Pressures Developed in a Porous Granular System as a Result of Ice Segregation

EDWARD PENNER, Soil Mechanics Section, Division of Building Research
National Research Council of Canada, Ottawa

Introductory Remarks by the Chairman

The great French mathematician and philosopher, Poincaré, has pointed out on a number of occasions that even in mathematics true pioneering advance is usually made by the geometric and intuitive mind. This advance is subsequently rendered "secure" for science by the analyst or logician. Unfortunately, as Poincare also points out, this "securing" by the logician may often be likened to building a complicated scaffold around the simple intuitive creation, obscuring its beautiful lines and diminishing also its inspiratory power for further intuitive creation. In the present age, scientific and engineering education is becoming more and more analytical with the deplorable result that present college curricula often deprive engineering students of an opportunity to develop geometric and intuitive creative thinking. It is hoped that the fine example of geometrical thinking shown in the paper by Edward Penner and in other important contributions to this symposium will help to restore the needed balance between geometrical and analytical approach not only in this field, but also in other areas of engineering science.

● FROST ACTION in soils has been studied for a number of years by the Division of Building Research with a view to developing more adequate frost action criteria for soils engineering in regions of seasonal frost. The normal pattern of events that leads to the destruction of roads and airports is heaving of the soil when it freezes and loss of supporting strength when it thaws. The displacement of shallow foundations and the damage to cold storage warehouses due to frost action normally involves only the frost heaving aspect, the loss of supporting strength being of little consequence.

The expansion of water when it freezes accounts for a small fraction of the total heave. Although this in itself may be particularly destructive in many building materials, a large percentage of the displacement in soils is rightfully attributed to the formation of ice lenses at the freezing plane. The flow of moisture is normally assumed to be largely in the liquid phase under the influence of a so-called "suction" gradient. As a consequence, the development of this suction at the ice/water interface is the most essential element in the mechanism of frost heaving since it must precede and continue during the growth of ice lenses. In a closed system the suction increases to a maximum when ice lensing stops.

Recent experiments by the author (1) showed that the magnitude of the suction (soil moisture tension) at the ice/water interface, when the growth of the ice lens stops, depends upon the dimensions of the pore system in the soil. Such measurements were made in the absence of any appreciable external pressure on the ice phase which, however, exists in nature and its effect is therefore of significance in the formation of ice lenses. This paper gives the experimentally determined relationships between overburden pressures and the magnitude of the soil moisture tension when the ice lens growth has decreased to zero, that is, under equilibrium conditions. Some thermodynamic aspects of the freezing of moist soils have been described by Edlefsen and Anderson (2) and the ice lensing system has been described by Winterkorn (3), Powers (4), and Gold (5). Based on somewhat similar treatment the mechanism of ice lensing is discussed in the light of the experimental results.

EXPERIMENTAL

Material and Specimen Preparation

The granular system used consisted of powdered quartz known in the ceramic industry as potter's flint. The grain-size distribution based on the hydrometer analysis is given in Figure 1. Selection of this material was on the basis of chemical purity and fineness.

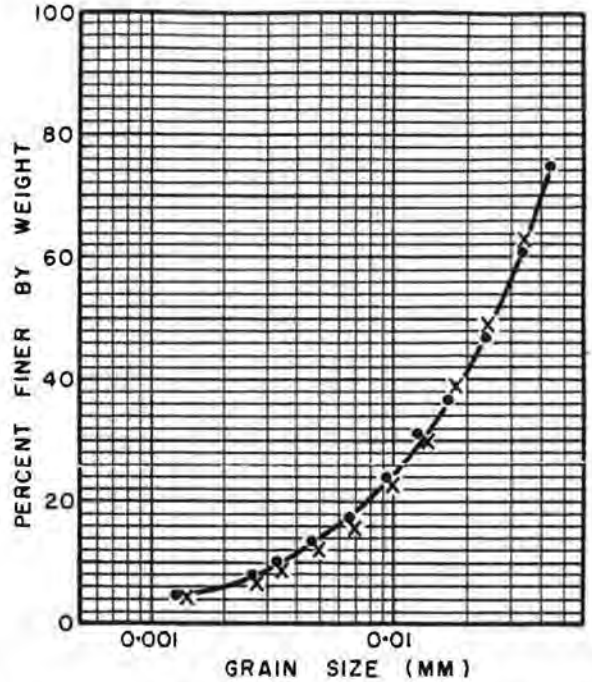

Figure 1. The grain-size distribution of the potter's flint used in these experiments.

The specimens were prepared at various densities in a Harvard Miniature Compaction Apparatus by controlling the moisture content and compactive effort. The dimensions of the specimens were $1\frac{5}{16}$ in. in diameter and approximately 3 in. long. In preparation for compaction, uniform moisture distribution was attained by applying water with a fine spray and subsequently storing the material in a sealed polythene bag. Uniformity of moisture content was ascertained by sampling and determining the moisture content at various locations in the moist material.

After molding in the compaction apparatus in $\frac{1}{4}$-in. layers the specimens were oven-dried at 105 C. Upon placement in the sample holder of the frost cell (Fig. 2) almost perfect saturation was achieved by permitting de-aired water to enter the specimen at the base and to spread unidirectionally. When the saturation of the specimen was complete the external source of water was cut off (closed system). Using this method of preparation the specimens showed no tendency to swell when saturated or shrink when desaturated. The specimens also had sufficient strength to resist deformation at the overburden pressures used in the freezing experiments. It may be noted here that the sample holder of the frost cell was designed to accommodate specimens prepared in the Harvard compaction apparatus.

Method of Freezing

The specimens were frozen unidirectionally, similar to the freezing of soils in nature. Antifreeze mixtures were circulated in the outer compartments of the frost cell to control the temperature of the specimen. In the bottom two compartments the circulating fluid was maintained at $+1\frac{1}{2}$ C. The temperature of the fluid circulating through the top compartment was -3 C. The variation in temperature was approximately ± 0.05 C in the conditioning fluid but was a small fraction of this within the specimen. Temperature measurements were made with a specially built, high precision millivolt recorder, using copper-constantan thermocouples. To avoid any disturbance in the material after preparation thermocouples were placed so that they would not coincide with the location of the equilibrium ice/water interface.

The method of freezing was first to temperature condition the lower end of the saturated specimen to $+1\frac{1}{2}$ C and then start the circulation of the -3 C fluid. This would freeze the specimen unidirectionally from the top, leaving at the completion of the experiment approximately 2 in. of unfrozen material beneath the ice lens. Ice crystallization was mechanically induced at about 2 C of supercooling. Greased lucite rings were provided around the specimen to reduce the side friction caused by heaving. It must also be emphasized that the freezing of the specimens did not comprise of a gradual lowering of temperature of the conditioning fluid. No further changes in the temperature were imposed on the specimen after the -3 C conditioning fluid was introduced.

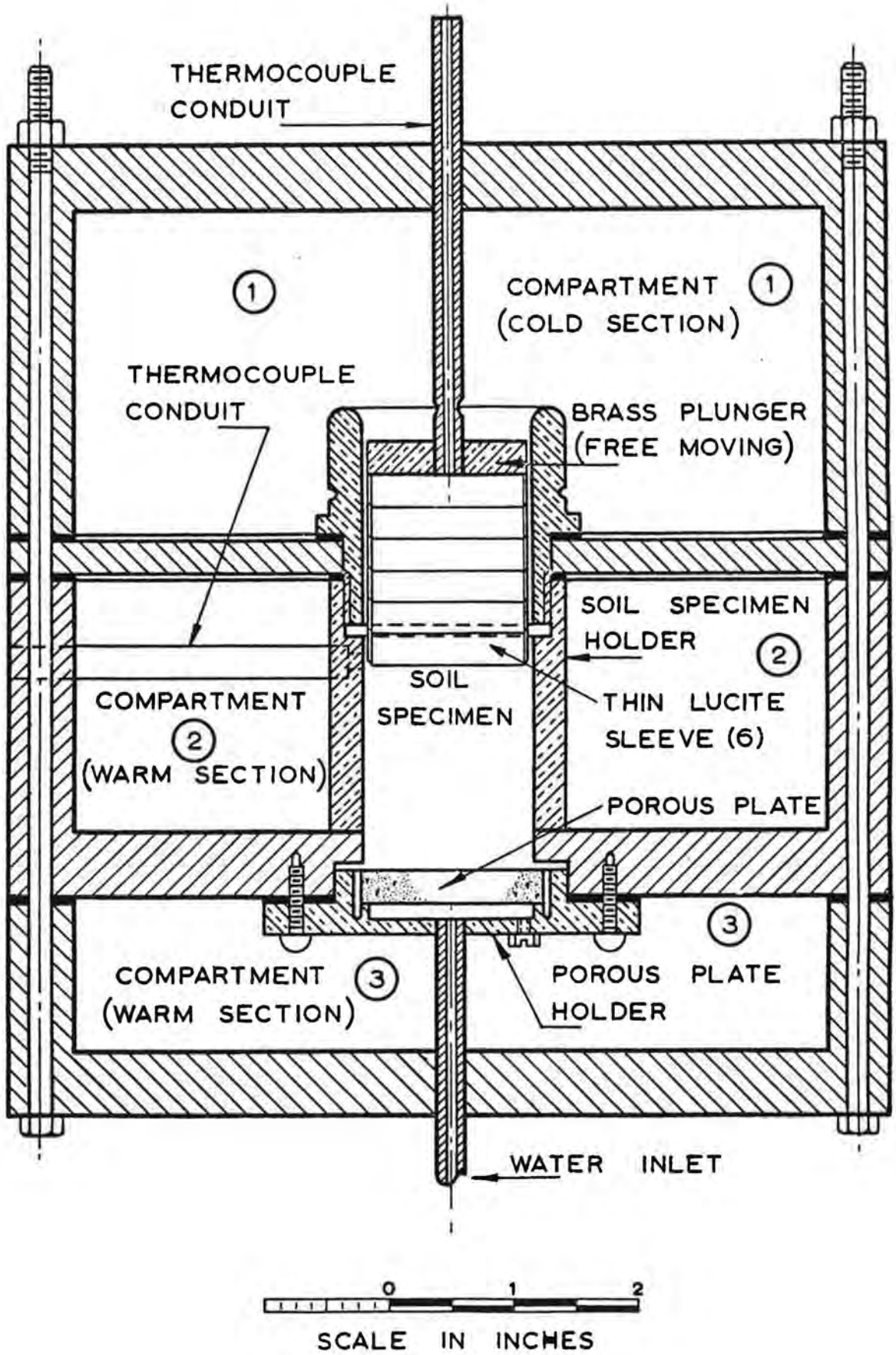

Figure 2. Section through frost cell.

Soil Moisture Tension Measurements and the Application of Positive Pressures

Heaving normally continued for several days depending largely on the overburden pressure. At the completion of heaving the unfrozen portion of the specimen was quickly removed from the frost cell and sliced in ½ in. lengths for moisture content determinations.

Two methods were used to determine the soil moisture tension induced in the unfrozen portion of the soil due to ice lens growth. From separately determined moisture content/soil moisture tension curves the induced tension could be evaluated from the moisture contents of the unfrozen portion. More details of this method may be found in an earlier publication (1).

In the second method a mercury manometer with a water connection to the base of the unfrozen portion of the specimen was used to give continuous moisture tension readings throughout the experiment. This second method was considered superior to the first since it did not involve the separate determination of the moisture tension curve. It is also considerably more accurate in the region where the moisture content change is small with increasing tension. One drawback of the second method is that it is limited by a maximum of about one atmosphere of tension.

RESULTS

The maximum soil moisture tensions induced by the growth of the ice lens were determined for three different overburden pressures: 23, 229, and 535 gm per sq cm. The lowest overburden pressure used represents the weight of the plunger only and the highest pressure was low enough so that some ice segregation would be permitted. The freezing experiments were carried out with specimens prepared at various dry densities ranging from 1.592 to 1.750 gm per cu cm. When heaving ceased, the degree of saturation was calculated from the moisture contents of the unfrozen soil. The degree of saturation was plotted versus dry density for the three different overburden pressures as shown in Figure 3. The quantities beside the plotted points in the figure give the amount of water lost per 100 gm of unfrozen soil. Knowing the relationship between percent saturation and moisture tension (Fig. 4) the moisture tensions induced at various densities and overburden pressures could be determined. These data have been plotted in Figure 5, curves A, B, and C.

To determine in a more direct way the relationship between moisture tension and overburden pressure a further series of experiments was conducted using the same type of material. These experiments were similar to those already described with the exception that a mercury manometer was used to measure the moisture tension in the unfrozen soil. This permitted direct readings of tensions as the experiment progressed. The final moisture tensions at various overburden pressures are plotted in Figure 5, curve D. The results were similar to those obtained by the former method.

From the results shown in Figure 5 the equilibrium conditions with respect to overburden pressures and soil moisture tensions may be summarized as follows for the particular granular material used: (a) the maximum moisture tension induced in the unfrozen portion due to ice segregation decreases with increasing overburden pressures; (b) the greater the packing density of the granular material the higher the moisture tension induced

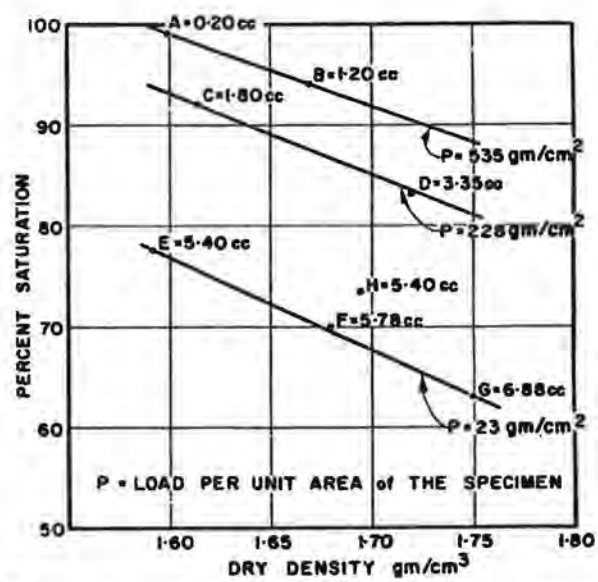

Figure 3. The relationship between dry density, overburden pressure and percent saturation beneath the freezing zone when heaving is reduced to zero in a closed system.

at the same overburden pressure; (c) frost heaving due to ice segregation can be limited either by the development of a sufficiently high moisture tension, by applying overburden pressures, or by a combination of both; and (d) expressed in gm per sq cm the limiting moisture tension is about half the limiting overburden pressure. (The overburden pressure was calculated in terms of load per unit area of the specimen.)

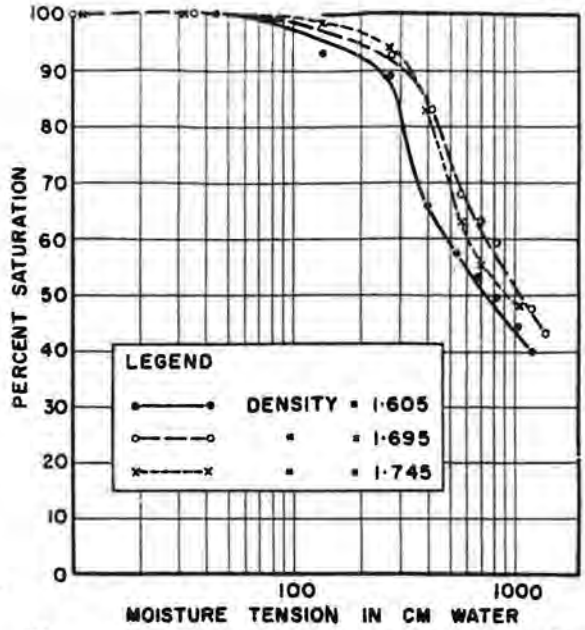

Figure 4. The relationship between moisture tension and percent saturation.

DISCUSSION OF THEORY

To facilitate the discussion a diagram (Fig. 6) has been constructed showing the relative position of the ice/water interface and ice lens with respect to the structure of the pore system.

The size of a stable spherical crystal of a solid in its own melt depends on temperature and may be expressed in the form used by Sill and Skapski (6). Using the subscripts i for ice and w for water:

$$\Delta T = \frac{2\, T\, \sigma_{iw}}{r\, \rho_i\, Q_f} \tag{1}$$

where:

r = radius of the crystal, cm
ρ_i = density of the ice, gm per cu cm
σ_{iw} = interfacial energy, ergs per sq cm
Q_f = latent heat of fusion, ergs per gm

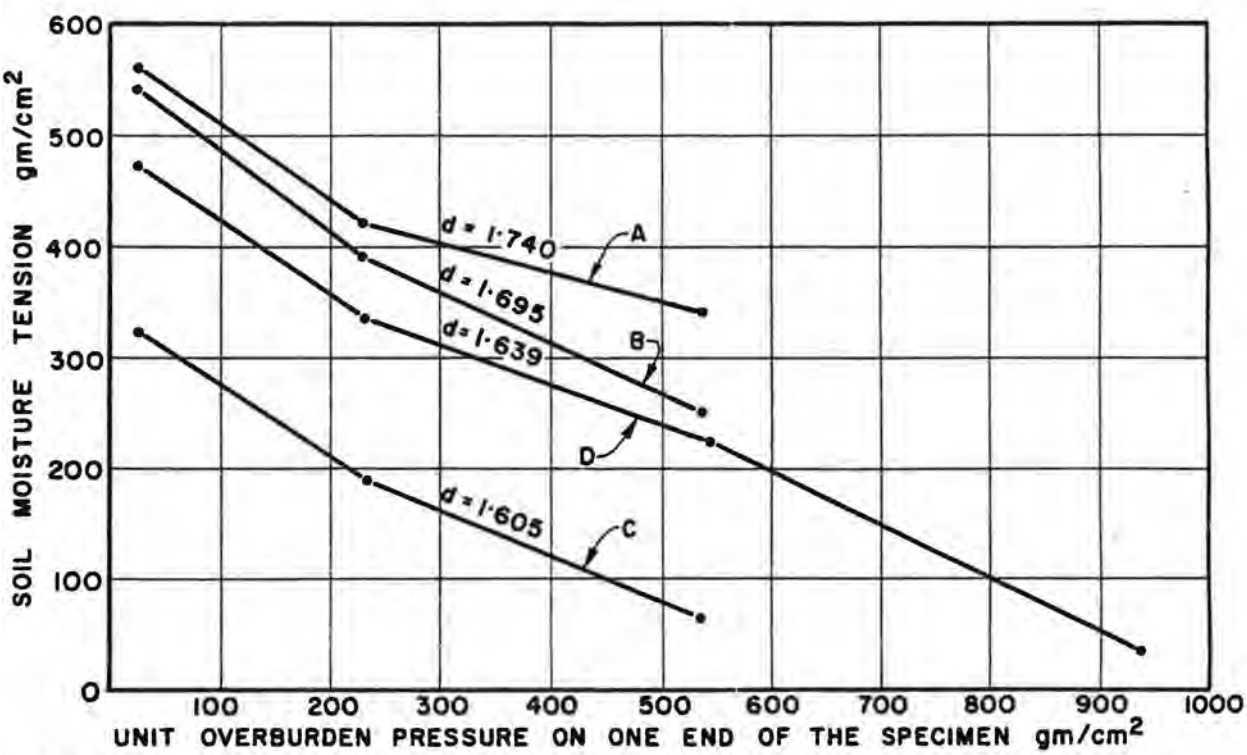

Figure 5. Relationship between soil moisture tension and overburden pressure when heaving ceased.

T = temperature of melting at zero curvature of the solid/liquid interface, K

ΔT = freezing point depression below T

Assuming that this relationship holds for the freezing of water in small spaces, it follows that the temperature at which ice will propagate through a soil depends on the pore dimensions. By freezing a saturated soil specimen unidirectionally the advance of the ice is impeded as predicted by Eq. 1. This mechanism is believed to bring about the freezing point depression of such a system but the reaction of all parts of the system to this is not the same and brings about the growth of ice phase which results in the phenomenon of ice lensing.

The conditions in a saturated salt-free porous system immediately after crystallization is induced are as follows: (a) the pressure in the pore water is zero and the adsorbed layer is essentially fully developed; (b) the overburden pressure is small, since the ice lens has just begun to grow; (c) the temperature along the ice/water interface

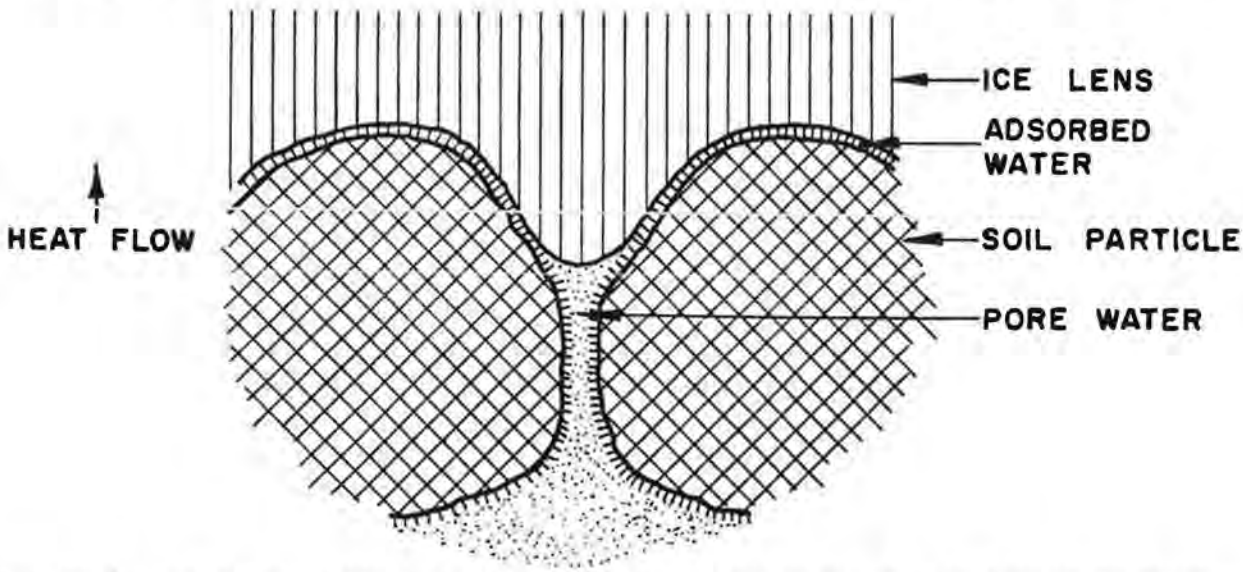

Figure 6. An enlarged schematic diagram showing a section of the ice lens with respect to the soil particle and soil pore.

is everywhere the same and has been lowered as predicted by Eq. 1.

In the pore the ice/water interface has assumed a critical radius and the rate of melting and freezing here is equal. Above the soil particle, however, the ice/water interface is either flat or has assumed a negative curvature. The freezing point of the water at the ice/water interface above the soil particle is close to that of free water, since the adsorbed phase is considered to be fully developed, but the freezing point of the pore water is given by Eq. 1. Consequently, the ice phase will grow above the soil particles at the expense of the adsorbed phase. If such a system is kept saturated, an external pressure must be applied to stop the growth of ice above the soil particles. To fix the thermodynamic equilibrium condition, two variables, in this case temperature and pressure, are considered simultaneously. If the two phases are to be in equilibrium the free energy of the ice must be equal to the free energy of the water, that is, $f_i = f_w$. This means that when any change occurs in the system the free energy of each phase changes by an equal amount: $df_i = df_w$. It follows that:

$$v_i \, dP_i - s_i \, dT = w_w \, dP_w - s_w \, dT$$

where:

v_i and v_w = specific volume of ice and water, respectively,

dP_i and dP_w = change in pressure on the ice and water, respectively,

s_i and s_w = specific entropy of the ice and water, respectively,

dT = freezing point depression below that of bulk water.

Rearranging the terms and dividing by dT:

$$\frac{v_w \, dP_w}{dT} - \frac{v_i \, dP_i}{dT} = s_w - s_i$$

Substituting $\frac{Q_f}{T}$ for $s_w - s_i$, where Q_f is the latent heat of fusion and considering finite changes, the expression becomes:

$$\frac{v_w \Delta P_w - v_i \Delta P_i}{\Delta T} = \frac{Q_f}{T} \tag{2}$$

Since the ice above the soil particle is postulated to be in direct contact with the adsorbed phase, any change in total pressure is felt equally by both the ice and water phases. As a consequence, $\Delta P_w = \Delta P_i$ and Eq. 2 in terms of the total pressure becomes:

$$\Delta P_i = \Delta P_w = \Delta P_{iw} = \frac{Q_f \, \Delta T}{T(v_w - v_i)} \tag{3}$$

ΔP_{iw} is the pressure required to bring about equilibrium expressed in terms of the freezing point depression. Eq. 3 predicts that for a freezing point depression, ΔP is positive, since Q_f is positive and the quantity $v_w - v_i$ is negative. The equation holds equally when ΔP is negative but in this case ΔT is positive.

Example 1. Ice Lensing Stopped with a Positive Pressure by Loading the Specimen

A sample calculation will illustrate the maximum pressure required to stop ice lens growth when the system remains saturated, assuming a pore radius r with a freezing temperature of -0.01 C compatible with Eq. 1. Substituting the following values into Eq. 3:

Q_f = (79.8) 4.184 x 10^7 ergs per gm
T = 273 K
v_w = 1.00 cu cm per gm
v_i = 1.09 cu cm per gm
ΔT = -0.01 C

gives a pressure of 1.356 x 10^6 dynes per sq cm. Applying this pressure to the system causes the temperature of freezing of the pore water and the ice/water interface above the soil particle to be equal.

Stating this in another way, before the pressure was applied to the ice/water interface the freezing point at that location was T_1 which, according to the moisture conditions imposed, was approximately 273 K. In the pore water the freezing point was T_2 as predicted by Eq. 1, so that $T_2 < T_1$. Since the influence of the pressure is not felt by the pore water T_2 does not change but T_1 decreases by an amount Δt with increasing P until $T_1 - \Delta t = T_2$. As a consequence there is no further tendency for the ice lens to grow.

In the above example the case has been considered where ice lensing is stopped by applying a positive pressure to the ice/water interface. This load is not transmitted to the pore water because the porous system is considered sufficiently rigid to resist deformation.

The growth of the lens can also be stopped by applying a suction to the water in the pore system. When suction is applied to the water in the system some of the larger pores may empty but the water in those that remain filled is under tension. At the same time the films of water that surround the individual particles decrease in thickness. Returning to Figure 6, applying a suction to the water has the effect of drawing the ice/water interface into the force field of the particle and can then be considered to be under compression. As a result of this pressure the temperature of freezing at the ice/water interface above the soil particle decreases as the soil grain is approached.

Eq. 3 predicts that the freezing point increases when water and ice together are placed under tension. As a consequence the water in a pore of size r which freezes normally as predicted by Eq. 1 now has a higher freezing temperature. The opposite

is true at a position above the soil particle because here the tension tends to draw the ice/water interface into the adsorptive field and the resulting pressure lowers the freezing point. The maximum tension is developed when the resulting freezing point of the pore water and the water at the ice/water interface above the soil particle are equal. If the influence of the tension were not considered to place the ice/water interface above the soil particle in a state of compression and thus lower its freezing point, one would arrive at the false conclusion from Eq. 3 that the tension necessary to stop ice lens growth would be numerically equal to the pressure given in Example 1. Restating this, in the case where ice lens growth is permitted to induce a tension in the pore water (closed system), the freezing point of the water at the ice/water interface above the soil particle and of the pore water are again T_1 and T_2, respectively, where $T_2 > T_1$. T_1 is approximately 273 K and T_2 is set by Eq. 1. As the tension increases in the pore water its freezing point increases to some value equal to $T_2 + \Delta t_2$. At the ice/water interface above the soil particle the freezing point decreases due to the reasons given above to some value equal to $T_1 - \Delta t_2$. When $T_2 + \Delta t_2 = T_1 - \Delta t_1$, no further ice growth can take place and describes the equilibrium condition. The case where $\Delta t_2 = \Delta t_1$, describes the situation where the positive pressure in the ice/water interface above the soil particle is equal to the tension in the pore water. In fact whether this is a special case or if equilibrium conditions arise where Δt_2 and Δt_1, are not equal but have values such that $T_2 + \Delta t_2 = T_1 - \Delta t_1$, is not known. In any case when $\Delta t_1 = \Delta t_2$ the theoretical magnitude of the maximum tension is one half that given in Example 1 for a sample of similar pore dimensions.

Curve D in Figure 5 shows that in a saturated system the external pressure required to stop ice lens growth is approximately twice as great as the tension when no external load is applied. Although this is supporting evidence it is still too limited to be accepted as complete confirmation of the theory.

There are two additional complicating features of the system which must also be considered. Firstly, the area of the ice/water interface is not known in the experimental determinations of pressure. Pressures are expressed in this paper as loads applied per unit area of sample. Secondly, a pressure applied at one point in the ice, for example, above the soil particle, is not fully transmitted to the section of the ice above the pore, in fact, it tends to decrease. It is thought that adjustments in the ice are accomplished by the ice assuming changes in the curvature and, consequently, in the internal pressure, both above the particle and above the pore. Further, a granular system which is heterogeneous with respect to particle size such as was used in these experiments adds to the complexity of the system, in particular because of the emptying of the larger pores as the moisture tension in the pore system is increased.

In spite of these uncertainties there is general agreement between the theory and experimental results. It follows from the theory that the maximum moisture tension or suction induced becomes less if any external overburden pressure is applied. This is also shown by the results in Figure 5.

If the freezing point depression in such systems is related to the dimensions of the pores compatible with Eq. 1 the maximum heaving pressures or the maximum soil moisture tensions induced should be greater if the density of the granular material is increased. The curves relating overburden pressures and corresponding moisture tensions determined experimentally fall in the order predicted by the theory. This was shown in another way in previous experiments with respect to soil texture and maximum moisture tension. In coarse-grained soil the moisture tension developed was much less than in fine-grained soils.

Experimentally, the limiting overburden pressure expressed in grams per unit area of sample is approximately double the limiting tension in curve D, Figure 5. Theoretically the magnitude of tension when ice lens growth stops can be shown to be less than the external pressure required when the system is kept saturated. Whether the 2 to 1 relationship shown in Figure 5 holds for all soils is not known. Further substantiating proof would involve determining pressure versus tension relationships at equilibrium for soils with different grain-size distributions. At present, no way is known of evaluating the area of contact between the ice phase and the soil particle, consequently the overburden pressures for the experiments are expressed in load per

unit area of sample. There are also thought to be important factors unaccounted for by using the relationship between ΔP_{iw} and ΔT. These involve the adjustments in the curvature of the ice resulting from difference in overburden pressure at a point above the particle to a point above the pore.

The theory predicts that ice lensing may be halted by overburden pressure, by tension in the pore water, or a combination of both. This has been shown to be possible experimentally.

Finally, attention is drawn to the different relationships that may be derived between ΔP_i and ΔT, ΔP_w and ΔT, and ΔP_{iw} and ΔT from Eq. 2. A detailed discussion may be found in the publication "Thermodynamics of Soil Moisture" by Edlefsen and Anderson (2). In an earlier paper (1) the author tended to be in agreement with the theoretical treatment by others. This treatment, however, appears valid only when the ice and water phases are considered to be isolated from each other in the system. Experience with the model described in this paper, in which the ice and water phases are in intimate contact, supported by the experimental results, suggests that there is no way in which either phase can be independently subjected to tension or pressure in a system where ice lens growth is possible. Nevertheless, since only general agreement between the theory and the experimental results can be claimed, complete confidence in the ice lensing mechanism discussed is at present not possible.

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