SOIL FREEZING AND PERMAFROST

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PREFACE

This report of the study on Soil Freezing and Permafrost concerns itself in part with a review of existing theories on factors contributing to soil freezing and also in part with ideas on the nature of the phenomenon. A portion of the material contained herein is not new and can be recognized as being derived from certain previous published studies. What the author has done is to gather the more significant studies to build up the basic theory of soil freezing, the aim of which is to bring to the reader a coherent picture of the phenomenon. With this background, the author has used results from studies conducted in the Soil Mechanics Laboratory of McGill University to project further with the intention of obtaining a better understanding of the behaviour of soils subject to subfreezing temperatures.

Only the nature of the soil freezing phenomenon is presented here. Frozen soil strength and factors relating thereto will be considered in a separate report.

Evidently, the handling of references in this report can be achieved in many ways. The author has chosen for many reasons to list the references as general credit to the whole report so as not to detract from the development of the general theory. Some of the portions contained therein can be easily recognised by the reader who is familiar with the references listed in the end of the report. The author wishes to emphasize that due credit must be given to the references listed.

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In regions where surface temperatures fall below the freezing point of water, freezing of the subsoil is possible. This is especially true for land areas located close to the Arctic and Antarctic. These areas constitute the frozen belt. Subsoil conditions within this belt may be completely frozen throughout the entire year, or may be frozen only in the winter months. The limits of the frozen belt can be defined as the frost boundary. This is not rigidly established since there is considerable fluctuation in winter temperatures for these areas. Figure 1 shows approximately the limits of subsoil that is permanently frozen throughout the entire year.

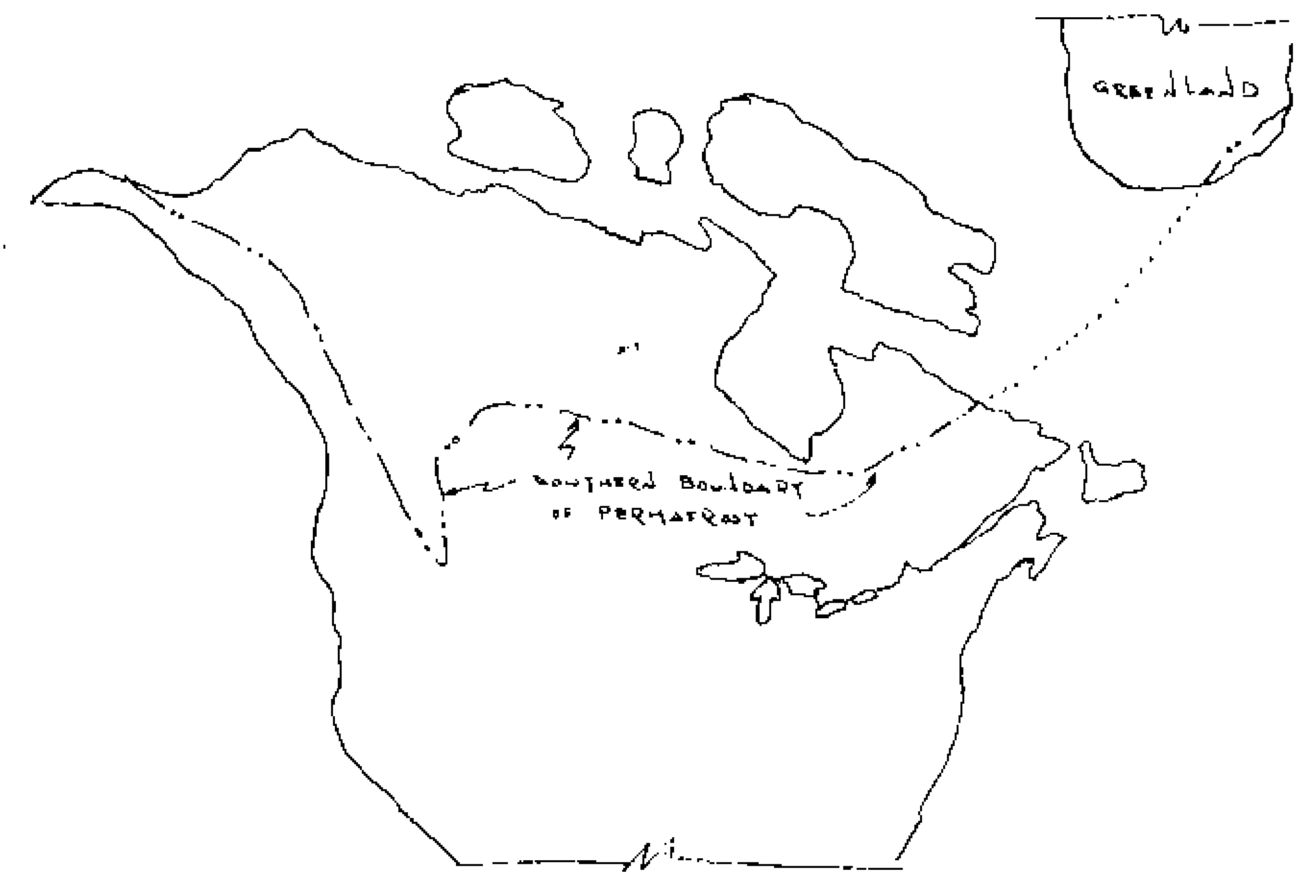


Figure 1 - Approximate boundary for permafrost for North American Continent

The variation of temperature with depth can be plotted for any one time period to show the limits of penetration of the cold front into the soil - for any one location. The cold front can create freezing of the pore water in the subsoil and as such is generally defined as the frost front. In Figures 2a and 2b, two conditions of the frost front are given to show the effect of deep penetration of the front.

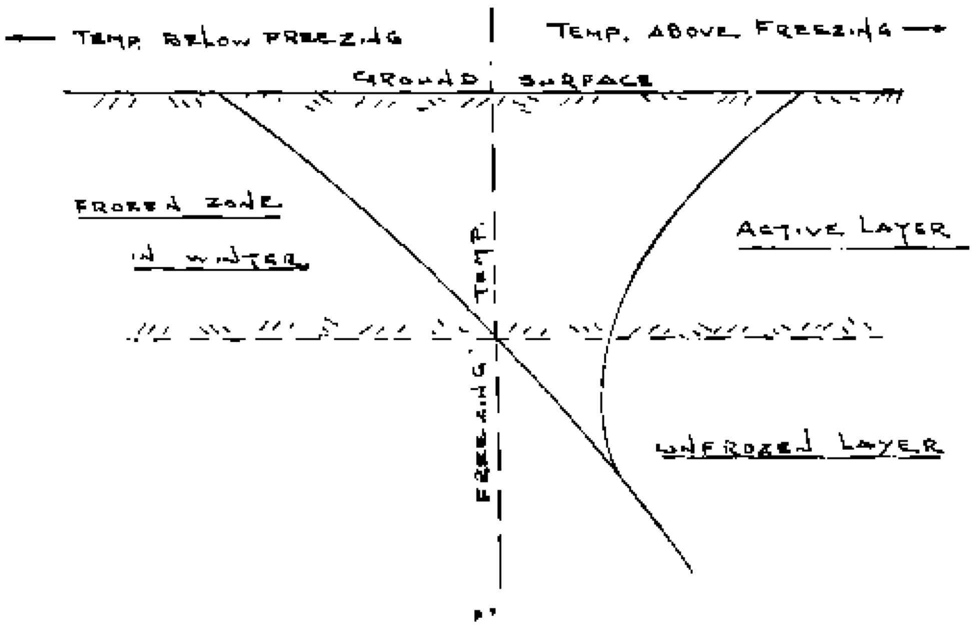


Figure 2a - Ground Temperature Profile showing Active layer only

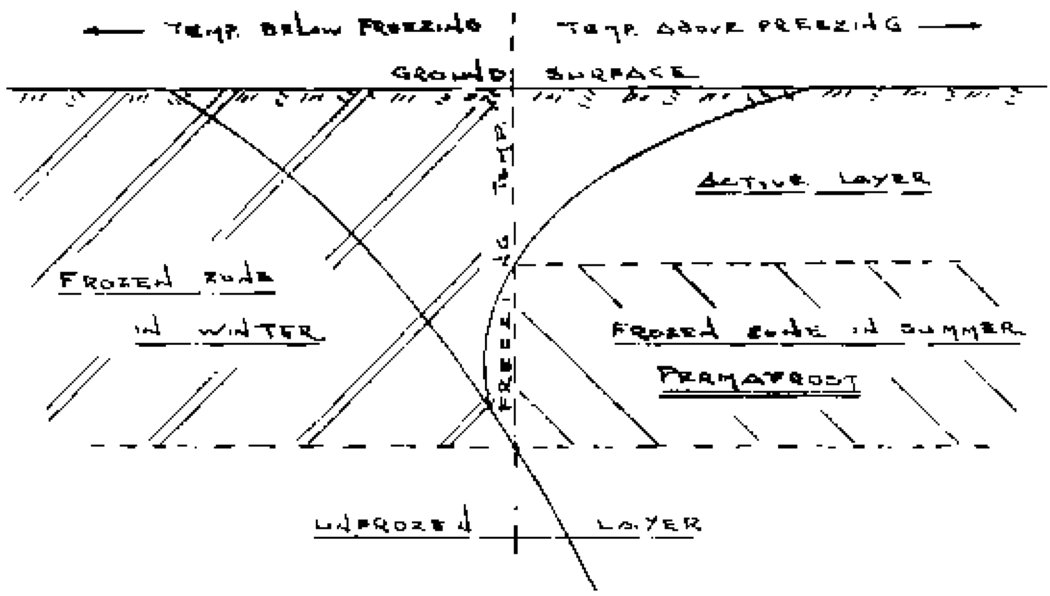


Figure 2b - Ground Temperature Profile showing Permafrost and Active layer.

The 'active' layer shown in Figures 2a and 2b is the layer of subsoil that freezes in winter and thaws in summer. The thickness of this layer depends upon several factors - but chiefly upon the penetration of the frost front into the subsoil. If frost penetration is deep and if the right conditions prevail, then it is possible to have a layer of soil that will still remain frozen in summer. This is shown in Figure 2b. The permanently frozen subsoil layer is defined as the permafrost layer. Here again, although the thickness of this layer depends on many of the soil properties, the prime factor is the duration, intensity and penetration of the frost front. The permafrost layer has been found to vary in thickness from a few inches to hundreds of feet.

About one fifth of the land area in the world is underlain by permafrost. These areas lie close to or border the Arctic and Antarctic Oceans and the thickness of permafrost will naturally vary according to the geography of the area. The closer one gets to the North or South Pole, the greater will be the thickness of the permafrost layer. In contrast to this, the further one is away from the North or South Pole, the thicker will be the active layer.

The resultant behaviour of soils within the permafrost zone or the active layer is designated as 'frost action'. In general, since the active layer freezes and thaws seasonally, and the permafrost layer is relatively stable, frost action is a direct function of freezing of the active layer.

Freezing Index

The variation of temperature with time can be plotted graphically to show the intensity of temperature in terms of duration of existing temperature. Since there is the local fluctuation in temperature between day and night, the mean daily temperature is used. This is shown in Figure 3. The temperature intensity is the area under the curve which would be defined as the number of degree days. This is time-temperature phenomenon showing as a finite quantity, the temperature intensity factor vital to the consideration of frost penetration and its associated problems.

In soil freezing, the temperature intensity considered in terms of degree days (below freezing) is important since this is an indication of the length of the freezing period , which coupled with the magnitude of the surface freezing temperature contributes directly to the penetration of the frost front. The term 'freezing index' F refers specifically to the number of degree days below freezing and is computed with the aid of a graph similar to that shown in Figure 4.

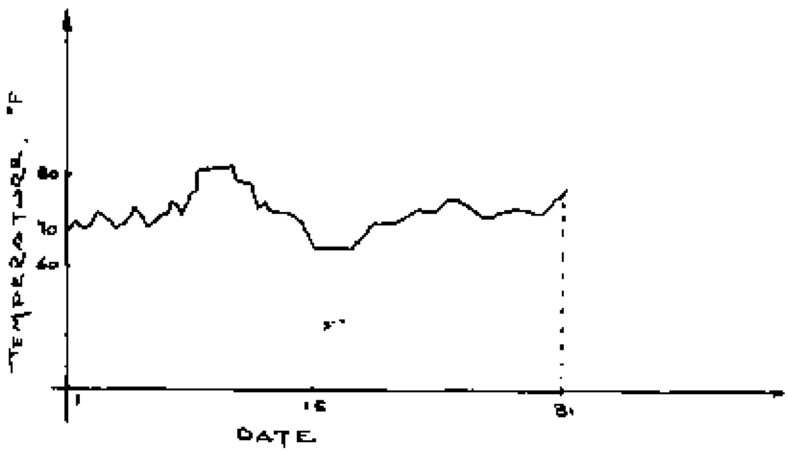


Figure 3 - Typical mean daily temperature for the month of August.

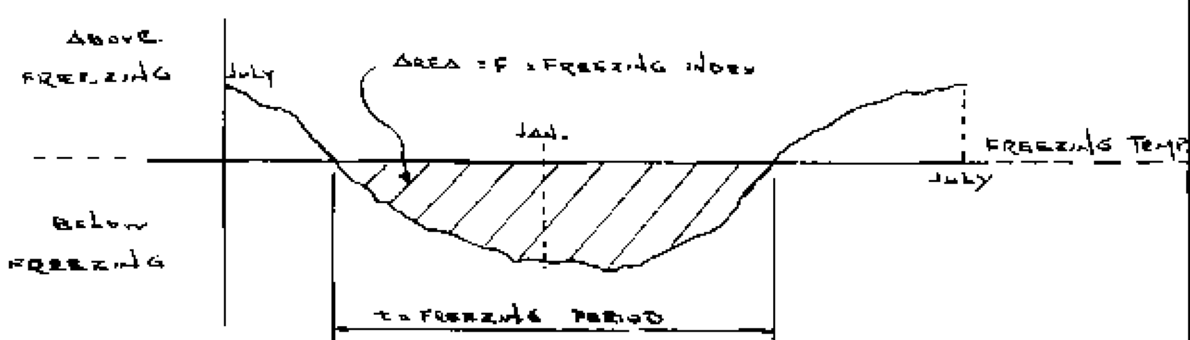


Figure 4 - Freezing Index from annual variation in surface temperature.

The mean daily temperature is plotted for a period of one year. The freezing index F is the shaded area defined by the temperature curve. If T_f represents the mean surface temperature during the freezing period t, then the freezing index F is $T_f.t$ degree days. It is evident that the higher F is, the more critical would be the frost penetration problem.

Frost Penetration

Frost penetration or the advance of the frost front into the subsoil, depends upon several factors. These are:

1. Freezing index and associated temperature factors.
2. Soil type and grain size distribution.
3. Thermal properties of the soil-water system.
4. Nature of the pore water.

Except for the freezing index and associated temperature factors, all the factors mentioned in (2), (3), and (4) are intrinsic properties and characteristics of the soil-water system. The 'heat' constants (thermal properties) considered important are:

a. Specific heat of the mineral particles, S_p ;

b. Volumetric heat of the system, C ;

c. Latent heat of the pore water, L ;

d. Thermal conductivity of the soil, k ;

The units for specific heat are generally given as BTU/pound/deg.F. or calorie/gram/deg.C. This represents the quantity of heat required to raise a unit mass of material one degree (Fahrenheit or Centigrade) compared in terms of a ratio to the heat quantity needed to raise a unit mass of water one degree (Fahrenheit or Centigrade).

The volumetric heat is dependent upon the specific heat and can be obtained b multiplying the specific heat by the dry density of the material. This varies when both frozen and unfrozen soils are considered. Since this definition is the quantity of heat needed to raise a unit volume of material one degree, the units used are BTU/cubic foot/deg.F. or calorie/cubic centimeter/deg.C. For unfrozen soils, if C_u is the volumetric heat, then:

$$C_u = \gamma_o \left[0.17 + \frac{\omega}{100} \right] \qquad \ldots\ldots \quad (1)$$

where γ_o = dry density of the soil,

and ω = water content.

In the case of frozen soils, if C_f is the volumetric heat, then:

$$C_f = \gamma_o \left[0.17 + \frac{0.5\,\omega}{100} \right] \qquad \ldots\ldots \quad (2)$$

The heat content and the change in thermal energy of a soil-water system as it freezes or thaws depends upon C_u, C_f and L. From Figure 5 the relationship between these may be seen. The thermal energy change is linear with temperature both below and above freezing, but is interrupted by the latent heat of fusion of the pore water at the freezing point. Whilst it is recognized that there could be dissolved foreign matter in the pore water, the latent heat L for the pore water is generally taken to be that of water.

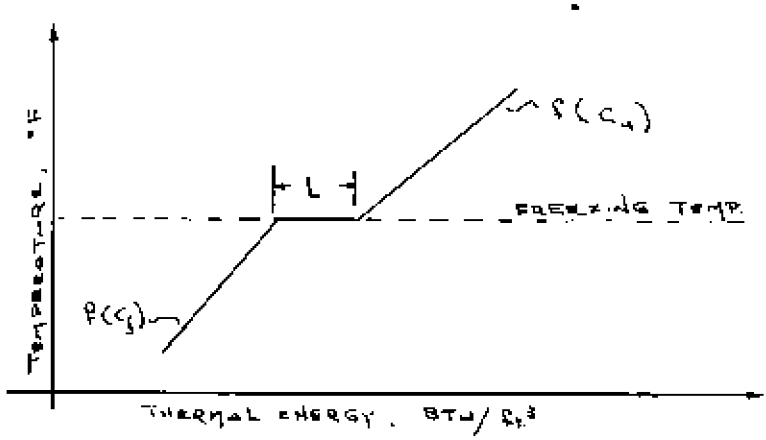


Figure 5 - Heat Content or Thermal Energy Diagram for an idealized soil-water system.

For the soil-water system, since one pound of water releases 1.434 BTU as it freezes,

$$L = 1.434\, w\, \gamma_d$$

This represents the change in thermal energy per unit volume of soil when the soil moisture freezes or thaws.

Diffusion

Idealized heat flow through soil in terms of heat transmission is necessary as a preliminary step towards estimation of depth of frost penetration. Heat transfer can be achieved by means of radiation, conduction, and convection. In partially saturated soils, radiation and conduction are the possible mechanisms for heat transfer, with conduction playing the major role. In fully saturated soils however, radiation is reduced to a negligible quantity and heat transfer can be analyzed solely on the basis of heat conduction without appreciable errors. In this instance, this is the transfer of kinetic energy from the molecules in the heat sink (from the warm portion of subsoil at lower depths) to those in the cooler portion of the subsoil - closer to the ground surface. If the temperatures of all bodies are considered in relative terms, all physical bodies can be considered as heat storages. If the temperature surrounding the bodies is much lower than that of the bodies, some of the thermal energy contained within the bodies will be released - in order to maintain thermal equilibrium (and in accordance with the second law of thermodynamics).

Considering temperatures above and below the freezing point - i.e. apart from the latent heat of fusion, for both the frozen and unfrozen body, the change in thermal energy from u_1 to u_2 is given as follows:

$$u_1 - u_2 = C\,[T_1 - T_2] \qquad \ldots\ldots \quad (3)$$

where C = volumetric heat of the body in BTU/cu.ft./deg.F.

u = thermal energy in BTU/cu.ft.

T_1 and T_2 = temperature in degrees Fahrenheit corresponding to thermal energy states of u_1 and u_2 respectively.

It will be noticed that the general term for C has been used in the equation. However, it is understood from Figure 5 and equations (2) and (3) that either C_u or C_f should be used as the case may be.

For small changes,

$$du = c\,dT \qquad \text{or} \qquad \frac{\partial u}{\partial T} = C \qquad \ldots\ldots \quad (4)$$

In the case of heat transfer by conduction, Q is given by the Fourier equation:

$$Q = k\,i\,A = k\frac{T_1 - T_2}{l}A \qquad \ldots\ldots \quad (5)$$

and more basically as:

$$q = -k\frac{\partial T}{\partial x} \qquad \ldots\ldots \quad (6)$$

where Q = heat transer in BTU/hour.

i = thermal gradient in degrees Fahrenheit/foot

T_1 and T_2 = temperature in degrees Fahrenheit.

k = thermal conductivity in BTU/hour/foot/deg.F.

A = area in square feet.

q = Q/A

x = depth taken as downward from top of ground surface.

For simplicity, only one dimensional flow of heat is considered, i.e. in the x direction. If thermal continuity is restricted to absence of freezing or thawing - without introduction of the term L as shown in Figure 5, then it follows from the conservation of thermal energy that:

$$\frac{\partial u}{\partial t} + \frac{\partial q}{\partial x} = 0 \qquad \ldots\ldots \quad (7)$$

where t refers to the particular instance of time.

From equation (4):

$$\frac{\partial u}{\partial t} = C\frac{\partial T}{\partial t} \qquad \ldots\ldots \quad (8)$$

By making the appropriate substitutions and since

$$\frac{\partial q}{\partial x} = -k\frac{\partial^2 T}{\partial x^2} \qquad \ldots\ldots \quad (9)$$

Therefore

$$\frac{\partial T}{\partial t} = k/c \cdot \frac{\partial^2 T}{\partial x^2} \qquad \ldots\ldots \quad (10)$$

Defining k/C as 'a' the diffusivity constant,

$$\frac{\partial T}{\partial t} = a \cdot \frac{\partial^2 T}{\partial x^2} \qquad \ldots\ldots \quad (11)$$

Equation (11) is the diffusion equation. This will represent the temperature profile in the subsoil at any instantaneous time. Its importance and its role will be demonstrated in the prediction of the depth of frost penetration.

Estimation of Depth of Frost Penetration

The simplest assumption for estimation of frost penetration into the subsoil is that the variation of temperature from the top of the ground surface to the frost line is linear. This means that the diffusion equation is not represented for this assumption. A further assumption is that the temperature remains constant below the frost line. Figure 6 shows the assumptions stated which provide for an approximate analysis. This is the Stefan model.

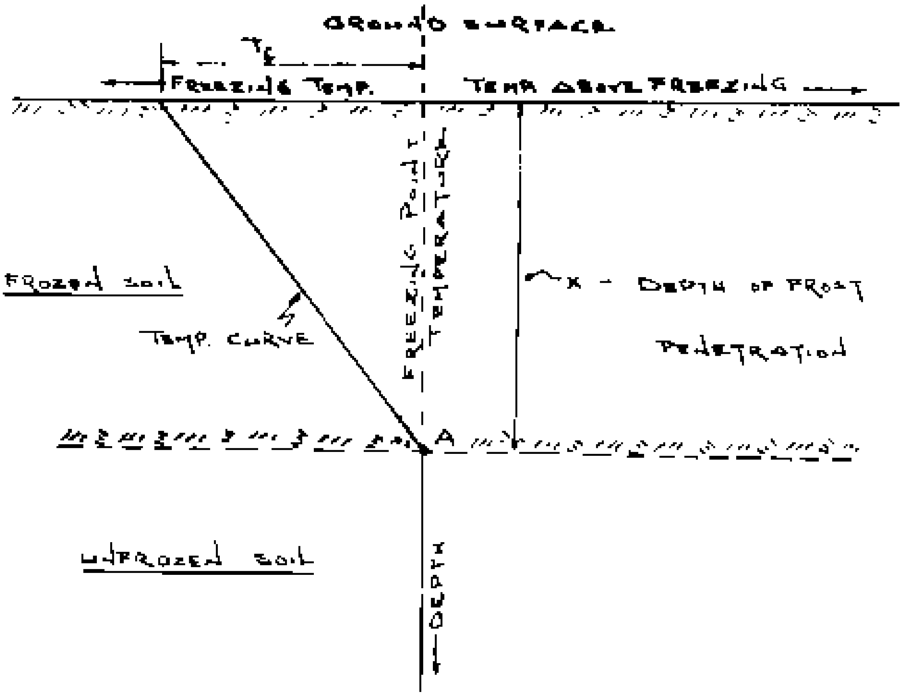


Figure 6 - Thermal conditions assumed for the Stefan Model.

At point A on the interface, the equation of continuity must be met and satisfied. This means that at point A, as the pore water freezes, the latent heat released by the soil moisture as it freezes to a depth dx in time dt must be equal to the rate of heat conducted to the ground surface. This is shown in equation (12).

$$k_f \frac{T_f}{x} = L \frac{dx}{dt} \qquad \ldots\ldots \quad (12)$$

where T_f is the temperature below freezing as shown in Figure 6,

and $L\frac{dx}{dt} = q$, $\frac{T_f}{x} = i$

$$\frac{k_f}{L} \int T_f \, dt = \frac{x^2}{2} \qquad \ldots\ldots \quad (13)$$

Therefore

$$X = \sqrt{\frac{2k_f \int T_f \, dt}{L}} \qquad \ldots\ldots \quad (14)$$

$\int T_f dt$ in degree hours is equal to the freezing index F reported in degree days with the appropriate correction from Figure 4.

Therefore

$$X = \sqrt{\frac{48 k_f F}{L}} \qquad \ldots\ldots \quad (15)$$

Equation (15) is the Stefan equation derived solely from the model shown in Figure 6. The limitations other than those contained in the linear variation of temperature from the ground surface to the frost line and the constant temperature below the frost line, include the volumetric heat factors of both the frozen and unfrozen soil. It has been found that prediction of the depth of frost penetration X made on this basis tends to be on the conservative side.

The use of the diffusion equation presents a more rigid analysis for estimation of frost penetration. This method of treatment was developed by Berggren and later modified by Aldrich and Paynter. In the modified Berggren model, the diffusion equation is used to define the subsoil temperature profile shown in Figure 7. The soil temperature profile is drawn for any instantaneous time t. The thermal properties for both unfrozen and frozen soil layers are given as follows:

Table 1

Notation of Thermal Properties of frozen and unfrozen soils

	Unfrozen soil	Frozen soil
Thermal conductivity	k_u	k_f
Volumetric heat	C_u	C_f
Diffusivity coefficient	$a_u = k_u/C_u$	$a_f = k_f/C_f$

For any reasonable mathematical analysis, it must be assumed that conditions are analyzed for that particular instantaneous time period - which may then be integrated to cover the interval under consideration.

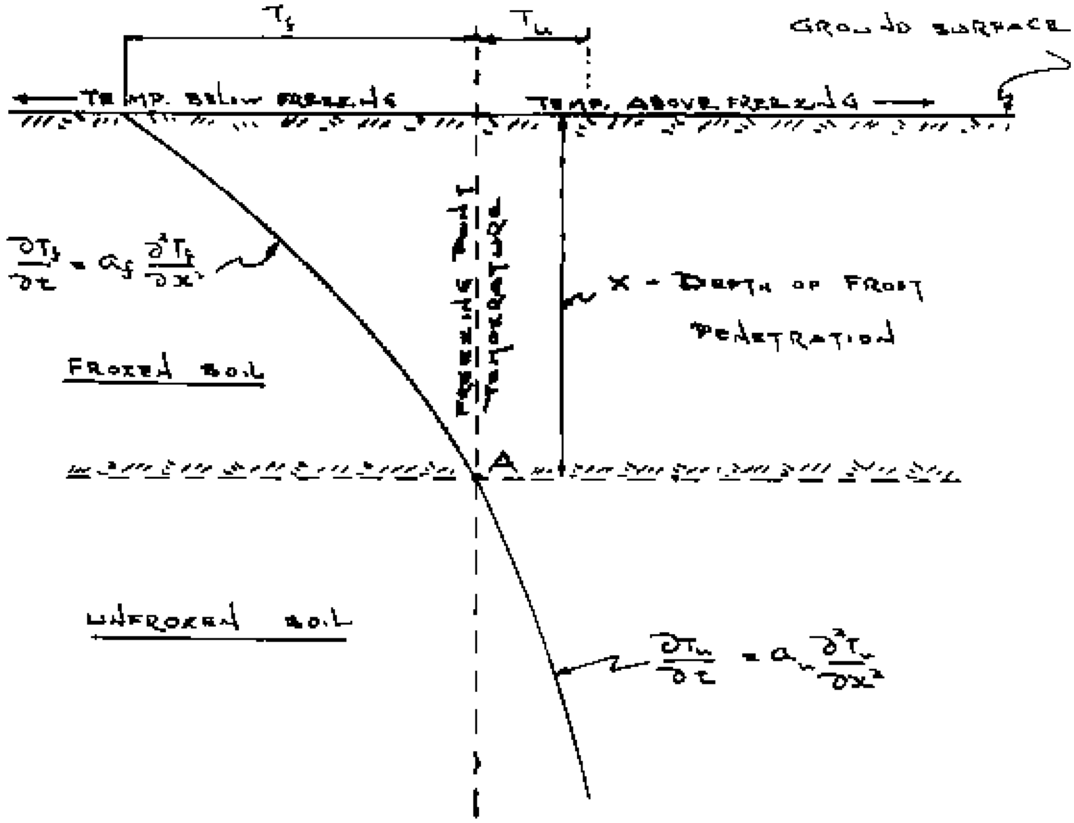


Figure 7 - Ground Temperature Profile for Modified Berggren Model.

In the frozen soil layer, the ground temperature profile is given by the diffusion equation with the appropriate thermal constants as follows:

$$\frac{\partial T_f}{\partial t} = a_f \frac{\partial^2 T_f}{\partial x^2} \qquad \ldots\ldots \quad (16)$$

Similarly, in the unfrozen soil layer:

$$\frac{\partial T_u}{\partial t} = a_u \frac{\partial^2 T_u}{\partial x^2} \qquad \ldots\ldots \quad (17)$$

must be valid.

At point A on the frost interface, the equation for continuity must be satisfied. This means that the net rate of heat flow from the frost interface must be equal to the latent heat supplied by the soil moisture as it freezes to a depth dx in time dt.

Hence $$L\frac{dx}{dt} = \Delta q \qquad \text{......} \quad (18)$$

where Δq is the net rate of heat flow at the frost interface.

Therefore $$k_f\frac{\partial T_f}{\partial x} - k_u\frac{\partial T_u}{\partial x} = L\frac{dx}{dt} \qquad \text{......} \quad (19)$$

The solution for X , the depth of frost penetration into the subsoil, as defined from the boundary conditions stated has been given by Aldrich and Paynter as:

$$X = \lambda\sqrt{\frac{48kF}{L}} \qquad \text{......} \quad (20)$$

The correction coefficient λ is seen to depend upon the thermal properties of both the frozen and unfrozen soils. Values for λ can be obtained from Figure 8.

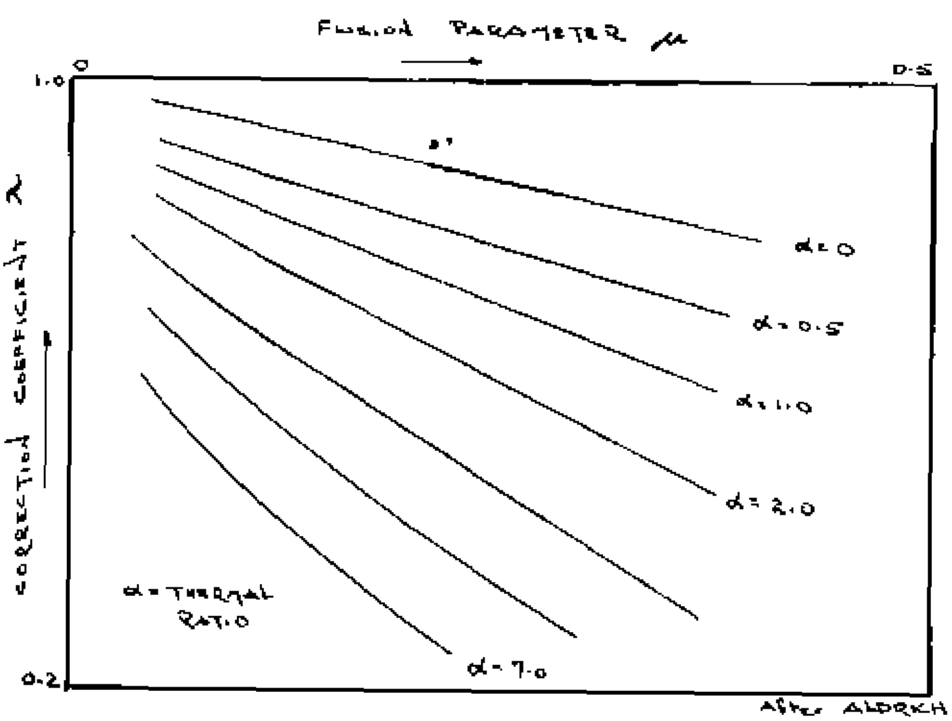


Figure 8 - Correction coefficient λ

The dimensionless fusion parameter μ is given as:

$$\mu = \frac{C_f}{L} T_s \simeq \frac{C_s F}{L t} \qquad \ldots\ldots \qquad (21)$$

It is fairly obvious from examining the modified Berggren equation that both ideal heat transfer and storage conditions are assumed. The thermal conductivity of the soil mass varies for different soil types and temperatures. (Figures 9 and 10).

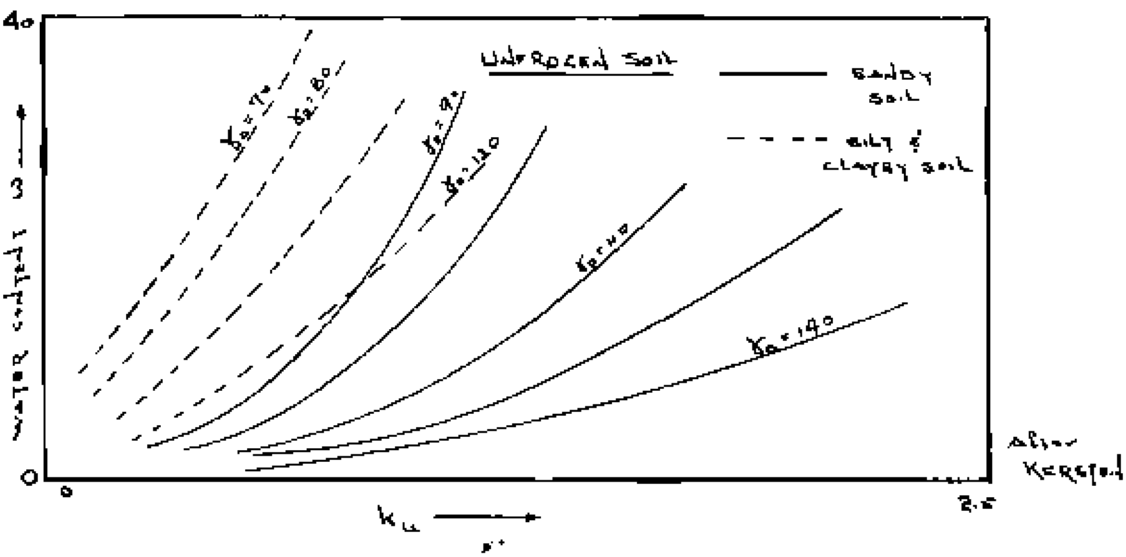


Figure 9 - Thermal conductivity k_u.

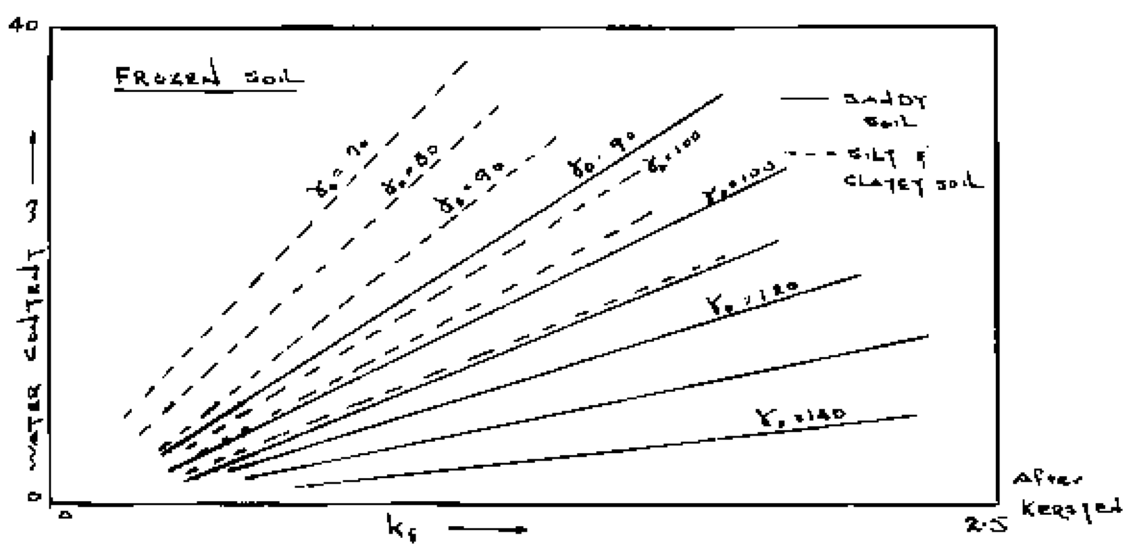


Figure 10 - Thermal conductivity k_f.

In order to obtain the correction coefficient λ , both the fusion parameter and thermal ratio α are needed. The thermal ratio is defined as the ratio between the temperature above freezing to the temperature below freezing, i.e. $\alpha = T_u/T_f$. As an approximation, T_f may be taken to be equal to F/t . The values for T_u and T_f are absolute values and are measured in terms of temperature difference from the freezing temperature (generally taken as 32°F.).

For example:

Given a mean annual surface temperature of 40°F. and a mean surface temperature during the period of freezing of 10°F., then:

$T_u = 40° - 32° = 8°$

and $T_f = 32° - 10° = 22°$

The following example illustrates the difference in estimation of depth of frost penetration using the Stefan and Modified Berggren equations - i.e. equations (15) and (20).

Given a uniform homogeneous subsurface soil deposit - silty soil;

water content $w = 20\%$, dry density $\gamma_o = 110$ pcf.

Temperature conditions are as follows:

Freezing index $F = 2110$ deg.F. days.

Freezing period $t = 160$ days.

Mean annual temperature $= 34°$F.

Therefore $T_u = 2°$F.

From Figures 9 and 10, the values for k_u and k_f may be obtained.

$k_u = 1.02$ and $k_f = 1.30$ (all in BTU/hr./ft./deg.F.)

$k_{effective} = (k_u + k_f)/2 = 1.16$ BTU/hr./ft./deg.F.

The latent heat of fusion may now be calculated since both water content and dry density are known.

$L = 1.434 w \gamma_o = 3157.8$ BTU/cubic foot.

The Stefan equation may now be used to estimate the depth of frost penetration. From equation (15):

$$X = \sqrt{\frac{48 k_f F}{L}}$$

$$= \sqrt{\frac{48 \times 1.3 \times 2110}{3157.8}}$$

Therefore $\underline{X \quad 6.46 \text{ feet.}}$

In order to use the Modified Berggren equation, it is necessary to calculate both C_u and C_f. From equations (1) and (2) :

$$C_u = \gamma_o \left[0.17 + \frac{w}{100}\right] = 110\left[0.17 + 0.2\right] = 20.9 \text{ BTU/cu.ft./deg.F.}$$

and $$C_f = \gamma_o \left[0.17 + \frac{0.5}{100}\right] = 110\left[0.17 + 0.1\right] \quad 19.8 \text{ BTU/cu.ft./deg.F.}$$

Therefore $C_{effective} = \frac{1}{2}\left[C_u + C_f\right] = 20.35$ BTU/cu.ft./deg.F.

To calculate the fusion parameter μ and the thermal ratio α needed to use Figure 8 to determine the correction coefficient, α is taken to be equal to $\frac{T_o t}{F}$.

Therefore $\alpha = \frac{2 \times 160}{2110} = 0.152$

From equation (21), $\mu = \frac{CF}{LT} = \frac{20.35 \times 2110}{3157.8 \times 160} = 0.085$

From Figure 8, $\lambda = 0.97$

Therefore

$$X = \lambda \sqrt{\frac{48 F k}{L}} \quad \text{..... from equation (20)}$$

which gives $\underline{X \quad 5.92 \text{ feet.}}$

The overestimation for the depth of frost penetration using the Stefan equation can be seen from the preceding example – which pays no attention to the volumetric heat of the soil mass and which further simplifies the estimation for X by assuming a linearity in temperature distribution in the soil mass. For multi-layered soil profiles, the effective values for latent heat of fusion and volumetric heat of the subsoil must be computed on a weighted basis -

since these are dependent upon both water content and dry density of the soil. In the same manner, the thermal conductivity must also be computed for the total subsoil thought to be within the zone of frost penetration. Evidently a first estimate of the depth of frost penetration must be obtained. The Stefan equation can be used most appropriately for this.

Freezing in Coarse-Grained Soils

In coarse-grained soils, because of the size of the particles, gravity forces predominate both in the mineral and liquid phases. The surface forces that may be in existence are, by comparison with the gravity forces, so small that their effect may be neglected. The major portion of the water in a saturated granular soil (coarse-grained soil) may then be considered as free water.

When such a soil-water system freezes, because of the magnitude of the gravity forces involved in the bulk water, migration of water to any incipient bud of ice crystallization is difficult. In consequence, freezing of the water contained within the soil voids occurs as growth of individual ice crystals without benefit of migratory movement of water. Experimental investigations, supported by field studies indicate no resultant heaving of soils as a result of freezing of the granular soil-water system. It is quite conceivable that this resultant frozen soil mass may then be visualized as an ice matrix studded with granular soil particles. There is experimental evidence to show that a liquid-like film bounds the ice phase. Therefore, the mineral particles within this frozen granular soil-water system may not be in direct total contact with the ice phase; but rather would be separated by the liquid-like film.

Since the free or bulk water phase is relatively free from forces other than gravity forces - hereafter designated as tension-free water, initiation of ice growth in a saturated soil-water system composed of coarse-grained particles can well be thought of as that of ordinary freezing of water within the interstices of the porous soil mass.

Following ice nucleation at any one point, growth of the ice crystal will progress as an advancing front in all directions. Such growth will only stop when progress cannot occur due to particle barrier or a deficiency of water. However, it would seem likely that each void space in the soil mass would contain one or more ice crystals. The formation of ice crystals may occur on the basis of both heterogeneous and homogeneous nucleation; i.e. heterogeneous nucleation being the initiation of growth or formation of an ice crystal by a foreign substance, and homogeneous nucleation being initial growth on the basis of a bud of crystallization formed within the water phase.

If water within the soil mass is supercooled and subjected to a sudden jarring action, spontaneous nucleation would be likely to occur. The soil-water system would freeze instantaneously thus giving rise to multicrystal formation. If non-spontaneous nucleation were to occur, less crystals would be formed and the resultant ice mass would be composed of larger crystals which may grow as a result of propagation of ice fronts. This however must depend upon other factors such as temperature and duration of freezing.

The basis for spontaneous and ordinary nucleation is not quite clear. When water is supercooled, ice will nucleate and water will subsequently freeze if the temperature in the water is below equilibrium. However, because equilibrium temperature exists in the water, this does not mean that freezing automatically occurs. By definition, if the liquid and solid phases coexist at some equilibriu temperature, then melting will occur at temperatures above this equilibrium temperature and freezing will occur at temperatures below the equilibrium temperature. While homogeneous nucleation cannot be explained satisfactorily, heterogeneous nucleation may be explained on the basis of the presence of foreign bodies that act as buds of crystallization thus causing the resultant freezing. Quite possibly, homogeneous nucleation in a pure water system containing no foreign bodies may occur when a cluster of the water molecules attains a certain critical radius. The cluster radius will be determined by the free surface energy of the molecules, and the critical cluster radius is in turn a function of the temperature.

In a soil-water system, the conditions prevailing are shown in Figure 11.

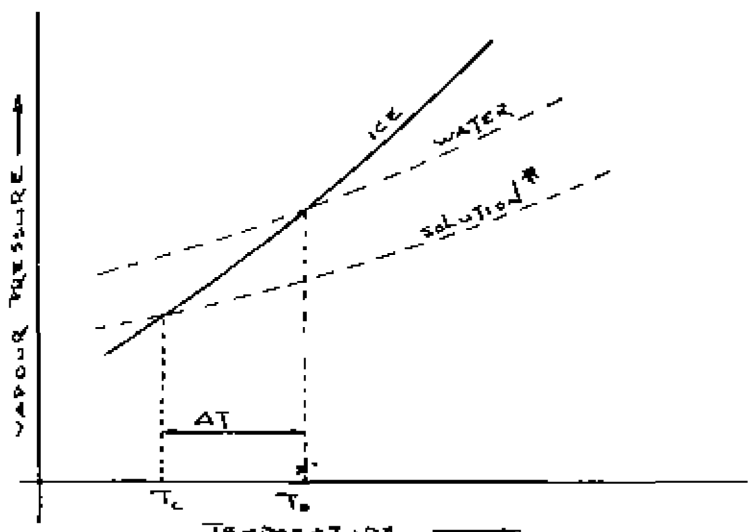


Figure 11 - Vapor Pressure Curves for soil-water system.

where T_c = critical temperature of solution

freezing point of solution which varies with

a) water content,

b) soluble salts,

c) negative pore pressure.

T_o = freezing point of water.

Solution* = solution composed of water and some other non soluble matter (granular soil particles).

$$\Delta T = \text{freezing point depression}$$
$$= 1.86M \; ; \; (M = \text{molal concentration}).$$

At any level in the subsoil, energy is required to support the overburden pressure. This places the soil-water system under a state of stress and consequently tends to lower the critical temperature T_c. If T_n is the nucleation temperature, then for ice to begin to form - i.e. for nucleation to occur, the pore water in the soil-water system must be cooled to the nucleation temperature before ice can begin to nucleate. Experimental tests have shown that T_n must be at least 7°F. less than T_c. Nuclei form slightly below T_c, but because of the thermal energy of the water molecules, the statistical odds are greatly in favor of immediate disintegration. The thermal energy is also supplied in the form of water being transported to the nuclei. Obviously the temperature of the system must be lowered in order to decrease the possibility of disintegration of nuclei -- which then establishes the nucleation temperature T_n where ice can begin to nucleate and water will begin to freeze.

The ability of water molecules to move from the water structure to any incipient crystal nucleus will govern the probability of the formation of nuclei. Surface forces that contribute to the electro-chemical action in clay soils do not play such an important part in coarse-grained soils. They are effective only within the immediate proximity of the solid surfaces. This tends to restrict the establishment of nuclei immediately next to the particle surfaces.

Figure 12 shows a schematic view (enlarged several times and considerably exaggerated) of soil freezing in a goarse-grained soil-water system. The system is assumed to be completely saturated for simplicity in presentation. A liquid film separates the ice phase from the mineral phase because of the altered structure of the water next to the surface of the particles. This has been designated as supercooled water in the schematic picture of granular soil freezing.

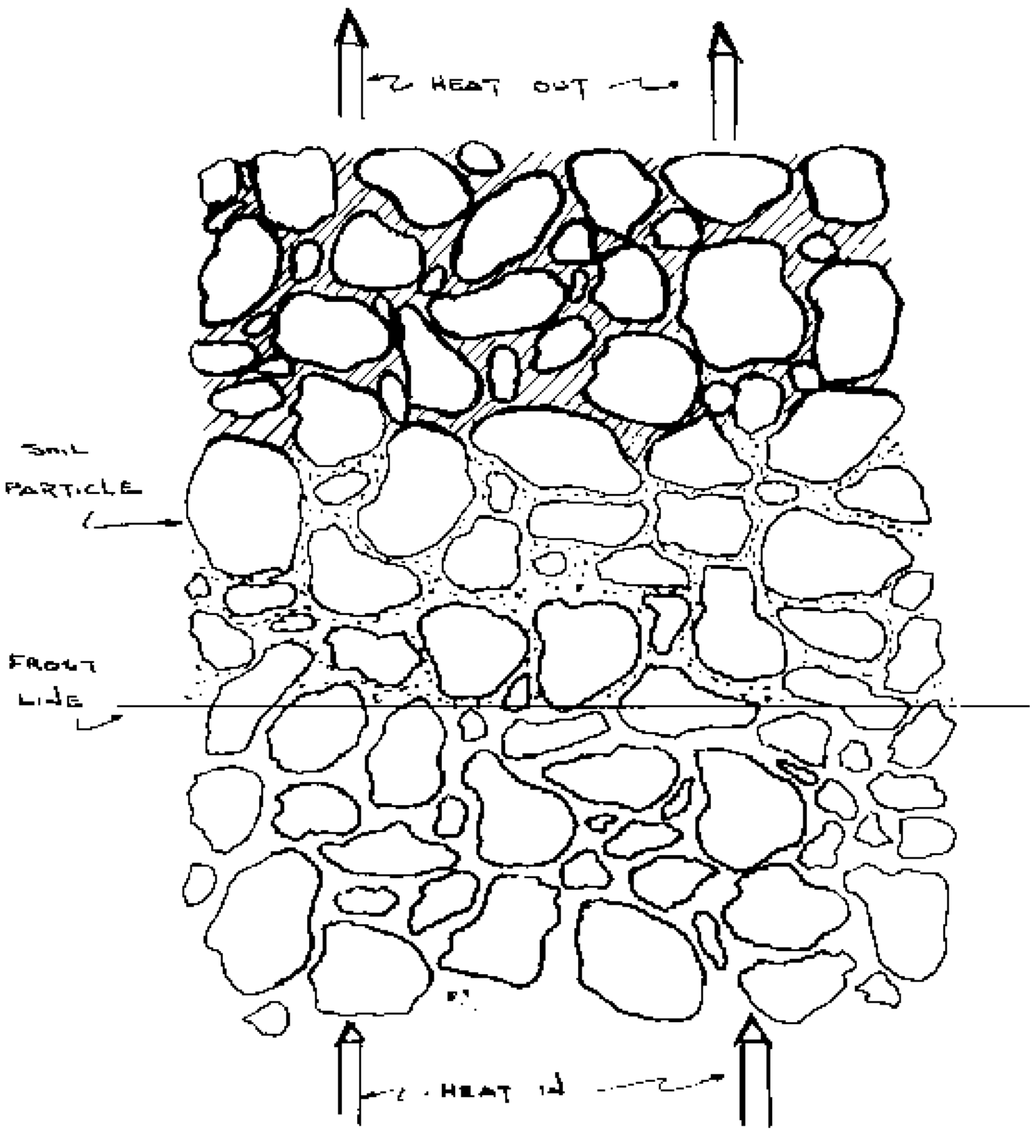
For a semi-infinite subsoil system, an uniaxial direction of freezing as shown in Figure 12 is a valid assumption. The frost line represents the position of the T_c isotherm. This is not necessarily a straight horizontal line as several other physical properties of the soil mass have to be considered. The water contained in the soil pores immediately behind the frost line is supercooled and will nucleate when the frost line advances further thus lowering the temperature to T_n the nucleation temperature.

Freezing in Fine-Grained Soils

Measurements on the total volume expansion in open systems of fine-grained soils subjected to freezing temperatures indicate that the amount of volume increase is not proportionate to the amount of increase in volume due to freezing of the water in the soil. Instead of the expected 10% to 11% increase in volume of the pore water, a larger total volume increase is experienced. This overall increase in volume may sometimes amount to 100% or more, and is the result of formation of lenses of ice in the subsoil. Heaving of the ground surface results and detrimental action to surface structures can arise from this resultant frost heave.

Conditions necessary for frost heaving to occur are:

1. Frost susceptible soil - Casagrande has shown that for well graded soils, if 3% or more of the soil particles is less than 0.02 mm. the possibility of frost action in such soils is good. In the case of uniformly graded soils, if 10% or



Supercooled water in contact with surface of particles and subject to surface forces.

ice

Supercooled water in bulk water phase

Figure 12 - Schematic View of Soil Freezing in Coarse-Grained Soils.

more of the soil particles are less than 0.02 mm. in size, then frost action in such soils is possible.

2. Temperature - Subfreezing temperatures must be such that they penetrate into the subsoil. The rate of change must be relatively slow to allow for a build-up of ice lenses.

3. Availability of moisture - There must be a supply of water to foster the growth of ice lenses. This generally means that the ground water level should be at least 6 feet from the ground surface - if not closer.

In the previous chapter, it has been shown that there is moisture migration under a thermal regime. However, the actual mechanism involved is not too well defined. In saturated fine-grained soils subjected to freezing temperatures, freezing will not occur when the critical temperature is reached. Nucleation will only occur when the temperature in the liquid phase is depressed much lower than the critical temperature T_c. In this case however, T_c may be less than the critical temperature of the pore water in comparable coarse-grained soils - since the pore water in fine-grained soils would be under some tension arising from the interaction of interparticle forces.

In the chapter on physico-chemical properties of clays it was shown that the character of water surrounding the clay particle is altered and oriented to conform to certain structural patterns. For an understanding of the phenomenon of ice lens growth, the water surrounding the soil particles may be classified into two categories:

a) Structured or oriented water,

b) Free or bulk water.

This simplification in classification is valid in this instance since the mechanism involved describes qualitatively the role of soil water in the development of ice lenses. The distinction between these two classes is shown in Figure 13. Because of the electro-chemical interaction of the colloidal-sized particles, water within the soil voids is subjected to some tension. This varies exponentially with the greatest force closest to the surface and the least at some distance away from the surface of the particles. Tension free water is represented by the bulk or free water.

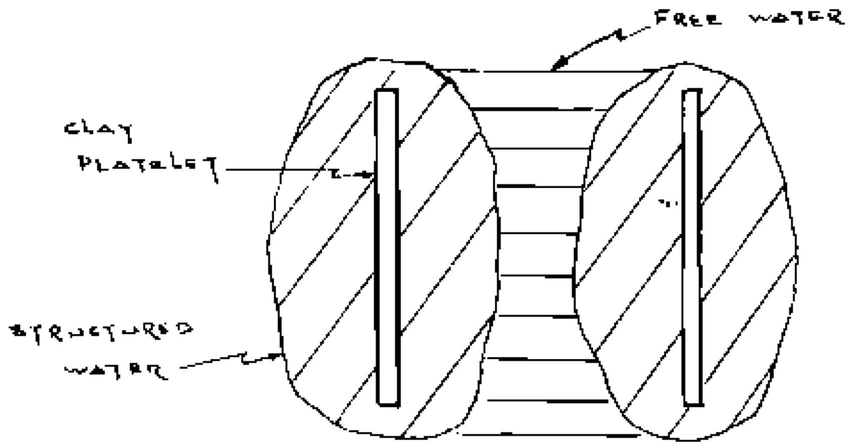


Figure 13 - Schematic Picture of the two classes of water in a saturated fine-grained soil.

When nucleation and subsequent crystallization occurs in the free water portion (assuming that free water does exist in the soil voids) growth would continue if heat loss is fractionally larger than heat gained. Considering water as a heat quantity, then any addition of water to the bud of crystallization would mean an addition of heat. It follows then that unless heat lost from this bud is equal to or greater than the heat gained from water brought in to the bud to foster growth, subsequent melting would occur. If heat loss is equal to heat gain, equilibrium is maintained.

For open systems, where water is available (over and above the original water content of the soil) and under favorable conditions, all the free water in the immediate pore space would be used up for crystal growth. Either one of two things can happen if further growth is to occur.

a) The structured water would be used to foster further growth,

or b) more free water is drawn up or to the bud of crystallization.

Depending upon the ease with which the heat loss can be replenished, a combination of these two actions is possible. However, the temperature must now be lowered significantly as (a) the structured water is under tension, and (b) energy would be required if water is to be drawn up to the growing bud. No further growth occurs if heat balance is maintained after all the free water in the immediate pore space has been expended. If however the temperature is depressed further, then subsequent growth may occur. As the temperature is depressed, there is an induced pressure deficiency at the ice front. Whether this deficiency in pressure is sufficient to result in movement of water to the growing bud would depend upon the mobility of the free water in the adjacent pores - i.e. pore spaces not within the immediate vicinity, some of the structured water would probably be used to add to the growing ice crystal. The heat balance or unbalance would be greater because of the ever growing crystal thus requiring more free water. This process can be carried further and further and more free water would be brought in from pore spaces not in the immediate vicinit More structured water from the immediate pore space and from the adjacent pore spaces would also be used to satisfy the demand for water. However, a point is reached whereby the crystal can no longer be satisfied in terms of demand for heat balance or unbalance and hence growth stops. The energy required to sustain growth would be too large. In such a case, another nucleus would be formed further ahead of the ice front - where the temperature may be well within the nucleation temperature range. The pictorial sequence for growth of the ice lens is presented in Figure 14.

In Stage 1, the bud of crystallization is formed in the free water phase found within theboundaries defined by the limits of the structured water surrounding the soil particles. The ice crystal may grow if the heat balance conditions are satisfied. All the free water within this pore space will now be used to add to the growing crystal.

When all the free water within the pore space has been used up - as shown in stage 2, free water is drawn from the adjacent pore within the immediate vicinity to foster growth. The outer limits or fringes of the structured water would also be used to add to this growth. Some particle displacement occurs as a result of this - induced by the developing size of the growing crystal.

With further depression of the temperature, more particle displacement occurs when water is drawn from sources further away from the bud of crystallisation and also because of the growing size of the ice crystal. This is shown as stage 3 in Figure 14c. Since heat transfer is essentially uni-directional, the crystal begins to assume the shape of a lens in its continued growth. If growth of the ice lens is to continue - remembering that the temperature is still being depressed further and that the heat transfer will be consequently much greater, more of the structured water in the immediate pore space and more free water from adjacent pore spaces must be drawn up to the ice lens.

Stage 4 shown in Figure 14d of the growth of ice lenses occurs when all the available water supply within the neighbouring area has been expended and further supply cannot be made available because of the energy requirements involved. When this happens, and with the further progress of the cold front, other lenses will be formed on the same basis as the preceding one. This process will be repeated as long as the cold front is mobile.

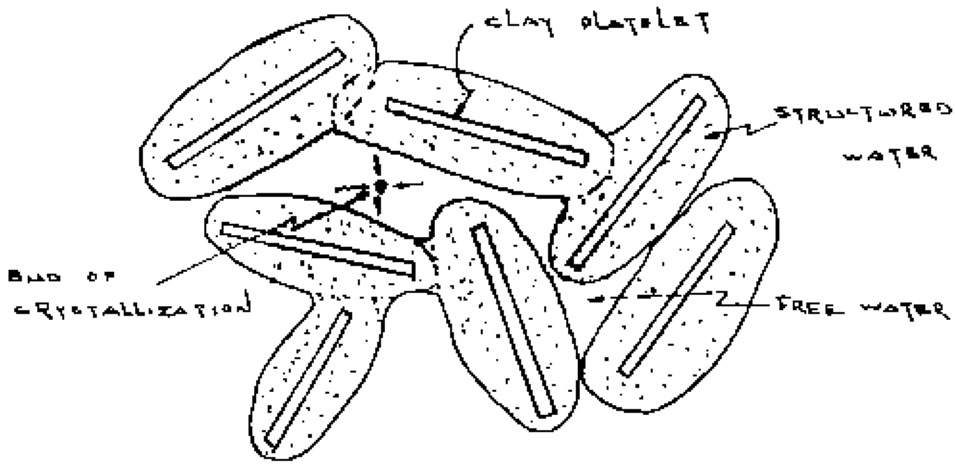


Figure 14a - Stage 1 - Free water being used in immediate pore space for growth of ice crystal.

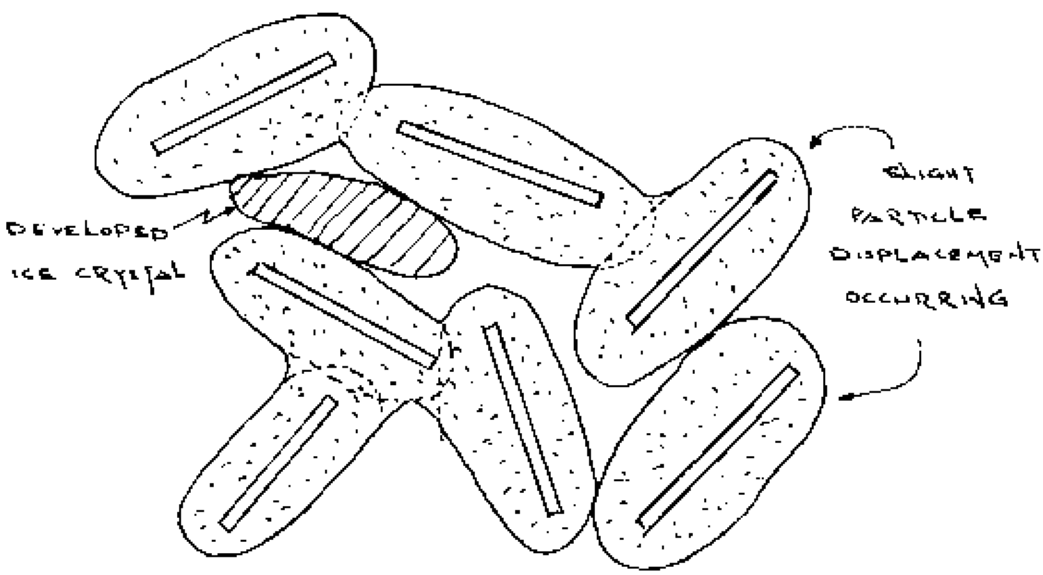


Figure 14b - Stage 2 - Free water being drawn from neighbouring pores and some structured water being used to further crystal growth.

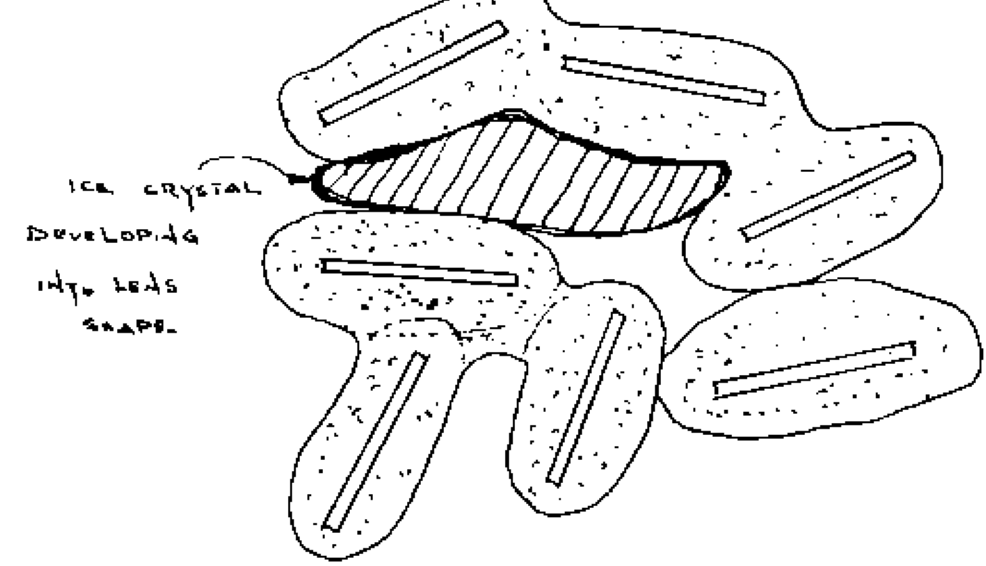


Figure 14c - Stage 3 - Free water is being drawn in from pore spaces further away, and more structured water in the immediate pore space is being used up. Particle displacement occurs because of growth of crystal into lens shape.

Figure 14d - Stage 4 - Macroscopic view of formation formation of ice lenses in subsoil due to progress of frost line and depletion of water supply around immediate crystal growth.

Growth of the crystal takes the shape of lenses which form perpendicularly or transversely to the heat loss. With the completion of growth of an ice lens, and if the temperature is decreased further, more structured water in the immediate pore space would be used to add to the growth of the lens. This however, does not add significantly to the size of the lens. The temperature in advance of the ice front drops to the nucleation temperature T_n and the possibility of nuclei forming is favorable. There is deficiency of water in the immediate vicinity of the ice front, but not too far ahead, nucleation can and does occur. The cycle of ice lens formation and growth continues as long as conditions favoring such growth are available.

The growth of ice lenses displaces the soil particles surrounding the lens causing in general a total volume change, and in particular, a resultant upheaval of the soil mass on the surface. This is the contributory cause to frost heaves.

Ice lenses may still be formed in closed systems - where water is not readily available, but such lenses would be minute or small since only the original water content provides the source of water for ice lens formation and growth. As a result, little or no upheaval occurs. Energy required for water transport to any growing crystal is generally too much for any measurable growth to take place.

Unfrozen Water in Frozen Soils

The mechanism used to describe soil freezing demonstrates that there is the possibility that not all the water in the void spaces is frozen - for a soil mass subjected to subfreezing temperatures. This has been shown to be true for soils containing a high percentage of fines. Electro-chemical interaction of the fine particles - considered as platelets and as charged particles in an electrolytic system, results in the creation of charged fields. These constitute and define the nature and limits of the structured or oriented water that surrounds these particles. The effect of these charged fields is felt in the form of temperature depression in the structured water. The closer one approaches the particle surface, the higher is the activity of interaction and the higher is the force required to move a molecule of water into or out from this area - as shown in the Chapters on Soil Water and Physico-Chemical Properties of Clays. The temperature requirement for freezing of the structured water will accordingly vary with the intensity of the interaction within the structured water. Because of this, partial freezing of the water phase under subfreezing temperatures results.

The quantity of unfrozen water expressed in terms of unfrozen water content or percent unfrozen water varies with

a) Original water content,

b) percent saturation,

c) freezing temperature,

d) clay content (percent of active clay particles in the soil-water system),

e) charge density of the soil particles,

f) electrolytic concentration.

Figures 15 and 16 show the form of variation of unfrozen water with the conditions stated above. In some instances, the freezing point depression caused by the intensity of interaction of the interparticle forces may be as high as 15°C. at a distance of about 10 A° from the surface of the particle. From the curves in the figures on unfrozen water, it is evident that the temperature depression for many active clay soils will be more than 20° C. - and certainly much more at lower initial water contents. (Temperature depression

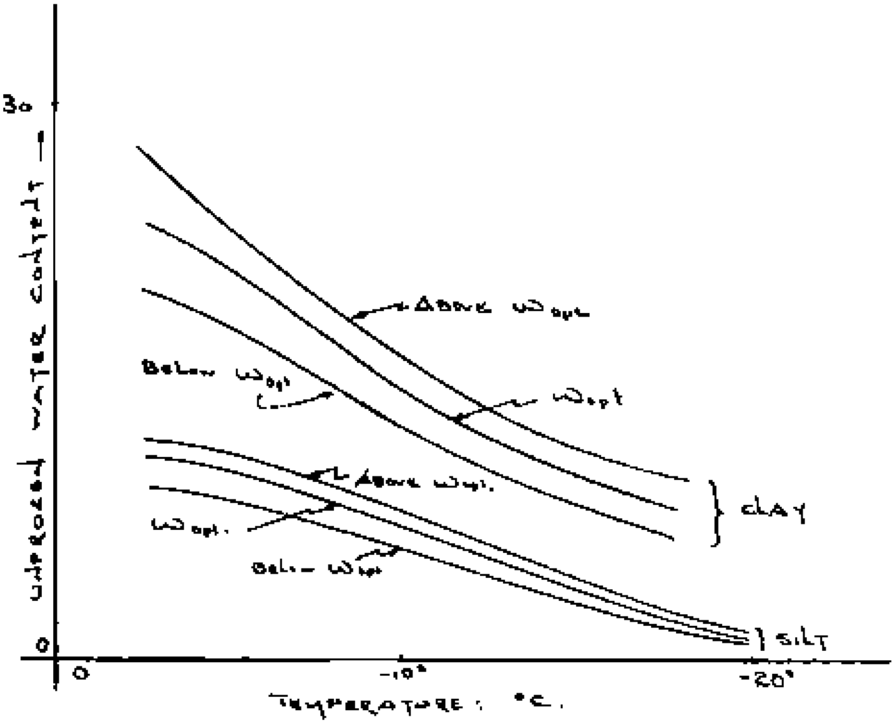


Figure 15 - Relation between unfrozen water content and temperature for clay and silt.

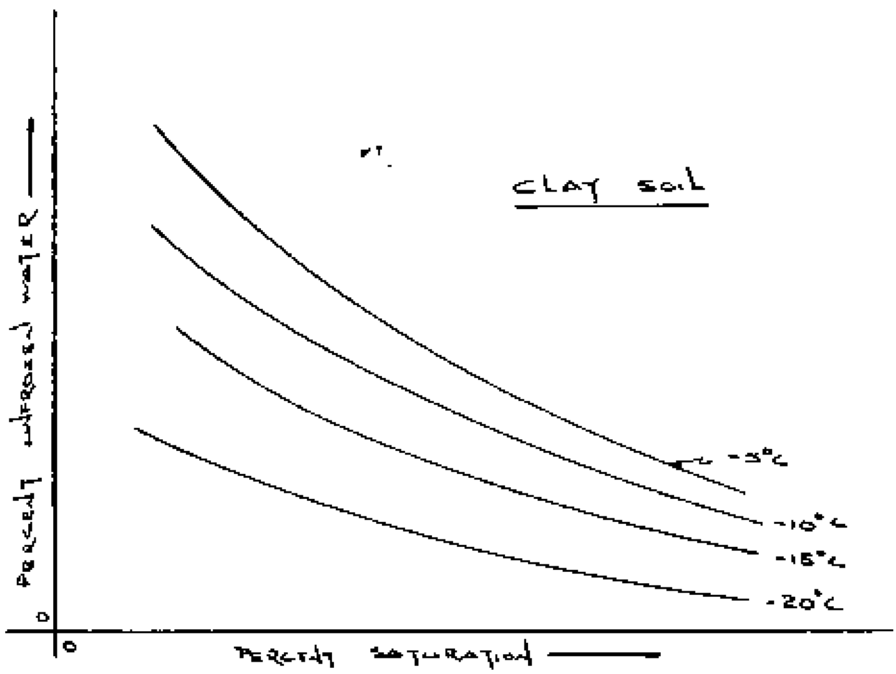


Figure 16 - Relation between percent unfrozen water and percent of original saturation.

is the difference between the freezing point of water and the freezing point of the structured water surrounding the soil particle).

The calorimetric method is a simple method that can be used to determine the ice content or unfrozen water content of partially frozen soils. If this method is to be used successfully, it is essential that radiation loss during calorimetric testing must be accounted for. This can be achieved by using the rating procedure. If

W_s = weight of soil particles,

W_w = weight of water in the soil sample prior to freezing,

C_w = specific heat of water,

C_i = specific heat of ice,

C_s = specific heat of soil particles,

L_w = latent heat of fusion,

T_i = initial specimen temperature,

ΔT_1 = temperature change of calorimeter and contents during test,

$\Delta T_2 = T_f - T_1$

T_f = final temperature (equilibrium temperature),

W_1 = weight of water in calorimeter,

W_2 = calorimeter equivalent,

$W = W_1 - W_2$

X = weight of unfrozen water,

$\Delta T_i = 0^\circ C. - T_1$

$\Delta T_3 = T_f - 0^\circ C.$,

then for thermodynamic equilibrium:

$$W_s C_s \Delta T_2 + [W_w - X] C_i \Delta T_i + [W_w - X] L_w$$

$$+ [W_w - X] C_w \Delta T_3 + X C_w \Delta T_2 = W C_w \Delta T_1 \quad \ldots\ldots \quad (22)$$

Solving for X the weight of unfrozen water:

$$X = \frac{W_w\left[C_i\Delta T_1 + L_w + C_w\Delta T_3\right] + W_s C_s\Delta T_2 - W C_w\Delta T_1}{C_i\Delta T_1 + L_w + C_w\Delta T_3 - C_w\Delta T_2} \quad \ldots\ldots \quad (23)$$

Determination of ΔT_1 from the rating method is shown in Figure 17.

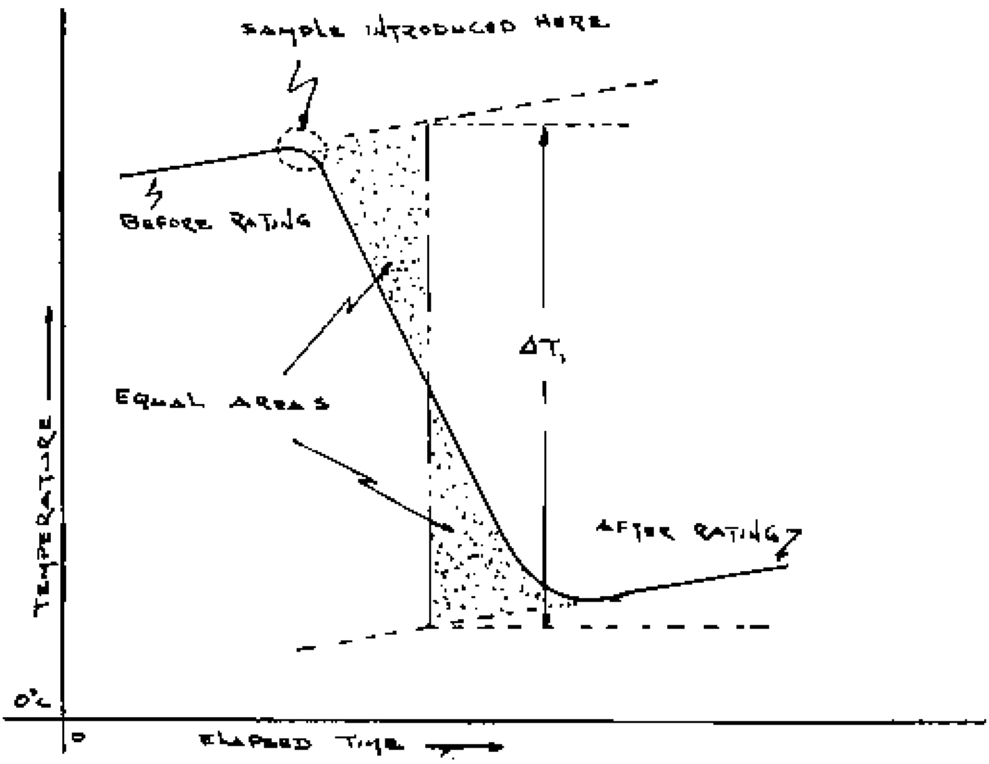


Figure 17 - Schematic picture of calorimeter correction during test.

It is essential that the freezing history of the soil to be tested is known since the ice content of the soil will vary depending on whether the sample is cooled or warmed to the temperature at which the ice content or unfrozen water content is to be evaluated. The reasons for the difference in values for either ice content or unfrozen content determined from varying cooling histories lie in the fact that particle orientation and arrangement may be changed during freezing and thawing - thus causing a change in the interaction of interparticle forces as shown in the previous chapters.

The difference in unfrozen water content at the same test temperature is shown quite markedly in Figure 18. The bands represent the variation in unfrozen water content at the same test temperature and initial water content. The upper limit of the band is the unfrozen water content measured as the soil freezes to the test temperature, and the lower limit of the band represents the unfrozen water content for the same soil frozen to a much lower temperature but warmed to the same test temperature. For the example shown in Figure 18, a medium clay was chosen and frozen to the desired test temperature and also to a temperature of 2°C. lower than the test temperature before warming to the test temperature. The degree of variation in unfrozen water content is much greater at higher temperatures.

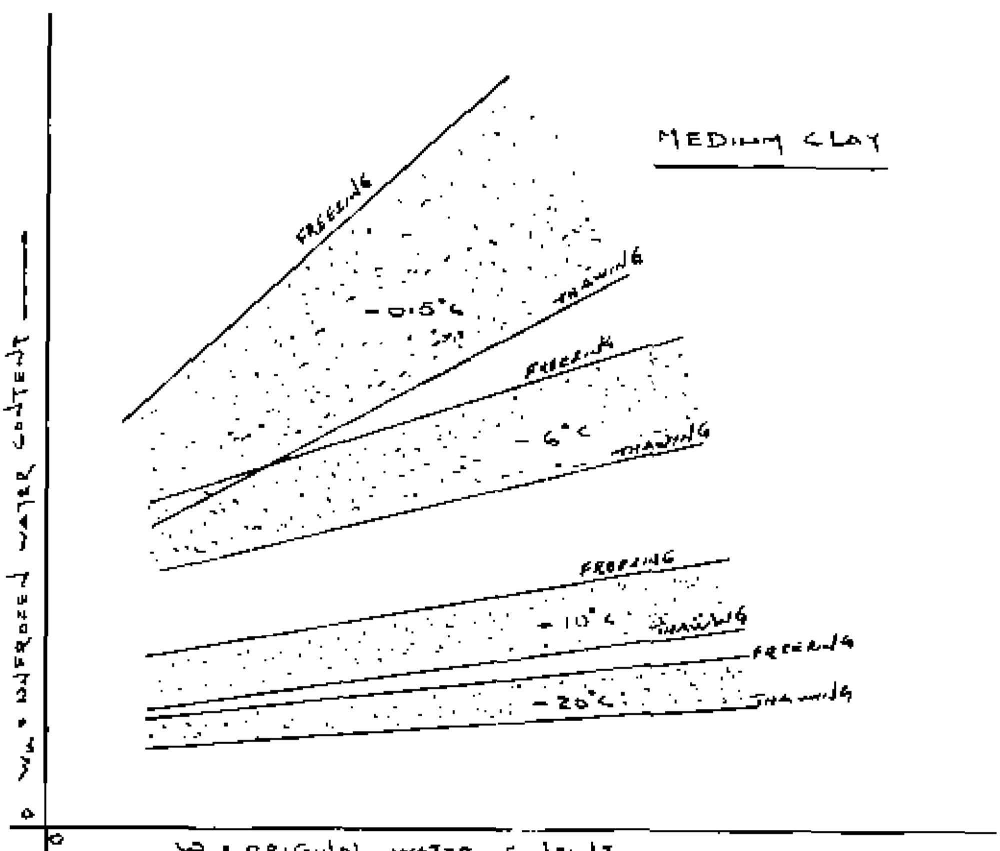


Figure 18 - Unfrozen water content variation with original water content and freezing history.

Frost Heaving

The effects of frost heaving are detrimental in two ways. (a) Heaving of the ground surface due to the formation of ice lenses in the subsoil, and (b) loss of bearing support in the subsoil when the ice lenses thaw and consequently leave pockets of water in their place. The basic conditions giving rise to formation of ice lenses necessary for frost heaving have been detailed previously.

The development of freezing pressures contributing to ground surface heaves may be treated thermodynamically for the more granular soils - considering the interface condition for ice and solid particles. This does not necessarily give the actual heave pressure at the ground surface, but does for the first approximation give an indication of the pressures that may be necessary to counteract heaving due to subsoil freezing.

The free energy for the phases on either side of the interface can be written in terms of Gibb's thermodynamic potential. Assuming that a film of supercooled water separates the ice phase from the mineral particles, then:

$$F = u + pv - Ts \qquad \ldots\ldots \qquad (24)$$

where F = Gibb's free energy,

u = internal energy

p = pressure

v = specific volume

T = temperature

s = specific entropy.

The two variables involved are p and T.

Since $du = -pdv + Tds$

Therefore:

$$dF = vdp - sdT \qquad \ldots\ldots \quad (25)$$

Using subscripts i and w to denote the ice and water phases respectively,

$$dF_i = v_i dp_i - s_i dT_i \qquad \ldots\ldots \quad (26)$$

and

$$dF_w = v_w dp_w - s_w dT_w \qquad \ldots\ldots \quad (27)$$

Following a change, the conditions for equilibrium are that:

$$dF_i = dF_w$$

Therefore:

$$v_i dp_i - s_i dT_i = v_w dp_w - s_w dT_w \qquad \ldots\ldots \quad (27)$$

But since $dT_i = dT_w =$ temperature depression,

therefore:

$$\frac{v_w dp_w - v_i dp_i}{dT} = (s_w - s_i) = \frac{L}{T}$$

where L = latent heat of fusion.

Hence:

$$v_w dp_w - v_i dp_i = L\frac{dT}{T} \qquad \ldots\ldots \quad (28)$$

Assuming that

$$dp_w = dp_i = dp$$

then

$$(v_w - v_i)\,dp = L\frac{dT}{T}$$

Therefore: $$(v_w - v_i)\,\Delta p = L \ln \frac{T_2}{T_1} \qquad \ldots\ldots \quad (29)$$

Hence $$\Delta p = \frac{L}{v_w - v_i} \ln \frac{T_2}{T_1} \qquad \ldots\ldots \quad (30)$$

Equation (30) gives the pressure increase at the interface due to a temperature depression in the pore water. Assuming that $v_w = 1.00$ cc/gm. and $v_i = 1.09$ cc/gm. and using $L = 79.8 \times 4.184 \times 10.7$ ergs/gm. and $T_1 = 273°K$.

relationship between Δp and T_2 may be drawn - (Figure 19).

Figure 19 - Temperature and equilibrium pressure.

The pressure predicted and shown in the graph in Figure 19, is the pressure existing at equilibrium conditions. Considered on a small differential element, this would be the pressure needed to maintain equilibrium for the depressed temperature. If the process is reversible, then at any depressed temperature, if no volume increase is allowed and if specific entropy remains constant, the equilibrium pressure would be the pressure resulting from the temperature depression after equilibrium has been re-established. This reasoning is valid for a small differential element under consideration. If however the entire soil-water system is considered from the integration of these differential elements, the process may not be reversible. The equilibrium may not be the resultant freezing pressure. There are too many uncertainties or variables in the ice phase which would rule out the possibility of reversibility.

The model assumed for reversibility in the system considered would have to depend upon:

(a) Homogeneous, isotropic, uniform and elastic conditions in the ice and mineral phases,

(b) no air voids or air spaces,

(c) no energy losses or volume change, and

(d) constant specific entropy.

The pressures measured at any freezing temperature with the above model would be the actual freezing pressures. However, any of the stated shortcomings or limitations existing in a soil mass and necessarily required by the model woul affect actual freezing pressures. For this reason, freezing pressures measured either as a result of restraint of ground heave, or internally in the subsoil, would not correspond to the theoretical pressures predicted from equation (30). However, the model studied here does serve to demonstrate:

1. The maximum possible heaving pressures - under very ideal conditions and restricted limitations, and
2. the very high counteracting pressures needed to prevent ground heave - even if ideal conditions are not met.

Experimental results have shown that pressures as high as 20 p.s.i. were needed to restrict heaving at temperatures just below freezing - (-5°C.). In actual practice, surface structures in general do not provide sufficient overburden pressure to restrain ground heave due to subsoil freezing or to formation of ice lenses. The most common victim of detrimental frost heaving is highways. In this case, very little if any extra overburden pressure is present, and because of the protective covering of the highway, there is in general a greater amount of stored moisture. The general profile for a highway founded on frost susceptible soil in winter is one with excessive bumps and cracks, and in spring, potholes and sinks.

It is evident that to prevent detrimental frost heaving from occurring, it is necessary to eliminate or restrict the conditions giving rise to frost heave. Since there is nothing that can be done with the temperature, corrective action will be restricted to the subsoil. The following methods describe procedures that counteract the conditions favoring frost heaving.

1. Replacement of frost susceptible soil - This is the most obvious method. Following the criterion established by Casagrande, frost action would be reduced if the subsoil gradation is adjusted such that the percentage of fines in the subsoil would not fall within the limits established for frost susceptibility. Although the gradation limits defined are not rigidly set, they act as a guide for comparison of frost susceptibility, - i.e. if a well graded soil has 2% of its fine particles less than 0.02mm. in size, this does not necessarily mean that it is not frost susceptible. It is possible that the soil with 2% of its fines less than 0.02mm. in size may be frost susceptible, but the chances of the same soil with 3% of it's fines less than 0.02mm. in size being more frost susceptible are very good.

   To correct this, it is best to replace the frost susceptible soil with granular material. In this way, freezing of the soil will be restricted to the similar situation of freezing of coarse-grained soils - without development of ice lenses.

2. Lowering the freezing point of the pore water - With the addition of salts, it may be possible to lower the freezing point of the pore water such that freezing in the subsoil will be minimized. However, with the passage of time, it will be necessary to recharge the pore water since drainage and groundwater flow during the summer months may carry away the dissolved salts in the pore water.

3. Restricting the water supply - In effect this means creating a closed system. The water supply can be eliminated or reduced by installing a cut-off blanket in the subsoil. This cut-off blanket may be an impervious clay layer, a bituminous membrane or even a concrete membrane. The idea involved here is to limit the supply of water so that ice lenses may not develop. This method may be feasible, but may not be too economical.

4. Additives - The use of additives to change the properties of the subsoil may take the form of either:

   a. Dispersants, or

   b. aggregants.

Either of these will change the soil properties to make the subsoil more or less permeable - together with further preparatory compaction. If water is fed too fast or too slowly to the bud of crystallization, the bud will either melt or be restricted in size since water supply is one of the prime factors contributing to the growth of the ice lenses. The use of additives to change the permeability characteristics tries to alter the ideal heat balance condition, which in turn either destroys the bud or inhibits its growth. Laboratory tests on the subsoil must be conducted to establish whether dispersants or aggregants can be used feasibly for this purpose.

5. Increase the surcharge pressure - This method relies on the imposition of a higher surcharge pressure which serves to counteract the heaving pressure, and more important, raise the frost line possibly away from the influence of the ready supply of water. Since it is essential that the water supply must come under the influence of the thermal regime - in the nature of the frost front, then removing the influence of the

thermal regime on the water supply would prevent water from being drawn to the growing bud of crystallization. Experience has shown that if the water table is more than six feet below the ground surface, the growth of ice lenses is made difficult. Hence adding a surcharge load not only creates an additional surcharge pressure which will lower the critical temperature of the pore water, it also serves to lower the effective ground water table.

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