The Mechanism of Frost Heaving in Soils

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The "mechanism of frost heaving" involves the interaction of the three frost action factors: a water supply, a frost-susceptible soil, and below-freezing temperatures.

The propagation of ice between soil particles depends on pore size, that is, the smaller the pores and channels between pores, the lower the temperature necessary before the ice front can advance. This provides a means for supercooling the pore water beneath an actively growing ice lens. The subsequent release of energy in such systems is utilized to create a moisture suction gradient which induces a moisture flow to the ice front and also to develop a positive pressure to raise the overburden and provide a space for the ice lens. Consistent with the theory, it can be shown that compact clay soils, which have the greatest resistance to ice propagation, can develop the largest moisture suction and heaving pressure in a closed system and coarse-grained soils, the lowest.

In the over-all phenomenon of frost heaving the most difficult combination of related processes to treat, even on a semi-quantitative basis, is the heat and moisture flow. This difficulty arises not only from the complexity of the mathematics but also from the lack of experimental measurements of heave rates, heat flow, moisture flow, temperature distributions, and moisture tensions while ice lensing is in progress. In the absence of such information the quantitative treatment of the combined heat and moisture flow appears impossible.

● FROST ACTION in soils consists of two different phenomena. It involves frost heaving resulting mainly from the accumulation of moisture in the form of ice lenses at the freezing plane in the soil and also the decrease of supporting strength when thawing takes place.

Frost action is contingent on the existence of a combination of frost action factors. These factors are a frost-susceptible soil, a moisture supply, and sufficiently low soil temperatures to cause some of the soil water to freeze. The process which results from the interaction of these factors during the freezing period is commonly referred to as the "mechanism" of frost heaving. The other phenomenon involved in frost action, the decrease of supporting strength of the soil during the thawing period, is particularly important in the performance of highways and airports. This problem, however, has not received much attention by research workers.

This paper is devoted to the interaction of the frost action factors in frost heaving and not to the details of any one factor.

Although some basic research has been carried out in the field of frost heaving the mechanism is still not completely understood. This has been and still is a real obstacle to the complete solution of problems of frost damage to engineering structures constructed of soil or other porous material. In recent years a number of research workers have made important contributions on certain aspects of the frost heaving process, but the early published work on the mechanism of frost action by Taber and Beskow still stands as the most complete coverage of the subject.

Since the frost heaving process is extremely complicated and much experimental work is still needed, the theory outlined is tentative and may be changed or modified as more information becomes available. Nevertheless, it is based on the work published by others and the results of research carried out in recent years by the author and his colleagues.

The material in this paper is divided into two sections. The first section deals with the phenomena of soil freezing based on experimental evidence obtained mostly in the laboratory. The second section is mainly concerned with the theory of frost heaving in an attempt to explain the observed phenomena.

PHENOMENA OBSERVED DURING FREEZING

In Soils That Support Ice Lens Growth

Ice Lensing and Frost Heave. The cause of frost heaving can be attributed mainly to the formation of ice lenses in the soil. This was first shown in 1916 by Taber (1) at a time when the popular belief was that frost heaving resulted solely from the volume change of water in changing from a liquid to a solid.

Ice lenses normally grow parallel to the ground surface and perpendicular to the direction of heat flow. The former is not always true since there are a number of different ice forms known; the latter, however, is always true. The thickness of the ice may vary from small hairline lenses to those several inches thick (Fig. 1) depending on a number of factors to be discussed later.

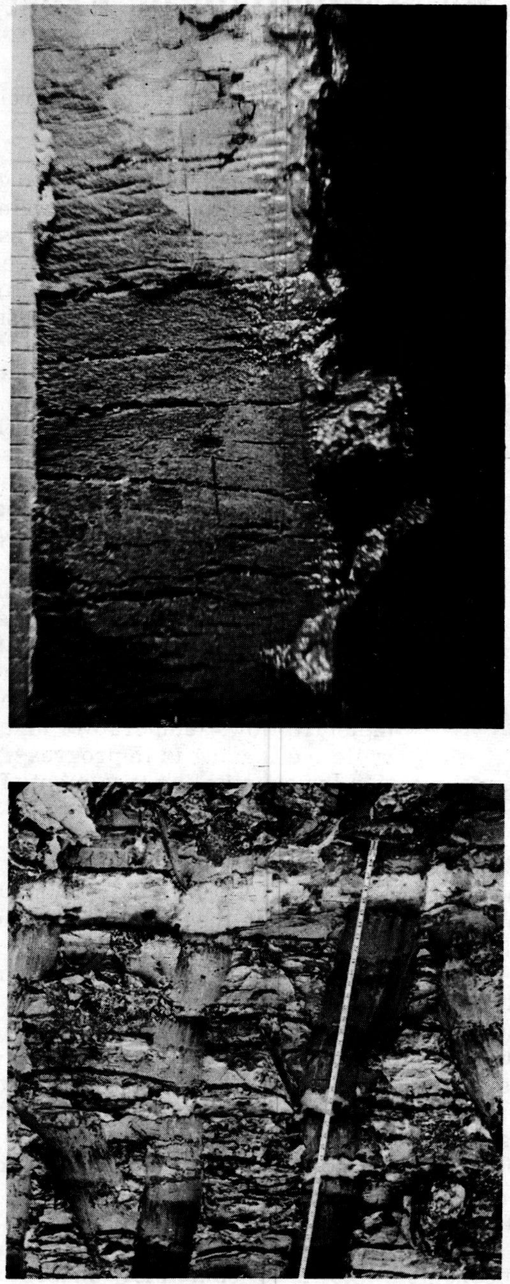

Figure 1. Small hairline ice lenses in silty soil (above). Ice lens, approximately 5 in. thick, in silty soil.

The heave in a saturated non-compressible soil in a closed system originates from the expansion of the water frozen in situ plus the volume of water moved to the freezing zone and its expansion. It is noted that the volume change of water on freezing is in the direction of the heat flow. In a closed system containing a compressible soil which is saturated before freezing the volume increase due to ice segregation is offset, except for the 9 percent expansion, by the consolidation of the soil. This is true in the region where the shrinkage curve is linear. If, on the other hand, additional water is supplied to the specimen from an outside source (open system) the shrinkage may be more than offset.

The soil between successive ice lenses is often relatively dry. Whether some of the soil water in these layers is frozen depends on the moisture status of the layers and the temperature. The latter is primarily determined by its position in the frozen soil profile.

Induced Suction and Moisture Flow. The flow of moisture to the freezing zone in relatively moist soils appears to start immediately after crystallization of the water begins. The effect is so pronounced that it can be observed some distance away from

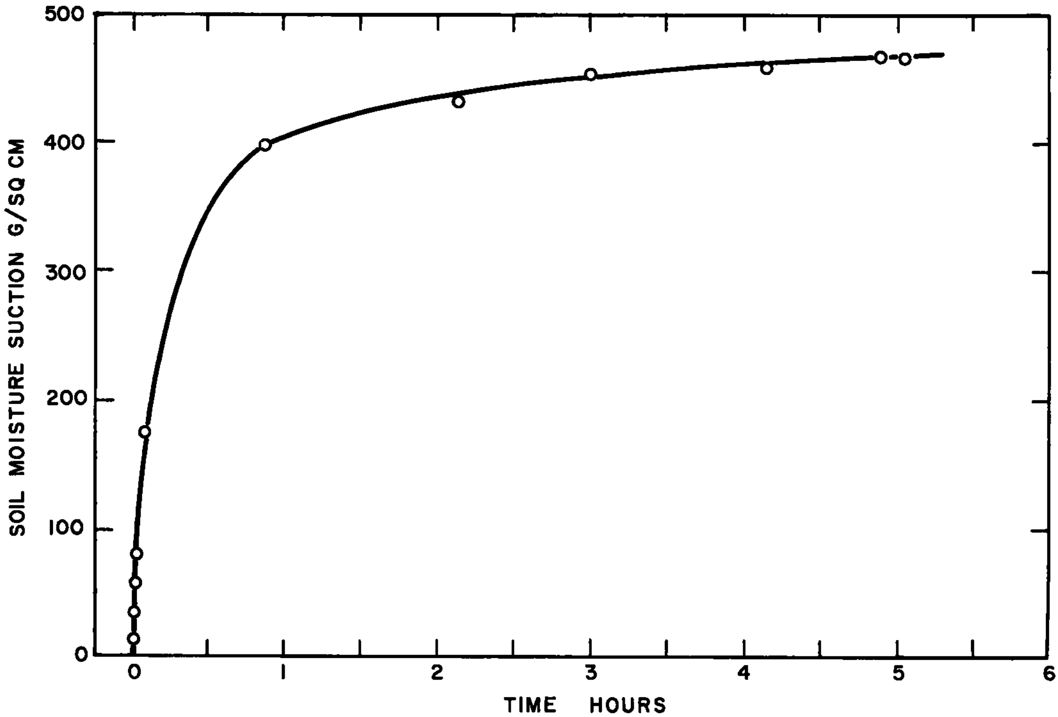

Figure 2. Soil moisture suction increase due to ice lensing as a function of time in a closed system containing Potters flint. Cold side temperature -3 C, warm side temperature 1.5 C.

the freezing zone. This indicates that a suction gradient is set up in the soil water. The phenomenon can be demonstrated by connecting a mercury manometer through a water connection to the soil water in the specimen. Measurements such as this have been made by several observers (2, 3).

The actual rate at which suction increases in a closed system is a function of a number of variables such as the suction-moisture content relationship, moisture permeability, and rate of heat extraction. The results shown in Figure 2 give the time-suction relationships during ice lens growth in a sample of Potters flint. This material is composed of about 6 percent clay-size particles with the remainder in the silt-size range. The temperature on the cold side of the specimen was held at -3 C with the warm side at +1½ C. Crystallization was mechanically induced at the cold end of the specimen at approximately -2 C.

The suction developed at the ice lens induces a suction gradient in the soil moisture. This is the main driving force for water movement to the ice lens. Since the driving force is a suction gradient, as opposed to a positive pressure gradient, the principles of unsaturated permeability apply. This type of flow should not be confused with saturated permeability. The significant difference lies in the fact that the unsaturated permeability coefficient is not a constant but is rather a function of the average suction, decreasing as the average suction increases. This principle is illustrated in Figure 3 showing the unsaturated permeability coefficient and the moisture content as functions of the average moisture suction.

Heaving Pressures. When vertical displacement is prevented in a frost-heaving soil a positive pressure is developed at the ice-water interface. This pressure is known as the heaving pressure. Such pressures can be sufficiently high to destroy foundations and lift buildings.

The author has measured the heaving pressure as a function of dry density for Potters flint. At constant moisture suction the heaving pressure increased with increasing density (Fig. 4). In another experiment using a different preparation of Potters flint the increase in pressure was measured as a function of time with a suitably mounted ring dynamometer. An adequate supply of water was assured by maintaining the water table at the base of a 3-in. specimen throughout the experiment. On the basis of Figure 4 this moisture condition should be potentially the most favorable for the development of maximum pressure. Figure 5 shows the relationship between time and pressure. The pressure eventually terminates the ice lensing process. At this point the heaving pressure is at a maximum.

Rate of Frost Heave. Beskow (4) demonstrated that the heaving rate was not always influenced by the rate of frost penetration as shown by Figure 6. In his experiments the temperature was varied between -2 C and -10 C above the sample without affecting the heave rate. Beskow pointed out that the maximum rate of heave was achieved when the cold side temperature of the specimen was -2 C. Colder temperatures down to -10 C, although increasing the rate of frost penetration, did not increase the heaving rate. It is evident, however, that, over a certain range of temperatures, increasing the rate of frost penetration by applying lower cold-side temperatures does increase the heave rate (Fig. 7). Two different cold-side temperatures were used, -3 and -6 C.

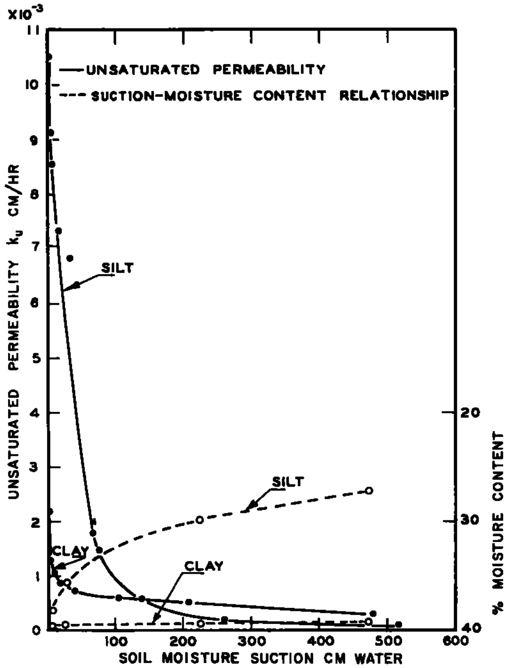

Figure 3. Unsaturated permeability and suction-moisture content relationship.

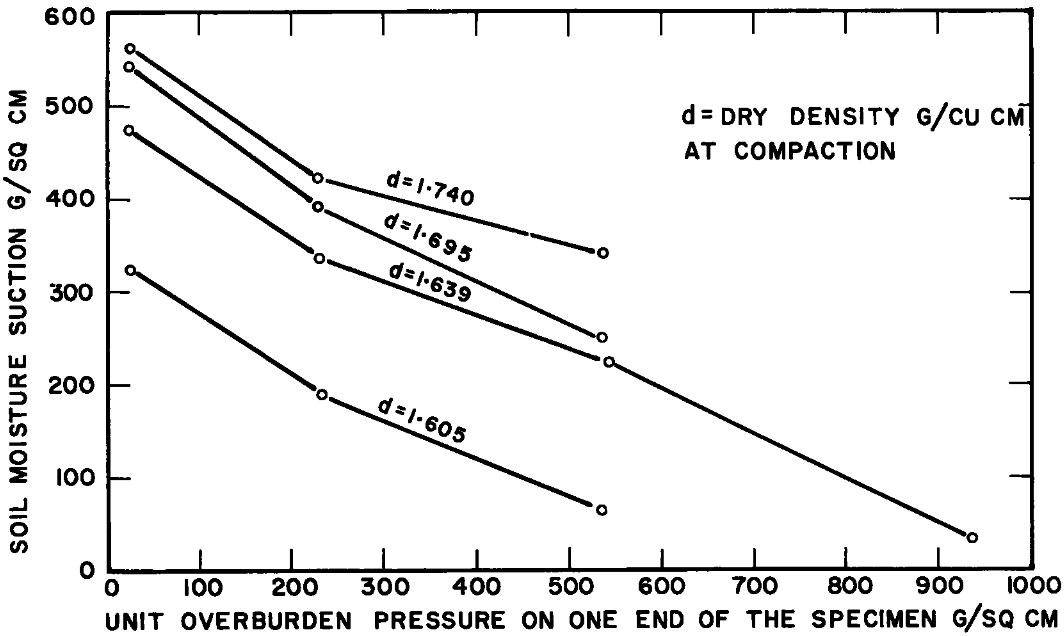

Figure 4. Relationship between soil moisture tension, overburden pressure, and dry density when heaving ceased.

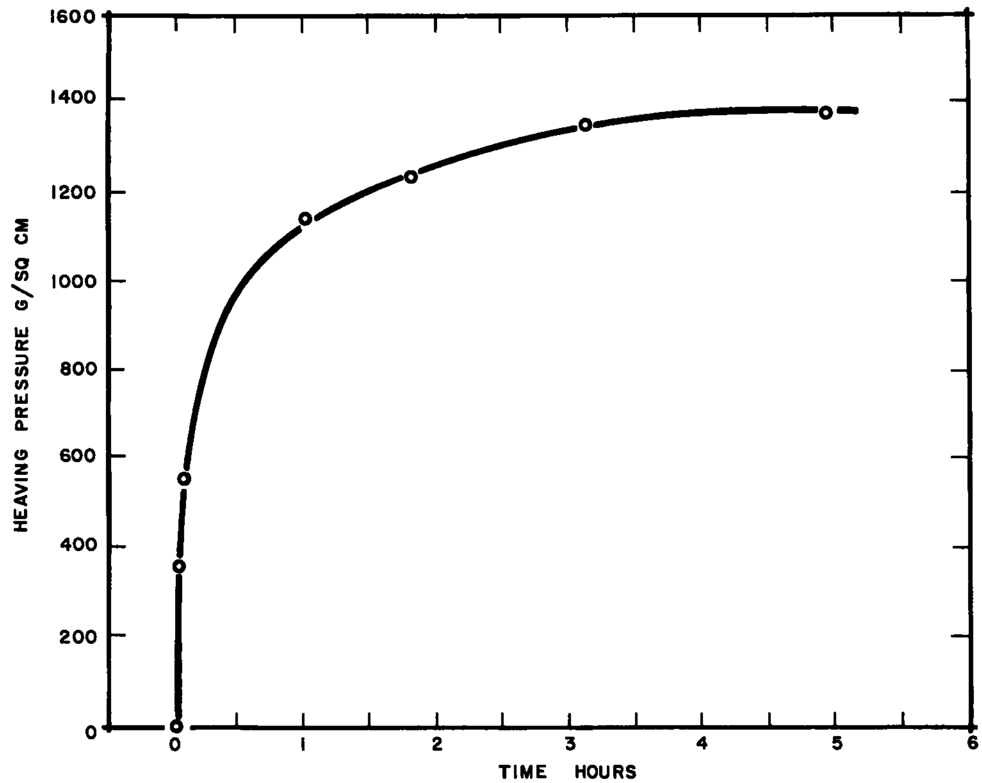

Figure 5. Heaving pressure increase due to ice lensing as a function of time measured with a ring dynamometer in a saturated sample of Potters flint. Cold side temperature -3 C, warm side temperature 1.5 C.

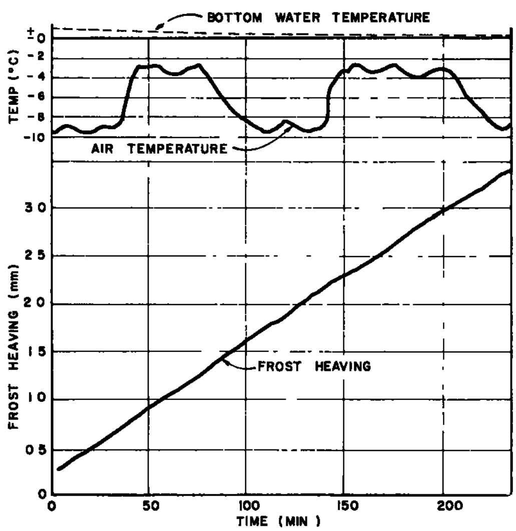

Figure 6. Another example showing that frost heave is independent of rate of freezing. Soil—very fine silt, pressure—410 g/sq cm (4).

The specimen consisted of a homogeneous mixture of 45 percent silt and 55 percent clay compacted to a dry density of 1.26 g/cc. Free water was provided continually at the base of the 3-in. specimen. The rate of heave was a function of the rate of heat removal. Increasing the temperature gradient within a certain range increases the rate of heave. If the heaving rate reaches a maximum value as Beskow suggests, it is still a matter of speculation whether the rate of heave stays constant or decreases as the temperature gradient is still further increased. Such maximum values of heat removal may well lie beyond those encountered under natural conditions.

There appears to be general agreement on the influence of overburden pressure and/or soil moisture suction level on the rate of heaving. Beskow's results (Fig. 8) illustrate what has been generally observed, that is, increasing either the overburden pressure or soil moisture suction simultaneously or independently reduces the rate of heaving.

At this stage it should be pointed out

that the heave rate is dependent not only on the rate of heat removal from the freezing zone but is intimately associated with the unsaturated permeability and the induced suction gradient. This will be discussed more fully later.

In Soils That Do Not Support Ice Lens Growth

There is very little information available on the freezing behavior of soils that do not show ice segregation. Two different phenomena were recognized when saturated specimens of this kind were subjected to unidirectional freezing. Even under rather small loads some laboratory-prepared specimens exuded water from the unfrozen end to accommodate the volume increase as the initial freezing occurred. The amount of water exuded has not been measured. The phenomenon is also mentioned by Beskow (4). In all cases the exudation of water coincided with active penetration of the freezing zone.

Other specimens showed heaving during the initial freezing which terminated when the freezing plane stopped penetrating. Soils that exhibit this second type of phenomenon are thought to be borderline with respect to frost damage. How these soils react to different rates of freezing has not been determined experimentally.

FUNDAMENTAL FEATURES OF THE ICE LENSING PROCESS

The growth of ice lenses in soils is a fascinating subject and has recently caught the attention of a number of research workers who have made useful contributions

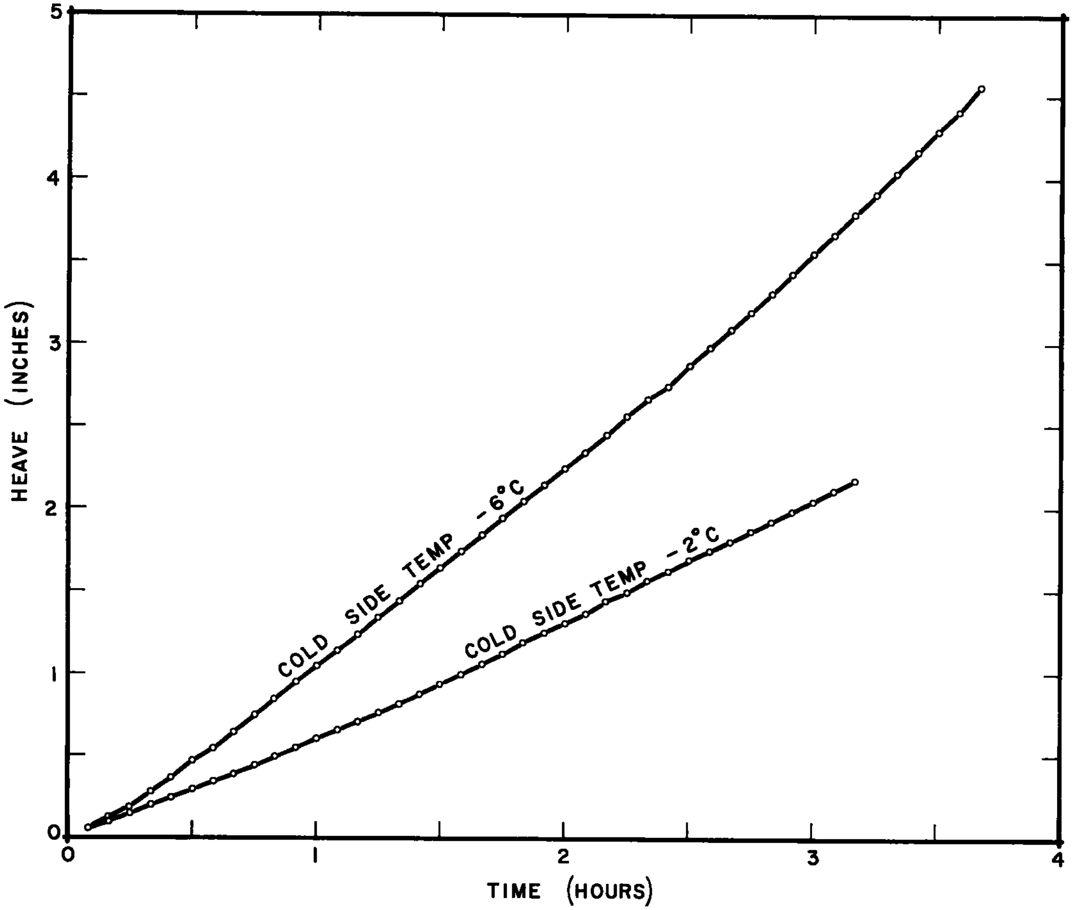

Figure 7. The amount of heave as a function of time for two different cold side temperatures. The specimens were prepared at a dry density of 1.26 g/cc from crushed air dry Leda clay.

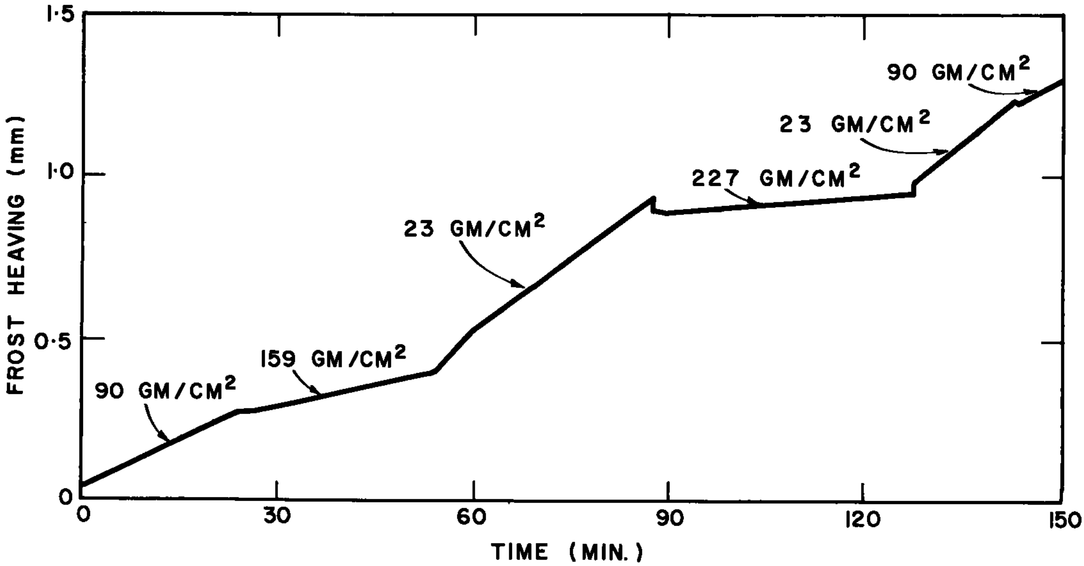

Figure 8. Diagram showing frost heaving rate for different pressures, surface load or capillary pressure. For any given pressure there is a certain slope of the curve, i.e., a definite rate of heave. For each slope the corresponding pressure is given in g/sq cm. Soil pure fractions, 0.01 - 0.005 mm. (4)

(6, 7, 8). As has been pointed out, some disagreement still exists about the mechanism but this stems from a lack of experimental results. Any consideration of the fundamental features of the ice lensing process in nature is therefore somewhat speculative. An attempt has been made in this paper to support the theory by experimental results wherever possible and to include the opinions expressed in the literature particularly where general agreement exists.

Pore Size as a Mechanism for Supercooling

In the unidirectional freezing of a saturated soil the dimensions of the interconnecting channels determine the temperature at which ice propagation may proceed. This effect of channel or pore size provides a means for the supercooling of the soil water below the freezing point near the ice-water interface. The freezing of soil water at supercooled temperatures was suggested by Taber (5) and Jackson et al. (6) as a necessary feature of the ice lensing process, as it provides the energy for the development of heaving pressure and the creation of a suction gradient.

The relationship between the size of a stable spherical crystal in its own melt and the absolute temperature can be shown by:

$$\Delta T = \frac{2T \sigma_{iw}}{r \rho_i Q_f} \quad (1)$$

in which

r = radius of the crystal (cm);

ρ_i = density of the ice (g/cc);

σ_{iw} = interfacial energy (ergs/sq cm);

Q_f = latent heat of fusion (ergs/g);

T = temperature of melting at zero curvature of the solid-liquid interface (°K); and

ΔT = freezing point depression.

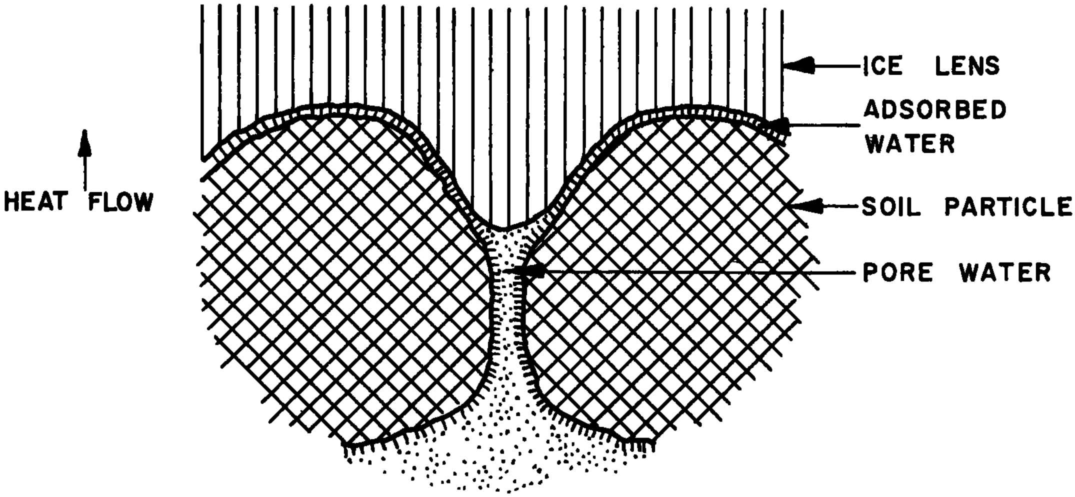

Figure 9. An enlarged schematic diagram showing a section of the ice lens with respect to the soil particle and soil pore.

Eq. 1 recently used by Sill and Skapski (9) for the determination of the surface tension of solids in thin wedges, states that the product of the curvature radius and freezing point depression is a constant determined by the interfacial tension and the bulk properties of the substance.

Assuming that the size of the soil pore determines the size of the advancing ice crystal the quantity r in Eq. 1 may be interpreted as the radius of the pore. A part of the soil pore is occupied by the adsorbed phase which probably places additional size limitations on the ice crystal. This mechanism appears to be responsible for the growing of the ice phase at the supercooled temperatures necessary to release the energy required for the work involved in heaving and moisture movement. Accordingly, the smaller the pore radius, r, the lower the temperature necessary for the ice front to advance, that is, $\Delta T \alpha \frac{1}{r}$. Measurements of heaving pressure and suction pressure indicate that these quantities do increase as the pore size of the porous material is reduced. The difficulty with a more rigid application of Eq. 1, although desirable, is beset with many difficulties since a gradation of pore sizes normally exists in soils.

Pressure Relationships at the Ice-Water Interface

The heaving pressures that are developed at the ice-water interface depend to a large extent on the moisture status of the soil. When the soil system is maintained completely saturated, given sufficient time, the maximum heaving pressure possible for a given soil is developed because under these conditions the suction pressure in the water is essentially zero. According to Figure 4 increasing the suction reduced the ultimate heaving pressure. In the absence of any overburden pressure the maximum suction pressure is possible. An attempt will be made in this part of the paper to justify theoretically this relationship. Figure 9 is a schematic drawing showing the ice phase and water phase in relation to the soil pore and soil particle. Attention is drawn to the intimate contact that exists between the ice and water phases as this is of some importance in developing the theory.

The temperature at which the ice phase grows depends on the pressure imposed. The pressure may be imposed on the water phase, or on both the ice and water phases simultaneously or on the ice phase alone. In each case the equilibrium freezing temperature is different. The complete development of the pressure-freezing point depression equations are given by Edlefsen and Anderson (10). The final equations developed by Edlefsen and Anderson are as follows.

Case 1. The total change in pressure on the ice is always equal to the total change in pressure on the water.

$$\frac{dP_t}{dT} = \frac{Q_f}{(v_w - v_i)T} \tag{2}$$

in which

dP_t = total change in pressure;

Q_f = latent heat of fusion;

v_w = specific volume of water;

v_i = specific volume of ice;

T = the absolute temperature at which the phase change occurs; and
dT = change in freezing point temperature.

Substitution of the proper values for v_i, v_w, T, and Q_f shows that the freezing point is lowered by 0.00748 C per atmosphere of pressure increase.

Case 2. The pressure on the water remains constant while the pressure on the ice is changed.

$$\frac{dP_i}{dT} = -\frac{Q_f}{Tv_i} \tag{3}$$

where dP_i is the pressure change on the ice; the other symbols are the same as previously designated. In this case the freezing point is lowered by 0.0899 C per atmosphere of pressure increase.

Case 3. The pressure on the ice remains constant while the pressure on the water is changed.

$$\frac{dP_w}{dT} = \frac{Q_f}{Tv_w} \tag{4}$$

In this case a positive pressure raises the freezing point temperature by 0.0824 C per atmosphere of pressure, but a decrease in pressure lowers the freezing point.

In the light of the different relationships between pressure and freezing point depression it is necessary to assume the actual disposition of the water relative to the ice phase and soil grains. It is believed that in a saturated system the relationship that applies is given in Case 1. The fact that the characteristics of ice lensing show no abrupt change in going from a completely saturated to a partially saturated system seems to indicate that an intimate contact between the water phase and the ice phase extends into the unsaturated range. One need not exclude the possibility of moisture transfer in the vapor phase to the ice lens but it must be accepted that, at the face of the growing ice lens, the water and ice phases exist in contact with each other.

If pressure is applied to the ice phase the water between the ice and soil particles is placed in a state of compression. The pore water is not affected if a rigid non-compressible material is being considered. Applying suction to the pore water would place the pore ice in a state of tension and consequently Case 1 still seems to apply.

The Mechanism of Ice Lens Growth

The mechanism of ice lens growth together with the development of heaving pressures and suction in the soil moisture can be described as follows, assuming that Eqs. 1 and 2 apply. If the system is saturated, as depicted in Figure 9, the absorption forces are fully satisfied. This means that if it was not inside a soil pore the outermost layer of water around the particle would freeze at nearly the temperature of bulk water. It is believed that the initial crystallization of water begins either in the soil pore at the ground surface of the soil and propagates downward or, in the case of ice lenses separated by relatively dry layers, crystallization begins most easily in large pores or discontinuities in the soil.

After crystallization has occurred its subsequent growth into an ice lens involves the manifestations of heaving pressures and suction pressures that accompany the process. Referring to Figure 9, the ice front will be temporarily prevented from propagating downward between the soil particles until the temperature has been lowered sufficiently to satisfy Eq. 1. Before this occurs part of the adsorbed water above the particle will freeze. As water is being removed from the adsorbed layer into the ice phase it is replaced from below and an equilibrium thickness of water is maintained around the soil particle by continual replacement with supercooled water molecules. This is really no more than film adjustment around the particle and will continue until the temperature drops sufficiently for the ice front to propagate through the soil pore. The mechanism really hinges on the existence of supercooled water in contact with the adsorbed phase and continual replacement of water to the adsorbed phase as more water molecules enter the ice phase. It can also be seen that the existence of the adsorbed phase is a vital link in the movement of water from a supercooled state into the adsorbed phase and hence into the ice phase. Similarly it may be noted that if the propagation of ice occurred at the freezing temperature of bulk water, 0 C, the evolution of energy necessary to cause heaving and moisture movement would not occur. This is well supported by experimental evidence and is the justification for replacing fine-grained soils with gravels when frost heaving cannot be tolerated. In going from porous systems containing small pores to those containing large pores no abrupt change in the heaving tendency is predicted but would be in accordance with the amount of supercooling possible which is proportional to the radius of the pores according to Eq. 1.

The growth of such an ice lens may be halted in two ways. Firstly, if the ice lens is loaded, causing a pressure at the ice-water interface above the soil particle, the freezing point of the water would drop according to Eq. 2. The limiting pressure to stop ice growth would occur when the freezing point of the water above the particle has been lowered (by positive pressures) to the same temperature as is necessary for ice to propagate through the pore constriction. The experimental justification is shown in Figure 5 which shows that ice lens growth can be stopped in a saturated soil by loading the soil.

Ice lensing may also be halted by applying suction to the water in the pore system. A suction or negative pressure in the pore water raises the temperature at which ice can propagate through a pore of given size. This is based on Eq. 2. At the same time application of suction has the effect of drawing the ice-water interface toward the soil particle. This induces a state of compression at the ice-water interface above the soil particle and a lowering of the temperature at which freezing occurs.

Based on these considerations it is thought possible that the maximum overburden pressures to stop ice lensing should be about twice as great as the maximum suction. From limited experimental evidence using Potters flint as the soil media this appears to be the case (11).

Under natural conditions in the field the positive pressures on the ice-water interface are the naturally occurring overburden pressures due to the weight of frozen soil. The suction or negative pressure gradient is induced by the ice lens in the soil water. The induced suction gradient will never be greater than that required to supply the demands of the growing ice lens. When the demand for water is great the suction gradient increases. This tends to lower the unsaturated permeability coefficient, however, resulting in a diminishing water supply. It follows therefore that the most favorable conditions for frost heaving in any frost-susceptible soil is when the frost line is close to the surface (low overburden pressure) and when the water table is high (low suction).

HEAT AND MOISTURE FLOW AS RELATED TO ICE LENSING

In the over-all phenomenon of frost heaving the most difficult combination of related processes to treat, even on a semi-quantitative basis, is the heat and moisture flow. This difficulty arises not only from the complexity of the mathematics but also from the lack of experimental measurements of heave rates, heat flow, moisture flow, temperature distributions, and moisture tensions while ice lensing is in progress. In the absence of such information, the quantitative treatment of the combined heat and moisture flow appears impossible.

Some attempt at a quantitative theoretical treatment for soils was first made by Winterkorn (12). Following Winterkorn's method of reasoning, Powers (13) made some tentative calculations of relative rates of heat flow due to conduction and heat flow arising from the latent heat of fusion in the freezing of green concrete. Although these authors have indicated the type of information that is necessary, the correctness of the computations depends on whether valid coefficients were used. These coefficients are not constants but vary as the system changes. Perhaps all that can be done at this stage is to point out the various factors that are known to be involved and to speculate on the progress of a continually changing system.

As the moisture tension increases in the unfrozen zone beneath the ice lens the unsaturated permeability coefficient may also change. In relatively uniform sands and silts the change is abrupt and occurs at relatively low moisture tensions consistent with the size of the pores. In well-graded sands and silts the change is less abrupt but decreases continuously with increasing moisture tension (Fig. 3). The varying permeability coefficient is known to be related to the desaturation of these systems without any consolidation occurring. In systems consisting of compressible soils the permeability coefficient is also a function of the tension but the rate of change is less abrupt due to the consolidation of the clay. Because the tension or suction gradient is thought to be the driving force for liquid moisture flow in frost-heaving soils, it can be assumed that the unsaturated permeability coefficient will also change during ice lensing if the tension changes.

A portion of the moisture flow during ice lensing is attributable to flow in the vapor phase if some of the voids are air filled. Therefore unsaturated permeability coefficients determined normally under isothermal conditions cannot be strictly applied.

The thermal conductivity of frozen soil is higher than that of unfrozen soil at moisture contents above about 10 percent according to Kersten (14). The ratio for frozen to unfrozen soil increases to values exceeding 1. 5 as the moisture content increases. Referring now to the thermal conductivities of a frozen layer of soil above an unfrozen layer it may be correct to assume a constant conductivity for the frozen layer but as the moisture content beneath the ice lens changes so does the thermal conductivity. In addition, the changing dimensions of the specimen due to heaving and the layering of the ice phase with its unique thermal conductivity must also be taken into account. Superimposed on this complicated system is the climate-controlled temperature fluctuation which adds further to the difficulty of unravelling the phenomenon as it occurs under field conditions. Complicated as it may be the consecutive formation of ice lenses is, nevertheless, the product of the combined heat and moisture flow patterns.

Much speculation surrounds the phenomenon of consecutive ice lens formation. The growth of an ice lens is thought to terminate when the rate of heat removal exceeds the total heat arriving at the lens. This can be shown to be the case if a reduced rate of moisture flow, resulting from increased tensions, is postulated. The reduction in flow rate of moisture is not entirely necessary for consecutive ice lens formation. Increasing the rate of heat removal may also drive the freezing zone further into the material until a more favorable heat and moisture flow balance is encountered. An important difference exists between the two cases. When there is a reduced rate of moisture flow and desaturation occurs beneath the ice lens, ice crystal nucleation must precede the formation of a new ice lens. In the case where the rate of heat removal is suddenly increased, ice propagation proceeds through the pore system and the nucleation of ice crystals at the new site is not involved. This has been observed by the author in unidirectional freezing of saturated soil specimens.

Practical Considerations Based on Basic Principles

The amount of guidance that the practicing engineer can obtain from basic considerations is limited at this stage in the understanding of basic phenomenon of frost heaving. In many instances the suggestions which stem from a fundamental approach support the measures that are used in practice based on experience in the field and laboratory freezing experiments.

Frost Susceptibility Based on Grain Size and Grain-Size Distribution. According to theory, grain size is not as important as the resultant pore size but there is a relationship between the two. In relatively uniform soils pore size increases with grain size. The theory predicts that the maximum moisture suctions and heaving pressures should decrease with increasing pore size. The importance of pore size is implicit in the frost action criteria commonly used which permit a larger percentage of fines in uniformly graded material than in well-graded material. The theory therefore supports the practice of using coarse-grained materials with gradation limitations such as the Casagrande criteria. No rigid guidance, however, can be obtained from the theory as to the exact grain size or grain-size distribution above which no frost heaving will occur under favorable moisture supply. It would seem reasonable to categorize soils in practice according to the degree of frost susceptibility recognizing no abrupt delineation based on grain-size considerations between frost-heaving and non-frost-heaving soils. The influence of grain size on the rate of moisture movement must also be taken into account if the rate of heave is considered. Although the maximum moisture suctions possible increase with decreasing grain size, the moisture permeability is decreased. Consequently, as is observed in the field, heavy clays will heave at a much slower rate than silts and the total amount of heave during one winter season would be much less. In coarse-grained soils, the moisture suctions will be low or negligible and the permeability parameter need not be considered. Silts which are notoriously treacherous from a frost action point of view have a combination of moisture suction and permeability which lead to an extremely high frost susceptibility and are avoided when possible in current practice.

Density and Frost Susceptibility. The effect of increasing the density is similar to decreasing the grain size, that is, the soil pores are reduced in size. High densities may be desirable and necessary in achieving the required bearing capacity but at the same time soils which are borderline with respect to frost susceptibility would become more frost susceptible with increasing density.

Homogeneity and Differential Heave. A non-frost-susceptible material containing pockets of silt or clay which are frost susceptible may show characteristic differential heaving when intercepted by the frost line. It has been shown that normally non-frost-susceptible soils can act very effectively in transmitting moisture (3). There are other reasons for differential heaving; variations in soil texture is one of the more important.

Moisture Supply and Frost Susceptibility. Without moisture no soil is frost susceptible. Normally the assessment of frost susceptibility is made under the most favorable moisture supply. It is shown theoretically that the lower the moisture supply (high suctions) the smaller the maximum heaving pressures and the lower the rate of heave (Figs. 4 and 5). An expression of frost susceptibility for a given soil should also be based on the moisture status likely to be encountered at a given site. Drainage and the dissipation of seepage forces is therefore most significant. Hydrostatic pressures which result in the supply of free water to the freezing plane will increase the maximum heaving pressures possible and increase the rate of heaving. This will also lead to differential heaving with the same outward manifestations as non-homogeneous soils. Frost heaving will not occur, however, even with adequate water supply unless the soil pores are sufficiently small to induce some supercooling. When the soil consists of coarse uniform sands and gravels, no amount of water can possible result in heaving.

CONCLUSIONS

The mechanism of frost heaving and all its ramifications are still not completely understood. This is particularly true in resolving the combined heat and moisture flow in frost heaving systems.

In some aspects of the mechanism the process is fairly well known. This applies to the understanding of how heaving pressures and suction potentials develop. The independent role of liquid moisture flow under suction potential gradients and the variation of flow with average suction is also reasonably well understood. In the development of consecutive ice lens formations and the rate of ice growth the mechanism can be only qualitatively described and a more rigid mathematical development would be useful.

The assistance the practicing engineer can expect from basic studies is mostly qualitative in nature. In many instances the theory supports the kind of solutions developed from many years of field experience. At the same time it offers a reasonable tentative working basis and future studies can be more directed toward finding solutions to frost heaving in soils and frost action generally.

ACKNOWLEDGMENTS

This is a contribution from the Division of Building Research, National Research Council, Canada, and is published with the approval of the Director of the Division.

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Discussion

R. TORRENCE MARTIN, Research Associate, Soil Engineering Division, Massachusetts Institute of Technology—It is not the purpose of a discusser to introduce new evidence with the aim of either substantiating or refuting the thesis of the author. On the other hand, criticism alone is not sufficient. To admit a competitive hypothesis to the working list is a concrete form of expressing a doubt, while at the same time respecting existing hypotheses, and serves better than abstract criticism toward unravelling the intertwined complexities of nature. In brief the writer accepts T. C. Chamberlain's system of multiple working hypotheses as furnishing the most wholesome conditions for research and that any additional hypothesis not in itself incredible will be welcomed.

In order to keep the discussion within tolerable limits, the remarks shall be confined to possible alternative interpretation regarding the significance of (1) pore size (Eq. 1 in Mr. Penner's paper) and (2) pressure upon freezing point depression (Eq. 2 in Mr. Penner's paper), relative to the theory of ice lens formation. At the outset it must be clearly stated and with emphasis, that the author's hypothesis concerning Eq. 1 and Eq. 2 appears to be completely rational and self-consistent with the experimental data presented. Therefore, the author's arguments must be respected, at least for the present, as one of a group of working hypotheses.

Pore Size

The author attributes to the small pores and the even smaller pore constrictions two vital effects related to the mechanism of ice lens formation: (1) supercooling and (2) retardation of ice front advance.

Supercooling, ΔT, is the temperature difference between the actual temperature at which the ice is forming, T_x, and the equilibrium temperature, T_e, at which the liquid phase under its existing activity could coexist with the solid phase; i. e., $\Delta T = T_e - T_x$. Supercooling is frequently confused with freezing point depression. Freezing point depression, dT, is the temperature difference between the equilibrium temperature for the activity of the liquid in the system under consideration, T_e, and the equilibrium temperature for pure liquid under no restraint, T_o; i. e., $dT = T_o - T_e$. For pure water $T_o = 0.00$ C, water in a clay soil system may have a freezing temperature, T_e, of -5 C; therefore, if the water in such a soil system is being converted to ice at a temperature, T_x, of -6 C, the supercooling for the system is -1 C and the freezing point depression is -5 C.

The full realization conerning the meaning of these definitions is essential. Penner correctly defines dT in Eq. 1 as a freezing point depression; however, he then states "This mechanism (referring to Eq. 1)[1] appears to be responsible for the growing of the ice phase at the supercooled temperatures necessary to release the energy required for the work involved in heaving and moisture movement . . ." which can hardly be true since dT of Eq. 1 is a freezing point depression and not a supercooling.

Futher, very pure water in bulk has been supercooled to at least -39 C; if this be fact, then small pores are not a necessary prerequisite for supercooling. Nevertheless, the pore size has a profound influence upon supercooling because pore size controls the statistical probability of obtaining sufficient ice nucleation to reach a measurable growth rate. To illustrate this concept, the following hypothetical example is given—Case A: ten large water filled pores each pore having one nucleus for ice formation; the temperature is lowered until ice starts to nucleate. Ice growth is rapid because the volume of water at the proper temperature, instantaneously available to each ice nucleus, is very large. Case B: use the same volume, the same water, and the same number of nuclei as in Case A but now with a porous system containing 1,000 pores. Here there is a nucleus in only one pore per 100. The temperature is lowered and at about the same temperature as in Case A ice nuclei form in the 10 pores; however, the volume of water at the proper temperature available to each ice nucleus is now 1/100 what it was in Case A. Total ice growth is very small; therefore, the temperature must be lowered (or additional water supplied) before an appreciable growth rate is reached.

Cooling curves (temperature vs time) on various porous systems with different pore fluids should provide the data necessary in order to decide the proper relationship between pore size and supercooling.

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[1] Parenthetical insert by the writer.

Retardation of ice front advance is clearly demonstrated by Eq. 1; however, there is an equally valid counter-proposal which states that the ice front has no desire to advance through the pore constriction provided that a supply of water can be maintained at the ice front. Then, by the time the ice front wants to advance it is too late, ice formation has already begun further down in the soil.

This additional hypothesis arises from a consideration of crystal growth rate independent of any pore constrictions. The first condition, for a crystal of a given size in its own melt, is that the rate of crystal growth increases at a fantastic rate as the temperature is lowered below the equilibrium temperature (for this case $T_e = T_o$). The second condition, given a fixed amount of supercooling, is that the larger the crystal size the more rapid the growth rate. Returning to a soil system, suppose that a small crystal (a whisker) is attempting to grow perpendicular to a large pore crystal, any water available will go to the large pore crystal rather than the whisker because (a) the pore crystal is larger and thus grows faster, and (b) the pore crystal is colder, thus it grows faster. Both of these situations rob the small whisker in favor of the large pore crystal since the larger crystal is energetically more stable than the whisker.

One may phrase the question another way. Which requires the least expenditure of energy, water transport or ice front advance? A crude calculation from very meager data indicates that water transport requires only a fraction of the expenditure of energy required for ice front advance. This energy consideration is not an additional hypothesis, but should provide a means of testing between different hypotheses when better experimental data become available. Data needed are temperature and pressure measurements in both phases at a freezing ice front. Some way must be devised to differentiate between freezing point depression and supercooling. In fact, Penner's hypothesis and the alternatives herein suggested, both tacitly assume that supercooling does occur. There can be no doubt but that supercooling will provide the energy required; however, if experiments show that there is no supercooling then some other source of energy must be found and any acceptable working hypothesis will have to be modified to include the new information. Since ice lensing is a rate process in which the rate is definitiely finite, there must be some infinitesimal amount of supercooling to provide a gradient in order to prevent the rate from going to zero.

Pressure upon Freezing Point Depression

The author prefers Case 1 where the total pressure change on the ice is always equal to the total pressure change on the water because of ". . . the intimate contact that exists between the ice and the water phases." That there is intimate contact between the phases has been verified by numerous workers since Taber's original work (author's ref. 5). Penner has very carefully measured the tension (-P) in the water phase during ice lensing; if Case 1, Eq. 2, is applicable it seems to imply that the ice phase can withstand no lateral stress.

Does intimate contact necessarily require that the pressure on the two phases be equal? Taber did not think so, he envisioned the adsorbed water film (which may be only a few molecular layers thick) as a two-dimensional liquid able to withstand normal stresses and at the same time retain relative free mobility laterally. In their discussion of pressure effects upon freezing point depression Edlefson and Anderson (author's ref. 10) were of the opinion that Case 2 and Case 3, Eqs. 3 and 4, would be the appropriate solutions for freezing a soil system provided that the percent air voids was greater than zero. It is certainly a rare soil where the voids are 100.0 percent water-filled.

Penner mentions ". . . that the characteristics of ice lensing show no abrupt change in going from a completely saturated[2] to a partially saturated system . . ." Applica-

[2] It is assumed that Penner is using saturation as previously defined by him (HRB Bull. 135, p. 109) which states, "At saturation the tension is zero, although in the case of light textured soils the soil pores may be partially filled with air."

tion of the combination of Case 2 and Case 3 likewise would provide a perfectly smooth transition. It might also be added that the freezing point depression would be increased 10 times for the same pressure change.

Taber (author's ref. 5) performed freezing experiments with benzene and nitrobenzene where $\frac{dT}{dP}$ from Case 1, Eq. 2 would be positive rather than negative as for water. The organic liquid systems gave marked "ice" lensing and appear to vary with pressure in the same manner as the water systems. By the use of Cases 2 and 3, Eqs. 3 and 4, one would expect similar behavior between the organic liquid and water systems. Because there is appreciable mass transfer, whether the volume change from liquid to solid is positive or negative is probably of no consequence.

From the present data, the pro and con arguments concerning the importance of pressure on freezing point depression are inconclusive; however, the organic liquids may prove advantageous toward obtaining definite data regarding the effect of pressure because the $\frac{dT}{dP}$ coefficients are much larger than for water. The coefficients for benzene and nitrobenzene are compared below with the water coefficients given by Penner.

	$\frac{dT}{dP}$ in C/atm. calculated from		
Fluid	Eq. 2	Eq. 3	Eq. 4
Water	-0.00748	-0.089	+0.0824
Benzene[a]	+0.040	-0.22	+0.25
Nitrobenzene[a]	+0.023	-0.25	+0.27

[a]Temperature of freezing, latent heat, and specific volumes necessary for these calculations were obtained from the International Critical Tables.

In conclusion, one of Penner's major points should be reiterated. Frost heaving is a dynamic unsteady state process; therefore, in any experiment designed to test any portion of any hypothesis concerning ice lensing, one must always keep in mind that all the variables are very strongly interrelated. For example, suppose one were to arbitrarily change the overburden pressure. In order to ascertain what effect this will have on ice lensing one must consider at the very least what happens to (1) the freezing temperature, (2) the nucleation point, (3) water transport, and (4) heat transfer through the soil and ice. Then, in turn, how each of these changes effects and is effected by the induced changes in the other three variables.

A. R. JUMIKIS, Professor of Civil Engineering, Rutgers, The State University, New Brunswick, N. J. —The aim of Penner's paper is, like that of the papers by the other authors partaking in this symposium, the review and assessment of the practical utility of the currently available knowledge as it pertains to the freezing of water in soils, mainly in relation to highway engineering. The author presents his paper in three principal sections, the last of which can be described as follows:

1. Phenomena observed by the author with his soil freezing experiments in the laboratory;
2. A condensed theory of frost heaving which serves here partly for the purpose of explaining the phenomena observed in the author's studies; and
3. Practical considerations based on fundamental principles.

Water, Temperature, Undercooling, Interaction—Important Factors

In general two things strike one immediately upon starting to study a freezing soil system and these are, first, the profound influence of temperature upon the soil moisture, and, second, the observation that the substance water contributes considerably to the performance of the soil, particularly when under freezing conditions. These two factors—temperature, or rather heat exchange with the surroundings of the freezing soil system on the one hand, and soil moisture migration induced by a thermal potential on the other hand—interact mutually, an interaction which endows the freezing soil system with great complexity, and consequently makes it very difficult to study.

In studying frost effects upon soil it must also be remembered that there is something else involved than merely the solid particles of the soil, viz., soil texture (refer to the textural criterion of frost-susceptible soils, for example). As just mentioned, in the soil freezing process an important factor, among others, is the soil moisture and, what seems to be more important, the interaction of physical forces between the surface of soil particles and the soil moisture films surrounding the soil particles. This is of particular significance in studying the soil moisture transfer in the film phase upon freezing.

From what is thus far known from literature, from the research work by the author, the discusser of the author's paper, and others, it seems that the key to the secrets of the freezing soil system lies in the substance water itself and in the understanding of the undercooling phenomenon taking place in the freezing soil system. Thus the liquid phase of the soil is not just an important constituent part of the soil as it concerns the performance of the soil under load, but it also plays an important role when subjected to temperature changes. Temperature, it is known, changes the properties of water. Variation in temperature starts a thermal potential which induces the soil moisture to migrate, and to induce between the ends of the freezing soil system an electrical potential. The influence of the latter on the other processes taking place in a freezing soil system seems at present to be very obscure.

Method of Study

Referring to the contents of the paper under discussion, it can be observed that the author and the discusser both study the freezing soil system in its entirety. The obvious reason for using this method is that unfortunately at present there are no satisfactory scientific tools available for handling all of the interior details of the system. Hence the author's working method is very advantageous for its simplicity and practical applications. 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 consequent frost heaving.

The author states, rightly it is felt, that the mechanism of frost heaving is still not completely understood. To this can be added that in the soil freezing system more than one mechanism is operative; besides the frost heaving mechanism there act also simultaneously several moisture transfer mechanisms, some of which are more effective than others, depending upon the degree of porosity of the soil. The details of the moisture transfer, too, are not too well understood. The lack of such knowledge, in the words of the author, is indeed a real obstacle to the complete solution of the frost action problem in highway, foundation and earthwork engineering. This is then one of the major reasons why the author studies the freezing soil system experimentally.

One also observes that Penner's manner of treating the soil moisture transfer relates to the mechanism of soil moisture transfer in the film phase.

Moisture Transfer

The moisture transfer through a homogeneous, isothermal porous medium is commonly characterized by the coefficient of permeability, k. In a freezing soil system where temperature varies with depth below the ground surface, the soil moisture film is also at different points below the ground surface at a correspondingly different temperature. It is gratifying to observe that this idea has also found its way into Penner's work. The author realizes that "the unsaturated permeability coefficient is not a constant but is rather a function of the average suction . . ." It is felt appropriate to say at this point that the prime cause of the processes in the soil system under study is the freezing thermal gradient, or simply thermal potential, the suction being just a function of the temperature difference acting on the soil system. Because the temperature changes with depth, the soil moisture transfer characteristic is not a constant.

For this reason it would probably be better to speak of a coefficient of the system's transmissibility, k_s, which varies with depth rather than permeability. In the case of moisture migration in soil in the vapor phase, the coefficient of vapor diffusion applies.

The degree of concentration of electrolytes, keeping in view the relationship of film flow to the zeta-potential, which acts across the electric diffuse double layer, may also have its effect upon the amount of soil moisture transferred upon freezing. It is understood that electrolytes have a great influence upon the amount of soil moisture transferred to the frozen zone: the fewer electrolytes the more moisture transferred.

Ice Lensing

Relative to the topic of ice lensing in soil, the following can be added to the author's presentation: the thickness of the ice layers depends, among other things, upon the rapidity of cooling and the concentration of the soil moisture as an electrolyte, as well as upon pressure conditions. Also, the amount of banded ice layers in a soil system (number of layers per unit thickness of the frozen zone, thickness of the ice layers and distribution of visible ice layers) depends very much upon the rate of nucleation, which in its turn leads to the subject of undercooling. Generally, it has been observed by the discusser's soil freezing experiments, and it is also known from physics and geology, that when the soil system is frozen quickly the crystals, viz., ice layers, are very thin, or even invisible by the unaided eye, even if the whole soil sample is frozen solid throughout. Slow crystallization, viz., freezing of soil moisture, brings about large, clearly visible crystals, viz., ice layers.

According to Tammann, the degree of undercooling is a function of temperature and so is the rate of nucleation. In undercooled water only molecules with sufficiently low kinetic energy are able to form nuclei upon which ice crystals can form. With the decrease in temperature the rate of nucleation increases, but only up to a certain point, when the viscosity of the water (which increases exponentially with the decrease in temperature) slows down the molecular movement to such a degree that the rate of nucleation decreases.

Crystallization velocity of undercooled soil moisture is frequently facilitated by colloidal substances the particles of which are non-spherical. Spherical particles, as well as truly dissolved substances, lower the velocity of crystallization.

The condition of unfrozen water in freezing or frozen soil also depends, of course, upon pressure.

Density and Frost Susceptibility

The author's view on this topic is fully in accord with the discusser's view, namely, that one should consider the dry density-optimum moisture relationship of a soil according to which there is a maximum dry density at a certain optimum moisture content. With increase in moisture content beyond the optimum the dry density decreases. As to the heat transfer through a freezing soil, the thermal diffusivity, $\alpha = \frac{K}{c \cdot \rho}$, depends upon the coefficient of thermal conductivity, K, specific heat, c, and the unit weight of the soil, ρ. Usually c does not vary widely; therefore, in large-scale field operations, little can be done to improve this factor. If K is decreased, α decreases automatically, but again in large-scale compaction operations K can be decreased relatively little. The only factor here which seems to affect the decrease of the thermal diffusivity, α, is the unit weight of the soil, ρ. The greater ρ is, the less α is. This implies that the compacted soil would have a decreased diffusivity, but only up to the maximum compacted density, which is limited by the optimum moisture content. After the optimum moisture content is reached, the density of soil decreases and consequently the coefficient of thermal diffusivity increases, with the result of quick frost penetration into the soil. Of course, the increase in moisture content past the optimum has more total latent heat, which upon freezing is released and retards somewhat the frost penetration rate and total depth.

This aspect of the frost penetration problem in soil implies that soil compaction on roads should be emphasized and the work supervised and executed more rigorously than ever before if an improvement in road performance under load and freezing temperatures and their consequences is to be achieved. It can be said, thus, that what is good for compaction of soil has also practical value relative to improved performance against frost action in soil.

Conclusions

From the author's paper, and from this discussion, it can be concluded that:

1. Knowledge is a universal tool in research work, but research, in its turn, is essential for progress.
2. The various concepts put forward by scientists, and some of the knowledge which is already available in other brances of science, when satisfactorily interpreted and explained, are to some extent also applicable to matters which are not perfectly homogeneous in structure, such as the porous medium of soil, for example, when subjected to freezing temperatures.
3. The mystery with which the frost penetration problem was surrounded until recently is gradually and steadily being dispelled.
4. A systematic study over the past years of thoughtfully organized freezing soil systems has already shed some light on the nature of the processes and changes taking place in a freezing soil system.
5. It is now fairly well understood how a freezing soil system works in its entirety as an organic unit connected to ground-water via the soil moisture films and when subjected to freezing temperatures.
6. There is needed, however, more knowledge for the explanation of certain details, factors and processes within the freezing soil system. Particularly, more information is needed on water properties in the film phase, and a better explanation of the phenomenon of undercooling in soil, nucleation, and possibly other factors.
7. All processes occurring in the freezing soil system are in some way connected with the surface phenomenon of soil colloidal particles. Water in the form of soil moisture films is the medium where many changes in the soil system take place under the influence of temperature changes. The property of a colloidal soil particle of carrying on its surface an electrical charge and the functioning of the soil moisture as an electrolyte are of fundamental significance in the process of the translocation of soil moisture in the film phase when the soil system is subjected to an external, primary, freezing thermal gradient.
8. Evaluating the contents of Penner's contribution to this symposium, it can be said that he has made positive progress in his research activities pertaining to frost action research in soils, and this certainly adds to the store of knowledge on the important subject of frost action in highway soils.

The real understanding of these factors promises to explain better the freezing soil system and the consequences such a system brings about. It is hoped that in a not-too-distant future the studies of the freezing soil system, as knowledge increases, will be guided by more quantitative theories than by merely qualitative principles.

R. D. MILLER, Professor of Soil Physics, New York State College of Agriculture, Cornell University—The role of supercooling in frost heaving deserves careful attention, for there is some danger of confusing cause with effect. There is also danger of confusing supercooling with freezing point depression.

The Thompson equation (author's Eq. 1) is a freezing point depression equation for ice in porous media where the geometry of the voids imposes size restrictions on ice crystals formed in rigid pores. If an ice crystal in such a pore attempts to grow through a capillary neck into an adjacent pore, and if the interaction with the particle surfaces requires that the ice interface be parallel to the particle surface at its points of closest approach, the ice-water interface must be convex, and the ice and water can be at equilibrium at temperatures below the normal ice point. Under these conditions, the water is not supercooled with respect to the convex ice-water interface. During lens formation, when ice is forming at a finite rate, the water must be supercooled to a slight extent for the process to proceed, but this supercooling is related to the rate of ice formation rather than to the curvature of the ice-water interface. The temperature at which ice forms will be less than the ordinary ice point by an amount which represents the sum of the freezing point depression and the rate-dependent supercooling. Hence, calculations of energy available for heaving which relate freezing point depression to supercooling are misleading. Moreover, there is doubt that associating the energy required for heaving with supercooling is logical in the first place.

It is possible, and probable, that water in large, unfrozen pores will be supercooled in the sense that the water in these pores would freeze spontaneously if nucleated in an appropriate manner. However, during lens formation, water present in capillary necks which cannot freeze because of geometrical restrictions would not be supercooled more than the amount required to sustain freezing at a finite rate. If the system were brought to uniform temperature, equilibrium could be established between water in the necks and the curved ice-water interface. In this case, there would be no supercooling of neck water, but unfrozen water in large pores could persist in a metastable equilibrium (supercooled) state. This metastable condition would persist, if the Thompson equation applies, so long as ice already present was excluded from the supercooled pore by geometrical restrictions and the temperature was not low enough to initiate nucleation within the pore.

It follows that if water which is supercooled while in a large pore is transferred from the pore to the ice-water interface, it moves to a part of the system in which it can no longer be regarded as supercooled with respect to the ice present. If this is true, its free energy is the same as that of the ice phase, and the energy source proposed by Jackson and Chalmers vanishes.

The persistence of supercooled water in large pores below an ice lens may play an important (but passive) role in heaving, for it permits free conduction of water through the pore. If ice particles appeared in these pores, but were not connected to the main ice lens above, the latter might continue to grow by utilizing water conducted through unfrozen films surrounding the ice crystal.

The active part of the heaving system is not opposite the capillary necks, but opposite the particles, which actually provide the support for the ice lens and frozen soil above. Here the curvature of the ice-water interface may be zero, if the particles are flat, or concave if the particles are rounded. In this case the Thompson equation would predict elevation of the freezing point so that if curvature alone were considered, water at the ordinary ice point would be supercooled with respect to the ice at this interface. Thus, if the mechanism of frost heaving were dependent on energy derived from the freezing of supercooled water this mechanism would still exist as the temperature approached the normal ice point. The Thompson equation can be interpreted here to mean that a depression in an otherwise flat ice crystal would be unstable at the normal ice point and would fill with ice spontaneously at the expense of ice from the flat portions of the crystal.

Taber's conclusion that an unfrozen film of water persists between the ice lens and the soil particles is generally accepted. When a part of this film water freezes, there will be an uplift corresponding to the volume change of the water as it solidifies. This volume change is but a small fraction of the net uplift in the heaving process. The major uplift occurs when the film is reinflated to its original thickness. Hence, the major part of the energy required for heaving is derived from the forces which draw fresh water into the film to replace that lost to the ice phase. Recharge of the film does not involve a phase change and the freezing of supercooled water cannot be invoked as the source of energy for this process. The Thompson equation does not give any basis for supposing that film water can be supercooled with respect to adjacent ice, for as has already been shown, it would predict that the film water would freeze spontaneously, eliminating the film entirely.

The freezing point of film water must be depressed by interactions with the particle surface, as pointed out by Taber. These interactions may be expressed in terms of "adsorption forces" which serve two functions. The first is to depress the freezing point so that the film remains unfrozen at heaving temperatures, and the second is to draw fresh water from below to recharge the film when it is depleted by ice formation. Professor Low's contribution to this symposium reviews current ideas on the nature of these forces. Further studies of these forces and their nature are being made at Cornell.[3] It seems evident that the recharge function of these forces is identical with their function in producing swelling in clays, and that the heaving process is merely a special case of swelling. Water acquired by the surface film is constantly being borrowed and stored as ice and heaving continues indefinitely if heat is being extracted from the system and other necessary conditions are satisfied.

It is possible to construct a model which can simulate the function of the surface film and to produce heaving in the absence of soil and in the absence of geometrically induced supercooling. This model consists of a simple osmometer made in the form of a cylinder containing a salt solution. The lower end of the cylinder is a semipermeable membrane in contact with pure water in a reservoir. Resting on the solution is a loaded piston which simulates overburden. This system will spontaneously adjust to an equilibrium condition by transfer of water across the semipermeable membrane until the solution has an osmotic pressure which will just support the loaded piston. If some of the water from the solution is made to freeze on the underside of the piston, the equilibrium will be disturbed, and the solution will absorb fresh water, recharging the solution to approximately its original volume. Since the weight of the ice formed has been added to the overburden, the new equilibrium concentration will be slightly larger than before, but it can be shown that if the solution is present as a very thin layer, a great deal of ice must be formed to change the thickness of the solution appreciably. Hence, this model simulates the heaving process in all important respects. It can be elaborated to simulate other soil conditions, such as depth to the water table and soil permeability.[4]

With the proper geometry and temperature gradient, this model will produce heaving in the absence of any supercooling beyond that required to freeze ice at a finite rate. To make it operate, all that is needed is a heat sink to assure the conversion of water in the solution to ice. If the source of energy for most of the actual work done in lifting the overburden must be indicated, it might be said to be osmotic pressure (in the case of the model).

The role of supercooling in heaving, according to this discussion, is a passive one. The Thompson equation has not been questioned, and its consequences in preventing proliferation of ice through soil pores are presumed to be important to the efficiency of the heaving process. On the other hand, supercooling in large pores as a consequence of the Thompson equation is not accepted as the origin of the energy required for heaving.

E. PENNER, Closure—The author is grateful for the lengthy discussions and criticisms submitted by Jumikis, Martin and Miller. Unfortunately in the case of Martin and Miller, they were mostly related only to one aspect of the paper. An extensive rebuttal is obviously not warranted at this stage since substantiation or disagreement depends to a large extent on further experimentation. That limitations exist in the theory was recognized and stated by the author. The paper was, however, presented in the light that some useful discussion would develop. This, in the author's opinion, has been achieved.

With reference to Martin's discussion, his chief disagreement centers around the temperature and pressure relationships at the ice-water interface. The author can find no evidence to disagree with the model showing that ice and water are in contact

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[3] Contract DA-11-190-ENG-23, Phase II, Snow, Ice and Permafrost Research Establishment, Corps of Engineers, U.S. Army.

[4] This model and the Gouy-Chapman model of the electrical double layer have been examined in relation to the mechanism of frost heaving in an unpublished report prepared by L. A. Cass and R.D. Miller for the Snow, Ice and Permafrost Research Establishment, Corps of Engineers, U.S. Army, in fulfillment of contract DA-11-190-ENG-23, Phase I.

at the heaving front above the soil particle and that the "growing" ice phase rests on the adsorbed phase. Until more information becomes available on this point, the thermodynamic expression used in the paper appears to be consistent with the model. It may well be that the use of liquids other than water in a heaving system as suggested by Martin, may be helpful in unraveling the phenomenon.

Miller questions the suggested mechanism of supercooling as a source of energy for the work such systems can perform. The alternative offered that frost heaving results from osmotic pressures, as suggested in his unpublished report and in his discussion appears to have much merit. Undoubtedly, Miller recognizes that similar effects may result from different causes. The predicted heaving in his model osmometer in itself does not prove that this happens during frost heaving in soils.

Miller's suggestion seems more understandable in the case of clays where osmotic pressures arise from differential ion concentrations in the system to which swelling is attributed. In the case of coarser materials such as fine sands, these osmotic effects are more difficult to visualize since no adsorbed ions need necessarily exist. In fact, the author has measured heaving pressures of considerable magnitude in systems which have no possible exchange capacity and are devoid of any extraneous ions. In these systems classical osmotic pressures arising from ion concentrations do not exist. What is involved is a phenomena associated with the adsorbed water phase.

While reinflation of the film around the particle is brought about by differences in the free energy of the water in the unfrozen portion of the soil, one must also explain where the energy arises initially to remove adsorbed water for ice lens growth. This in fact initiates the process, and moisture flow from the unfrozen soil is an effect not a cause and is only necessary to sustain heaving.

In earlier work, the author showed experimentally that the maximum heaving pressure was related to the dry density of the porous medium. At high densities, the highest heaving pressures occurred; at low densities, much lower heaving pressures resulted. By changing the dry density the pore dimensions were obviously altered. Since the same material was used for all densities, it is difficult to ascribe these effects to other causes than those outlined by the author; perhaps these effects can also be explained in the light of the osmotic concept.

Finally, whatever its origin, if supercooling at the ice-water interface is necessary for ice lens growth and heaving, its magnitude would appear to be related to the pore restriction dimensions between adjacent particles. If this were not the case, unrestricted ice propagation between particles would prevent supercooling and only in situ freezing would result. This is the case of a non-frost susceptible soil even in the presence of an ample water supply.