SOIL MOISTURE TENSION MEASUREMENTS: THEORETICAL INTERPRETATION AND PRACTICAL APPLICATION

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ABSTRACT

The tension phenomenon described herein occurs in a wide variety of porous materials, including sands, clays, agricultural soils and porous rocks. When some of the water is removed from a water-saturated porous system, the residual water evidently remains physically interconnected, judging from the fact that water can be transmitted through the system at reduced water content by suction.

The removal of water may result in contraction of the system, as in the case of clay, or in the entry of air, as in the case of sand. The liquid phase and the solid phase in contact with it comprise a closely linked force system. Equilibrium can be established between the system at reduced water content and a separate mass of water at reduced pressure through a porous membrane in contact with both.

The equilibrium tension required in the external water phase is considered an attribute of the moist, porous, system itself. From this point of view, the tension originates through the combined action of the internal forces of the system in a virtual displacement of water. It follows from this and from the principle of virtual work that the tension is numerically equal to the differential work done by the internal forces per unit volume of water absorbed.

The movement of water, under tension, through porous systems represents a special class of flow phenomena in which tensiometers or equivalent devices are required for measuring the hydraulic potential. Flow patterns can be determined in much the same way as in systems characterized by positive hydrostatic pressures, but special attention must be paid to the Darcy coefficient (the capillary conductivity) which varies with the tension.

The theoretical conditions for the equilibrium of water in the soil and for emergence from the soil have been developed in terms of the tension and certain applications have been indicated.

The phenomenon referred to in the soil science literature as moisture tension has been recognized for almost forty years and has been used as a means of explaining the absorption and movement of water in the soil. It is closely related to osmotic pressure but its mechanism cannot in general be identified with the traditional mechanisms of osmotic pressure. Moisture tension has been observed in wet clay soils and in other finely divided porous systems containing interstitial water, but the phenomenon is not confined to colloidal systems, since moist sand and moist porous rock, such as pumice, show similar effects.

RETENTION OF WATER BY SOIL ON A SUCTION FILTER

The following simple experiment serves to demonstrate the phenomenon. Figure 1 shows an apparatus consisting of a sintered glass filter funnel attached to a measuring pipette with a rubber tube. The lower filter chamber and the connecting tube contain water, free of air bubbles. The appara-

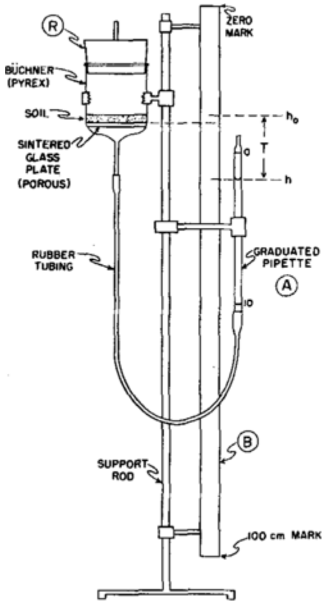

FIGURE 1. — Suction filter apparatus.

tus is tested to insure that air will not pass the filter plate when the measuring pipette is lowered to its full extent.

A sample of soil is placed on the filter and the pipette is raised until the soil is flooded with water. A one-hole rubber stopper (R) is inserted to suppress evaporation of water. The pipette is lowered slowly, in successive small steps, and the amounts of water retained by the soil at different elevations of the pipette are determined from the pipette readings after movement of water has ceased.

Figure 2, curve ABC, shows the results for a sand whose particles are from 0.25 mm. to 0.50 mm. in diameter. The horizontal axis in Figure 2 represents the tension (in terms of height of water column) in the water caused by the difference in the heights of the water columns on the left and right sides of Figure 1.

The sand remains saturated until a tension of approximately 10 cm. is reached (point B). Between B and C, a certain amount of water passes from the sand into the filter chamber with each additional increase of tension. In the given case the water content of the sand diminished from 29 percent at zero tension to 3 percent at 50 cm. tension.

Desorption curves can be determined by this procedure for many porous materials, including agricultural soils, clays, and porous rocks. Although water may be held by various different mechanisms in these widely divergent materials, there are certain general features of the measurements which apply to all such porous systems. These will be discussed below.

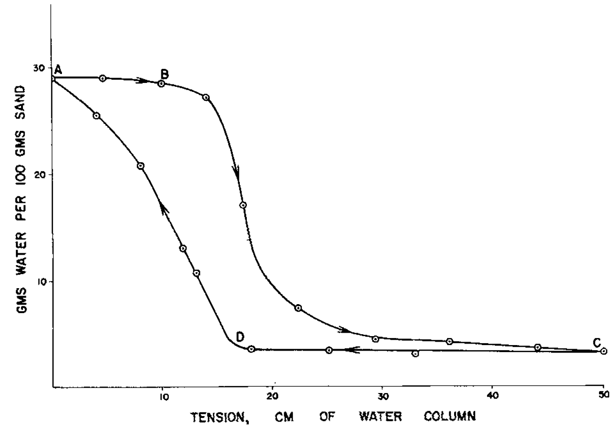

FIGURE 2. — Relationship between water tension and water content for quartz sand, 0.50-0.25 mm.

The water in the soil is obviously connected with the water on the outflow side of the filter plate because of the fact that water moves out of the soil when the pressure of the water is decreased by lowering the pipette. Moreover, the various parts of the liquid phase of the soil must be interconnected and some of the water translocated within the soil under the influence of the altered pressure.

When transfer of water ceases for a given applied tension, the system must be in a state of stable equilibrium. This can be verified experimentally by adding a small amount of water to the pipette by means of a medicine dropper, or by withdrawing a small volume of water by means of a small tube inserted in the pipette. In either case the level of the water returns approximately to its initial level in a short time. The restoration of initial conditions by the action of the forces of the system is a sensitive and general test for mechanical equilibrium.

In general, water is held in the soil by a complicated system of forces whose joint action produces an apparent tension in the liquid phase, manifested by the amount of tension required in a contiguous liquid phase to maintain equilibrium with the soil-water system in its given state of moistness and structure. Thus, the tension is not merely an externally applied constraint, as in the above experiment, but is an intrinsic property of the system which depends upon the mutual affinity of the soil and water, and which indicates quantitatively the collective action of the internal forces in a differential or virtual displacement of water.

RETENTION OF WATER BY CAPILLARITY

The particular case shown in Figure 2 can be explained entirely from the principles of capillarity. The phenomenon was discussed by Versluys

(1917) and was studied later in greater detail by Haines (1930). The pressure difference between the atmosphere and the liquid phase of the soil is equivalent to the pressure difference across the various curved air-water interfaces brought about by the retraction of the water into the interstices of the soil. Since the shrinkage of the sand is necessarily small, the withdrawal of water is accompanied by the entry of air, starting at point B. At all points beyond B, each increment of tension causes a displacement of water by air at atmospheric pressure. The air is not confined to the periphery of the soil mass, but invades the interior spaces of the soil.

The geometrical shape of the liquid phase adjusts to accommodate the volume of air which enters. Both liquid and gas phases become multipliconnected continuous phases, the liquid maintaining hydraulic contact with the liquid in the filter plate, and the air remaining at atmospheric pressure through its connection with the external air.

The branch CDA of Figure 2 represents the re-entry of water induced by slowly raising the pipette from the lowest position reached in the desorption curve ABC. The separation of this curve from the branch ABC is a typical hysteresis effect, attributed by Haines to entrapping of air and to the altered configuration of the liquid phase in the reverse part of the cycle. The occurrence of hysteresis demonstrates that although the tension is a function of water content, it is affected by other additional factors.

SOIL MOISTURE TENSIOMETERS

In the apparatus described above for the demonstration of the moisture tension phenomenon, the tension was adjustable and therefore served as an independent variable, with water content the dependent variable. It is often necessary, as in experiments on water movement, to measure tension as a dependent variable. The soil moisture tensiometer is a device suitable for measuring tensions up to a value of nearly one atmosphere. A successful device of this kind was first demonstrated and interpreted theoretically by Willard Gardner and associates (1922). It consists of a water-filled porous cone or filter cylinder, attached to a manometer or vacuum gage, and embedded in the soil. Detailed descriptions of such devices and their operation have been given by Richards (1949).

The water content and tension are unaffected by the tensiometer in the zone of the soil in which it is placed, except for local changes of water content resulting from exchange of water between tensiometer and soil during approach to equilibrium. Therefore the tensiometer serves as a means of determining soil moisture tension in both static and dynamic systems.

MOISTURE EQUILIBRIA IN CLAY AT HIGH TENSIONS

Tensions greater than one atmosphere cannot be measured satisfactorily by means of tensiometers. However, it is possible to establish soil moisture equilibria at high tensions by means of a device known as the pressure membrane apparatus (Richards, 1940). This method is similar to the filter funnel method except that a positive pressure of nitrogen gas is applied to the gas space above the saturated soil instead of a negative pressure to the liquid. Water passes through the membrane (cellophane) and emerges at atmospheric pressure. The water content of the soil is measured after outflow ceases. The difference between the gas pressure on the soil and the water pressure on the outflow side of the membrane is generally referred to as the moisture tension, as in the simple filter funnel method.

Richards (1949) carried his measurements to tensions of 100 atmospheres, and showed that displacement of water occurs for each increment of tension throughout this range. Figure 3 shows his results for Chino clay, an agricultural soil.

Childs and George (1948) studied the desorption of water from kaolinite by means of pressure membrane equipment. They found that until a tension of 4 atmospheres was reached the decrease of volume of the clay-water system was equal to the volume of water removed. Air began to enter the clay at this point, but at all tensions less than 4 atmospheres the system remained a 2-phase clay-water system. Similar results have been found for other clays.

In sands, the increase of tension which accompanies a decreasing water content is a capillary phenomenon associated with the changing configurations of the water-air interfaces throughout the system. In saturated clay, the decrease of water content is associated with a volume contraction of the entire system. Evidently the water is held by different mechanisms in these two types of systems. The capillary mechanism has played a prominent part in the development of ideas pertaining to the retention and movement of water in soil. However, the above experiments with clay indicate that in general other mechanisms also play a part in the tension phenomenon.

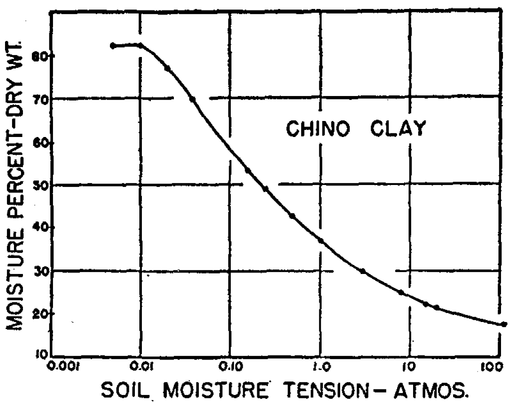

FIGURE 3. — Soil moisture tension vs. moisture content, Chino clay (from Richards, 1949).

THEORETICAL INTERPRETATION OF SOIL MOISTURE TENSION MEASUREMENTS BASED UPON THE PRINCIPAL OF VIRTUAL WORK

Since several mechanisms may operate concurrently to produce moisture tension, a general treatment of the phenomenon is required which is independent of mechanism. Consider the hypothetical device shown in Figure 4. Let the pressure P of the piston be adjusted until the water absorptive forces are exactly counterbalanced and the system is in equilibrium. We know from the preceding results that the pressure P at equilibrium is generally less than the atmospheric pressure P_A acting on the exposed faces of the block.

Let the pressure P be increased by an infinitesimal amount, and let a volume dV of water be drawn into the soil. Designate by dW the total amount of work done by the water absorptive forces. The amount of work done by the piston will be equal to PdV. When the water enters the soil, a volume dV of air will be displaced at atmospheric pressure, and an amount of work equal to $P_A dV$ will be done by the system against the pressure of the atmosphere. (This relationship is valid for soils which expand during absorption of water and also for 3-phase systems in which air is displaced by the entering water.)

From the mechanical principal of virtual work, the total work done in a virtual displacement is equal to zero, so

$$PdV - P_A dV + dW = 0.$$

The work done by the absorptive forces per unit volume of water absorbed is therefore equal to

$$\frac{dW}{dV} = (P_A - P).$$

Since the pressure difference $(P_A - P)$ represents the moisture tension, it is evident that the tension is a measure of the mechanical work available

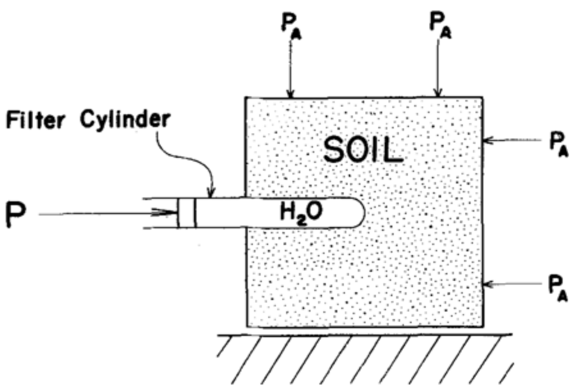

FIGURE 4. — Hypothetical device for relating soil moisture tension to available work.

from the forces of the system in the absorption process, for each unit volume of water absorbed.

The principle of virtual work has been used previously by Buckingham (1907) and by Israelsen (1927) for equilibrium of water in vertical soil columns.

From the method of development, one can see that the above relationship is independent of the nature of the forces which hold the water in the soil. A measurement of tension does not in itself reveal the mechanism which gives rise to it. It may be caused by capillary effects (as in sand), by swelling or contractile forces (as in clay), and perhaps by other mechanisms.

CAPILLARY MOVEMENT OF WATER IN THE SOIL

The movement of water under tension is usually referred to as "capillary flow." An understanding of capillary flow involves theoretical considerations beyond those already presented and brings out a second feature of the tension — the part which it plays in the transmission of water through the soil.

Consider a small element of volume within the liquid phase. In general, the pressure will be different on the different faces of this element, and the resultant force acting on the volume element will not be equal to zero. If the force per unit mass of water in the element due to pressure is designated by a vector F_p, we know from fluid mechanics that

$$F_p = -\frac{1}{\rho}\nabla \mathrm{P}$$

where ρ is the density of the fluid and $\nabla \mathrm{P}$ is the pressure gradient.

The magnitude of the downward force per unit mass of water due to gravity is equal to g. In vector notation, this force can be presented as

$$F_g = -\nabla gz,$$

where z is the vertical coordinate, directed upwards, and gz is the gravitational potential.

Combining the force due to pressure with the force due to gravity, we have the vector sum

$$F = -\frac{1}{\rho}\nabla \mathrm{P} - \nabla gz = -\nabla\left(\frac{\mathrm{P}}{\rho} + gz\right) = -\nabla\Phi,$$

where $\Phi = \left(\frac{\mathrm{P}}{\rho} + gz\right)$. The quantity $\frac{\mathrm{P}}{\rho}$ is usually referred to as the pressure potential (or frequently, in the case of capillary flow, as the capillary potential). We shall designate Φ as the hydraulic potential, noting that it is equal to the sum of the pressure potential and gravitational potential. (This terminology is analogous to the practice in hydraulics of defining the hydraulic head as the sum of the pressure head and the gravity head.)

The force F, called the driving force or motive force, causes water to move through the porous medium against the viscous shear forces, which are transferred from point to point transversely through the liquid to the solid. Consider the amount of work W done by the force F against viscous shear forces during the transfer of a unit mass of water from a point Q_1 to a point Q_2 in the soil:

$$W = \int_{Q_1}^{Q_2} F \cdot dS,$$

where dS is a line element in the direction of flow.

If the soil is isotropic, the force F is collinear with the line element dS, and the work integral can be written in terms of the corresponding scalar magnitudes F and dS as follows:

$$W = \int_{Q_1}^{Q_2} F dS = \int_{Q_1}^{Q_2} -d\Phi = (\Phi_1 - \Phi_2).$$

Now W must be positive, because of the fact that energy is dissipated in viscous shear. Therefore, $\Phi_1 > \Phi_2$, showing that the movement can occur only from points of higher to points of lower hydraulic potential.

In capillary flow, where the pressure must be measured by means of tensiometers, the flow system can be analyzed on the basis of potential theory, in much the same way as in systems characterized by positive hydrostatic pressures.

For example, the seepage of water in soil often consists entirely of capillary flow. Day and Luthin (1954) have shown from potential theory, and have verified experimentally, that water moving through the soil from a furrow and into a gravel substratum remains under tension throughout, and that experimental study of the flow system requires the use of tensiometers.

The tension, which originates physically in the water-absorptive forces of the solid-liquid system, plays a role in capillary flow identical to that of the hydrostatic pressure in positive pressure systems, except that by convention the algebraic sign of the tension is opposite to that of the pressure.

APPLICATIONS OF SOIL MOISTURE TENSION MEASUREMENTS

The moisture tension phenomenon has many practical implications which can be more fully appreciated as a result of the theoretical developments which followed its discovery. Several examples will be given.

Consider a region of the soil immediately above a water table. This region remains moist due to its proximity to the water table, and contains water under tension, as one may readily verify by means of a tensiometer.

If the water in this moist zone (commonly called the capillary fringe) is at rest, viscous shear forces in the fluid will be absent. Therefore

$$F = -\nabla\left(\frac{P}{\rho} + gz\right) = 0,$$

from which it follows that

$$\frac{dP}{dz} = -\rho g,$$

or

$$\frac{dh_T}{dz} = 1,$$

where h_T represents the tension in terms of equivalent height of water column. Thus, the condition for equilibrium in the capillary fringe is that the tension will increase with height above the water table in accordance with the simple hydrostatic pressure law, each cm. increase in height being characterized by an added cm. of equivalent water tension.

The same equation applies for equilibrium of water in the soil in the absence of a water table, as verified experimentally by Richards (1950a). The condition for equilibrium holds for soils of all texture, uniform or stratified, and saturated or unsaturated with water, provided only that the liquid phase be hydraulically connected throughout.

The condition for emergence of water in the liquid state from the soil may be deduced as follows: Let Φ_1 be the hydraulic potential at a point Q_1 in the soil near an opening (*e.g.* an empty drain) and let Φ_2 be the potential at a nearby point Q_2 in the opening, in a drop of liquid adhering to the soil. The general condition for flow is that $\Phi_1 > \Phi_2$. Now, let P_1 represent the pressure in the liquid phase in the soil, and P_2 the pressure in the external drop of liquid (at atmospheric pressure). Flow will occur from Q_1 to Q_2 only if

$$\frac{P_1}{\rho} + gz_1 > \frac{P_2}{\rho} + gz_2.$$

Since the two points are at approximately the same elevation, the requirement for flow is then simply that $P_1 > P_2$, where P_1 represents the pressure which one would observe in a tensiometer or piezometer located at point Q_1 in the soil, and P_2 represents atmospheric pressure. Hence, if the water in the soil is under tension, no water can emerge. This is the so-called ***outflow law*** (Richards, 1950b), which has numerous applications in irrigation and drainage problems. For example, a drain will not operate if situated in a region of the soil where the water is under tension. The water can flow around the drain, but not into it.

The foregoing conclusions have been arrived at from general considerations and involve no assumptions as to the nature of the forces holding the water in the soil. Therefore they hold for soils of all textures, including clays, and do not depend exclusively upon the capillary mechanism of absorption.

The identification of the driving force with the hydraulic potential gradient is of great importance in soil moisture dynamics. Darcy's law, commonly employed in ground water flow, can be applied to capillary flow under the following conditions: that the hydraulic head be measured by means of tensiometers, or equivalent devices, and that the factor K in Darcy's equation be considered a variable but measurable quality of the soil.

Darcy's equation may be written in vector form as follows, where v is a vector in the direction of flow whose magnitude is equal to the volume of flow per unit area per unit time:

$$v = -K \nabla \Phi.$$

It is known from numerous studies that K (the capillary conductivity) decreases with increasing tension because of the decreasing water content. Recent studies by S. J. Richards and L. V. Weeks (1953) have shown, in a soil of loam texture, that the soil is able to conduct water at a finite rate at a tension of 600 cm. of water, where the water content had been reduced to 9 percent, or about one-third of the water content at saturation. However, the capillary conductivity value is very low at this tension. The variable characteristic of K and its relationship to the tension must be taken into account in all capillary flow studies.

REFERENCES

Buckingham, E. (1907) *Studies on the movement of soil moisture:* U.S.D.A. Bur. Soils Bull., vol. 38.

Childs, E. C., and George, N. C. (Collis-George) (1948) *Soil geometry and soil-water equilibria:* Discussions of the Faraday Society, vol. 3., pp. 78-85.

Day, Paul R., and Luthin, James, N. (1954) *Sand-model experiments on the distribution of water-pressure under an unlined canal:* Soil Sci. Soc. Amer. Proc., vol. 18, Part 2, pp. 133-136.

Gardner, W., Israelsen, O. W., Edlefsen, N. E., and Clyde, H. S. (1922) *The capillary potential function and its relation to irrigation practice:* Phys. Rev., vol. 20, p. 196.

Haines, W. B. (1930) *Studies in the physical properties of soil. V. The hysteresis effect in capillary properties and the modes of moisture associated therewith:* Jour. Agric. Sci., vol. 20, pp. 97-116.

Israelsen, O. W. (1927) *The application of hydrodynamics to irrigation and drainage problems:* Hilgardia, vol. 2, pp. 479-528.

Richards, L. A. (1940) *A pressure membrane apparatus for soil solution:* Soil Sci., vol. 51, pp. 377-386.

Richards, L. A. (1949) *Methods of measuring soil moisture tension:* Soil Sci., vol. 68, pp. 95-112.

Richards, L. A. (1950a) *Experimental demonstration of the hydraulic criterion for zero flow of water in unsaturated soil:* Int. Cong. of Soil Sci., Trans. Amsterdam, vol. I, pp. 66-68.

Richards, L. A. (1950b) *Laws of soil moisture:* A.G.U. Trans., vol. 31, Part 5, pp. 750-756.

Richards, Sterling J., and Weeks, Leslie V. (1953) *Capillary conductivity values from moisture yield and tension measurements on soil columns:* Soil Sci. Soc. Amer. Proc., vol. 17, Part 3, pp. 206-209.

Versluys, J. (1917) *Die kapillarität der boden:* Int. Mitt. f. Bodenkunde, vol. 7, pp. 117-140.