THE ENERGY CONCEPT OF SOIL MOISTURE AND MECHANICS OF UNSATURATED FLOW[1]

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SYNOPSIS

The moisture content of many unconsolidated porous bodies is of considerable importance in determining their physical properties. The characterization of moisture conditions in terms of moisture percentage or by such terms as "gravitational water," "capillary water" or "hygroscopic water" is not wholly satisfactory particularly in moisture flow studies Soil moisture conditions may be described in terms of the security with which the water is held by the soil. This security can be measured in terms of the thermodynamic free energy of the water itself and is, therefore, independent of the nature of the porous body in which the water is distributed Measurements of the pressure, vapor pressure, freezing point depression, etc, may be used to evaluate this free energy function.

Curves relating the moisture content of soils to a logarithmic function of the free energy, known as pF, reveal that a continuous functional relationship exists over a moisture content range extending from saturation to oven dryness Because of the continuous nature of the free energy-moisture content relationship, the difficulties involved in any attempt to classify the moisture into distinct categories become evident

Moisture conditions in situ can be followed with a minimum of disturbance to the surrounding soil by the use of a tensiometer This instrument is so designed that it enables the investigator to measure continuously the pressure in the soil water without significantly altering the moisture conditions of the soil. Such measurements are limited to negative pressures not exceeding one atmosphere, but, as pointed out below, this includes the range of moisture contents within which the rate of unsaturated moisture flow is of importance Tensiometers are of use in following fluctuations in elevation of water tables and in tracing the advance of a wetting front through a soil following the additions of water by rainfall or by irrigation.

The energy concept of soil moisture aids materially in explaining moisture flow phenomena. For saturated flow Darcy's law states that the rate of flow is proportional to a potential gradient called the hydraulic gradient. The proportionality constant is known as the coefficient of saturated permeability. In problems involving the flow of moisture through an unsaturated porous media the rate of flow is again proportional to the potential gradient The numerical value of the proportionality constant, known as the coefficient of unsaturated permeability, has been shown to vary widely and to be a function of the free energy of the moisture in the unsaturated soil; in fact, experimental evidence indicates that the value of this coefficient decreases so rapidly that the flow of moisture in the liquid phase practically ceases when the pF of the soil moisture is increased to the neighborhood of 2 7 which corresponds to a moisture content approximating the centrifuge moisture equivalent

In a macroscopically homogeneous material moisture tends to flow from regions of high moisture percentage to regions of lower moisture content However, if a textural gradient exists, flow may occur from regions of low moisture content into regions of higher moisture concentration. This emphasizes the fact that unsaturated moisture flow occurs as the result of a pressure gradient which, because of textural differences, may be quite independent of the moisture per-

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centage gradient It becomes evident from this discussion that moisture movement through unsaturated materials is largely a function of the free energy of the water in the soil rather than of the actual amount of moisture present

The moisture retaining and transmitting properties of unsolidified porous materials is of considerable importance in determining their physical properties and their suitability for certain engineering applications. For example, the stability or resistance to deformation of the subgrade of a highway or airport runway surface, particularly those surfaces of the flexible type, is considerably influenced by the moisture content and the textural properties of the subgrade soil. Recent studies have indicated that the pattern of stress distribution on the surface of a subgrade under the influence of a vehicle wheel load applied at the pavement surface is likewise affected by the moisture content of the subgrade. It is widely recognized that the growth of ice lenses which produce detrimental frost heave of pavements is dependent upon the rate of replenishment of moisture in the soil below the growing ice. The subject of moisture flow and retention in subgrade soils is, therefore, a matter of paramount importance to highway and airport engineers engaged in pavement design. The flow of moisture in saturated soils is relatively well understood and while many questions in this field are yet unanswered, a fairly satisfactory technology for this type of flow is available. On the contrary, the flow of unsaturated soil moisture is not well understood and present design practices involving this type of phenomenon are almost wholly empirical in character.

The amount of moisture in soil is commonly expressed as the percentage of water per unit of oven dry soil. Experience has shown that such moisture percentages are of little significance in predicting soil behavior unless something is known of the texture and mineralogical nature of the soil itself. As will be pointed out, moisture percentages in themselves are unreliable bases on which to forecast unsaturated moisture flow phenomena.

Several attempts have been made to classify soil moisture into a definite number of categories as a means of more clearly describing it. One of the earliest and most familiar of such classifications is that developed by Briggs (3)[2]. In this system the total water content of soils is subdivided into three categories; viz, hygroscopic water which is held in thin films on the soil particles by adsorption; capillary water which is held in soil voids by surface tension; and gravitational water which moves in and through the voids under the influence of gravity and which drains from the soil when it is held at a higher elevation than the water table This classification, as well as others of the same general type (2, 8, 21), implies that the several kinds of water are separate and distinct Actually, as the subsequent discussion will emphasize, no abrupt change exists in any of the properties of the water in soil over the entire range of moisture content from saturation to oven dryness and the above mentioned classifications must be considered as qualitatively descriptive rather than quantitatively determinable.

In 1907 Buckingham (4) introduced a method of characterizing soil moisture conditions which was based on the security or tenacity with which the water is held by the soil. This so-called "energy concept" provides a means of describing soil moisture conditions in terms of a potential function which is a property of the state of stress of the soil water itself and whose measurement is, therefore, independent of the nature of the soil. The following discussion gives the basis for and the physical significance of the Buckingham potential function (1, 11, 20).

In Figure 1 is shown diagrammatically a vertical column of soil, the lower end of

[2] Figures in parentheses refer to list of references at end.

which is immersed in a water reservoir. If this soil column is allowed to remain at uniform constant temperature in contact with the free water surface and if evaporation from the upper end of the column is prevented, an equilibrium moisture distribution eventually will be established throughout the soil column If the soil column is texturally homogeneous, examination will reveal that, at equilibrium, the moisture content of the soil decreases progressively from a maximum at and below

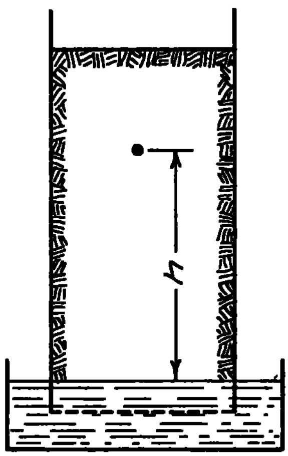

Figure 1. Diagram of a Soil Column at Moisture Equilibrium with a Free Water Surface.

the level of the water table to a minimum at the upper end of the soil column.

By taking the reservoir water surface as a datum level it is evident that each unit volume of water at a height, h, above this surface will possess a potential energy of position equal to h ft lb. per lb, or wh ft. lb. where w is the weight per unit of volume of the water The vertical gradient of this potential represents the gravitational field force which is being exerted on the water element Since, however, the water is at equilibrium in the soil column this gravitational force must be balanced by an equal force acting in the opposite direction. It is this counterbalancing force that Buckingham designated as the capillary field force. The potential that is associated with this field force is known as capillary potential and is designated by the symbol, ψ. It can be seen, therefore, that ψ may be defined as the work done against the capillary field force in moving a unit volume of water from a free water surface to the point in question. Some writers prefer to use the term "moisture potential" instead of capillary potential, and this viewpoint has some merit in that it serves to emphasize the fact that surface-tension forces are only partially responsible for the attraction between soil and water.

Although the capillary potential function was first proposed in 1907, its usefulness in soil moisture studies was not widely recognized until methods for its measurement were described by Gardner (6) in 1920. The capillary potential is equivalent to the pressure potential in Bernouilli's equation [3] and consequently can be determined by measuring the pressure of the soil water. If the pressure at the reservoir surface in Figure 1 is taken as zero the pressure at each point below that surface will be positive and a linear

[3] Bernouilli's equation is a statement of the law of conservation of energy in a liquid in steady flow and indicates that the sum of the gravitational potential energy, the pressure potential energy, and the kinetic energy is a constant

$$h+\frac{P}{w}+\frac{V^2}{2g}=\text{constant}$$

in which

- h = the head above any chosen reference level
- P = the fluid pressure
- w = the weight per unit of volume of the liquid
- V = the velocity of flow
- g = the acceleration of gravity

For the case under discussion, the water is at rest and the flow is at the limiting state of zero velocity. Therefore, Bernouilli's equation may be written $h+\frac{P}{w}=\text{constant}$ If the reference level is chosen at the surface of the free water, the constant becomes zero and we may write $h=-\frac{P}{w}$.

function of the vertical distance below the surface; conversely the pressure in the soil water at each point above the water surface will be negative. Therefore, the capillary potential at any point in the soil column may be determined by measuring the pressure deficiency or the tension in the water at that point and dividing it by the unit weight of the water. This pressure deficiency represents the amount by which the pressure in the soil water is less than atmospheric pressure

Properties of soil water other than its negative pressure can be used to evaluate the potential, ψ. The curvature of the air-water interfaces in the unsaturated soil, the aqueous vapor pressure, and the depression of the freezing point are all thermodynamically related to the capillary potential, and these properties are useful in determining values of ψ in relatively dry soils where the negative pressures are relatively great.

Centrifugation presents another means of determining soil moisture energy relations, providing the centrifugation is complete, that is, provided it is carried on long enough for the soil to reach a constant moisture percentage. Centrifugation can be carried out at various values of centrifugal force to obtain a range of determinations of the capillary potential.

The relationship between the moisture content of a soil and the capillary potential of the soil water has been determined by several of the foregoing methods for four Iowa soils (16) throughout the entire range of moisture content from saturation to oven-dryness. In Figure 2 the graphical expression of the above relationship, called a soil moisture sorption curve, is shown for each of the four soils. When a moisture sorption curve covers a wide range of moisture contents, it is convenient to express the energy as the logarithm of a function of the capillary potential, called pF The pF function is defined as the logarithm to the base ten of the numerical value of the negative pressure of the soil moisture expressed in centimeters of water (19). The four soils studied represent a rather wide range of

TABLE 1

MECHANICAL ANALYSES, "SOIL MOISTURE CONSTANTS," AND HEAT OF WETTING DATA FOR FOUR IOWA SOILS (16)

	Soils			
	Dickinson	Clarion	Marshall	Wabash
Mechanical analysis				
Air-dry moisture, per cent	0 81	1 67	2 47	4 80
Organic matter, per cent	2 13	3 01	3 58	5 91
Clay, 0 002 mm., per cent	6 71	18 80	31 20	40 20
Silt, 0.05–0.002 mm , per cent	9 81	28 60	63 30	48 20
Sand, 2 0–0 05 mm., per cent	82 10	51 00	2 49	7 00
Moisture equivalent, per cent[a]	7 70	15 90	24 40	31 20
Moisture equivalent, per cent[b]	7 50	15 20	23 70	29 60
Maximum water-holding capacity, per cent	44 50	58 00	76 50	87 00
Permanent wilting, per cent	3 70	7.20[c]	12 70	20 60
Heat of wetting, cal. per gram	1 03	2 21	4 16	6 76
Hygroscopic coefficient, per cent[d]	3 41	6 93	10 40	16 10

[a] Determined by Mr Read W. Bailey, Director of Intermountain Forest and Range Exp. Sta Ogden, Utah.

[b] Determined by Dr. N. E Edlefsen, Agr. Exp Sta , Davis, Calif

[c] Determined by Dr. W E. Loomis, Botany Department, Iowa State College, Ames, Iowa

[d] Determined by Dr. H. F. Rhoades, Agronomy Department, University of Nebraska, Lincoln, Nebr.

textures as the mechanical analysis data in Table 1 indicate. The absence of discontinuities in the desorption curves in Figure 2 supports the viewpoint that no distinct "kinds" of water exist in these soils. A graph showing the same data up to represent quasi-equipotential values in Figure 2 aids materially in establishing their significance.

Several workers (16, 18) who have studied the distribution of moisture in centrifuged porous media have concluded

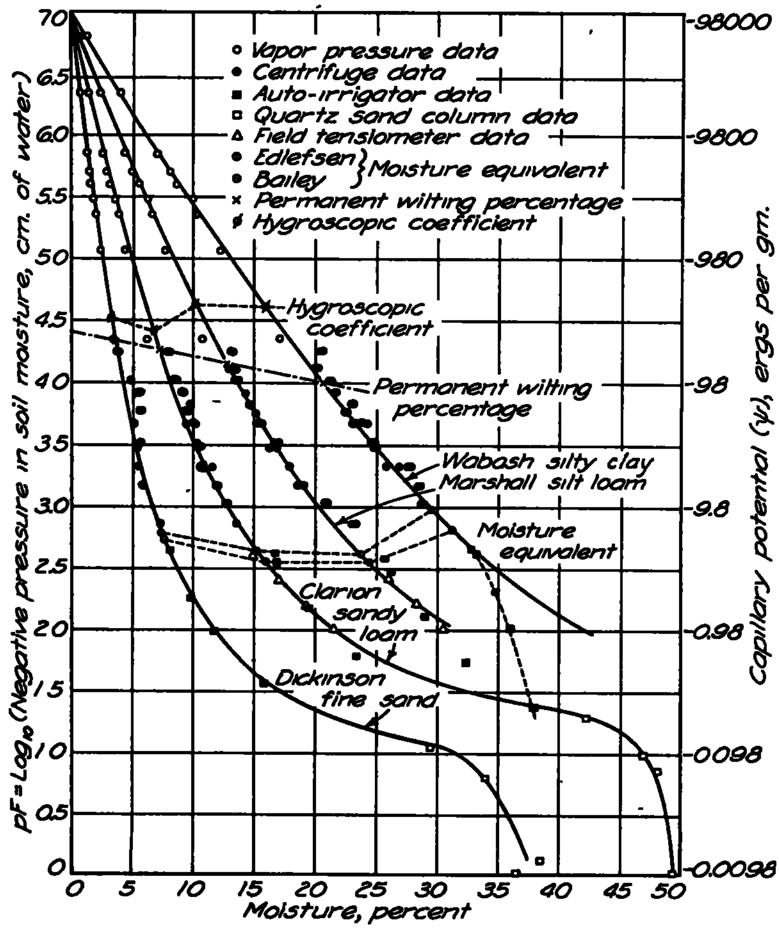

Figure 2. Soil Moisture Sorption Curves for Four Iowa Soils (16)

to pF 2.95, plotted to a linear scale, is given in Figure 3.

The moisture retaining ability of soil is frequently evaluated in terms of such experimentally defined quantities as hygroscopic coefficient and moisture equivalent.[4] The fact that these quantities seem

[4] In engineering practice, a similar test is known as the centrifuge moisture equivalent

that the outer boundaries of such samples were saturated during centrifugation. If such a condition exists in the moisture equivalent sample, we can predict the nature of the moisture distribution in such samples and arrive at a theoretical pF value for the moisture equivalent (16).

At equilibrium in the centrifuge the gradient of the capillary potential represents the force that balances the centrifugal force, and we may write

$$\frac{d\psi}{dr} = r\omega^2 \qquad (1)$$

in which

ψ = the capillary potential
r = radius of centrifuge
ω = angular velocity
Let r_1 = radial distance to outer boundary of sample
h = height of sample
$(r_1 - h)$ = radial distance to inner boundary of sample
ψ_1 = capillary potential at outer boundary
ψ_h = capillary potential at the inner boundary

If the angular velocity is held constant, as it is in the standard[5] moisture equivalent test, equation 1 may be integrated between the limits r_1 and $(r_1 - h)$ to give:

$$\psi_1 - \psi_h = \frac{\omega^2}{2}[r_1^2 - (r_1 - h)^2] \qquad (2)$$

If the sample is saturated at the outer boundary as postulated, then $\psi_1 = 0$. Since ψ is, as a first approximation, a linear function of the height of sample, h, it follows that $\psi_{av} = \frac{\psi h}{2}$. Therefore, the average capillary potential for the whole sample may be written:

$$\psi_{av} = -\frac{\omega^2}{4}(2r_1h - h^2) \qquad (3)$$

On the basis of these assumptions a calculation of the ψ_{av} for the standard moisture equivalent samples gives a value of 4.91×10^5 ergs per gram or pF 2 70 (501 cm. H_2O or 7.1 lb. per sq. in.)

The assumption that the outer surface of a centrifuged soil sample is saturated cannot be readily verified by the experimental determination of the moisture gradient in such samples after centrifuging, since at such high moisture contents appreciable moisture movement will occur after the removal of the centrifugal field. If the assumption is correct, however, the moisture content of a soil sample that has been centrifuged with a free water table maintained at the outer boundary of the sample should be the same as that of a similar soil sample that has been similarly centrifuged out of contact with a water table. Obviously, the first soil sample must not remain in contact with the free water after removal or reduction of the centrifugal field or it will take up considerable water before its moisture content can be determined.

The validity of the foregoing calculation was investigated by centrifuging simultaneously two samples of wet soil. One sample was suspended above a free water surface in the centrifuge bucket by springs of known strength such that at a known rate of rotation the brass sample container moved away from the axis of rotation until it rested on the bottom of the centrifuge bucket and the outer soil boundary was just in contact with the free water surface When the rate of rotation was reduced the springs pulled the container and soil away from the free water surface, thus preventing any rewetting. The second soil sample was placed in the other centrifuge bucket at a position such that it was the same distance from the axis of rotation as the first sample cup after the latter had contacted the free water surface.

Both samples were centrifuged at a rate slightly higher than that required to cause the spring supported cup to contact the free water. After being centrifuged for a known length of time the samples were removed from their respective cups and the moisture content of each was determined. The determination was made five times on each of two soils and the results are tabulated in Table 2

These data seem to justify the assumption that the outer surface of a centrifuged

[5] Briggs and McLane, *Proceedings* Am Soc. Agron. Vol. 2, 1910.

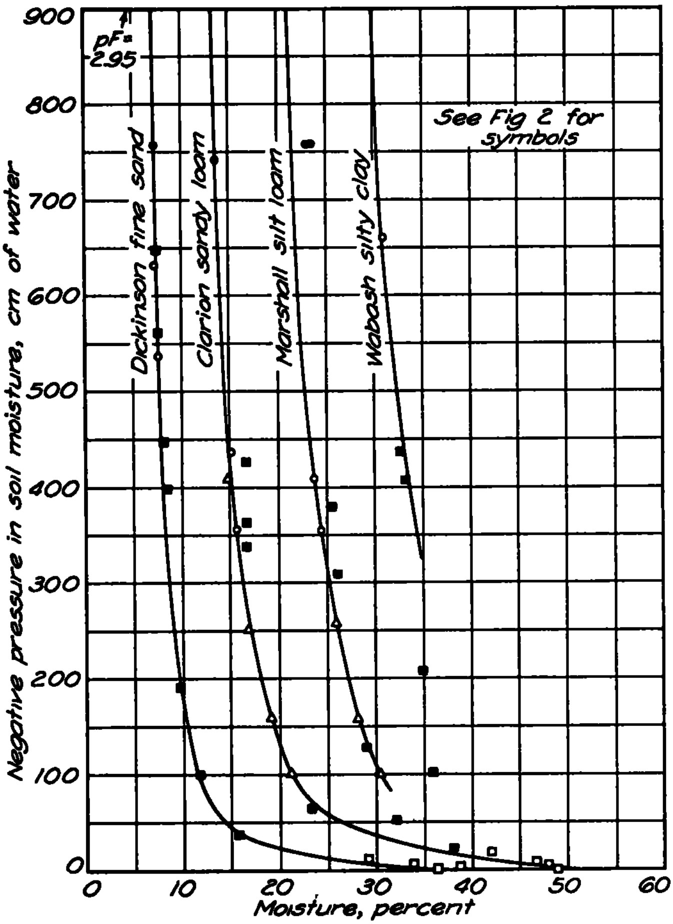

Figure 3. Moisture Sorption Curves Plotted to a Linear Negative Pressure Scale

TABLE 2

THE PERCENTAGE OF MOISTURE IN SOIL SAMPLES AFTER CENTRIFUGING 30 MINUTES AT 460 TIMES GRAVITY (16)

	Marshall silt loam		Clarion sandy loam	
	In contact with free water surface	Without free water surface	In contact with free water surface	Without free water surface
	27 7	27 5	16 4	15 7
	27 1	26 9	17 2	16 0
	27 4	28 0	14 9	15 1
	30 3	28 1	17 2	15 4
	29 4	28 0	17 6	15 9
Average	28 4	27 7	16 7	15 6

soil sample is saturated during centrifugation Therefore, the theoretical value of the pF at the standard moisture equivalent is 2.70 which is in full agreement with the average value of 2 66±0 14 obtained for

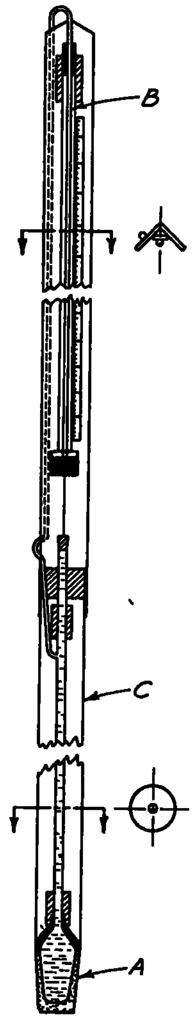

Figure 4. Sketch of a Field Tensiometer

the four soils whose desorption curves are shown in Figure 2.

Richards (15) has recently shown that soil samples at equilibrium with a free water surface 16 ft below have moisture contents in close agreement with the moisture equivalent. These data support the hypothesis that the moisture equivalent corresponds to a pF of 2 7 and tend to justify the assumptions involved in the theoretical development of this value

The capillary potential of the water in

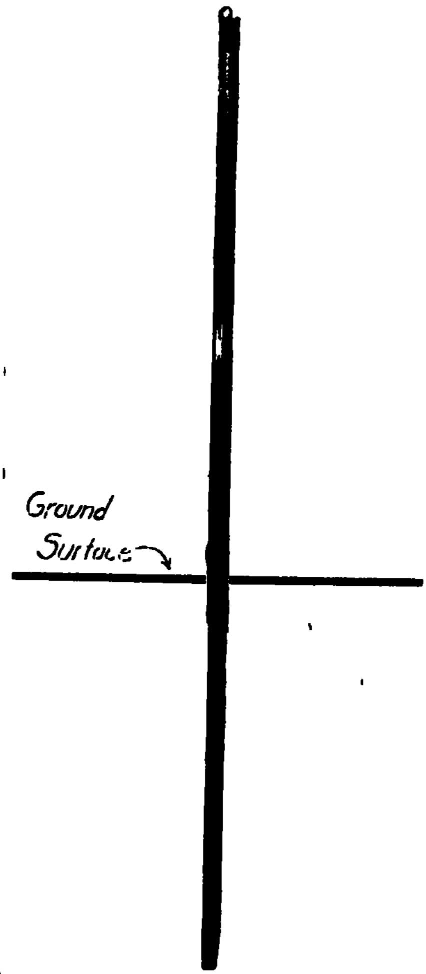

Figure 5. Photograph of a Field Tensiometer

soils in situ can be followed continuously in the field with tensiometers (11). These instruments consist of a porous ceramic cup, A, in Figure 4, attached through a continuous, water filled system to a mercury manometer B. A photograph of the instrument is shown in Figure 5. The tensiometer attached to the steel case, C, is inserted to the desired depth in an auger hole, care being taken to insure good contact between the soil and the porous cup. If the soil moisture content is below saturation, water moves out through the porous cup. As a result mercury is drawn up in the manometer until the pressure difference across the porous wall is balanced by the pressure difference due to the column of mercury in the manometer tube When a continuous record of the pressure in the soil water is desired, a recording vacuum gage can be substituted for the mercury manometer. Tensiometers may be used for pressure deficiencies up to about one atmosphere or about to pF 3 0. No satisfactory method is now available for measuring in situ negative pressures of more than one atmosphere but, as the subsequent discussion will explain, most moisture flow seems to occur in soils in which the pF of the soil water is below 2 70 or about ½ atmosphere.

One of the uses of tensiometers is in following the position of ground water tables. Since these instruments measure the pressure differences between the soil water and free water, tensiometer readings may be interpreted in terms of the equilibrium height of the instrument above the free water surface Such calculation implies that the soil water at the point of measurement is in static equilibrium with the water table. The velocity of penetration of a wetting front into dry soil can be readily measured by noting the time interval between abrupt changes in the readings of a series of tensiometers installed at regular intervals along the path being followed by the wetting front.

An interesting application of the use of tensiometers for study of sub-soil moisture conditions at the Sioux City, Iowa, airport by Christensen [6] may be cited. The object of this study was to determine the height of grade of runways above the effective ground water table at which the subsoil would remain sufficiently dry to insure stable subgrade conditions.

Two series of tensiometers were installed at points not far apart. The first series of six instruments was placed with the porous cups at depths of 0 7, 1 1, 2 1, 3 1, 4 1, and 5 1 ft The second series of five instruments was placed in a pit 4.8 ft. deep with the cups at depths of 5 3, 5 85, 6 85, 7 85, 8 85, and 9 85 ft below the natural ground surface After equilibrium was established between the negative pressures in the porous cups and the adjacent soil moisture, the various tensiometer readings were as shown in Figure 6.

In the report of this study Christensen states

"If a column of soil is in equilibrium with a water table and there is no tendency for the water in the soil to move either upward or downward, then for each foot of increase in elevation above the water table the tension in the water should increase by an amount equal to 1 foot of water This relation between the tension and the elevation in the column can be represented by a straight line extension upward from the water table with unit slope (45° for the scales chosen in Figure 6) When these plotted tension readings of adjacent cups lie on such a line, it is an indication that the soil water in the intervening space is at rest under gravity and the intercept of this line on the depth axis gives the elevation of the zero pressure level (water table) in the soil water

"It is interesting to note that the readings of the tensiometers at the 4 8 and 5 1 ft settings give a slope of 45° and indicate a water table actual or hanging at a depth of 9 6 ft below the surface at station I Similar tensiometers at station II setting at depths of 5 3, 5 85, 6 85, 7 85, and 8 85 ft indicate a water table situated approximately 10 ft below the surface Thus below approximately 4 ft the tensiometers indicate an equilibrium condition for soil moisture with water tables of 9 6 and 10 ft at stations I and II respectively From this we may conclude with some certainty that if the water table (phreatic surface or level of zero pressure) remains fixed at 10 ft the moisture content of the soil from 10 to 4 ft cannot be increased by upward capillary flow and any water getting into this soil layer from above will tend to pass downward to this table

"The low tension readings, corresponding to

[6] H R Christensen—personal communication

relatively wetter soil, for cups above the 4 foot level (station I) indicate that the wave of wetness from the recent rain has not yet penetrated to the 4 foot depth"

Christensen goes on to show that the hydraulic gradient at depths less than 4 ft. is negative which means that the moisture tends to move downward from this region,

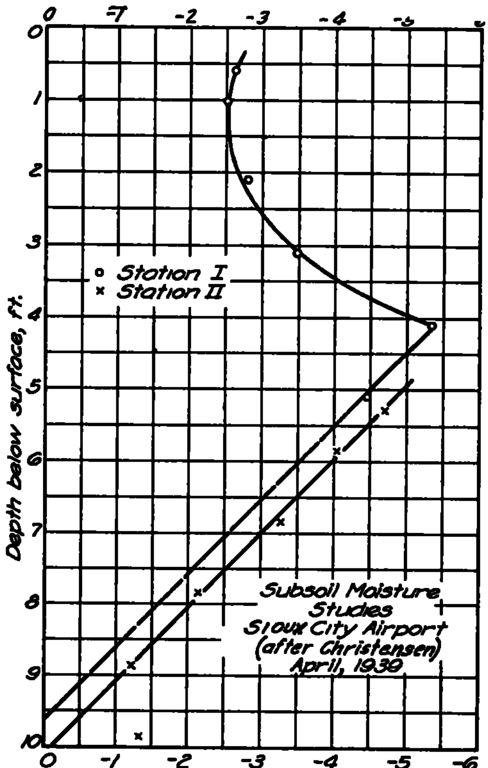

Figure 6. Curve Showing the Variations in Water Pressure at Several Depths Below the Soil Surface.

while between 4 ft and 10 ft. the hydraulic gradient is approximately zero, indicating that the moisture is in equilibrium with the effective water table.

MOISTURE FLOW

The study of the movement of water through saturated porous media is of engineering importance in connection with the design of filter beds, earth dams, underground drainage, and similar structures The character of such saturated flow is described by the well-known Darcy's law which states that the flow rate is proportional to a potential gradient known as the hydraulic gradient. The proportionality constant in Darcy's law is known as Darcy's coefficient or the coefficient of saturated permeability. Several interpretations of this coefficient may be found in physics and engineering literature. The significance and applicability of these several interpretations have been discussed recently by Richards (13).

Despite some unsolved problems, the flow of moisture through saturated porous media is much better understood than is the flow of moisture through unsaturated materials. The phenomenon of unsaturated moisture flow is of considerable importance particularly as related to the movement of water from adjacent zones of saturation into subgrades, earth dams, levees, embankments, etc. This type of moisture movement can be explained qualitatively by such terms as "capillarity," and "film adjustment," but since these rather indefinite terms are not susceptible to measurement, they are unsatisfactory for the quantitative evaluation of unsaturated flow.

In the light of the energy concept of soil moisture, the flow of moisture can be analyzed in a manner similar to that pertaining to other transport phenomena such as saturated soil moisture movement, the flow of electricity through a conductor and the flow of heat, in that the velocity of flow is proportional to a potential gradient. Darcy's law for saturated moisture flow is an example of this type of flow and may be expressed by the equation $v=ki$ in which v is the velocity of flow, i is the hydraulic gradient and k is the proportionality constant. In the case of unsaturated soil moisture the hydraulic gradient as indicated in the following equations may be the resultant of a capillary potential gradient and a gravitational potential gradient as is the case in vertical flow or, as in horizontal flow, it may be identical with the capillary potential gradient.

$$Q_x = k_u\left(\frac{d\psi}{dx} - g\right) \text{ upward flow}$$

$$Q_x = k_u\left(\frac{d\psi}{dx} + g\right) \text{ downward flow}$$

$$Q_x = k_u\frac{d\psi}{dx} \text{ horizontal flow}$$

Q_x = flow rate per unit area in x direction

k_u = coefficient of unsaturated permeability

g = acceleration of gravity

The proportionality constant between the velocity of flow and the potential gradient is called the coefficient of unsaturated permeability and may be designated by the symbol k_u and is as indicated later a function of the capillary potential ψ.

The proportionality constant in most types of flow equations is, as a first approximation at least, independent of the numerical magnitude of the potentials at the points between which the flow is taking place. For example, in Ohm's law the resistance of a given conductor is independent of the applied voltages Thus the current flowing through such a conductor is the same when the potentials at the two ends are 20 and 25 volts as when the voltages are 5 and 10. Similarly the rate of flow of heat through a given block of material is the same when the temperatures (thermal potentials) between opposite sides are 15° C. and 20° C. as when they are 45° C. and 50° C.

The coefficient of unsaturated permeability, however, is not independent of the magnitude of the potentials at the points between which flow occurs. The rate of horizontal flow of moisture through a block of soil when the negative pressures on opposite sides of the block are −0.1 and −0.6 lb per sq in. is considerably greater than the flow rate through the same block when the negative pressures are −2 1 and −2 6 lb per sq. in. In both cases the pressure difference is the same which indicates that the proportionality constant in the latter case must be less than in the former. This situation results from the fact that if the soil is unsaturated, the larger pore spaces contain air, and the effective cross sectional area of the water conducting region is reduced.

An apparatus for studying unsaturated flow through undisturbed soil samples and for measuring the coefficient of unsaturated permeability is shown in Figure 7 (5). The soil sample is sealed between two hollow flat porous plates B which are connected through flexible tubing to water reservoirs A small hole in the seal maintains atmospheric pressure in the soil air. These reservoirs are held at different distances below the soil column. Moisture can be made to flow from the upper reservoir through the soil column into the lower reservoir. Since the soil column is maintained above the free water surface of the reservoirs its moisture content will at all times be below saturation and flow will take place through an unsaturated soil column. The capillary potential at each end of the soil column is measured by tensiometers. By measuring the rate of flow under known potential gradients the coefficient of unsaturated permeability may be calculated.

In Figure 8 are shown curves obtained by the method described. These data indicate that in undisturbed Marshall silt loam the coefficient of unsaturated permeability, k_u, undergoes an 8,000 fold reduction in value when the pressure of the water in the soil through which flow takes place is reduced from −0.18 lb. per sq in. to −2 6 lb per sq. in. When the pressure in the soil water was increased by raising both reservoirs, k_u increased but did not return to its initial value. This hysteresis phenomenon occurs frequently in soil moisture problems and is attributable to the nature of the void labyrinth of the soil During a desorption process the moisture content and conductivity of soil are higher at a given negative pressure than they are at the same pressure during a wetting process The significance of the configuration of the soil pores as the cause of this hysteresis has been discussed by several workers (7, 10)

A comparison of curves A and B reveals that the relative ability of the Marshall silt loam and Shelby silt loam to transmit water reverses as the pressure in the soil water is continuously reduced. When the water pressure in each soil is −0 2 lb per sq. in the conductivity of the Marshall is 60 times that of Shelby. Both soils have the same ability to transmit water when the pressure is reduced to −0 47 lb. per sq in and at all lower pressures Shelby silt loam has a higher coefficient of unsaturated permeability than the Marshall silt loam.

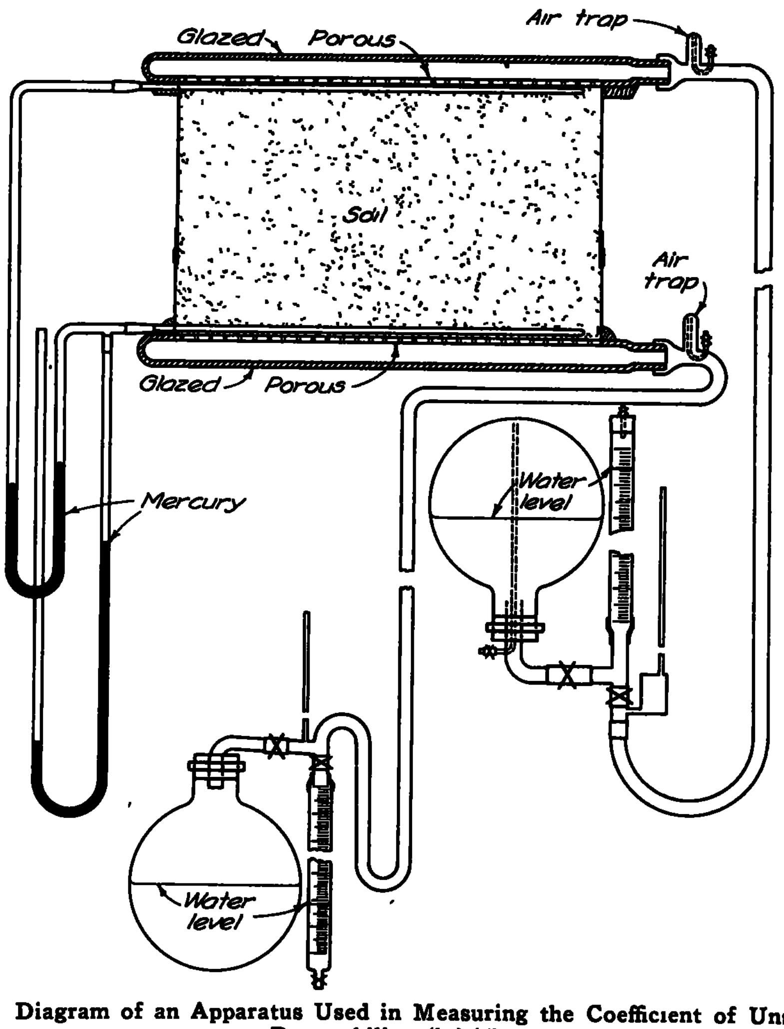

Figure 7. Diagram of an Apparatus Used in Measuring the Coefficient of Unsaturated Permeability (k_u) (5)

A second type of apparatus, described by Moore (9), can also be used to study the relation between pressure in soil water and the ability of the soil to transmit moisture By this method a soil column similar to that shown in Figure 1 is equipped with tensiometers at several elevations. Water is allowed to evaporate from the upper end of the column while the position of the free water surface in the reservoir is maintained constant by additions of water. When a steady flow state has been established in the column, as indicated by stable tensiometer readings, it may be assumed that the velocity of flow across each intertensiometer interval is constant and equal to the rate of removal from the reservoir. It is then possible from the dimensions of the column and the several tensiometer readings to calculate the coefficient of unsaturated permeability for each intertensiometer interval. Since the pressure in the soil water in each interval will be different, a value for the k_u versus ψ relationship is obtained for each intertensiometer interval Results by this method are in agreement with those obtained by the apparatus shown in Figure 7.

Moore found that for a series of Yolo soils studied, the saturated permeability increased with increasing coarseness of texture, while at a pF slightly greater than 2.0 the unsaturated permeability varied in the reverse order.

Saturated permeability
sand > fine sandy loam > light clay > clay
Unsaturated permeability
sand < fine sandy loam < light clay < clay

Data of the type shown in Figure 8 indicate that the ability of unsaturated soils to transmit moisture is largely determined by the negative pressure in the soil water. These data indicate that when the pressure in the soil water is reduced to the vicinity of −3 lb. per sq. in. the ability of the soil to transmit water falls to the vicinity of 0.01 per cent of its value at saturation A pressure of −3 lb per sq in in these soils is equal to that which would be found in soil water that is in static equilibrium with a free water surface 6½ ft below it The preceding statements indicate that moisture movement in the liquid phase to distances greater than 6 ft above a water table will be a very slow process in the two soils discussed above.

If at any time the rate of removal of water from an unsaturated soil, by growing plants or by evaporation, or in the case of highway subgrades by the growth of ice plates or lenses typically associated with frost heave, exceeds the ability of that soil to transmit water from regions of saturation, a reduction in moisture content will result This decrease in moisture content is accompanied by a further reduction of the pressure in the soil water which in turn rapidly reduces the ability of the soil to transmit water. This cycle, sometimes "vicious" and sometimes "benign," results in progressive reduction in moisture content of the soil from which water is being removed. Thus, if the moisture content of a given mass of soil from which water is being removed is to be maintained constant it must be held at such a position with respect to a free water surface that its conductivity will at all times equal or exceed the rate of moisture removal Conversely, if it is desirable to prevent the renewal of moisture in a soil from which the growth of ice lenses is depleting the moisture, it must be held high enough above a free water table to insure that its conductivity will at all times be less than the rate of moisture removal. The desirability of a low value of the coefficient of unsaturated permeability for subgrade soils to prevent frost heave, especially in situations where a relatively high water table persists, is therefore, apparent.

In a texturally homogeneous soil, moisture will tend to flow from regions of high moisture percentage to regions of lower moisture percentage because a high moisture content indicates a high capillary potential in such a soil However, if a textural gradient exists, it is possible that flow may occur from points of low moisture percentage toward points of higher moisture content As an example moisture may tend to flow out of Dickinson fine sand containing 15 per cent moisture into Clarion sandy loam containing 20 per cent moisture, since as shown in Figure 2 these moisture percentages correspond to pressures of −0 63 and −2.1 lb per sq. in , respectively, and the pressure gradient is downward toward the Clarion even though its moisture content is greater than the Dickinson The shortcomings of moisture percentages as a criterion for evaluating unsaturated flow become evident in the light of the preceding discussion.

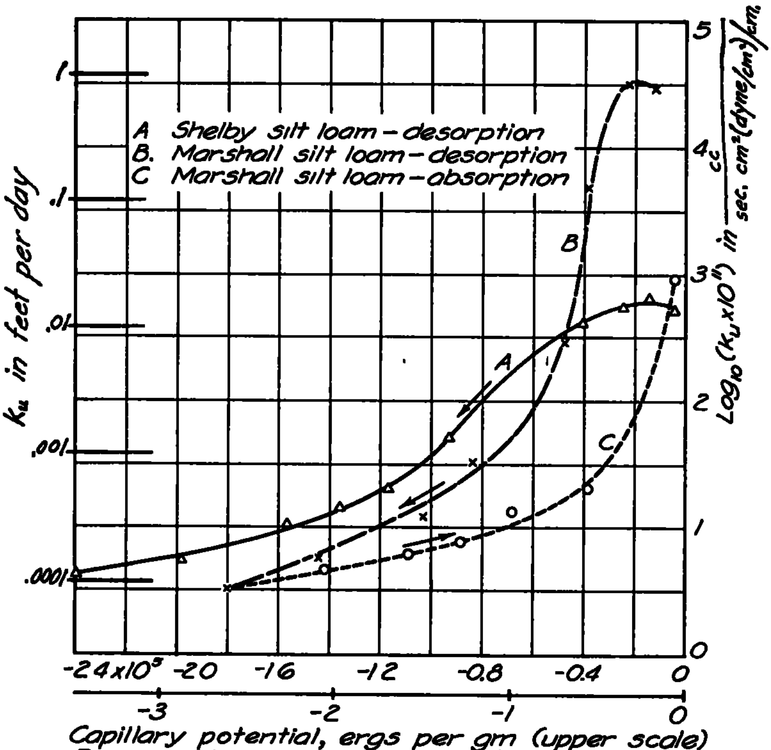

Figure 8. Curves Showing the Relation Between the Coefficient of Unsaturated Permeability (k_u) and the Pressure in the Soil Water

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DISCUSSION ON THE ENERGY CONCEPT OF SOIL MOISTURE AND THE MECHANICS OF UNSATURATED FLOW

DR. D. P. KRYNINE, *Yale University:* Referring to the determination of the gradient of the capillary potential from centrifuging, the writer wishes to emphasize two circumstances which may influence the results of the computations, namely: (a) the decrease of the height of the sample, h, due to consolidation or compaction during the centrifuging; and, (b) the possibility of waterlogging, even partial. Without discussing the latter item in detail the former may be clarified as follows:

The rate of change of the value of the capillary potential, ψ, when h decreases (a negative value of dh) is expressed by the derivative:

$$-\frac{d\psi}{dh} = + \frac{\omega^2}{2}(r_1 - h) \qquad (4)$$

Equation (4) means that a decrease in height of the sample during centrifuging diminishes the absolute value of the capillary potential ψ; and that the higher the sample (large value of h in Equation (4), the smaller the rate of this decrease. To avoid this influence, it is convenient to measure the height of the sample not before, but after centrifuging, which probably has been done by the authors.

Referring now to Table 2 it should be noticed that the standard moisture equivalent corresponds to the centrifugal acceleration of 1,000 times gravity. For such a case Professor Terzaghi estimated the equivalent compression stress at about 2 tons per sq ft.[1]

As to the tensiometers, they promise to

[1] *Public Roads*, vol. 7, No. 8, October, 1926, p 159.

be of real value to the highway engineer. First apparatuses of this kind have been described as early as 1926,[2] but they have been brought to the attention of the highway engineers only now through this paper The writer believes that as water flows out of the cup of the tensiometer, the reading of the latter should decrease since the surrounding soil is gradually saturated. If it is so, the writer would like to suggest for study a simple field procedure of estimating the coefficient of unsaturated permeability, k_u. Make the cup of the tensiometer cylindrical, with pervious bottom only, to permit the flow of moisture through the bottom only. In such a case the equation given in the paper for the vertical flow holds. Observe the tensiometer's readings during a certain time-interval, t, and plot them against time. The average ordinate of the area thus obtained is the average negative pressure in the soil under the bottom of the cup during the time-interval, t. Observe the levels of water in the cup at the beginning and at the end of and if possible, also during the time-interval, t. This permits to estimate the average rate of flow during this time-interval, and hence estimate the value of k_u.

The writer believes that when working with a tensiometer in the upper soil strata, due attention should be paid to the possible presence of the entrapped air.

DR. HANS WINTERKORN, *University of Missouri:* The energy concept of water in capillary systems has long been an accepted theory of the colloid scientist and it has been serving as the basis of the work of the "Committee on Physico-chemical Testing of Soils" as well as for the research on the properties of cohesive soils conducted at the University of Missouri However, as used in the latter work, and especially as employed in the fundamental research on the factors influencing the stabilization of cohesive soils, this concept was out of the realm of the practical soils engineer. Russell and Spangler by presenting this concept in conjunction with a valuable engineering technique have made the energy concept more obvious and more palatable to the soils engineer.

It is plain, that the most important application of this concept is in the field of highway drainage and of frost damage. Here we probably have gone as far as we can while using a purely mechanical point of view. There exists a dire need for a different type of theoretical tool and the energy concept appears to be the most promising. Since all energy must follow the laws of thermodynamics it is proposed that we use the latter for the twofold purpose of checking the correctness of our present concepts and as a guide for future explorations Thermodynamics can tell us why and under what circumstances water in capillaries freezes above, at, or below the normal freezing point of water. Also, its judicial application will help us to decide whether the strongly adsorbed water layers close to the mineral particles are in a solid, plastic, or highly viscous liquid state. All these matters must be known if the present state of confusion in the theoretical and practical aspects of the problem of frost damage is to be overcome.

The work by Russell and Spangler is an important step in this direction.

[2] B J. Korneff, "La Capacité d'Absorption du Sol" *Ann Sci Agronom*, Vol 43, No. 5, p 353 (1926), also "Handbuch der Bodenlehre" by E Blanck, Vol VI, page 102, Berlin, 1930