Supplementary Statements by Authors of Original SR-40 Papers

Streaming Potential and Moisture Transfer in Soil upon Freezing as a Function of Porosity of Soil

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This article brings up to date the author's work on soil moisture transfer upon freezing and verifies experimentally the existence of various soil moisture transfer mechanism ranges as a function of porosity, as theorized by the author in 1958.

● IN A PAPER presented at the Highway Research Board's International Symposium on Water and Its Conduction in Soils, entitled "Some Concepts Pertaining to the Freez ing Soil Systems," the author theorized about various soil moisture transfer mechanisms and their assumed effects on the amounts of soil moisture transferred as a function of porosity of the packing of the soil system. The degree of packing is very important to know, as this gives a clue to what mechanism in the upward soil moisture transfer in the freezing soil system would be most likely to take place; film flow, film-capillary flow, film-vapor flow, or pure vapor diffusion, or a combination of some of the aforementioned flow mechanisms.

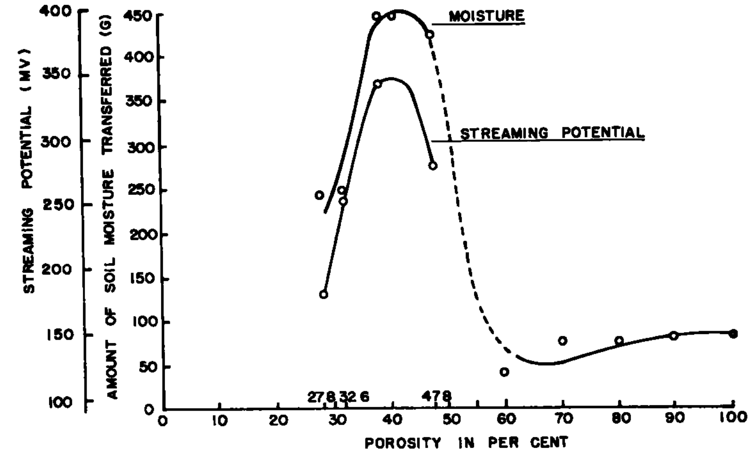
Since 1958 the author has been engaged in experimental studies to establish the porosity ranges of soil packings at which one or another soil moisture transfer mechanism would be most effective. There are, of course, no sharp porosity boundaries at which one kind of flow mechanism would cease and another, different mechanism assume its existence. Rather, there is a more or less pronounced transition from o moisture transfer mechanism to another depending on the porosity of the soil packing In these transition zones two adjacent effective moisture transfer mechanisms may c exist.

The instrumentation used in these experiments is described in the author's sympo ium paper.

The results of such an experimental study are shown in Figure 1. The soil packi were made of Dunellen soil, a silty glacial outwash. The amounts of soil moisture transferred and streaming potential measured in the freezing soil systems are given for the time lapse of 168 hr of freezing at temperatures T_S = 20 C at the upper surfa of the vertical cylindrical soil system and T_W = 8 C at the ground-water table (lower end of the system).

The summary of the test data is also shown in Figure 1. Between porosities of about n = 27.8 and about n = 50 percent (particles in contact) the effective soil moist transfer mechanism is by way of film flow; from porosity of about n = 50 percent to about n = 60 percent there exists simultaneous film and vapor flow (large voids, part cles still in contact). From porosity about n = 60 percent to about n = 100 percent (soil particles not in contact) effective soil moisture transfer mechanism is by way o pure vapor diffusion. Here porosity of n = 100 percent means an empty cylinder.

The maximum amount of vapor diffused (at n = 100 percent), though, constitutes only about 20 percent of the maximum amount of soil moisture transferred in the eff tive film phase (at about n = 40 percent).



TEST NO		B-6	B-9	B-4	B-7	B-5	A-6	A-5	A-3	A-4	A-7
EFFECTIVE MOISTURE TRANSFER MECHANISMS	LOWER POROSITIES THAN N = 27.8 % DIFFICULT TO ATTAIN IN PRACTICE	EFFECTIVE FILM FLOW				FILM AND VAPOR FLOW	PURE VAPOR TRANSFER				
OPTIMUM M C IN %		12 6	15 3	13 8	12 8	12 4	-	-	-	-	-
MAXIMUM DRY DENSITY IN LB/FT^3		119 8	119 7	102 1	97 7	86 7	63 0	46 5	29 9	13 4	0
VOID RATIO (e)		0 365	0 484	0 626	0 695	0 916	1 50	2.33	4 00	9 01	∞
AMOUNT OF MOISTURE TRANSFERRED: ABSOLUTE AMOUNT IN GRAMS		239 0	.250 0	445 6	445 0	424 0	41 0	77 0	75 0	82 0	83 0
AMOUNT OF MOISTURE TRANSFERRED: RELATIVE TO MOISTURE TRANSFERRED AT 100 % POROSITY		2 88	3 01	5 47	5 46	5 11	0 49	0 93	0 90	0 99	1 00
STREAMING POTENTIAL IN MV		180	250	340		275					

igure 1. Moisture transfer and streaming potential in soil upon freezing as a function of porosity.

In conclusion, these experiments in general make clear that:

1. The amount of soil moisture transferred upon freezing as a consequence of an xternally applied freezing temperature gradient to the soil system is a function of orosity of the packing of the soil;

2. Depending on the porosity of the packing, moisture may be transferred upward rom ground water towards the cold front by way of various moisture transfer mechanisms; and

3. Vapor transfer is a relatively ineffective soil moisture transfer mechanism; at is, soil moisture transfer in the film phase takes place virtually unaccompanied y vapor diffusion.

Water Movement in Porous Solids: Some Recent Progress

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This report gives some recent contributions to the diffusion analysis of water movement in unsaturated solids, to the thermodynamics of water held in such solids, to moisture movement under temperature gradients, and to the study of the effects of entrapped air*. The latter, rather novel, field of inquiry has theoretical and practical implications of great importance.

● THIS SHORT communication is essentially a footnote to the author's symposium article (1). In accordance with the Chairman's suggestion, certain more recent work with which the author has been associated is reported.

LIQUID FLOW OF WATER IN UNSATURATED POROUS SOLIDS

Early Stages of Absorption and Infiltration

The author's article (1) stated that it is "possible that perceptible deviations from Darcy's law may occur during the very early stages of absorption or infiltration into unsaturated systems." This was expected because the "diffusion analysis" predicts that, very close to the start of these phenomena, the flow rate, and hence the Reynolds number of the system, must be so large that Darcy's law fails. Further, Darcy's law implies a force equilibrium with no resultant to impart momentum to the system, whic is initially at rest. These considerations suggested that the diffusion analysis might b open to some question, at least during the early stages of phenomena such as absorpti and infiltration.

An analysis based on Newton's second law has been carried out and has resolved these various difficulties. The net result is that the error in the diffusion analysis du to the neglect of inertia effects is entirely negligible, except for a short initial period of less than 10^{-4} sec; the maximum Reynolds number of the motion is shown to be finit and the observed small deviations from the diffusion analysis during the early stages o absorption and infiltration are in the wrong sense to be explained as due to inertia or high Reynolds number. They appear to be due to the effects of entrapped air. This work is fully reported by the author (2).

Viscous Dissipation of Energy During Absorption and Infiltration.

The problem of just when and where energy is dissipated in unsaturated porous solids when they are taking up water does not seem to have been investigated hitherto. An investigation of the viscous dissipation of energy during this process has been carried out, and is an extension of the previous diffusion analysis. One by-product of the study is a novel definition of hydraulic conductivity in which it is related to the point rate of viscous dissipation in the solid. The profiles of energy dissipation reveal a characteristic peak near the "wet front" in terms of energy dissipation. This study is described by the author (3, 4).

* Chairman's note: See statement concerning effect of entrapped air, HRB Special Repor 40:335 (1958); also, "Das Verhalten des Bodens gegen Luft," Handbuch der Bodenlehre, Julius Springer Verlag, Berlin, 6:253-342 (1930).

Absolute Thermodynamic Functions in Study of Porous Solids

The potential function commonly used in soil-water studies is equivalent to the specific differential Gibbs function. It has been found (5) that it is more useful in problems in which one wishes to examine changes in the total potential energy of the system to use the absolute form of thermodynamic function. As an example, the differential function does not distinguish between the energy state of water in a saturated porous solid and that of free water at the same level. The absolute function does so.

Mathematics of Concentration-Dependent Diffusion

The mathematics of concentration-dependent diffusion is basic to the diffusion analysis of water movement in unsaturated solids. Hitherto, numerical methods have been necessary to solve these problems, except in certain quite special cases. A general method of solution of problems in concentration-dependent diffusion by analytical means has been developed (6) and promises to make the mathematical problem more tractable. Details of a function entering into this new method are given in a second paper (7).

MOISTURE MOVEMENT UNDER TEMPERATURE GRADIENTS

Although there seems to be general agreement that the theory of moisture movement in porous solids under temperature gradients put forward by Philip and De Vries (8) is broadly correct (9), certain workers appear to have misunderstood some aspects and to have been led into erroneous criticisms (10). De Vries and Philip (1) emphasize the differences between the fine structure of the temperature field and the vapor field and clear up other misconceptions that have arisen.

EFFECTS OF ENTRAPPED AIR IN POROUS SOLIDS

For quite some time now, the presence of entrapped air in naturally saturated porous solids (12) and its effect on hydraulic conductivity of such solids (13) have been clearly recognized. Recognition of the importance of the air-phase in unsaturated solids has been somewhat more tardy.

The possibility that entrapped air would produce nonuniqueness of the moisture potential function in the surface layers of a porous solid was recognized (14) in 1955. This explained the characteristic "dog-leg" transition zone observable in moisture profiles during infiltration (15) and also the observed small deviations from the diffusion analysis (2).

Temperature Dependence of Moisture Potential

Another phenomenon that has long been puzzling is the failure of the temperature dependence of moisture potential to be related in any consistent manner to the temperature dependence of surface tension. A proper understanding of the temperature dependence of moisture potential is necessary before the problem of liquid phase transport under temperature gradients can be studied in a meaningful way.

In the author's symposium paper (1) it was stated that "the explanation seems to be that as temperature increases, the volume of totally entrapped air bubbles expands, leading to an altered configuration of the meniscal surface between the liquid water in the medium and the external atmosphere. Experimental study of this effect is in progress in the Australian C.S.I.R.O. Division of Plant Industry."

The experiments and a detailed working-out of the theory confirm the suggestion made in HRB Special Report 40. Peck has been responsible for the experimental program and for going into the details of the theory. He has reported part of the work (16) and has a further paper in preparation.

Effect of External Air Pressure on Moisture Potential

Intimately connected with the temperature effect previously discussed is the effect of changes of the external pressure on the volume of entrapped air, and hence on meniscus configuration and on moisture potential.

Experimental work has confirmed the reality of the effects of external air pressure which the "trapped air" theory demands (16). This effect is also of great practical importance. For example, systematic changes of water table level with atmospheric pressure are to be expected, and have been observed experimentally by Peck (17).

Perhaps of greater importance is the fact that this work indicates that moisture characteristics determined by pressure-plate methods do not necessarily agree with those determined by "suction" methods. There will certainly be important discrepancies at the wet end of the moisture range. It is more difficult to predict the importanc of this effect at moisture potentials greater than 1,000 cm.

The significance of this work on trapped air for soil mechanics is that it underlines the importance of treating the soil as a three-phase system—solid, liquid, and gas. Perhaps all have been too prone to work with the two-phase system of just soil particles and water.

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