The Effect of Freezing on a Capillary Meniscus

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● THE PURPOSE OF this article is to describe the effect of freezing on a capillary meniscus as observed in experiments performed at the Soil Mechanics Laboratory, Rutgers University, in pursuing the project "Upward Migration of Soil Moisture under Freezing Conditions," sponsored by the National Science Foundation. Experiments show that upon freezing the capillary meniscus disappears, and the water comes in direct contact with the downward-freezing ice lenses, thus furnishing the evidence for what was hitherto an assumption. This assumption forms a basis on which the project mentioned above partially rests.

Introductory Notes

In designing a soil freezing experiment and the necessary equipment for studying the upward transport of soil moisture upon freezing, it is necessary to make certain assumptions upon which to base the study. Among several assumptions the following one is made:

A growing ice lens is in direct contact with a thin hull or film of soil moisture similar to the adsorbed layers which form on many other solids that are in contact with water, permitting it to move up and supply the necessary moisture for the growth of the ice lenses. The moisture films, in turn, are in direct contact with the groundwater table (1). The question has often arisen as to what is the nature of the driving force for the upward flow of soil moisture upon freezing: is it the open, curved capillary meniscus, concave to its vapor, or is it something else?

The following has been indicated as the objection against the capillary theory: Under actual conditions, one has to assume that if on freezing the frost reaches the capillary meniscus, the lower boundary of the downward-growing frozen layer of soil (= ice lens) is in direct contact with the upper boundary surface (= menisci) of the capillary soil moisture. On the other hand, it is understood that the capillary forces are present only at the time when there are open or free-surface menisci present which form a moisture-air boundary. In other words, at the air-capillary water interface (= meniscus) the capillary water should be in contact with its own vapor. With regard to these two points, it is, therefore, difficult to imagine how a surface of free menisci at the lower ice boundary can exist, and at the same time capillary subpressure for the upward transport of soil moisture upon freezing develop. This inconsistency has been pointed out already by Taber (2, 3, 4).

Purpose of Experiment

From physics, it is known that under non-freezing conditions capillary water in an idealized, vertical capillary tube is in contact with its own vapor. The water and vapor are separated by a concave interface or meniscus relative to vapor. These conditions are illustrated in Figure 1.

However, very little is known as to what happens to the meniscus when frost penetrates the ground downwards, reaches the meniscus and passes by it. In other words, it is interesting to know, as illustrated in Figure 2 (a), whether the concavely curved meniscus under freezing conditions still exists, which would mean that between the downward-freezing ice layer or lens and the water in the capillary there is a space, probably occupied by aqueous vapor, or, as was assumed for the basis of study and as is illustrated in Figure 2 (b), the water is in direct contact with the downward-freezing ice lenses.

In order to learn what happens to a capillary meniscus or water-vapor interface upon freezing and to examine and verify the validity of the assumption that the soil moisture films are in direct contact with the freezing ice lenses, appropriate laboratory experiments were improvised.

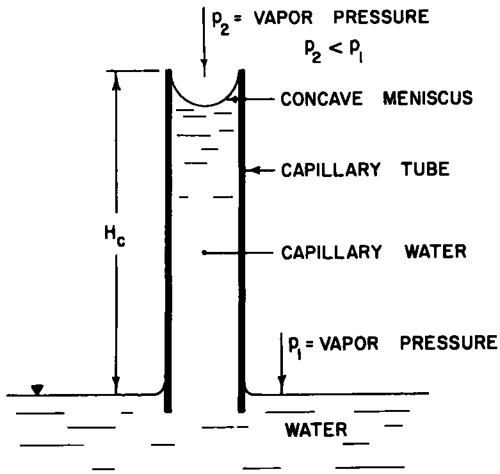

Figure 1. Water-vapor interface.

Method of Experiments

The method which has been used in these improvised experiments consists of freezing distilled water in a verticle capillary tube and observing by means of optical magnification the changes in shape a capillary meniscus undergoes under freezing conditions, and fixing the changes photographically (5).

Apparatus

The principle of the apparatus used in these experiments is shown in Figure 3. A capillary tube of pyrex glass of 1 mm I.D. was immersed in distilled water. The capillary height was observed to be H_C = 11.0 mm. The meniscus was kept at the upper end of the tube, upon which a container of dry ice was placed. This situation approximately corresponds to conditions in the field, the walls of the tube and the bottom of the container simulating the frozen mineral particles of the soil.

The dry ice had to be kept in a container because when a fragment of dry ice was placed directly at the upper end of the tube, the developing gas forced the meniscus vigorously down, and such a condition simply does not duplicate the phenomenon in the field. The use of ordinary ice was too time-consuming. The temperatures of the water and the environment of the upper end of the tube were measured by means of thermistors and a Wheatstone bridge. The changes in the meniscus upon freezing were observed by means of a 35 mm reflex camera with a lens attachment which magnified the object to be observed about twice. Also, by means of this camera photos of the menisci were taken.

As can be understood from this description, the apparatus seems to be relatively simple. However, the preparation of the meniscus specimen and the work of experimentation and observation are very tedious, cumbersome, time-consuming, and require much patience.

Observations

The experiments on the effect of freezing on a capillary meniscus permitted very

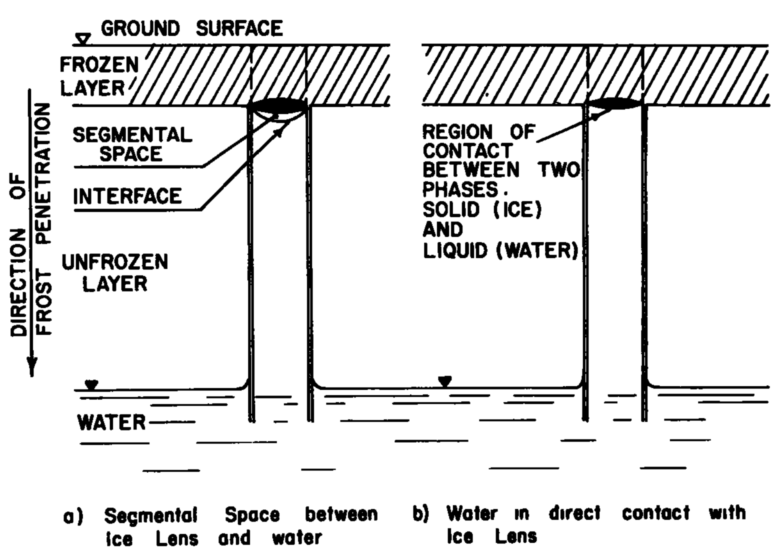

Figure 2. Ice-vapor and ice-water interfaces.

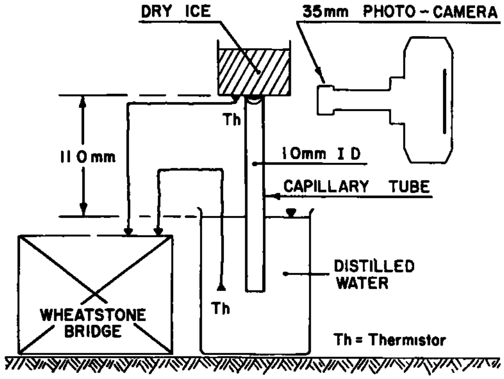

Figure 3. Apparatus.

clear observation of the following phenomena: After commencement of freezing of the meniscus in the direction of the inner part of the tube by placing the ice container, the outside bottom of which was covered with a thin sheet of clean ice, in contact with the upper end of the vertical glass tube, the meniscus flattens out, becomes shallower, narrower, decreases concentrically in size toward the center of the tube, and finally disappears entirely. Thus a direct contact between the ice and water is established as shown in Figure 2 (b), and the water is no longer in contact with its own vapor.

The stages of disappearance of the meniscus upon freezing are illustrated in Figure 4. This phenomenon takes place in one gradual, smooth, continuous process, and within a time of approximately 20 to 30 seconds, depending on the environmental temperature conditions around the meniscus. Also, the time depends upon whether the outside bottom of the ice container, which is covered with thin, clean ice, is covered with snow or not. In observing the disappearance of the meniscus one gets the impression that there exists some kind of a central, effective force lifting the meniscus and the water underneath the meniscus up and attaching the water flush to the ice lenses of the cold outside bottom of the ice container. Thus, the meniscus is no longer present, nor is there a segmental space between the ice container and the water in the tube (Fig. 5). Upon the lifting up of the water and attachment of the latter to the ice-covered bottom of the ice container no interruption of the water column in the tube was observed. This indicates that the amount of water which upon freezing is lifted up and attached to the freezing ice lenses is replenished in the glass tube or capillary from the beaker, viz., ground water. Continuing freezing, the water in the tube freezes, appearing opaque in color. The ice freezes and expands downward, i. e., in the direction of the least resistance. No heave could develop because of the weight of the ice container. To prevent supercooling the water the capillary was occasionally tapped (this simulated vibrations induced on roads by traffic). However, the disappearance of the meniscus upon freezing also took place without tapping the tube and without any noticeable difference in time as compared with tapping.

Discussion of Observations

The observations made in these experiments seem to indicate that whatever amount of moisture in the form of vapor there might have been on the concavely curved meniscus at the moment of commencement of freezing, all that moisture was frozen to form a direct contact between the capillary water and ice lenses. The swift lifting up of the meniscus and its direct attachment to freezing ice indicates that the vapor pressure over the curved meniscus (or water-vapor interface) is neutralized and the meniscus destroyed. Thus, upon freezing, the solid phase (= ice) replaces the vapor phase, and, as there is no meniscus nor any segmental space above the meniscus present, there is also no vapor pressure present, i. e., $p_2 = 0$. Hence, after the replacement of the vapor phase by ice, it seems practically that the capillary presupposition that capillary water is in contact with its own

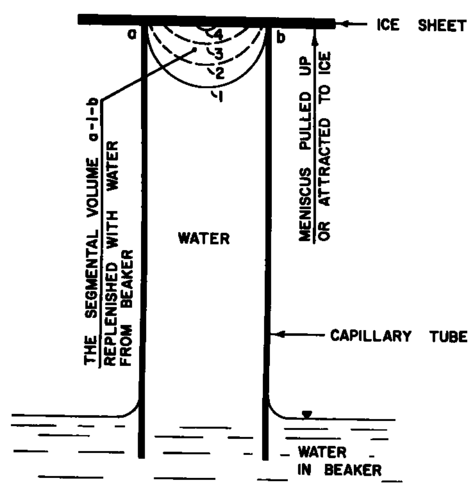

Figure 4. Stages of disappearance of meniscus upon freezing.

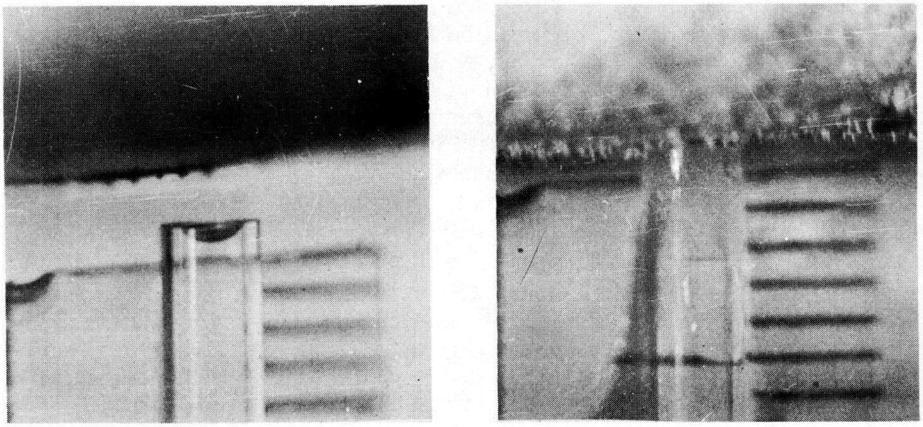

Figure 5. Action of freezing on a meniscus, showing (a) meniscus upon commencement of freezing and (b) water in direct contact with ice lenses.

vapor (which is true under non-freezing conditions) no longer holds. We must, therefore, assume (after freezing causes the transition from the vapor phase to ice) that for freezing conditions there exists a different concept of the mechanism of the driving force for the upward supply of soil moisture from the ground water to the downward-freezing ice lenses.

That water from a water reservoir (ground water), located at some distance below the downward-freezing soil layer, is being sucked up or, better said, moved upward is evidenced experimentally in a soil freezing experiment by the loss of water from a burette to the soil under controlled conditions and by the increase in the amount of water in the experimental freezing soil sample over the original moisture content present when the soil sample was prepared for the freezing experiment.

CONCLUSIONS

Although the freezing process by means of dry ice is an accelerated one, it is believed that it reflects pretty truthfully the stages of disappearance of the menisci.

The observations made in these experiments are valuable because they (a) throw light on what really happens to the meniscus in the region of contact between the water-vapor interface upon freezing; and (b) verify the soundness of the theoretical assumption made which, among other assumptions, forms the basis for the theoretical-experimental research on the upward migration of soil moisture upon freezing; (c) in particular, the results of these simple experiments establish the fact that upon freezing the upward-transported soil moisture is in direct contact with the downward-freezing ice lenses.

The research work on the upward migration of soil moisture upon freezing is being continued.

ACKNOWLEDGMENT

The effect of freezing on a capillary meniscus as reported in this article constitutes a phase within the scope of the research project "Upward Migration of Soil Moisture under Freezing Conditions" sponsored by the National Science Foundation.

Joseph D. Sage, Research Assistant in Civil Engineering, Rutgers University, performed with great patience the experiments relative to changes of menisci upon freezing.

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DISCUSSION

WILLIAM S. HOUSEL, Professor of Civil Engineering, University of Michigan, Ann Arbor, Mich., and Research Consultant, Michigan State Highway Department — This paper brings up the most intriguing subject of a mechanism for describing capillary phenomena and the forces which may be involved in the formation of a capillary meniscus. The growth of frost plates and the forces involved in the flow of capillary moisture to the freezing surface, which are discussed by Penner (1) and Gold (2) may be explained in several ways, depending largely on a matter of viewpoint or perhaps a matter of definition. On the other hand, this may be referring to the matter under discussion too casually, as the description of any physical phenomenon in anything but the most realistic terms may lead away from the truth. A theory has been most aptly defined as a logical description of the results of observation; so, after all, the validity of any theory will ultimately depend on the terms which have been used to describe the phenomenon under consideration, and whether these terms represent fact or fiction. The ingenious experiments conducted by Professor Jumikis may prove to be a valuable contribution in that they serve to demonstrate more clearly the real mechanism involved in capillarity.

For almost twenty years the writer has been trying without too much success to call attention to the misconceptions in the traditional concepts of capillarity (3, 4) and the confusion they have caused in soil mechanics. A substitute mechanism has been suggested which avoids the inconsistencies involved in surface tension as the basic concept. The suggested substitute postulates a fixed volume of water proportional to the maximum area under the meniscus, with the supporting reaction supplied by the internal pressure in the liquid. The necessary pressure differential to sustain a column of water in a capillary tube, or to cause capillary movement of moisture, originates in the molecular attraction of the solid surface. The forces involved are transmitted by the combined interaction of molecular attraction and repulsion in the liquid, and their action does not require a gas-liquid interface, vapor pressure, or other attributes peculiar to the capillary meniscus. The capillary potential of any combination of solid and liquid may be measured as an integrated boundary effect and expressed quantitatively as a fixed volume or weight of liquid per unit length of wetted perimeter. The dimensional properties of the capillary channels can then be conveniently evaluated in terms of their perimeter-area ratio (5, 6).

The explanation of the behavior of the capillary column in terms of surface tension and the capillary meniscus with the differential vapor pressure seems strained and unrealistic when it is considered that the analogy of surface tension cannot be stretched to imply that the water-gas interface or boundary of the meniscus is a tensile membrane attached to the freezing surface. Actually, physical chemists declare that there is no structural continuity in this surface and the molecules in the interface are free to migrate in and out of the surface even though they are acted upon by molecular forces of attraction as well as forces of repulsion. Although Professor Jumikis indicates some of the inconsistencies which have been generally recognized, he seems to have difficulty in freeing himself from the assumptions of surface tension outlined in his introductory statement. At one point he states: "It is understood that the capillary forces are present only at the time when there are open or free-surface menisci present which form a moisture-air boundary." Later he speaks of the lifting up of the meniscus and its direct attachment to the freezing ice, following which the meniscus is destroyed and water from some distance below is sucked up to maintain the continuity of the capillary column of water. He then states that, "We must, therefore, assume . . . that for freezing conditions there exists a different concept of the mechanism of the driving force for the upward supply of soil moisture from the ground water to the downward-freezing ice lenses."

This statement appears to be as far as the author was prepared to venture in departing from the traditional description of capillary flow in terms of surface tension. He has suggested no basic mechanism to take its place, although he recognizes the need for one. In the writer's attempt to explain these phenomena, the effort has been made to think in terms of both molecular attraction and repulsion as forces acting on the molecules. In so doing, it frequently seems to be more realistic to explain capillary movement of moisture in terms of pressure differentials as a push rather than a pull. Formulating a mechanism to explain frost plate formation provides an excellent example to illustrate the use of internal pressure rather than the mythical surface tension as the driving force.

Molecular repulsion is associated with the kinetic energy of the molecules, the forces which cause them to push about generating internal pressure in the liquid. At the beginning of the author's experiment, when the temperature begins to decrease, the kinetic energy of the molecules in the vicinity of the freezing zone is correspondingly decreased. The result is to create a pressure differential with respect to the main body of water which increases the capillary height and moves the column of water toward the ice lens. When molecules reach the freezing surface, the attractive forces exerted by the solid ice neutralize correspondingly greater amounts of molecular repulsion. This decreases the mobility of the molecules and causes a sharp drop in the kinetic energy of the molecules and the pressure which they exert in the liquid phase. This pressure drop causes a more marked pressure differential within the liquid and the water column is drawn quickly into contact with the freezing surface. It may be pertinent to note that this pressure differential remains long after the meniscus has disappeared and the water column continues to feed the growing ice plate. At no time in such a sequence of events is there any necessity for surface tension, the fictitious membrane which it implies, adsorbed layers of the wall of the capillary to serve as channels for the water to flow to the ice lens, or a pressure differential across the gas-liquid interface which inconveniently disappears as the experiment concludes.

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ALFREDS R. JUMIKIS, Closure — Professor Housel's comment that the validity of any theory will untimately depend on the terms which are used to describe the phenomenon under consideration is quite pertinent. In this connection it suggests that in the progress in frost action research in soils sometimes several terms are used to designate one and the same thing; for example, driving force, driving pressure, pressure deficiency, subpressure, suction force, moisture tension, and other concepts. It seems that a point has been reached where revisions and definitions of the various concepts are in order. The discusser's comments strengthen this point indirectly.

In his third paragraph Professor Housel cites the sentence: ". . . It is understood that the capillary forces are present only at the time when there are open or free-surface menisci present which form a moisture-air boundary" as a source of argument, without apparently fully appreciating the spirit of the corresponding part of the original text. At the end of the pertinent paragraph of the original article it is mentioned that a certain inconsistency has been pointed out already by Taber. The logical content of the matter is that in the original article, before describing observations from experiments there were presented at the beginning some concepts from the capillary theory under nonfreezing conditions in an open capillary tube (not voids nor capillaries in soil).

The object of the author's article is solely to report on the experiments; not to suggest any new basic mechanism to take the place of the capillary, or any other theory. In this respect, the title of the article seems to be satisfactorily limiting through inclusion of the words "Capillary Meniscus."

However, the following point of Professor Housel's discussion is in agreement with the author's view; namely, that "when the temperature begins to decrease, the kinetic energy of the molecules in the vicinity of the freezing zone is correspondingly decreased. The result is to create a pressure differential with respect to the main body of water toward the ice lens."

Because the ice lenses are coated with a film of water, under certain packing conditions of soil the ice lenses are connected, via the moisture films, with the ground water.