Some Concepts Pertaining to the Freezing Soil Systems

ALFREDS R. JUMIKIS, Professor of Civil Engineering,
Rutgers, The State University, New Brunswick, New Jersey

Introductory Remarks by the Chairman

Aristotle wrote about the necessity for stopping once in a while and looking over the path traversed or the material or mental possessions accumulated. This necessity of stopping and looking is especially important if one deals with complex systems and phenomena. Professor Jumikis, who has worked long and intensively on the frost problem in soils, is taking such a stop and is relating what he sees from the perspective of his own research in this field and that of others. The situation is indeed complex, but it is a system and not chaos; and while the intertwining and coupling of many processes occurring simultaneously in the system can as yet be traced only qualitatively, such tracing is the first step toward ultimate clarification of the picture and the desired quantitative treatment of the processes involved. We are grateful to Dr. Jumikis that he has taken the time to stop and look.

● THIS ARTICLE pertains to the subject of soil thermodynamics. In preparing it the author tried to give proper emphasis to some of the important concepts and processes which take place in a soil system upon freezing. Basic physical concepts such as the process, the system, primary and induced potentials, and some modes of possible soil moisture transport in a freezing soil system are presented.

The contents of this article are intended primarily as a guide for those who are not yet familiar with the various physical concepts used in engineering soil thermodynamics in connection with frost action research. However, it is hoped that it may also be of some benefit to others interested in this subject as review material; that it may assist in the consolidation of the framework of engineering soil thermodynamics as a scientific and technological method; and that it will stimulate constructive discussion concerning a subject of great importance.

NEED AND PURPOSE FOR RESEARCH IN FROST ACTION IN SOILS

Purpose

The purpose of frost action research in soils is to study the interrelationships of the various factors involved in damaging roads by frost in interaction with soil moisture, and how to combat effectively frost in highway engineering. As the amount of theoretical and experimental facts gained in frost action research increases in volume, there arises a need for generalization and consolidation of the knowledge, as well as for a generalized review on this subject. It is believed that such a review can be accomplished briefly by presenting a description of some fundamental concepts pertaining to the freezing soil system. It is also hoped that the generalization, although picturing an ideal condition, will differ but little from the real, natural conditions.

Effects of Freezing upon Soil

Freezing causes the soil moisture to translocate from warm regions to the cold ones. The freezing process in soil and the heat and moisture transfer in soil induced by freezing are very complex phenomena. Indeed, some of the processes which take place upon and during freezing of a soil system are not yet well understood, or are even unknown.

Observations, experiments and studies show that a variation in any one of the factors partaking in the soil freezing process influence to a greater or lesser extent the other factors, such as the properties of soil, water and ice. This is to say that the whole system "soil-water-temperature" is influenced by the application of a freezing thermal potential. In other words, energy in the form of heat is applied to or abstracted from this system. This implies that, because of the variation in properties effectuated by temperature and moisture in it, soil is a difficult engineering material to deal with and to study, particularly when subjected to freezing temperatures.

Methods of Study

Because the soil freezing problem in highway technology in the United States and elsewhere is of national importance, much effort is being spent at the present time and much more is still to be spent in trying to solve several problems. These involve an attempt to learn and understand the basic phenomena relative to frost action in soils and to use several lines of attack and methodology in attacking these problems. Some engineers and scientists pay more attention to the interior of the freezing soil system; some others—for reasons that will be pointed out later—study the freezing soil system in its entirety, evaluating the performance of the freezing soil system by its total net end result.

Work done hitherto by other authors and by the author of this article reveals that the studies of the interior, or the details, of the freezing soil system are very difficult and complex. This is partly because of the many factors involved, and partly because of the many independently or mutually interacting processes these factors induce when subjected to thermal potentials. For example, an effort was made to solve many problems relating to the details of the interior of the soil system strictly by means of thermodynamics alone. But, although very useful in many ways, by its very nature thermodynamics ignores the internal structures of the system. However, thermodynamics permits the treatment of the freezing soil system in its entirety, between the entrance of energy and its exit of the system, giving a net end result which then can be evaluated practically. Of course, the processes which take place in the interior of the freezing soil system are then masked out, but they are there.

To understand the soil freezing process, it is, of course, necessary to understand each of the partial processes and their effects on the total end result. Algebraic summation of the results of the singular processes should give a check for, or balance out, the total net performance of the entire system. These are then the primary reasons why the details of the interior of the freezing soil system, as well as the total performance of the entire freezing system should be studied. This detailed knowledge will then be basic for practical application in highway and airport engineering. It seems now that the unknown and obscured factors and their associated processes in a freezing soil outnumber the known ones. And this, in its turn, challenges the studies and justifies the efforts in pursuing frost action research in soils to learn all the factors and processes involved, and to understand more fully the freezing phenomenon as a whole.

Need for Experimental Studies of Frost Action Research

There are certain things which can be studied theoretically within the scope of a frost action research program. However, because of the complexity of the system "soil-water-temperature," and because of the even more complex factors in the freezing process involved as well as induced, there exists a great need for their experimental elucidation. Judging from the amount and variety of the experimental work that has been done so far, and from the published results on the various phases of frost action research, one gets the impression that such studies have now received a great impetus, and that some day the "grain by grain efforts" will fit together nicely, giving the engineering profession a framework so necessary in dealing with freezing soils. The knowledge of the performance of a soil system under freezing conditions in its entirety is necessary in designing and constructing highways, airports and other earthworks. The knowledge of the details of the interior of a freezing system, however, is an absolute necessity if frost in highway soils is to be combated effectively.

Until more definite knowledge becomes available as to what actually happens inside the freezing soil system in detail, and what are the various reasons and causes for a factor or process, or for changes in properties of the soil matter (soil, moisture, ice, air or gas) under freezing conditions, the author is at present trying primarily to detect the end result on soil caused by a freezing thermal potential as a driving energy for the upward transfer of soil moisture from the ground-water to the freezing ice lenses.

CONCEPTS

Process

A process is here defined as any event in nature and in the laboratory soil freezing experiment in which a redistribution of energy (heat energy), and moisture transport takes place.

In order to transfer moisture between two points within the soil system there is needed a driving pressure, or more generally, a potential difference between these two points, for example, entrance and exit of the system.

System

The soil system which is subjected to freezing for study purposes is a separated, free finite part of matter (imagine free body) such as the soil sample separated from its surroundings by its container and insulation material. Thus, the system is clearly defined by spatial boundaries. For a detailed description of a soil system and its surroundings see Jumikis (1). In the system changes in the state of matter (for instance water) and transfer of energy and mass, for example heat and water, respectively, upon freezing can be studied. The soil system to use in the experimental frost action research is an open one to correspond to the conditions as they prevail in nature. According to De Groot (2), an open system is one which can exchange matter as well as heat and energy and work with its surroundings. A closed system is one which cannot exchange matter, but can exchange heat, energy and work.

Referring to Margenau (3), "completely closed systems, however, are never found in nature . . . ," although he admits that under certain circumstances closed systems can exist.

Potential

In engineering and in science, the term "potential" has many meanings. In some branches of science, such as in physics and the engineering sciences, this term, commonly used as an adjective, means "available." Thus, one speaks of potential energy or energy of state or position. In contradistinction, in soil science dealing with moisture migration in soil, and in thermal soil mechanics dealing with frost action in soils, the term "potential" is traditionally used as a substantive—for example, thermal potential, capillary potential, electric potential, concentration potentials (solvent, density, moisture potentials), gravity potentials, and other possible potentials. In this sense, "potential" at a point, or "potential difference" between two points of a freezing soil system would mean the energy, measured by work done, necessary to transfer a unit mass of soil moisture through the porous soil medium from a given position in reference to another particular point within the system, as for instance, from the ground-water table to the downward penetrating cold front, or any other coordinate point within the system. The potential as the energy or driving pressure for the moisture transport in soil, hence, must be capable of being expressed by means of a certain function from which the intensity of the driving pressure, and/or the velocity and amount of the upward-migrating soil moisture passing a horizontal cross-section of the system in question at any point can be mathematically defined. From this, one immediately realizes that in the evaluation of frost penetration depths, where it is necessary to know the rate of the upward flow of soil moisture (4), the latter must be expressed as a well-defined function of the driving pressure if quantitative results in frost action research are to be obtained. It is to be remembered that among the many

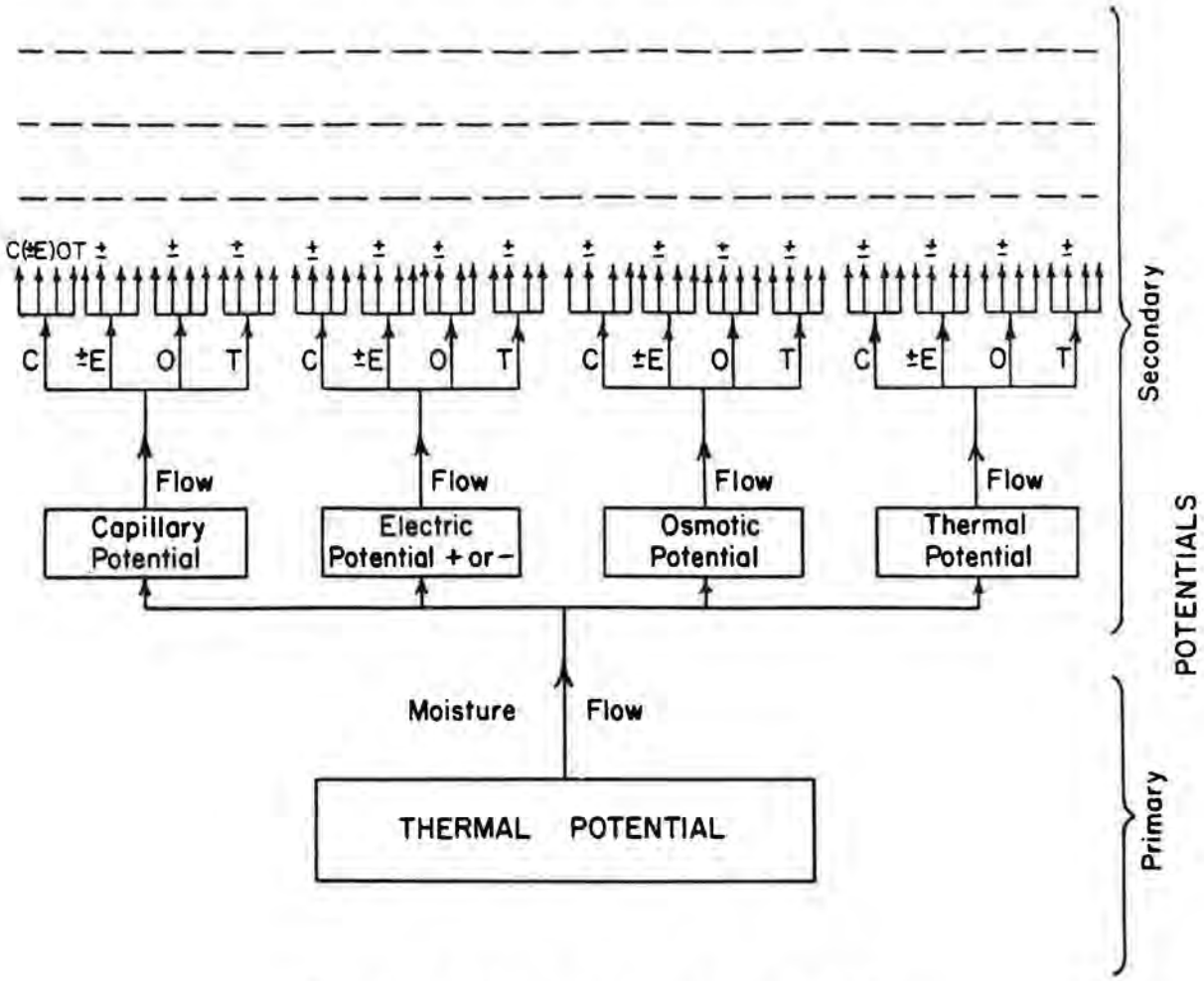

Figure 1. Primary and secondary potentials.

factors, temperature and position (coordinates) of the points between which the pressure difference is to be measured, are of very great importance. Sometimes the driving pressure is also termed the driving force, pressure deficiency (relative to atmospheric pressure), subatmospheric pressure, soil suction, suction pressure, soil moisture tension, capillary tension and suction force. Because of the negative characteristic of the capillary water suspended at its meniscus (negative pressure or tension), the stress in the capillary water is called suction pressure, pressure deficiency, soil moisture tension, and other terms as above. Now, the tension of the soil moisture is not just an externally applied constant like that which can be produced, for example, by means of Beskow's capillarimeter, which is of the hydraulic type and can be operated with water or mercury (5). On the contrary, the moisture tension is an intrinsic property of the soil system. This property, in its turn, depends upon the mutual affinity of the water to the surfaces of the solid soil particles, or rather to the adsorbed, static or immobile, stressed moisture films around the soil particles. Quantitatively, thus, the soil moisture tension would manifest the total joint and net action of all the system's internal forces in displacing an elementary or differential volume of soil moisture.

The energy potential is a simple concept and easily applied in studying freezing soil systems.

Classification of Potentials

For the purpose of convenience and simplicity, the various potentials which might occur under varying conditions in the freezing soil system may be classified into two

broad groups as follows (6): (a) primary potentials, and (b) secondary, or induced potentials.

A primary potential is one applied externally to the system. For instance, a primary potential may be a thermal potential, an electrical potential (causing the phenomenon known as electro-osmosis), a gravity potential, and other possible potentials.

A secondary potential is one which is induced within the soil by an externally applied primary potential. Any primary potential may induce one or several secondary potentials as new processes or mechanisms for the translocation of soil moisture (7), such as new heat potentials, electric potentials, concentration potentials, (moisture, soluble salts), but probably no gravity potentials. These conditions are illustrated in Figure 1. For example, a primary thermal potential may cause the change in soil moisture densities, which in their turn, may induce hydro-dynamic pressure differences. Or, a concentration gradient may induce an energy flow, which in its turn induces a temperature difference. Thermal potentials in a freezing soil system, according to the author's observation induce electric potentials. The magnitude of the induced electromotive force depends largely upon the strength of the concentration of the electrolyte (viz., soil moisture containing some amount of soluble salts) in the soil present. Induced electromotive forces in freezing soil systems composed of Dunellen soil (glacial outwash material) were measured in the laboratory by the author from 40 to 120 millivolts.

Induced potentials may act and contribute to moisture flow in the same direction as the flow which is caused by a primary potential, or it may act in the opposite direction, depending upon the properties of the porous material or membrane, and other factors still not clearly known (8). This reference source (8) contains also a note that the phenomenon of thermo-osmosis was discovered by Lippmann in 1907.

Hence, the net amount of the upward moisture transport in a soil system upon freezing, or the end result of the entire system, is an algebraic one. This once more points out the convenience of working with an entire thermal system. The effects of a secondary or induced potential are called by De Groot "cross-phenomena" or "cross-effects" (2, p. 2); De Groot, Winterkorn (9), and Bosworth (10) term the induced potentials also the "coupling effects."

It is here pertinent to note that the many terms now in circulation and used to designate one and the same thing (for instance the driving pressure, or the induced potentials, or many other descriptions) merely indicate that in the progress in frost action research in soils the point has been reached where revision, re-evaluation and coordination in the corresponding terminology is in order.

PREPARATION OF SYSTEM

Preparation

Before the freezing experiment, the soil sample must be prepared and the type of the system—open or closed—provided. The preparation consists of ascertaining the grading and weight of the dry soil, the density obtained by means of the standard compaction test at its optimum moisture content, determination of porosity of the soil packing and, in the case of an open system, permitting the soil sample to come into moisture equilibrium by taking in water from the "ground-water." Obviously, the soil sample is not fully saturated, but this condition would correspond very nearly to the field conditions which exist in the soil just before the freezing season sets in. This is in accord with Winterkorn's opinion that "for engineering purposes the most suitable type of test is one in which the soil system is permitted to saturate itself in capillary contact with free water" (meant ground-water) (11). By doing so, the adsorption process of soil moisture on the surfaces of the soil particles is already accomplished and the moisture films around the particles and the connecting of the ground-water table are established under natural conditions before the freezing of the soil system begins. Again, one should see that the soil system is prepared for the freezing experiment in such a way as to simulate natural field conditions as nearly as possible.

Depending upon the texture of the soil, the state of packing, the configuration, that is, geometry and surface topography of the soil particles, the voids within the soil

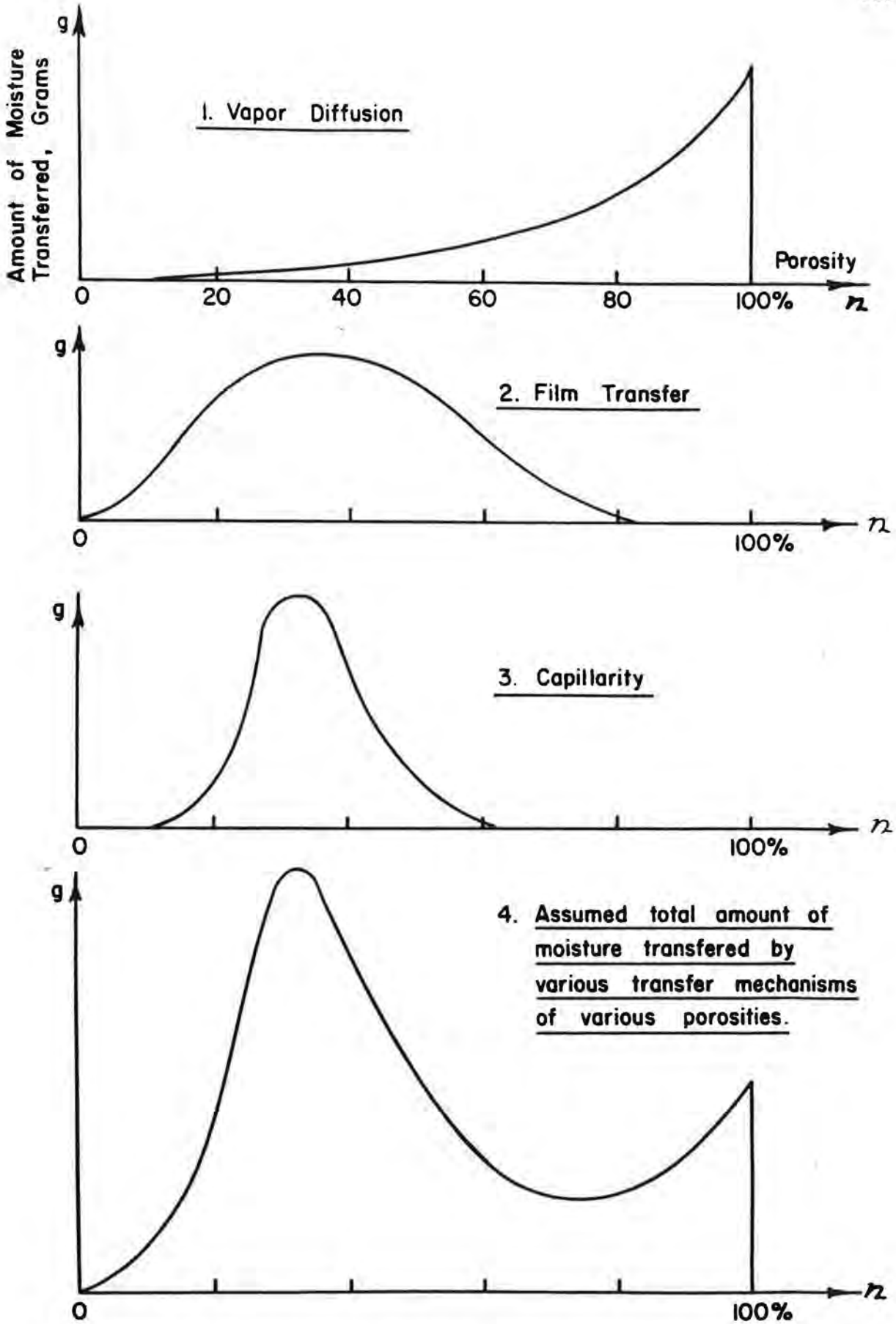

Figure 2. Various moisture transfer mechanisms and their assumed effects on the amounts of moisture transferred.

system form interconnecting channels of various sizes, shapes, and roughness for the passage of moisture and air. Thus, the soil moisture flows upward through poorly defined flow paths in a zig zag-like motion, also dispersing sideways through the constrictions of the void network.

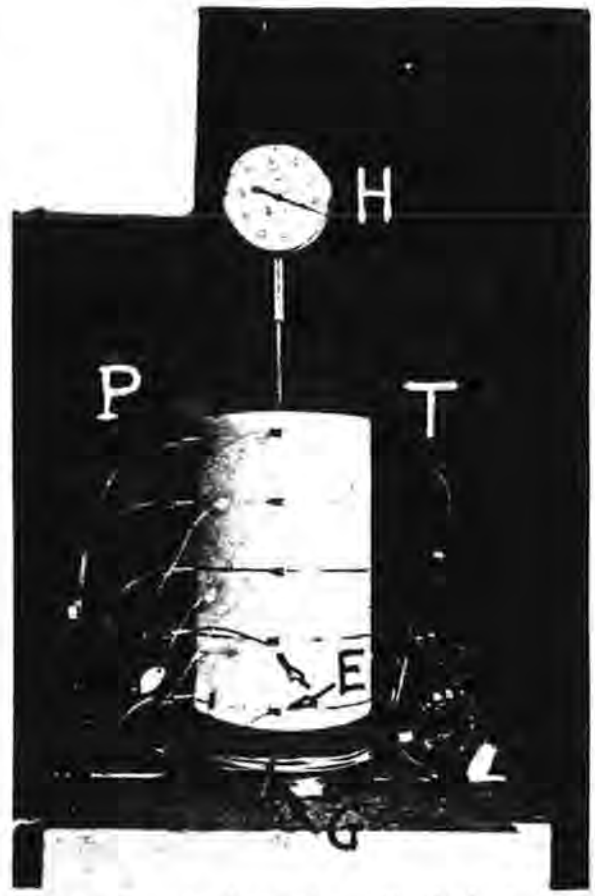

Figure 3. Instruments attached to the soil system: P - pressure measuring devices, H - frost heave measuring devices, T - temperature measuring devices, E - electrodes for measuring induced electric potentials, and G - connection to ground-water supply.

Packing

The degree of packing is very important to know and to report, as this gives a clue as to what kind of mechanism in the upward soil moisture transfer in the freezing system would be most likely to take place: film flow, film-capillary flow, film-vapor flow or pure vapor flow (6). These conditions are illustrated in Figure 2. Under certain conditions, however, a combination of all the afore-mentioned moisture transfer mechanisms may take place simultaneously, depending upon the changing temperature and vapor pressure conditions, or the type of electrolyte present, the freezing soil and the distribution of the variously sized voids.

A pure capillary moisture flow (capillary water in direct contact with the bare surfaces of soil particles) within a soil medium is in all probability to be ruled out because it is difficult to imagine such an ideal porous medium, which usually consists of voids of various shapes and sizes, where absolutely all voids would be filled with water. In a capillary system, there whould be no discontinuities in the system of capillary water channels and passages. According to capillary theory, all voids should be fully saturated with soil moisture at every point between the ground-water table and the freezing ice lenses. If there are plugs or air gaps, or bubbles of gas in these flow channels, and yet upward supply of soil moisture is observed, then the flow is not a pure capillary one, but takes place by way of other mechanisms: film, film-vapor transfer, or pure vapor diffusion, or in combination with capillary flow. Since the soil particles in the soil are in a humid environment, they are already, before freezing more or less coated with a moisture film. If the porosity of the soil is such as to give rise to capillary moisture transfer, and all void-channels are filled with water, then the capillary moisture flows through channels, the walls of which are covered with film moisture. In other words, the capillary water would not touch the bare surfaces of the soil particles directly. In such an instance a combined flow, namely film-capillary upward flow of soil moisture upon freezing, would take place, the velocity of the capillary flow being then greater than that of the stressed film on the surfaces of the soil particles. Simple as these conditions can be imagined to be, there is, however, a quite good agreement among engineers and scientists that up to now the various modes of mechanisms of the upward migration of soil moisture upon freezing are not, unfortunately, yet fully understood, and that much study is still to be devoted to elucidate these processes.

After the films are established within the soil system, the instruments are attached to the soil system for the measurement of temperature within the soil and its environ-

ment, driving pressure differences, electromotive forces, consumed supply of ground-water during freezing, and for the measurement of frost heaves (Fig. 3). The soil system is insulated laterally and finally subjected to freezing from its top downwards (Fig. 4).

FREEZING THE SOIL SYSTEM

Application of Thermal Gradient

After the soil system has been prepared and laterally insulated against transverse flux of heat, it is subjected to freezing. Freezing is accomplished by applying cold to the upper horizontal surface of the vertical soil cylinder, the lower end of which is inserted in a water bath (T = 8C) to simulate the source of ground-water or perched ground-water. Upon freezing the upper part of the soil system, after releasing the latent heat of the soil water, freezes, that is, changes phase from liquid to solid, and, in general, temperature change takes place within the system. This means that across the soil system, from top down, a curvilinear temperature gradient is set up. If so, then an upward heat transfer from a region of higher temperature in the soil system (ground-water) towards a region of colder temperature (frozen layer of soil) takes place. Thus, the application of a thermal gradient to the soil system means that heat energy is applied to the system. The source of heat, after full establishment of the thermal gradient, is the ground-water in the soil freezing experiment as well as in the field in winter. The soil receives its heat from the radiation of the sun and also partly by the conduction from the interior of the earth. The heat, as has been said, flows upward in such a soil system as is dealt with here. The transfer of the thermal energy in its turn, starts the upward migration of moisture in the porous soil system (12). During the course of the upward migration, the flowing water loses some of its driving

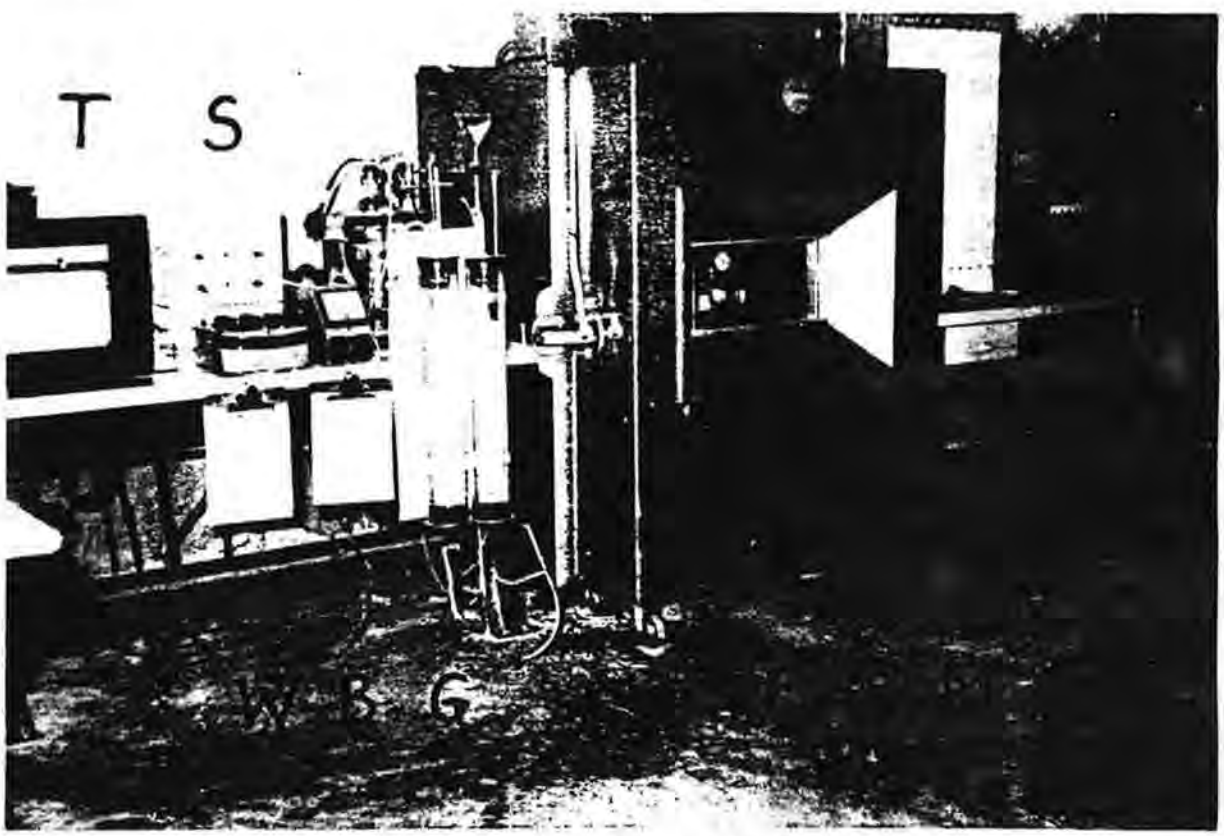

Figure 4. The soil system is subjected to freezing in a freezing chamber. T - temperature recorder; S - switches; W - Wheatstone bridge; B - bridge balancing apparatus; G - devices for maintaining constant ground-water level, and for measuring the amount of ground-water supplied to the freezing soil system; F - freezing chamber; M - manometer board; and P - pressure recorder.

pressure. This means that the driving pressure performs some mechanical work which becomes lost. In doing external, over-all work, the entire soil system loses some of its energy, so that the system in nature does not work with 100 percent efficiency. Here it has to be said that depending upon the state of packing, the soil moisture may first undercool, and then freeze.

During the freezing process in soil a good many other changes than those outlined take place, namely, changes in thermal properties of the various matters present in soil, undercooling of water (in proper environment), change in density and viscosity of water, change in the dielectric constant of water, changes in the structure of the double layer around the soil particles. The resulting frost heaves, frost penetration depth and thawing of the frozen soil are also changes within the soil ultimately contributing to the damage to roads.

SOME PRINCIPAL MODES OF MOISTURE TRANSPORT UPON FREEZING

Basically, soil moisture can be transported upward through the porous medium of soil upon freezing (a) as a liquid (bulk or film), (b) as a vapor, or (c) as liquid and vapor.

Vapor Transport

If the voids are relatively large, and there is no continuous moisture in the liquid form in the voids connecting the ground-water with the downward freezing ice lenses, the moisture from the ground-water is transported upward by way of vapor diffusion. The driving pressure is here the vapor pressure difference between the partial vapor pressure at the warmer end (the free water surface = ground-water table) and the partial vapor pressure in the upper region of the soil system just below the frozen ice where it can be very small, or even negligible as compared with that at the free surface (13). This is to say that moisture migration takes place in the direction along the drop of the thermal gradient. The vapor pressure decreases from the ground-water table up to the freezing isothermal surface.

Vapor diffusion in soil upon freezing along soil particles coated with film moisture is difficult to comprehend analytically because of the difficulty in expressing mathematically by an equation the geometry of the voids of the system or the surface topography of the soil particles.

If soil is fully saturated with water, the moisture migration cannot take place in the vapor phase. If the packing of the soil is very dense, moisture transfer in the vapor phase is ineffective.

If there is no ground-water present (approximately a closed system), the soil freezing is then a drying process until all of the soil moisture has been transferred into the freezing zone.

Film-Capillary Transport

The moisture migration process determines the moisture distribution in soil, and thereby the so-called drying out of the soil. Upon this the thermal properties (heat conductivity, viz., diffusivity) of the moist soil change, and the frost line penetrates deeper into the soil.

If the state of packing is such that the soil moisture can occupy absolutely all voids, then, upon freezing, an upward motion of film-capillary soil moisture from the ground-water table takes place. Because of the temperature difference between the warmer ground-water and the downward freezing isothermal surface, the driving pressure for the upward-directed capillary moisture flow is again the difference in the vapor pressure at the free water surface and the one at the curved surfaces or menisci at the freezing ice lenses, plus the flow pressure (molecular, or viscous, or both) caused by molecular motion of the warmer particles of water from the ground-water upward toward the cold front. Under certain temperature conditions, and surface topography and configuration of soil particles and the ice lenses, the magnitude of the vapor pressure at the freezing isotherm might be negligible, or even non-existent (13, 14).

It has been reported that M. Faraday (1850) and J. Tyndall (1858) presented a theory which is plausible even today, in which it is assumed that ice is coated by a mobile, noncrystalline film of water which is stable even below the freezing point (15). The surface film on ice represents a gradual transition layer from the rigid structure of the bulk of the ice crystal to the double layer of soil moisture on the surfaces of the soil particles.

Nakaya and Matsumoto (16) performed experiments on the adhesive force between two ice particles and observed a phenomenon which seems to show the existence of a liquid water film around two small ice spheres. This liquid-water film is not supercooled water but is in equilibrium with its vapor phase on one side and with the ice crystal on the other.

To continue the discussion on film-capillary transport, it is assumed that the ice lenses are connected via the ice water films and further via the soil moisture films and capillary moisture (where such exists) with the ground-water (1). In such a case the film-capillary water supply to the freezing ice lenses is secured uninterrupted. Because the capillary water is less stressed by molecular forces attractive to the soil particles than the films surrounding the particle, the capillary moisture transport mechanism seems to be more effective in the combined film-capillary flow than the moisture transport via the capillary moisture and films surrounding, viz., separating the soil particle. One remembers that stressed film water has properties different from those of moisture in bulk.

Film Transport

In a very dense, close packing of soil (for which there is a theoretical and practical limit), where the soil particles are packed so close to each other (small porosity) that the moisture around and between the soil particles forms uninterrupted liquid films through the entire soil system down to the ground-water supply, then, depending upon the texture of the soil (whether silt, silty clay, clayey silt, or clay) the film transport mechanism becomes more effective than the capillary one (Fig. 2). The moisture transport in the vapor phase is then very ineffective as compared with the movement of liquid. Of course, the process of the upward moisture migration via the films in the freezing soil is slow. However, a considerable amount of soil moisture can flow from the ground-water upward during a relatively long period of time, for example, during the winter months. It is the slow flow process indeed, which often is overlooked and forgotten, and which contributes to the danger of damage to highways and runways.

In the film transport mechanism, the ice lenses are thus connected via the moisture film at the ice surface and via the soil moisture films with the source of ground-water supply. The driving pressure is the pressure difference between two points under consideration effected by thermo-viscuous flow of the film moisture plus possible other potentials. These may be differences in density of moisture at different temperatures, concentration differences in electrolyte at different elevations in the soil column (temperature), induced secondary electrical potentials effecting additional flow of soil moisture up or down, depending upon the properties of the porous material, and other possible conditions. The film seems to be two-dimensional, that is, it is immobile perpendicular to the surface of soil particle, but is mobile parallel to the surface. The movement of the film moisture is hence a slip, by overcoming the shearing resistance of the liquid.

The amount of moisture transferred by means of film flow, it can be understood, is proportional, among other things, to the specific surface area of the soil particles in a unit of volume. The increase in density of the soil means more soil particles packed within a unit of volume, which in its turn means more specific surface, more moisture films, and consequently more film moisture transferred.

Combination of Various Modes of Transport

Depending upon the texture and gradation of the soil, and the degree of the packing, or the presence of a multi-layered soil-system, a combination of the various soil moisture transport mechanisms may exist simultaneously upon freezing. For example,

with large porosities, it is more likely that upward soil moisture transport in the vapor phase will be more effective than a film flow. In a densely packed clayey silt or silty clay the film transport mechanisms will be more effective than vapor flow. Between the maximum possible and minimum possible densities, and for different textures of soil, and in various combinations, other than gravel and clay, several upward soil moisture transport mechanisms, and in various proportions may set in. There are no sharply defined boundaries between the various modes of transport mechanisms and processes. It is quite reasonable to assume, rather, that a transition from one mode to another constitutes the combination of the simultaneously acting various modes of transport. One deduces that in reporting research results on moisture transfer in soils upon freezing, it is essential to report also the porosity of the soil, because for each degree of packing there may be a different moisture transport mechanism in action.

ICE SEGREGATION

The amount of segregated ice in a frozen soil system (number, thickness and distribution of visible ice layers or lenses) depends very much upon the intensity and rate of freezing. When the soil system is frozen quickly, say 8 in. frost penetration in three days at a temperature difference between surface and ground-water of 45 F, no ice layers are visible. The whole soil sample may be frozen through solid. Upon splitting the soil sample longitudinally immediately after the test, examination of the frozen sample by eye or with the aid of a magnifying glass does not reveal any ice segregation in layers, although the moisture content in the soil after the freezing test is larger than before the test, and the moisture content is larger at the ends of the soil cylinder than at its midheight. Slow freezing, on the contrary, brings about clearly visible ice layers of various thicknesses, for example from one-half of a millimeter to about 12 millimeters in thickness. If there are layers in the soil with layered voids or with air gaps, and combination of moisture transport mechanisms are active, segregated ice layers of about 4 in. in solid thickness are observed at midheight of a 12 in. high cylindrical soil sample.

Ice segregation in soil takes place also under cyclic freezing and thawing conditions when the thawed ice waters freeze again. This also occurs when the frozen soil thaws from the bottom and then the thawed section freezes again. This can happen when the freezing surface temperature on the top of the soil sample remains constant for several days (thus, frost would not penetrate deeper than its established position, but the temperature of the ground-water increases for one or another reason to such an extent that the upward flowing soil moisture can thaw the frozen soil from below).

Of course, ice segregation is influenced by differing thermal properties of the soil material and by the various types of soil moisture and electrolyte, as well as the ice in soil, or rather the properties of the frozen soil itself. Heat conduction through unfrozen and frozen soil particles is different from that through unfrozen water, chilled water and ice. Thus, ice lenses develop in the downward freezing soil in jump-wise layers, leaving unfrozen water between two separately spaced ice lenses. This phenomenon is analogous to the rhythmic precipitation of the Liesegang Rings as brought out by Winterkorn (17). Hence, in a frozen soil there may be ice as well as unfrozen water at the same time. As the temperature conditions may change to the negative, some of the unfrozen water may also freeze as time passes or the frost intensity increases.

CONCLUSIONS

Soil systems are most difficult to treat where various modes of upward soil moisture transport are active. Such systems, however, are encountered very frequently in nature and, although the heights of the upward transported soil moisture in such systems may not be large, they cause enough trouble relative to the performance of roads to become of real concern, and to warrant the effort to do something about them.

Study of the freezing soil system in its entirety and of the net end result of the performance of the entire system by means of the energy concept is thus seen to

be very advantageous for its simplicity and practical application, particularly as related to combined moisture transport mechanisms. This method comprehends all the factors and potentials—although some of them may be masked out—which might contribute to the net amount of the upward flow of soil moisture upon freezing and the total performance of the soil system. Any flow in the system is the result of all of the contributing factors. And, because the soil system in nature does not work with 100 percent efficiency, it is most appropriate that such freezing soil systems be studied experimentally.

This review of the various concepts used in the soil freezing experiment and the many factors with their associated and induced processes strengthens and consolidates the theory on the freezing soil system, and indicates that much frost action research is to be done along many lines and in all phases.

ACKNOWLEDGMENT

The author is greatly indebted to the National Science Foundation for sponsoring financially a research project at Rutgers, The State University, on upward migration of soil moisture under freezing conditions. This article constitutes part of an initial, theoretical phase of this work. Sincere appreciation is here expressed to E. C. Easton, Dean, College of Engineering, and J. J. Slade, Jr., Director, Bureau of Engineering Research, both of Rutgers, The State University of New Jersey, for their hearty support in providing means for the preparation of this paper for publication; to H. F. Winterkorn, Director of the Soil Physics Laboratory at Princeton University for encouragement, suggestions, and review of this article; and Ruth Ahrens for preparing the original typescript.

REFERENCES

1. Jumikis, A. R., "The Soil Freezing Experiment." Highway Research Board Bulletin 135, Washington, D. C., pp. 151-152 (1956).

2. De Groot, S. R., "Thermodynamics of Irreversible Processes." North-Holland Publishing Company, Amsterdam; Interscience Publishers Inc., New York, p. 32 and p. 171 (1951).

3. Margenau, Henry, "The Nature of Physical Reality—A Philosophy of Modern Physics." McGraw-Hill Book Co., New York, p. 399 (1950).

4. Jumikis, A. R., "The Frost Penetration Problem in Highway Engineering." Rutgers University Press, New Brunswick, New Jersey, p. 121, pp. 124-131 (1955).

5. Beskow, G., Tjälbildningen och Tjällyftningen; Statens Vaginstitut, Stockholm, p. 134-135 (1935).

6. Jumikis, A. R., Frost Action Research Memorandum, 1948-1956: "Formulation of Upward Moisture Transfer Upon Freezing by Various Moisture Transfer Mechanisms." Submitted to the Engineering Research Advisory Committee at Rutgers, The State University, College of Engineering, New Brunswick, New Jersey, p. 3 (1956).

7. Winterkorn, H. F., "Potentials in Moisture Migration." Proceedings of the Conference on Building Materials, October 1953, Ottawa, Canada; Bulletin No. 1, Division of Building Research, National Research Council of Canada, pp. 86-101 (1955).

8. Hutchison, H. P., Nixon, I. S., and Denbigh, K. G., "The Thermo-Osmosis of Liquids Through Porous Material." Discussion of the Faraday Society, Vol. 3, Gurney and Jackson, London, pp. 86-94 (1948).

9. Winterkorn, H. F., "Water Movement Through Porous Hydrophilic Systems under Capillary, Electric and Thermal Potentials." Symposium on Permeability of Soils, Special Technical Publication No. 163, American Society for Testing Materials, Philadelphia, pp. 27-35 (1955).

10. Bosworth, R. C. L., "Heat Transfer Phenomena." Associated General Publications PTY, LTD., Sydney, p. 172 (1951).

11. Winterkorn, H. F., and Eyring, H., "Theoretical Aspects of Water Accumulation in Cohesive Subgrade Soils." Proceedings, Highway Research Board, Vol. 25, Washington, D. C., pp. 422-431 (1945).

12. Winterkorn, H. F., Discussion of Jumikis' paper on "Suction Force in Soils Upon Freezing." Proceedings—Separate No. 656, American Society of Civil Engineers, Vol. 81, New York, pp. 6-9 (March 1955).

13. Jumikis, A. R., "Soil Moisture Transfer in the Vapor Phase Upon Freezing." Highway Research Board Bulletin 168, Washington, D. C. (1957).

14. Jumikis, A. R., "The Effect of Freezing on a Capillary Meniscus." Highway Research Board Bulletin 168, Washington, D. C. (1957).

15. Weyl, W. A., "Surface Structure of Water of Some of Its Physical and Chemical Manifestations." Journal of Colloid Science, Academic Press, Inc., New York, Vol. 6, pp. 389-405, p. 395/396 (1951).

16. Nakaya, U., and Matsumoto, A., "Evidence of the Existence of a Liquidlike Film on Ice Surfaces." Research Paper No. 4, Snow, Ice and Permafrost Research Establishment, Corps of Engineers, U. S. Army, Wilmette, Illinois, p. 1, 6 (1953).

17. Winterkorn, H. F., "Principles and Practice of Soil Stabilization." Colloid Chemistry, Jerome Alexander, Vol. VI, Reinhold Publishing Corporation, New York, pp. 469-470 (1946).