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COLLEGE ON SOIL PHYSICS

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SOIL WATER POTENTIAL

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LECTURE NOTES

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Table of contents

p.

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1. 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 for each parcel of matter 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 of 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 employin 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 transport 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-plant-atmosphere-system" (Figure 1).

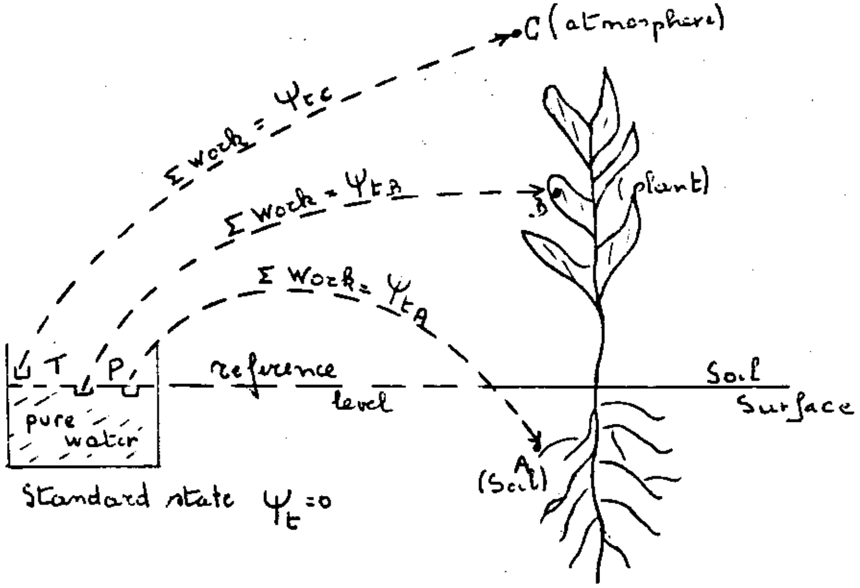

Figure 1 : Potential of soil water, water in plant cell and water in the atmosphere.

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 fields 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 :

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

where:

ψ_t = total potential,
ψ_m = matric potential,
ψ_g = gravitational potential,
ψ_o = osmotic potential,
ψ_p = pressure potential.

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.

2. Quantitative expression of soil water potential

The soil water potential can be expressed in at least three ways :

a) as an energy per unit mass of water :

$$\mathrm{erg.g^{-1}}$$

b) as an energy per unit volume of water (unit of pressure) :

$erg.cm^{-3}$ or dyne cm^{-2} (bars, atmosphere, etc...)

c) as an energy per unit weight of water (unit of head) :

$erg.dyne^{-1}$ or cm (head)

Whatever can be expressed in units of hydrostatic pressure can also be expressed in terms of an equivalent head of water, which is the height of a liquid column corresponding to the given pressure. For example, a pressure of 1 atm. is equivalent to a vertical water column or hydraulic head of 1033 cm and to a mercury head of 76 cm. This method of expression is certainly simpler, and often more convenient then the previous methods. Expression in terms of unit weight is simple and attractive for applied work. Hence it is common to characterize the state of soil water potential in terms of the total potential head, which are usually expressible in centimeters or meters of water.

3. 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.

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.

Conversion table for units of soil water potential (1).

Specific potential units		Volumetric potential units				Weight potential units
ergs/g	joules/kg	bar	millibar	centibar	atmosphere	cm
-1	-0.000 1	-0.000 001	-0.001	-0.000 1	-0.000 000 987	-0.001 017
-10 000	-1	-0.01	-10	-1	-0.009 87	-10.17
-1 000.000	-100	-1	-1 000	-100	-0.987	-1 017
-1 000	-0.1	-0.001	-1	-0.1	-0.000 987	-1.017
-1 013 000	-101.3	-1.013	-1 013	-101.3	-1	-1 030
-983.3	-0.098 33	-0.000 983 3	-0.983 3	-0.098 33	-0.000 970 3	-1

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(1) 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.

At a height z above a reference the gravitational potential energy of a mass M of water, occupying a volume V is :

$$M\,g\,z = \rho_w\,V\,g\,z$$

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

Gravitational potential can be expressed :

per unit mass : $\psi_g = g\,z\ (\mathrm{erg.g^{-1}})$

per unit volume : $P_g = \rho_w\,g\,z\ (\mathrm{dyne.cm^{-2}})$

per unit weight : $z = z\ (\mathrm{cm})$

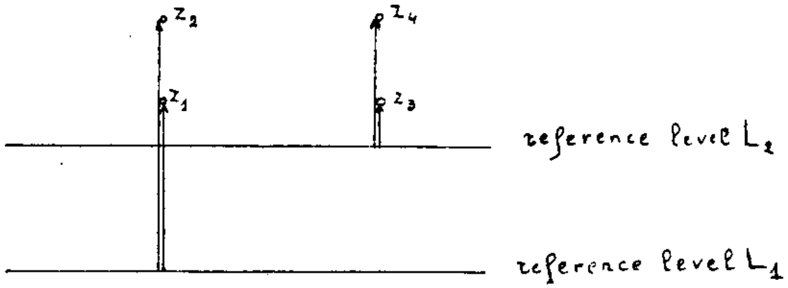

Figure 2 : The difference in gravitational potential between two points is identical for different reference levels.

Assume a reference level L_1 (Figure 2) and the presence of 1 gram of water at different heights z_1 cm and z_2 cm above that level. The gravitational potential (z) is now z_1 cm and z_2 cm respectively. The reference level, which is arbitrary, can be shifted to level L_2. Then the z potentials are z_3 cm and z_4 cm respectively.

Still the difference between the two $(z_4 - z_3)$ is equal to the earlier difference when the reference level was at L_1 $(z_2 - z_1)$. Differences in potential are generally more important than their absolute values when studying water movement in soils. The reference elevation can usually be arbitrarily chosen. For the sake of convenience it is costumary to set the reference level at the elevation of a pertinent point within the soil. In practice it means normally the soil surface.

4. Osmotic potential

The presence of solutes in soil water lowers its potential energy. Indeed the fact that water molecules move through a semi-permeable membrane from the pure free water into the solution indicated that the presence of solutes reduces the ability of water to perform work (Figure 3)

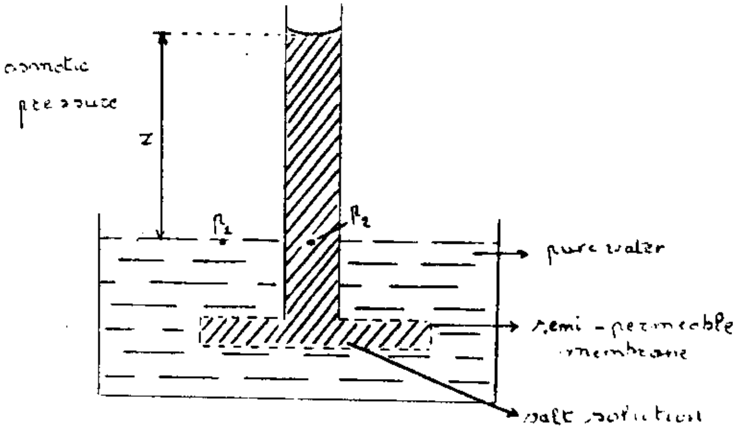

Figure 3 : Schematic presentation of osmosis.

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).

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_o will no longer exist. Therefore osmotic potential does not act as a driving force in water flow. (Barriers for the movement of salts are formed by the surface of roots). Nevertheless the osmotic potential is important as it has to be add to the matric potential in order to estimate how much work the plant must expend to extract a unit amount of water from the soil.

The magnitude of the osmotic potential can be calculated by means of following equation (law of Van 't Hoff)

$$\pi = -\frac{n}{v} RT$$

where :

π = osmotic pressure (atmosphere),

R = universal gas constant (0.082 l atm mol^{-1} K^{-1}),

$\frac{n}{v}$ = molarity of salt solution (mol l^{-1}),

T = absolute temperature (273 + t°C).

Example : Solution containing 0,01 N NaCl at 25°C

$$\pi_{Na} = \frac{0.082 \times 298 \times 0.01}{1} = -\ 0.25 \text{ atm.}$$

$$\pi_{Cl} = \frac{0.082 \times 298 \times 0.01}{1} = -\ 0.25 \text{ atm.}$$

Total osmotic potential equals - 0.50 atm.

5. Matric potential.(1)

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 (law of Laplace):

$$p_o - p_1 = \Delta P = -\ \gamma \left(\frac{1}{R_1} + \frac{1}{R_2}\right)$$

where p_o is the atmospheric pressure, conventionally taken as zero; p_1 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.

As we assume the soil pores to have a cylindrical shape (Figure 4) the meniscus has the same curvature in all directions and equation above becomes:

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

since:

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

$$\Delta P = -\ \frac{2\gamma}{r}$$ with ΔP also equals h $\rho_w g$

where: h = height of capillary rise,

ρ_w = density of water,

g = acceleration of gravity

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

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 5.

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.

In general, however, the negative 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:

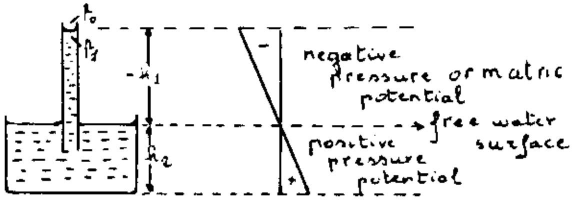
$$gh = - \frac{2\gamma}{r\rho} \quad (\mathrm{erg.g^{-1}})$$

- per unit volume:

$$P = - \frac{2\gamma}{r} \quad (\mathrm{dyne.cm^{-2}})$$

- per unit weight:

$$h = - \frac{2\gamma}{\rho g r} \quad (\mathrm{cm})$$



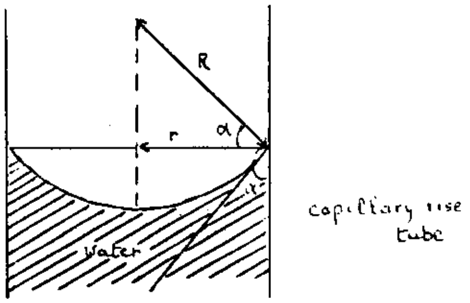


Figure 4 : Capillary rise of water into a capillary tube.

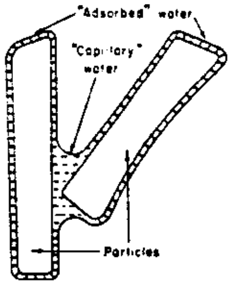


Figure 5 : Water in an unsaturated soil is subject to capillarity and adsorption, which combine to produce a matric suction (matric potential).

The matric potential is a dynamic property of the soil. In a saturated soil ψ_m is zero, in unsaturated soil ψ_m is negative.

6. 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 air pressure results in a pressure different from that at the standard reference state which gives origin to the so called pneumatic potential, ψ_p^n (See laboratory for the determination of the soil water characteristic curve).

Situation with water table.

In saturated soil the liquid phase is at hydrostatic pressure greater than atmospheric and thus its pressure potential is considered positive (Figure 4). Thus water under a free water surface is at positive pressure potential, 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.

Some soil physicists prefer to separate the positive pressure potential from the matric potential assuming the two to be mutually exclusive and has been termed the submergence potential, ψ_p^u. Accordingly soil water may exhibit either of the two potentials, but not both simultaneously.

Nevertheless it is an advantage in unifying the matric potential and the positive pressure or submergence potential ψ_p^u, 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 region into the unsaturated region, below and above the water table.

In the field ψ_p^u is measured with a piezometer and it is the vertical distance from the point under consideration in the profile to the water surface of a piezometer connected to the point in question if expressed per unit weight.

7. Hydraulic head.

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

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

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:

$$\psi_m + \psi_g + \psi_p = \text{constant} = \psi_H \qquad (1)$$

called hydraulic potential.

It is often usual to designate the potential in terms of head (potential energy per unit weight).

In nonequilibrium conditions under isothermal conditions, water flow occurs from locations where the total water potential is high to locations where the total water potential is low. For example, if the total water potential at point A in a soil is - 200 cm and the total water potential at point B is - 350 cm, the water will flow from point A to point B.

As already stated, the pneumatic potential ψ_p^n for field studies may be assumed to be zero. Also the soil water within a profile may exhibit either matric or submergence potential (Figure 4) but not both 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.

In the unsaturated zone (above the water level), equations (1) becomes:

$$\psi_m + \psi_g = \psi_H$$

or in terms of head:

$$h + z = H$$

where: h = soil water pressure head (cm)
z = gravitational head (cm)
H = hydraulic head (cm)

This 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 6 the condition is applied to a vertical soil column in equilibrium with a water table. No water movement occurs in the column. The groundwater table is taken as the reference level for the gravitational potential.

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

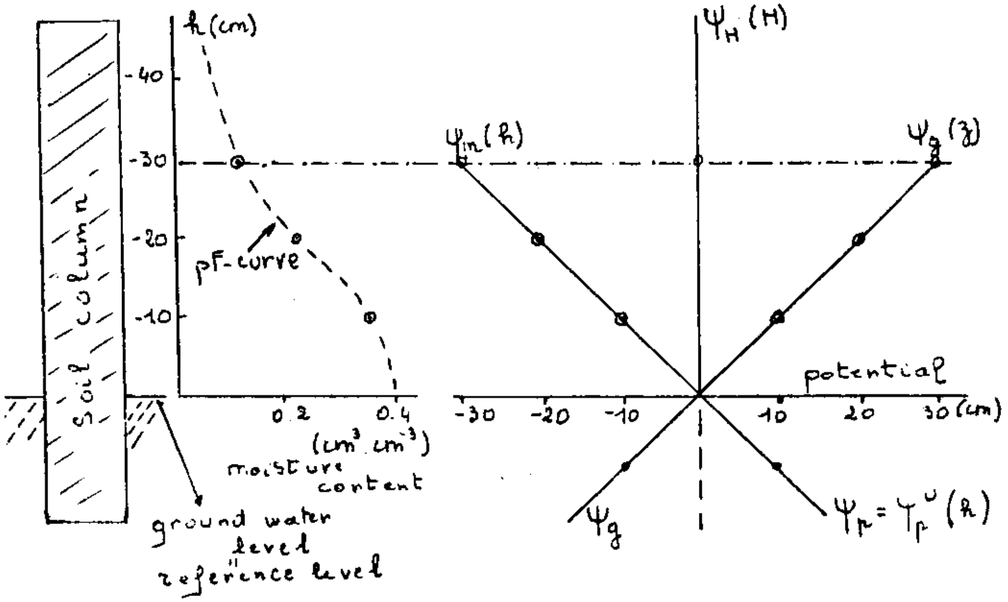


Figure 6. Equilibrium condition in a soil column.

height(cm)	ψ_g (z,cm)	ψ_m (h,cm)	ψ_p (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