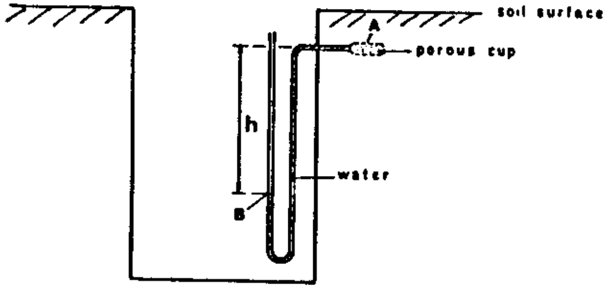


Figure 9. Tensiometer for measuring pressure potentials in soils.

The drier the soil, the higher the suction and the lower the water level at equilibrium in the U-tube. The height h of the liquid column that has moved into ("sucked into") the soil in figure 9 is therefore an index of the magnitude of the potential, or:

$$P_A = - \rho_w g h$$

As h is measured downwards the minus sign is introduced so that P_A gives a negative pressure.

This type of tensiometer is very simple and useful to illustrate the basic principles involved. Practical applications often do not allow the use of the water manometer because the U-tube extends below the level of the tensiometer cup and measurements thus requires inconvenient, deep pits. Therefore open manometers, filled with immiscible liquids of different densities such as mercury are used so that these problems do not arise (figure 10).

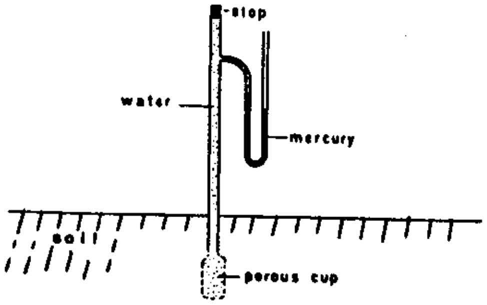


Figure 10. Tensiometer with mercury manometer.

Using mercury implies that a relatively short height indicated a relatively large pressure difference in the manometer (1 cm of mercury corresponds to 13.55 cm of water). Besides the simple water or mercury manometer a vacuum gauge or an electrical transducer is also used.

4. How to calculate the soil water pressure head h and the hydralic head H.

Let x be the height of the mercury in the manometer (in cm) and z the vertical axis. At the interface water-mercury in the manometer, the pressure is the same in water and in mercury (being P_B). The repartition of the pressure is hydrostatic in the water column between point B and the tensiometer cup (point A), but also between point B and the free surface of the mercury in the reservoir (point C).

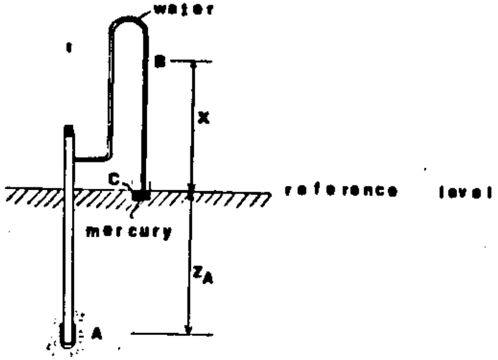


Figure 11. Tensiometer installation with the mercury level in the reservoir at the soil surface being the reference level.

Using the hydrostatic law for liquids in equilibrium one obtains per unit weight of liquid the following hydraulic head equation:

$$z + P/\rho g \quad \text{constant}$$

where: z = gravitational head,
P/ρg pressure head.

From figure 11 one obtains:

- <u>in water:</u>

$$z_A + \frac{P_A}{\rho_w\, g} = z_B + \frac{P_B}{\rho_w\, g}$$

Because soil surface is taken as reference level for the gravitational potential, and point A is located below that level, the gravitational head is negative ($- z_A$).

$$P_A - z_A \rho_w g = P_B + z_B \rho_w g$$

$$P_A = P_B + z_B \rho_w g + z_A \rho_w g = P_B + \rho_w g(z_A + z_B) \qquad (1)$$

- <u>in mercury:</u>

$$z_B + \frac{P_B}{\rho_{Hg}\, g} = z_C + \frac{P_C}{\rho_{Hg}\, g}$$

because: $z_C = 0$ reference level
P_C = atmospheric pressure = 0

the equation becomes:

$$Z_B + \frac{P_B}{\rho_{Hg}\, g} = 0$$

or:

$$P_B = - \rho_{Hg} g\, z_B \qquad (2)$$

(2) in (1) gives:

$$\frac{P_A}{\rho_w\, g} = \frac{- \rho_{Hg}\, g\, z_B}{\rho_w\, g} + z_A + z_B \qquad (3)$$

Since: $\rho_{Hg} = 13600 \text{ kgm}^{-3}$
$\rho_w = 1000 \text{ kg m}^{-3}$

(3) becomes:

$$h_A = - 13.6\, z_B + z_A + z_B$$

or:

$$h_A = - 12.6\, z_B + z_A$$

$$h_A = - 12.6\, x + z_A \qquad (4)$$

Normally the free surface of the mercury in the reservoir (point C) is located y cm above the soil surface (reference level) (figure 12).

Equation (4) becomes:

$$h_A = - 12.6\, x + y + z_A \qquad (5)$$

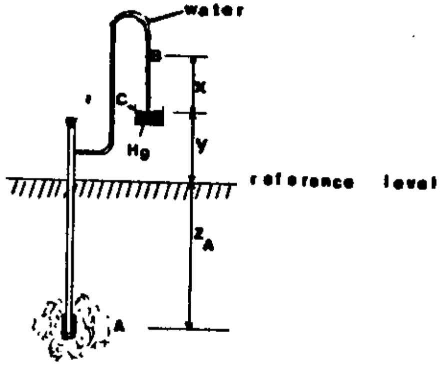


Figure 12. Tensiometer installation with the mercury reservoir y cm above soil surface.

The hydraulic head H, being the sum of the pressure head h and the gravitational head z, ($H = h + z$), becomes:

$$H = -12.6\,x + y + z_A + (-z_A)$$

$$H = -12.6\,x + y \qquad (6)$$

Example

Given: The porous cup of a tensiometer with mercury manometer is installed 0.3 m under the soil surface. The height of the mercury in the manometer is 0.31 m. The level of the mercury reservoir is located 0.4 m above the soil surface. Reference level is the soil surface.

Calculate: - soil water pressure head h
- hydraulic head H

Solution:

$$h = (-12.6 \times 0.31 + 0.4 + 0.3)\ \text{m} = -3.20\ \text{m}$$

$$H = (-12.6 \times 0.31 + 0.4)\ \text{m} = -3.50\ \text{m}$$

5. Some characteristics of the tensiometer.

- cup conductance:

$$K' = \frac{\Delta V}{\Delta t\ \Delta h}$$

being the volume of water passing through the cupwall under a unit pressure difference per unit time ($m^3\ s^{-1}\ Pa^{-1}$)

- sensitivity of the manometer:

$$S = \frac{\Delta h}{\Delta V}$$

being the change in manometer reading per unit volume change of water ($Pa\ m^{-3}$)

- response time of the system:

$$T_R = \frac{1}{K'S}$$

is a measure of the over-all responsiveness of the instrument to a change of soil-water potential at the cup surface (s)

6. Practices and limitations of tensiometers.

The purpose of the measurements with tensiometers is to characterize the existing pressure potential of the soil water.

Water within the tensiometer should be continuous throughout the system to allow a correct transfer of pressure from the soil to the mercury. Occurence of gas bubbles disrupts this continuity and makes the system inoperative. The fine porous cup has the function of not allowing penetration of air from the unsaturated soil into the water-filled tensiometer tube, even though water can and should move through it. The fine pores inside the wall of the ceramic cup have a high air-entry value which is the pressure needed to remove the water from the pores in the cup replacing it by air. Even with a high air entry value breakdown of the system occurs due to entrapped air within the tensiometer tube or to air coming out of solution at reduced pressure.

Due to the fact that the manometer measures a partial vacuum relative to the external atmospheric pressure, measurements by tensiometry are generally limited to about - 850 cm of water. Use of tensiometers in the field is therefore only possible when pressures do not fall below this value. However, the limited range of pressure measurable by the tensiometers is not as serious as it may seen at first sight. In many agricultural soils the tensiometer range accounts for more than 50 % of the amount of soil water taken up by the plants. To what extend the available water range expressed e.g. as a percentage of the water between pF 2 and pF 4.2, is covered by the tensiometer depends on the shape of the moisture characteristic curve (pF-curve) as shown for three soil types in figure 13.

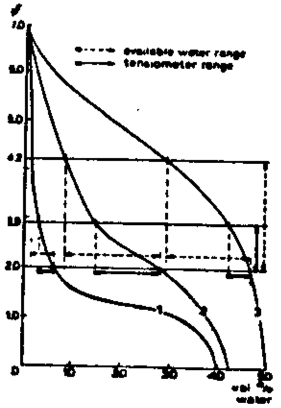


Figure 13. Part of the available moisture range covered by tensiometers, depending on soil type

1. Sand 50 % of available moisture
2. Loam 75 % of available moisture
3. Clay 25 % of available moisture

Thus where soil management (particularly in irrigation) is aimed at maintaining high pressure potential conditions which are mostly favorable for plant growth, tensiometers are definitely useful.

Air diffusion through the porous cup into the system requires frequent purging with desired water. Tensiometers are also sensitive to temperature gradients between their various parts. Hence the above-ground parts should preferably be shielded from direct exposure to the sun. Therefore it is also suggested to make readings always at the same time of the day (e.g. at 08.00 a.m.).

When installing a tensiometer it is important for proper functioning that good contact be made between the porous cup and the surrounding soil. Generally the porous cup is pushed into a hole with a slightly smaller diameter to ensure good contact. If the soil is initially rather dry and hard, prewetting of the hole may be necessary. In a stony soil a small excavation should be made and filled with very fine sand into which the tensiometer can be placed.

With mercury manometers, even when small diameter nylon tubing (+/- 2 mm) is used, often a considerable volume of water must be adsorbed by the soil (during water uptake or drying process) or by the porous cup (replenishing by rainfall or irrigation) before the potential that really exists can be read off correctly. A very convenient modern device, the electronic transducer can be used which reacts to very small changes in pressure and converts these changes in a small electrical current which can be registered and amplified by a voltmeter. This system is very accurate but also very sensitive to the occurence of small air bubbles in the tensiometer system. Moreover is it rather expensive.

Since the porous cup walls of the tensiometer are permeable to both water and solutes, the water inside the tensiometer tends to assume the same solute composition and concentration as soil water, and the instrument does not indicate the osmotic potential of soil water.

7. Applications of measurements.

By the use of several tensiometers at different depths the direction and magnitude of water movement can easily be as certained.

EXAMPLES

1. Determination of the direction of water flow at different levels in the soil profile (Figure 14).

The concept of the water potential is well suited for the analysis of water flow in soils, since all flow is a consequence of potential gradients. Darcy's law, though originally conceived for saturated flow only, was extended to unsaturated flow, with the provision that the conductivity is a function of soil water content θ.

For a vertical one dimensional water flow Darcy's equation can be written as follows:

$$q = -K(\theta)\,\frac{dH}{dz} \tag{7}$$

where: q = flux
K(θ) = hydraulic conductivity
H = hydraulic head
= h + z with h = soil water pressure head
z = gravitational head

The minus sign in the equation indicates that the flow is in the direction of decreasing potential. This means also that if we have two tensiometers located at depths z_1 and z_2 ($z_1 < z_2$):

- q will be negative (upward flow – evaporation) if $H_2 > H_1$; the rise of mercury in manometer n° 2 is lower than in manometer n° 1
- q will be positive (downward flow – percolation) if $H_2 < H_1$; the opposite situation is observed
- q will be zero (plane of zero flux) at a certain depth z when the curve H(z) will show a maximum or the rise of the mercury a minimum because dH/dz = 0. A graphical example is presented in figure 14.

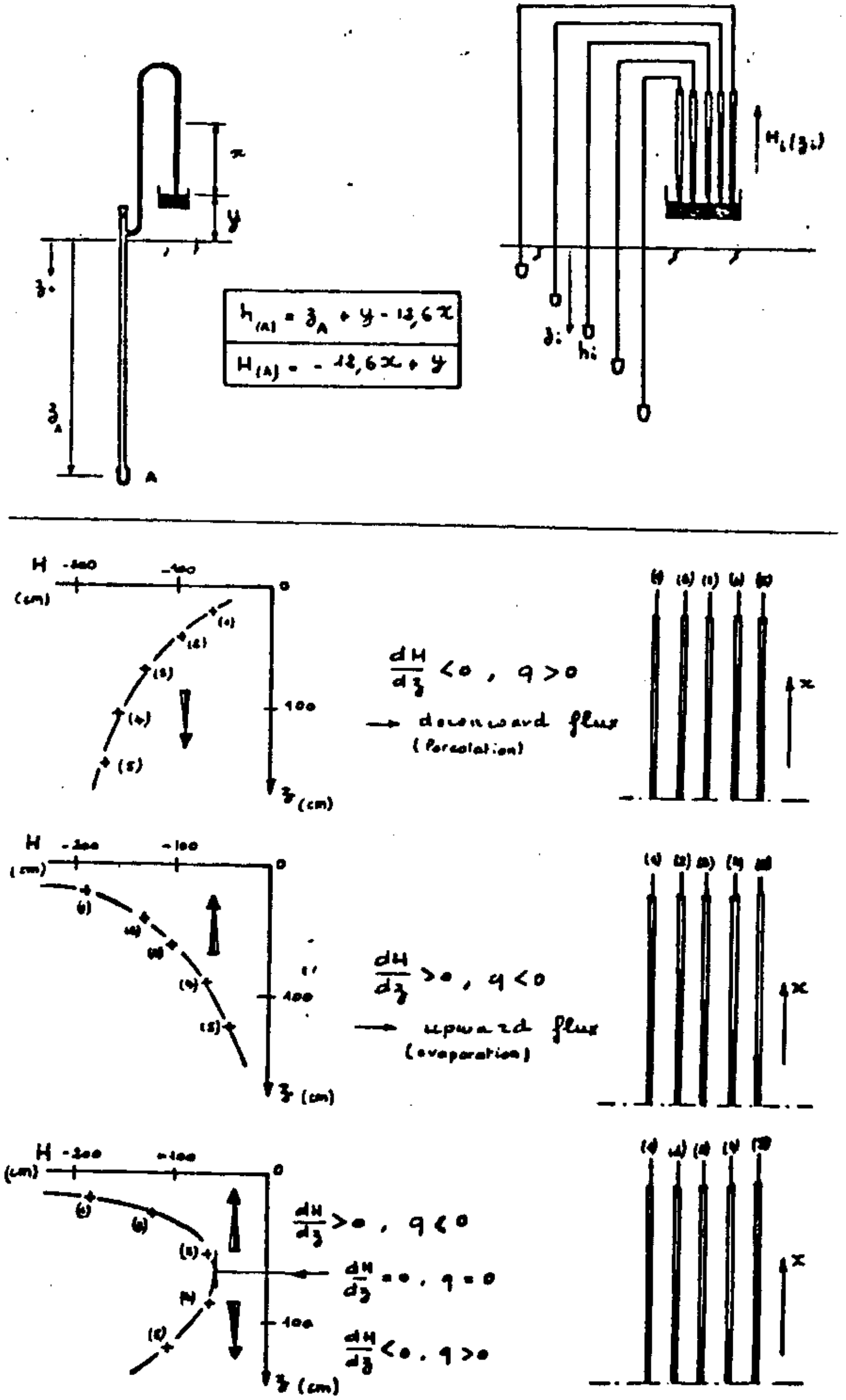


Figure 14. Hydraulic head profiles. The manometers from left to right increase with depth.

- **Numerical example.**

Reference level being the soil surface.

tensiometer z_1 = 50 cm   x = 10.7 cm   y = 20 cm

tensiometer z_2 = 75 cm   x = 13.8 cm   y = 20 cm

$H_1 = - 12.6\ x + y = - 1.05$ m

$H_2 = - 12.6\ x + y = - 1.54$ m

In this situation downward flow occurs since flow is towards the position with the lowest water potential.

2. Flux control at a certain depth.

From agricultural point of view it could be of interest to know if there is a recharge of the water table or capillary rise. Therefore only 2 tensiometers are needed with a depth distance of say 25 cm in the control zone. A simple reading of the rise of mercury in the manometer will indicate the flow direction.

Knowing the moisture content θ at the depth between z_1 and z_2, the $K(\theta)$ relation of that soil and the hydraulic head gradient dH/dz, one can calculate the instantaneous water flow q (see equation 7).

3. Determination of the soil water characteristic curve (or retentivity curve).

The h-θ relation (retentivity curve) of a soil layer in situ can be established:

- knowing the soil water pressure head (h) using tensiometers (see equation 5)
- knowing the soil water content (θ) using the neutron moisture meter.

4. Scheduling irrigation.

The root zone for most agricultural plants is limited to the unsaturated part of the profile because the plant roots do not proliferate in a saturated soil where aeration is limiting. Consequently in a non-saline soil the plant behaviour is largely determined by the matric potential of the soil water. Moreover the plant does not depend as much on the quantity of water present as it does on the water potential.

Water should be applied to the soil when the matric potential is still high enough that the soil can and does supply water fast enough to meet the atmopsheric demands without placing the plant under a stress that will reduce yield or quality of the harvested crop.

Although the tensiometers function over only a limited part of the available water range (0 to - 800 cm water) it is usually in this range that plants should be irrigated.

From practical point of view tensiometers are installed at minimum 2 locations. One unit should be placed in the zone of maximum root activity and another near the bottom of the active rootzone.

The time to irrigate is determined by following the matric potential readings in the zone of the greatest root activity. The exact value of the matric potential at which water should be applied is not the same for every crop. A good approximation of that matric potential is available for many common crops (table 1). For most crops it is time to irrigate when the top tensiometer reads - 300 to - 500 cm water and the bottom tensiometer begins to indicate drying.

Table 1. Matric potential at which water should be applied for maximum yields of various crops grown in deep, well-drained soil that is fertilized and otherwise managed for maximum production. Where two values are given, the higher value is used when evaporative demand is high and the lower value when it is low; intermediate values are used when the atmospheric demand for evapotranspiration is intermediate. (The values are subject to revision as additional experimental data become available). (TAYLOR and ASHCRIFT, 1972).

Crop	Matric potential (cm)
Vegetative crops	
Alfalfa	- 1500
Beans	- 750 to - 2000
Cabbage	- 600 to - 700
Canning peas	- 300 to - 500
Celery	- 200 to - 300
Grass	- 300 to - 1000
Lettuce	- 400 to - 600
Rootcrops	
Sugar beets	- 400 to - 600
Potatoes	- 300 to - 500
Carrots	- 550 to - 650
Cauliflower	- 600 to - 700
Fruitcrops	
Lemons	- 400
Oranges	- 200 to - 1000
Advocades	- 500
Strawberries	- 200 to - 300
Tomatoes	- 800 to - 1500
Bananas	- 300 to - 1500

III, SOIL WATER CONTENT.

.1. Introduction

The water content is a measure of the amount of water per unit soil mass or soil volume. The moisture content can be expressed:-

on dry mass "w"

$$w = \frac{m_l}{m_2} \qquad (M\,M^{-1})$$

where: m_l = mass of water
m_2 = mass of dry soil (after drying at 105°C)

on volume basis "θ"

$$\theta = \frac{V_l}{V_b} \qquad (L^3\,L^{-3})$$

where: V_l = volume of water in sample
V_b = bulk volume of soil sample

The moisture content is also frequently expressed as:
—a percentage of the dry mass of soil (w . 100)
—a percentage of the bulk volume of soil (θ . 100)

The following reference methods of measuring the water content of a soil will be described:
1. Gravimetric method
2. Neutron-scattering method
3. Gamma-ray attenuation method

.2. Gravimetric method

Is the simplest and most widely used method. It is frequently used for the calibration of other indirect methods as it remains the only direct way of measuring soil water.

Principle:
Disturbed or undisturbed wet samples are weighed, dried to constant weight in an oven at 105°C and reweighed. From the different weight measurements the water content on dry mass basis can be calculated.

Alternatively by multiplying by the bulk density the results may be expressed on a volume basis.

Equipment:
Sampling material (shovel, spade, auger, soil cores), soil containers with tight-fitting lids, oven desiccator with active desiccant, balance.

Procedure:
Place the sample of soil in weighing metal cans with tight-fitting lids. Weigh the samples immediately or store them in such a way that evaporation is prevented. Place the sample in a drying oven (105°C) with the lid off and dry it to constant weight. Remove the sample from the oven, replacing the cover, and place it in a desiccator containing active desiccant until cool. Weigh it again and also determine the tare weight of the sample container. Compute the water content.

Calculation:
The water content is calculated as follows:
—on dry mass basis:

$$W = \frac{m_{s+w} - m_s}{m_s} \qquad (kg\,kg^{-1})$$

where: m_{s+w} = mass of wet soil (kg)
m_s = mass of dry soil (kg)

—on volume basis:

$$\theta = \frac{m_{s+w} - m_s}{\rho_w \cdot V_b} \qquad (m^3\ m^{-3})$$

where: ρ_w = density of water (1000 kg m^{-3})
V_b = bulk volume of soil sample (m^3)

Knowing the bulk density of the soil (ρ_b), the water content on volume basis can be calculated as follows:

$$\theta = \frac{\rho_b}{\rho_w} \cdot W$$

Time required:
Apart from sampling and transportation time the water content determination takes a period of at least one day since 24 hr is normally necessary for complete oven drying.

Cost:
Equipment and running costs are low.

Accuracy:
It is a direct and reproducible measurement. The oven drying at 105°C is itself arbitrary. Some clays may still contain appreciable amounts of adsorbed water even at 105°C. On the other hand, some soil organic matter may oxidize and decompose at this temperature so that the weight loss may not be due entirely to the evaporation of water.

Advantages:
The main advantage of the direct gravimetric method is its simplicity. Moreover it is cheap and no particular skills are required at any stage of the process. It is used as a reference method for the calibration of other water content determination methods.

Disadvantages:
The main disadvantage of this direct method stems from the impossibility of repeating measurements at the same point, and the consequent need for a large number of samples to reduce the error caused by the variability of soil. On the other hand repeated sampling destroys the experimental area.

It requires a great deal of physical effort and time to collect and test samples and to calculate the water content.

References:

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.3. Neutron scattering

Principle:
The neutron-scattering method is based on the fact that fast moving neutrons emitted by a radio-isotope neutron source are slowed down or moderated by collisions with the nuclei of the soil and can be counted by a detector.

Because the moderation ability of the soil nuclei is small compared with that of hydrogen and since the amount of hydrogen associated with water in the soil is generally much greater than that associated with clay, organic matter or other soil particles, the flux of slow neutrons is proportional to the amount of water in a bulk volume of soil.

Equipment:
The portable neutron moisture gauge consists of a probe unit, which is stored in a special shield to protect the user against both neutrons and gamma rays, and a scaler.

The probe unit contains a fast neutron source, a slow neutron detector and an electronic device. The detector count rate is indicated on a scaler or ratemeter.

Access tubes, in which the probe can be lowered during the measurements and which are left in position as long as measurements are required.

Auger to insert the access tube vertically into the soil.

Procedure:
Before the probe is lowered into the access tube a measurement must be done with the probe unit in the special protection shield or by using water in a container as reference.

After determining the standard count, readings are taken at successive depth intervals. At the end of a series of readings in the access tube a new standard count is made.

Each reading is divided by the mean standard reading to obtain a count ratio and referred to the calibration curve to obtain, volumetrically, the water content.

Calculation:
The calibration of the neutron moisture gauge can be carried out in a number of ways viz. by:

gravimetric in situ sampling:
It is accomplished by comparing many field measurements by the neutron gauge with gravimetric analysis of representative samples taken from the field sites.

preparation of synthetic samples (containers):
A number of soil containers are filled as uniformly as possible with one soil containing various known amounts of water covering the range of water content that will be encountered in the field.

mathematical models:
This consists essentially of devising or accepting a model of the neutron gauge response which can be used to describe the gauge response over the entire range of water contents, soil minerals and dry densities encountered.

Time required:
The measurements can be carried out in a relatively short time. Little calculation is necessary to obtain the water contents once the calibration is available.

Cost:
The equipment is expensive. Costs are increased due to the need for a well trained operator.

Accuracy:
As it is an indirect method, the accuracy will largely be associated with the calibration curve viz:
measurement of mass basis water content
bulk density
and also the counting device.

Advantages:
Virtually the same soil sample is capable of being measured repeatedly for changes in water content (non-destructive method).
The time required for measurement is relatively short.
The results of measurement in terms of values of soil water content are immediately available.
Measurements can be taken with relative ease to great depths.
The relatively large volume monitored more truly represents the field soil than very much smaller samples taken for the gravimetric measurement of soil water content in water balance studies.

Disadvantages:

The neutron moisture meter is unsuitable for the detection of water content profile discontinuities and measurements close to the surface.

The gauge responds to total hydrogen content. In actual situations appreciable amount of hydrogen are present in clay and, particularly, in organic matter.

The calibration has to be obtained for each soil and soil layer.

The equipment is quite expensive and strict observance of safety rules is necessary.

Remarks:

The water content of the surface layer can be measured by specially adapted equipment. A surface neutron scattering unit is available when the probe is placed on the soil surface and the fast neutrons radiated downwards into the soil. The backscatter of slow neutrons is measured by a detector in the probe. It is important that the probe has intimate contact with the soil surface.

To obtain the water content volumetrically the bulk density of the soil in the vicinity of the access tube has to be known. Therefore different probes are now available containing simultaneously a fast neutron source for the water content determination and a gamma source allowing the determination of the bulk density together with their sensitive detector.

References:

Bell, J. P., (1976). Neutron Probe Practice, Report No. 19. Nat. Env. Res. Council Inst. of Hydrology. Crowmarch Gifford, Wallingford, OXON, England.

Gardner, W. H., (1965). Soil Moisture. *In:* "Methods of Soil Analysis", I. (Ed. C. A. Black), 82—127. Agronomy No. 9, Am. Soc. Agron., Madison, Wisconsin.

IAEA, (1970). Neutron Moisture Gauges. Technical Reports Series, No. 112, 1—95.

IAEA, (1976). Trace Manual on Crops and Soils. Technical Reports Series No. 171, 1—277.

Wilson, R. G., (1970). Methods of measuring soil moisture. International field year for the Great Lakes. Technical Manual Series, No. 1.

4. Gamma-ray attenuation

The gamma-ray attenuation method is used mostly in the laboratory although the method has also been adapted for field use.

A. Laboratory

Principle:

A radioactive source —mostly ^{137}Cs— whose emitted gamma-rays are collimated into a thin beam, is placed over one side of a soil column and a scintillation counter is located directly opposite.

The degree to which the beam of monoenergetic gamma-rays is attenuated in passing through a soil depends upon the overall density of the material through which it passes.

The changes in attenuation will only represent changes in water content if the density of the soil remains constant and only the water content changes.

Equipment:

A gamma-ray attenuation apparatus consists mainly of two spatially separated units:

—a source of gamma-rays, with a lead shield (for exposure protection) of proper size and a collimator

—a gamma sensitive detector, e.g. a scintillation counter with collimator, connected to a scaler or rate meter.

Also required is a soil container, a mechanism for positioning the container in the beam and a mechanical scanning system which allows the frame, on which source and detector are fixed, to lower or raise along the soil container. A preset timer is desirable.

Procedure:

The soil column is fixed in the gamma-attenuation equipment. Then scanned step by step at each measuring position. The values are used for subsequent computations of water content.

Calculation:

If the soil container has been filled with oven dry soil, the water content on volume basis (θ) can, after scanning, be calculated using the following equation:

$$\theta = - \frac{\log (N_w/N_d)}{0.4343\, \mu_w \,.\, d \,.\, \rho_w} \qquad (1)$$

where: N_d = the radiation flux transmitted through the container and oven dry soil
N_w = the radiation flux transmitted through the container and wet soil
μ_w = the mass attenuation coefficient of water
d = the thickness of soil through which the collimated gamma beam passes
ρ_w = the density of water

If the soil container has been filled with a soil at a uniform water content (e.g. air dry) other than oven dry the soil water content on volume basis can be calculated using the following equation:

$$\theta = \theta_{ad} - \frac{\log (N_w/N_{ad})}{0.4343\, \mu_w \,.\, d \,.\, \rho_w} \qquad (2)$$

where. θ_{ad} = the initial water content of the soil determined gravimetrically (e.g. air dry)
N_{ad} = the radiation flux transmitted through the container and air dry soil.

To solve equation (1) or (2):

—the mass attenuation coefficient of water can be determined experimentally or a reasonable estimate can be made from tables for particular gamma-ray energies.

—thickness of the soil column has to be measured at each measuring point.

Time required:

The measuring time is very short (1 minute or less) and the water content can easily be calculated.

Cost:

Very expensive. The setting-up of the experiment and the measurements have to be carried out by a well trained operator.

Accuracy:

The accuracy of the method appears to be about 0.5 to 1.0% by volume.

Advantages:

It is an easy method for monitoring transient water content distributions in soil columns.

Non-destructive, fast and reproducible method.

Disadvantages:

Expensive. Strict attention has to be paid to all safety rules. Can not be used for soils with important changes in bulk densities during wetting or drying processes.

B. Field

The double-probe gamma-ray method has also been adapted to field use. Two access tubes, one for the source and the second for the scintillation counter, are placed in the soil so that they remain equidistant at all depths.

Source and detector are both held in an access tube by a rod calibrated for depth and connected to a frame so that they are at the same depth.

For the rest see "Laboratory method".

Remarks:

In principle this technique offers several advantages over the neutron moisture technique in that it allows much better depth resolution in measurement of soil water content profiles.

Discontinuities between profile layers as well as movement of wetting fronts and conditions prevailing near the soil surface can be detected.

However, this field device is somewhat cumbersome for general usage due to problems related to:
—the accurate installation and alignment of the two access tubes which must be strictly parallel
—determination of the soil bulk density as it might vary in depth and time.

The technique can also be used for the in situ determination of the bulk density (see "Measurement of Soil Density in Situ by Gamma-ray Attenuation").

References:

Gardner, W. H., (1965). Water content. *In:* "Methods of Soil Analysis," I. (Ed. C. A. Black), Agronomy No. 9, Am. Soc. Agron., Madison, Wisconsin.
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IV. SOIL WATER RETENTION PROPERTIES.

.1 Introduction

As no satisfactory theory exists for the prediction of the matric potential versus soil water content relationship from basic soil properties, the relationship has to be determined experimentally. The relationship extends from 0 m water head or 0 bar (saturated soil) to approximately — 10^5 m water head or —10^4 bar (oven dry soil). Formerly a logarithmic scale was often used in which the symbol pF equals the ^{10}log of the negative of the matric potential when the latter is expressed per unit weight of water and having as dimension cm.

In general the relationship is established by equilibrating a saturated soil sample at a succession of known matric potentials and at each time determining the amount of water that is retained. Plotting the equilibrium water content against the corresponding matric potential gives what is known as the soil water characteristic curve.

It is imperative to use undisturbed soil samples for the high matric potential range (0 to —1 bar), since the structure is of influence on the water retaining properties. For the lower matric potential ($<$ — 1 bar or $<$ — 10^3hPa or $<$ —10 m water head or $>$pF 3 disturbed samples ($<$2 mm) may generally be used.

If the soil air is kept at atmospheric pressure and the pressure difference across the porous medium is controlled either by a hanging water column or by vacuum the minimum value is limited to —1 bar (Method 1, 2 and 3).

Matric potentials considerably lower than — 1 bar can be obtained by increasing the pressure of the air (Method 2).

The soil water characteristic curve, or a more descriptive name for it, the soil water retentivity curve, is used as follows:
—to determine an index of available water in the soil and to classify soil accordingly (e.g. for irrigation purposes).
—to determine the drainable pore space for drainage design.
—to check changes in the structure of a soil (e.g. caused by tillage, addition of organic matter or synthetic soil conditioners).
—to ascertain the relationship between the matric potential and other soil physical properties (e.g. hydraulic conductivity, thermal conductivity).
—to give a general assessment of pore size distribution.

It is recommended that in preparing water characteristic curves, the amount of soil water related to some standard values of the matric potential should always be included viz. at:

pF	Matric potential		
	bar	m(head)	hPa
1	—0.01	— 0.1	— 10
1.78	—0.06	— 0.6	— 60
2	—0.1	— 1.0	— 100
2.5	—1/3	— 3.4	— 333
3	—1	— 10.2	— 1000
4.2	—15	—153	—15.10^3

Descriptive information about the soil pore system—equivalent pore size distribution—can be obtained using the law of capillary rise:

$$h = \frac{2\gamma\cos.\theta}{\rho g r}$$

where: h = height of water rise in a capillary tube (m)
r = radius of the capillary tube (m)
γ = surface tension of the liquid (kg s^{-2})
ρ = density of the liquid (kg m^{-3})
g = acceleration due to gravity (m s^{-2})
θ = contact angle between water and the material composing the capillary and assumed to be zero.

The volume of water extracted from an initially saturated soil sample by a given negative or positive pressure h (dimension length) is equal to the volume of pores having an effective radius greater than the radius r corresponding to the selected value of h in the capillary equation.

The soil pores which differ in size and shape as a result of textural and structural arrangement and estimated from the soil characteristic curve are not only difficult to be classified but the results can be erroneous e.g. in clayey soils due to shrinkage.

If an adequate fitting of the measurement points (h — θ relationship) is possible the pore size distribution can be obtained by mathematical integration.

However storage, availability and transport of soil solution and soil air largely depend on how the total pore space is partitioned and therefore are sometimes classified in:
—macropores (or drainage pores): they affect aeration and drainage.
—micropores (or water holding pores): the remaining pores in which the soil solution is retained or moves very slowly and can be taken up by the plant roots.

As the boundary limits for macro- and micropores could be different from case to case no limits are proposed. However if a distinction is made between macro- and micropores the limits should be stated.

.2 Tension method

Principle:

Undisturbed soil samples are saturated with water and successively brought into equilibrium with the applied negative pressure to a water saturated porous medium on which the samples are placed in close contact. At equilibrium the water content is measured by weighing and related to the applied negative pressure or matric potential.

Equipment:
Sintered glass Büchner funnels connected to an overflow system by means of flexible tubing. Sampling cylinders, oven and balance. The plate in the funnel should be of sufficiently fine porosity to preclude air-entry over the range of negative pressure of concern.

Procedure:
Place undisturbed soil sample on the saturated sintered glass and ensure good contact between the sample and the porous medium. The soil is then fully wetted (saturated) from underneath by raising the point of outflow of the flexible water hanging column. After saturation, cover the Büchner funnel to prevent evaporation and lower the point of outflow until the desired matric potential is obtained.

At each equilibrium, when water flow through the outflow tube of the hanging column ceases, determine the water content gravimetrically.

Calculation:
Subtract the mass of oven-dry (105°C) soil from the mass of wet soil thus giving the equilibrium value "w" of water content per unit mass of oven dry soil at each matric potential level.

$$w = \frac{m_{s+w} - m_s}{m_s} \qquad (\text{kg kg}^{-1})$$

where: m_{s+w} = mass of wet soil (kg)
m_s = mass of oven dry soil (kg)

The water content can be converted to volume basis (θ), knowing the bulk density of the soil sample, using the following relation:

$$\theta = \frac{w\rho_b}{\rho_w} \qquad (\text{m}^3\ \text{m}^{-3})$$

where: ρ_b = bulk density of the soil (kg m^{-3})
ρ_w = density of water (1000 kg m^{-3})

Time required:
Depending on the composition and size of the sample and the applied negative pressure. In general it requires from 2 to 14 days to reach equilibrium.

Cost:
Material costs are low. Running of samples in laboratory is not expensive. Highly qualified personnel are not needed.

Accuracy:
Good since the matric potential and water content are directly and accurately determined. The accuracy of the water content by volume depends on the accuracy of the bulk density value.

Advantages:
Technically simple, inexpensive and well suited for routine analysis.

Disadvantages:
Only one sample can be treated per Büchner funnel. It is a desorption curve and the range is limited between saturation and a negative pressure related to the air-entry value of the sintered glass (approximately—0.5 bar or — 500 cm H_2O column).

Remarks:
Instead of a sintered glass plate sand can be used as a porous medium. The laboratory set-up consists of a sandbox with a drainage system, connected with an adjustable levelling bottle to realize the desired negative pressure. A great number of samples can be treated at the same time. The range is limited between saturation and a negative pressure of —0.1 bar.

If the porous medium consists of a mixture of sand and kaolin clay the range can be extended up to —0.5 bar.

References:

Stackman, W. P., G. V. Valk, and G. G. Van der Harst, (1969). Determination of soil moisture retention curves I. Sandbox apparatus. Range pF 0 to pF 2.7. ICW, Wageningen, The Netherlands.
Vomocil, J. A., (1965). Porosity. *In:* "Methods of Soil Analysis", I. (Ed. C. A. Black). Agronomy No. 9, Am. Soc. Agron., Madison, Wisconsin.
West-European Methods for Soil Structure Determination, (1967). Determination of the moisture retention curve up to pF 2.7 with the sandbox method. V, 53, Ghent, Belgium.

.3 Gas pressure method

Principle:
Soil samples on a porous medium (membrane) are saturated with water and successively brought into equilibrium with an applied positive pressure. At equilibrium the water content is determined and related to the applied positive pressure or matric potential.

Equipment:
The pressure apparatus, consists of a pressure chamber containing a porous ceramic membrane or a cellulose acetate membrane, a water delivery tube, an air pressure connection, a regulated source of compressed air. Balance and oven.

Procedure:
The measurement procedure begins with saturating the porous membrane, then the soil samples are placed on it, saturated with water and allowed to stand. Connect the membrane to the outflow system. Close the lid of the extractor. Compressed air or nitrogen is introduced into the chamber at the required pressure, causing water to flow from the soil through the porous membrane until equilibrium is reached.

Once equilibrium is reached—when readings on the outflow burette indicate that liquid water outflow has ceased—release the pressure in the chamber, open the chamber and transfer the samples in metal cans for gravimetric water content determination.

Calculation:
See method I.

Time required:
The time necessary for establishing equilibrium is dependent upon the sample size, soil type and applied pressure (2—14 days).

Cost:
The price is reasonable taking into account the number of samples which can be treated and the low costs for personnel.

Accuracy:
Good.

Advantages:
Can be used over a wide range of matric potential (0 bar—20 bar), using either undisturbed or sieved soil samples.

Disadvantages:
Due to entrapped air the actual matric potential can be less than that assumed to be applied. Even small air leaks can result in a continuous loss of vapour.

Remarks:
The limit of applied gas pressure is determined by the design of the chamber (i.e. its safe working pressure) and by the maximal air-pressure difference the saturated porous membrane can bear without allowing air to bubble through its pores. Ceramic plates generally do not hold pressures greater than 20 bar, but cellulose acetate membranes can be used with pressures exceeding 100 bar.

If the pressure apparatus is constructed for only one sample, then the air pressure can be increased stepwise. At each step the extracted water is collected and measured. After equilibrium has been reached at the final pressure, the sample is removed from the pressure cell and its water content determined gravimetrically. The water content at various pressure levels can then be calculated by taking into account the amount of outflow at each step.

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.4 Vapour pressure method

Principle:
It is based on the relation between the soil water potential—being the sum of the solute or osmotic potential (ho) and the matric potential (hm)—and the water vapour pressure (relative humidity) of the surrounding atmosphere. The sample under investigation is allowed to reach moisture equilibrium with an atmosphere of a known humidity, transfer of water taking place in the vapour phase. The water content of the sample at equilibrium is determined by weighing.

For non-saline soils the vapour pressure method can be used to establish the relation between the water content and the low matric potential (—10 bar to —10^3 bar).

Equipment:
Humidity chamber (desiccator), water bath. Saturated salt solutions. Balance. Oven. Waterjet pump or vacuum pump.

Procedure:
A (wet) sample is put in a separate wire basket and suspended inside a desiccator containing a saturated salt solution. The desiccator is put in a water bath (20°C) and evacuated with a waterjet pump or vacuum pump.

After three days the basket with soil is removed, weighed quickly and replaced inside the desiccator. The weighings are repeated at 24 hour intervals until a constant weight is obtained.

The water content at equilibrium is determined gravimetrically and converted to volume basis using the bulk density.

Calculation:
The value of the soil water potential for which the water content at equilibrium has been determined can be calculated using the following equation:

$$h_m + h_o = \frac{RT}{Mg} \ln P/Po \qquad (1)$$

where: h_m = matric potential (m)
h_o = osmotic potential (m)
R = universal gas constant (8.3 J mol^{-1} K^{-1})
T = absolute temperature (K)
M = molecular weight of water (0.018 kg mol^{-1})
g = acceleration due to gravity (9.81 m s^{-2})
P = actual vapour pressure of soil air (any unit)
Po = vapour pressure of saturated air (any unit at same temperature)

P/Po is the relative vapour pressure or (P/Po). 100 being the relative humidity of the atmosphere expressed as percentage.

For non-saline soil the osmotic potential ho may be neglected and the matric potential hm can be calculated from equation (1).

The equation (1) can be transformed in such a way that the following relation can be obtained:

$$pF = 6.502 + \log (2 - \log R.H.)$$

where: R.H. = relative humidity.

Time required:
It requires a long time before equilibrium is reached (5—15 days).

Cost:
Equipment and running costs are cheap.

Accuracy:
Good since the matric potential can be calculated accurately.

Advantages:
Direct measurement and cheap.

Disadvantages:
Accurate temperature control is needed, since humidity conditions are dependent on temperature. Long time is required before data are obtained. Condensation of water vapour on the soil sample could occur due to temperature fluctuations. Weighing should be carried out as fast as possible to avoid possible water loss by evaporation.

References:

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.5 In situ determination

Principle:
The relation between the matric potential and the water content is obtained in situ using tensiometers and the neutron scattering method or gravimetric method respectively. The soil water characteristic curve is obtained for the range 0 to —0.8 bar.

Equipment:
Tensiometers and neutron moisture gauge or auger and soil containers with tight fitting lids.

Procedure:
Tensiometers are installed in the field at different depths to estimate the matric potential. Simultaneously the matric potential from tensiometer readings and the water content (see methods for soil water content determination) using the neutron moisture gauge (non-destructive method) or gravimetrically (destructive method) are estimated.

Calculation:
The matric potentials are obtained from tensiometer readings while the water contents depend on the method used (see methods for soil water content determination).

Time required:
After installation of the equipment wait until the tensiometers are in equilibrium with the surrounding soil water. It takes a long time (several weeks) before a soil water characteristic curve in the field is obtained.

Cost:
Variable, depending on the method used for water content determination.

Accuracy:
The matric potential can be determined accurately. The accuracy of the water content will depend on the method used (see methods for water content determination).

Advantages:
The measurements are done in situ and consequently are more representative than laboratory measurements. The soil water characteristic curve is obtained from the same soil volume.

Disadvantages:
The obtained relationship (h — θ) will be different if it is obtained during a wetting or drying cycle due to hysteresis effect.

Due to possible entrapped air, the water contents obtained from direct field measurements will be mostly lower than those from laboratory determination.

Reference:

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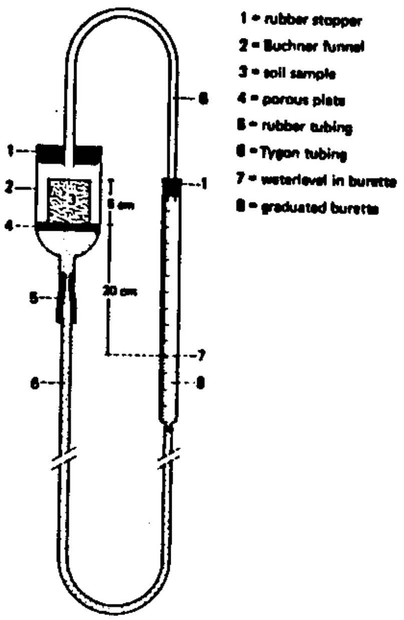
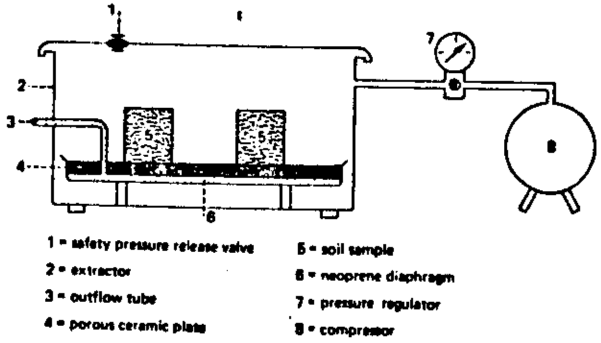
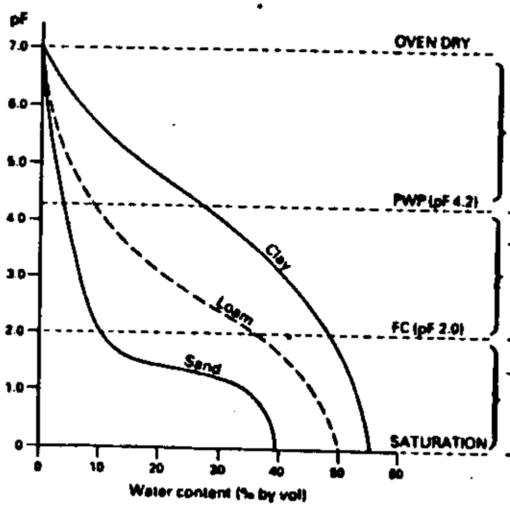


Schematic diagram of an apparatus for soil water retention measurements at high matric potential (tension method).



Schematic laboratory set-up of a pressure plate extractor for soil water retention measurements at low matric potential (gas pressure method).



CORRESPONDING WATER CONTENTS (vol %) Sand	Loam	Clay
Unavailable (or residual) water		
4	9	29
Available water		
6	29	20
Drainage water		
29	12	6

Indicative soil moisture characteristic curves.