Hydraulics of Water in Unsaturated Soil

By L. A Richards

CERTAIN problems on the flow and distribution of water in soil can be simplified if principles and concepts of hydraulics long familiar to engineers are applied: Hydraulic head and hydraulic gradient are in common use for expressing the flow of water in various types of conduits and in saturated soil, but water flow in unsaturated soil is not often thought to be a similar case. Commonly used types of gages or manometers can be employed for measuring the pressure in water in unsaturated soil providing a suitable porous medium is used for connecting the water in the measuring device to the water in the soil. These pressure measurements can be related directly to hydraulic head and hydraulic gradient.

By way of introduction, consider briefly the liquid system shown in Fig. 1. The "hydraulic head" at any given point in a liquid system may be taken as the elevation at which water stands in a riser or piezometer connected to the point in question, the connection being made in such a way that velocity head is not measured. (Generally in the treatment of hydraulic problems it is necessary to consider velocity head, pressure head, and gravity head, these quantities being defined by the respective terms in the Bernouilli equation, $v^2/2g + p/dg + h = C$. The sum $p/dg + h$ is equivalent to definitions frequently given for "hydraulic head", although "static hydraulic head" is sometimes used to indicate that velocity head is not included. Moisture movement in soils is, in most cases, so slow that velocity head is quite negligible.)

It is seen that the hydraulic head at the points, A, B, and C in the figure is the same, this being the condition that must hold if the water is at static equilibrium under gravity. It is noted that a pressure gradient does exist, but between A and B or B and C the difference in the pressure head is equal and opposite to the difference in the gravitational head. If there exists a difference in hydraulic head between two points in a connected liquid system such, for example, as is shown in Fig. 2, the presence of an unbalanced driving force is indicated and the flow takes place in the direction of the decrease in the hydraulic head as shown by the arrow.

For soil moisture work we may define the "hydraulic gradient" as the loss in hydraulic head per unit distance along an average or macroscopic flow line. Engineering literature contains at least two different definitions for hydraulic gradient but the above definition appears to be in harmony with current usage in soil mechanics. When the points at which hydraulic head readings are taken are on a flow line, as in Fig. 2, then the average hydraulic gradient in the space between D and E is simply the difference in the elevation of the surfaces d and e divided by the distance along the flow line from D to E.

Turning now to the case of water in unsaturated soil, consider the system illustrated in Fig. 3. The manometers are filled with water, are sealed to conical porous cups, and are inserted in the soil. Assume that in the absence of evaporation the soil moisture system is at rest under gravity. This requires, as was the case for Fig. **1,** that the hydraulic head throughout the system be the same and that the hydraulic gradient everywhere be zero. The pressure head in the soil water at the various cups is equal to the difference in elevation between a cup and the surface of the water in its corresponding manometer. For the lowest cup, it is seen the pressure head in the soil water is equal to the distance of the cup below the water table where the water has atmosphere pressure. (For certain purposes there is advantage in defining the "water table" as the locus of points in the soil water system where the pressure is the same as in the overlying connected gas-phase in the soil pores. This avoids reference to the state of saturation or unsaturation and also avoids uncertainties that arise in attaining equilibrium water levels for' test wells in either slightly permeable or stratified soils.)

Water transfer through the cup wall takes place until the water inside the cup has the same pressure as the water outside the cup at the same level. At the three cups above the water table it is seen that, when the soil moisture system is at rest under gravity, the pressure head in the water is less than atmospheric pressure head by the water-column length equal to the elevation of the cup above the water table. Fig. 4 shows a similar case, except there is no water table present. Since the water surfaces in the three manometers have the same elevation, we must conclude that the hydraulic head at the three cups is the same, that the hydraulic gradient between the cups is zero, and that the soil water, if it forms a continuous connected system, satisfies the condition assumed above, namely, static equilibrium under gravity. The pressure in the soil water is everywhere less than the atmospheric reference pressure and

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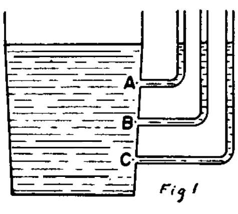

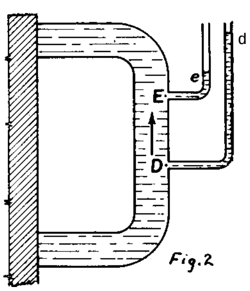

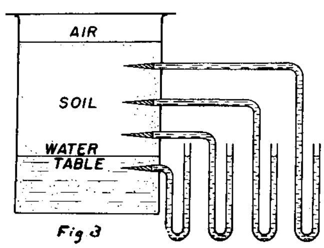

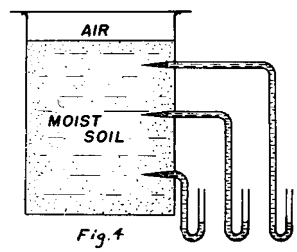

Fig. 1 In a hydraulic system at rest under gravity the hydraulic head is the same at all points. The gravity force is balanced by the pressure gradient • Fig. 2 Flow takes place in the direction of the decrease in hydraulic head • Fig. 3 The manometers indicate the hydraulic head and the negative pressure in the soil water at the various cups, the soil moisture being in equilibrium with the water table • Fig. 4 In this case the manometers indicate the soil moisture is at rest under gravity, there being no water table present

hence is negative. Water under negative pressure mav be said to be under tension and the combination of a porous cup and a pressure indicator for measuring the tension in soil water is called a soil moisture tensiometer. It is the function of the porous cup to permit contact between the manometer water and the microscopic bodies of water in the soil and at the same time to prevent air from getting into the manometer system which is subjected to partial vacuum pressure.

For field work it is expedient to replace the water manometers with mercury manometers as shown in Fig. 5. (When properly constructed, tensiometers give relatively trouble free operation[4]*. A paper summarizing recent advances at this laboratory in the design and construction of these units has been prepared for publication[2].) From the mercury column readings the tension in the soil water at the various cups can be calculated. The water manometers shown at the right of the figure could be used instead of the mercury manometers, but would require an excavation. If the soil surface is chosen as the hydraulic head reference datum, the hydraulic head at the various cups would be the elevation of the water surface in the various water manometers referred to this datum. Numerically this is the same as the water pressure in the respective tensiometers at the level of the soil surface when the pressure is expressed in water column units referred to the atmosphere as the reference pressure. With proper choice of scale units and zero settings, either soil moisture tension or hydraulic head values in either mercury column or water column units can be read directly from the mercury manometer scale. The manometer readings shown in Fig. 5 indicate that, on the average, moisture movement is upward in soil interval F, downward in interval H, and is at static equilibrium under gravity in interval G. This correspondence of flow direction to hydraulic gradient has been verified under field conditions[1].

Fig. 6 shows field data on hydraulic head under an 11-year-old navel orange tree. The tensiometer units were installed in a row 6 in apart, just under the ends of the longer branches, and the numbers on the respective curves indicate the depths (in feet) to which the porous cups were installed. The hydraulic head scale used is referred to the soil surface and hence indicates the distance below the soil surface that water would stand in water manometers connected to the various cups. The rise in the 1-ft curve that occurred at the beginning of April was caused by a 1½-in rain that did not appreciably affect the tensiometer readings at 3 ft or below. On April 15th and May 14th, four surface inches of irrigation water were applied in a basin surrounding the tree. The curves indicate this water quickly penetrated to the lo-ft depth, but did not appreciably change the tension at the 15-ft depth. The heavy line at the top of the figure indicates the time during which the moisture in the 8 to lo-ft soil layer was either at rest under gravity or moving up. Downward movement occurred for a time following each irrigation, the second downward flow period being shorter because of the heavier transpiration load and greater water deficit in the soil. The rate of moisture extraction at the various depths is indicated by the rate of decrease of hydraulic head after irrigation.

The depth of the porous cup substracted from the hydraulic head as plotted in Fig. 6 gives the soil moisture tension in feet of water. The tension or negative pressure in soil water is a direct measure of the security with which water is held by soil and is related in a general way to the moisture content of the soil[3].

It thus appears advantageous to use the concepts and methods of hydraulics in attacking certain moisture movement problems connected with the irrigation and drainage of soil. Direct applications can be made in studying the accumulation of salts in surface soil by upward movement from shallow water tables and in determining water applications required to produce root zone leaching. Similarly the procedure may be applied in studying or predicting moisture movements affecting the stability of earth foundations for buildings or surfaced highways and air fields.

*Superscript figures indicate references cited at the end of this paper.

REFERENCES

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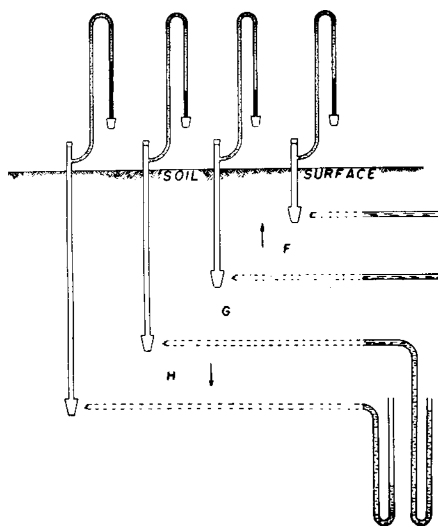

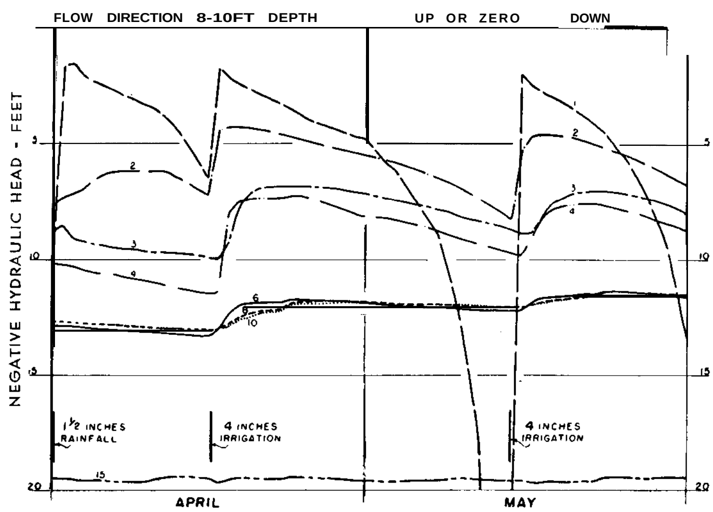

Fig. 5 (Left) A typical tensiometer installation employing mercury manometers. The equivalent water manometers are shown at the right. Fig. 6 (Right) A two months' record of the hydraulic head at eight depths under an ll-year-old orange tree. The soil surface is taken as the reference datum, and the numbers on the curves indicate the depths of the porous cups. On the average between the cups at adjacent levels soil moisture flow takes place in the direction of the decrease in the hydraulic head