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FROST-HEAVING PRESSURES

by

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PREFACE

The work reported in this paper was carried out by Dr. Hoekstra, Sp 5 E. Chamberlain, C. E. and Pvt. A. Frate, C. E., Research Division, James A. Bender, Chief, U. S. Army Cold Regions Research and Engineering Laboratory (USA CRREL).

The authors express their gratitude to Messrs. Linell and Kaplar for their combined interest and helpful discussion during the course of our experiment. Mr. Kaplar kindly made available data on some soils used in these experiments.

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SUMMARY

Upon freezing a saturated soil in an open system from the top down a considerable pressure develops. The pressure is the result of the surface energy of a curved ice-water interface. The curvature of the interface is necessary for ice to proliferate through the soil pores. The curvature is related to the pore size distribution of the soil.

The test chamber is designed to minimize the friction of the soil with the wall. An accurate control of heat removal is obtained by thermoelectric cooling. A load cell placed on top of the sample is used to measure the pressure developed and at the same time prevents heaving of the sample.

By measuring the pressure on a layered sample it can be shown that the pressure develops at the freezing front.

The results on several soils indicate that the maximum pressure that develops has a characteristic value for each soil. For each soil used the water content versus tension curve is given and the maximum pressure is related to this curve.
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Introduction

The establishment of reliable and readily workable frost-susceptibility criteria has long been under study. Many researchers have proposed criteria which have been useful in many cases. Yet it is apparent that the presently available criteria are nothing more than rules of thumb. All are based on grain size characteristics.

To establish a reliable criterion, i.e., one by which it can be stated that a soil is definitely frost susceptible or is definitely not frost susceptible, boundary conditions based on all the significant soil parameters must be established. The most significant of these parameters will have the greatest effect on the classification.

The hypothesis set forth in this report is that pore size governs the behavior of soils upon freezing, i.e., pressure that develops upon freezing a soil unidirectionally is a phenomenon that is governed by pore size. Experiments were conducted to relate pore size to heaving pressure. It was found that heaving pressure is a property that can be easily measured and is characteristic for each soil.

In order to establish frost-susceptibility criteria based on heaving pressure more soils have to be tested. However, a firm fundamental basis for routine testing by those concerned with frost heaving has been laid.

Review of the literature

Many investigators have been concerned with the pressure a soil develops as it freezes. Usually the problem is approached by placing a known surcharge on a soil sample and subsequently measuring the rate of heave associated with each surcharge. Actual measurements of the pressure required to prevent heaving have not been made. Taber (1918) placed weights on the surface of saturated soils and by freezing unidirectionally from the top down noted that the weights would continue to be lifted as long as water was available for ice growth and the temperature remained low enough to cause freezing. In a similar experiment Beskow (1935) found that the curves for rate of heaving versus pressure were hyperbolic, the rate of heave decreasing with increasing pressure. He also observed that the finer-grained soils were less affected by surface pressure, and that tension in the water has a similar effect on the rate of heave as does pressure.

Linell and Kaplar (1958) conducted experiments similar to Beskow’s and Taber’s. They did not measure the pressure required to prevent heaving, but again determined the relationship between the rate of heave and surcharge, and also observed that the finer-grained soils were less affected by pressure. Penner (1958) also noted that frost heaving could be reduced by applying a surcharge. Experimentally he determined the relationship between tension in the water, surcharge, and dry density when heaving stops. A specific tension in the pore water was found to be more effective in preventing heaving than its equivalent overburden pressure.

Taber (1929, 1930) in later experiments measured both the amount of heave and the heaving pressure. He found a maximum pressure of 105 psi upon freezing a clay. To overcome the frictional forces encountered, he estimated that an additional pressure of 215 psi was needed. More significant, however, was his observation that the pressure does not only develop in an ice-water system, but
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is common to all growing crystals. Balduzzi (1959) measured heaving pressure and pore water pressure simultaneously. He found that a force of 140 psi was required to prevent frost heaving and that any tension in the pore water reduced the heaving pressure. Kinoshita and Ono (1962) conducted field tests where they observed a maximum heave force of 415 psi for a heavy clay. They noted that the heave force decreases when heave stops, and inferred that this decrease was due to a relaxation phenomenon. Their experiment differs from the previous laboratory experiments discussed in that a center area was restrained from heaving, while the perimeter heaved freely. Friction forces along the loaded area added to the heaving pressure.

Townsend and Csathy (1963), in evaluating frost-susceptibility criteria, discussed the importance of the pore size characteristics of soil. They found that heaving pressure increases with decreasing pore size and that the pore size characteristics are related to soil parameters such as permeability and capillarity.

Linell and Kaplar (1958) observed that rate of heave in a given soil was related to the size and shape of the voids, but did not attempt to establish any relationship.

The thermodynamics of ice entry into pores has been discussed in several papers. Miller et al. (1960) measured the change in temperature with pressure at an ice-water interface in a silt bed. They state that the results could be predicted from equilibrium thermodynamics if the curvature of the interface (r) is taken into account. Everett (1961) drew a direct analogy between capillary water and capillary ice, and called the term, \( \Delta p \) in eq 1

\[
\Delta p = \frac{2 \sigma}{r} \tag{1}
\]

the heaving pressure. In the case of ice entry, \( \sigma \) is then the surface tension between ice and water. In comparing eq 1 with some rough field data, he claimed the agreement to be of the right order of magnitude. The presence of a large pore size distribution is naturally a drawback in making a rigorous comparison. Penner (1959, 1963) concluded from his extensive research on the mechanism of frost heaving that the pore size of the soil determines such quantities as heaving pressure and suction.

Although pore size was known to be a governing parameter (see also Chalmers, 1963), no systematic study relating pore size and heaving pressure has so far been reported.

The surface energy concept

The pressure developed upon freezing a saturated soil in an open system is due to the surface energy between ice and water. In equilibrium thermodynamics it can be shown that the chemical potential of a substance is changed by the curvature of the interface. The relation between the chemical potential of a flat interface, \( u_p \), and that of a curved interface, \( u_c \), is given by:

\[
u_c - u_p = \frac{2v_1 \sigma}{r} \tag{2}
\]

where:

\( \sigma \) = surface tension

\( v_1 \) = partial molal volume

\( r \) = effective radius of the interface.

Although this concept can be readily applied to liquid-vapor systems, it has been questioned if these principles also apply to solid-liquid interfaces. In a liquid, shear stresses are relieved by viscous flow, and there is no strain energy in the
interior from changes in shape brought about by surface tension. As a result, surface tension and surface energy are equal. This is not generally true in solids. It is only true when surface configurations are changed without introducing interior strain energy; this is for example the case when surface configurations are changed by solution, vaporization and grain growth. This last process occurs in soils (Herring, 1952; Kingery, 1960).

Since there is a temperature gradient maintained in our system, it is also necessary to consider whether or not the usual thermodynamic variables and properties are still valid. When a steady state is obtained, the properties of the system do not change with time, but there can be an irreversible flow of heat, matter, or electricity through the system. The theory of irreversible thermodynamics postulates that for a non-equilibrium steady-state process the equilibrium thermodynamics applies. Equation 1 would be valid only when a steady state is reached. A steady state in the system described later is approached when frost penetration has stopped, i.e., when the heat conducted to the freezing front equals the heat conducted away from the freezing front. The rate of frost penetration should be a criterion of how far the system is from a steady state. At a steady-state condition, when the temperature does not change with time, the chemical potential is a function of pressure only. Agreement with eq 1 has been presented by several authors (Everett, 1961; Miller, 1965; Penner, 1958) in the form

$$p = \frac{2 \sigma}{r}.$$  \hspace{1cm} (3)

Although $p$ should truly present a hydrostatic pressure, the one-dimensional heaving pressure has been substituted for $p$. Thus far there is no justification for this other than that it is far more convenient to use the heaving pressure than to consider the anisotropy in the pressure distribution.

**Determination of pore size distribution in soils**

There are in general two objectives for measuring soil water. One is to determine how much water is contained in the soil per unit weight or per unit volume. This is called the water content of the soil and is related to many important engineering properties of the soil. The second is to determine the magnitude of the work that must be done to remove a unit amount of the most loosely held water. This is called soil water tension, and is the tension that would develop in a column of water to prevent water transfer into or out of the soil. The establishment of relationships between tension of soil water and engineering properties is just beginning; e.g., recent papers by Yong (1963), Williams (1960), and Croney (1952); Croney et al. (1952) relate properties of soil to this tension. The tension of soil water also indicates in which direction water is going to move. For example, consider a layer of sand and clay of the same water content by weight. If the sand and the clay are brought in contact the water will move from the sand into the clay, since the tension of the water in the clay is higher.

Relationships between water content and tension can also be used to help define the structure in terms of the size of the pores which make up its pore space. Apparatus for measuring the tension in soils utilizes porous ceramic plates or porous membranes that allow water to pass, but, when moist, prevent air passage. The water content of a soil on a porous plate or membrane will attain a steady value if a constant pressure reduction is maintained across the porous plate. The water under the plate is at atmospheric pressure, a constant air pressure being maintained in the chamber above by compressed air. It is important that no air pass through the membrane and that the membrane remains moist. Otherwise the sample will not reach an equilibrium and will air dry. The usual capillarity equation can be written in the form
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\[ r = \frac{2 \sigma}{p} \]  (4)

Here \( r \) is the upper limiting effective radius of pores which can remain full of water when a tension is applied to the water in the soil, \( \sigma \) being the surface tension. The volume of water withdrawn when the tension is increased in an incompressible soil represents the volume occupied by pores of that particular size range, assuming the pores to be of circular cross section. The effective pore size range is given by:

\[ \frac{2 \sigma}{p} > r > \frac{2 \sigma}{p + \Delta p} \]  (5)

The effective pore size of a porous material can, therefore, be determined directly from the water content - tension relationship (Fig. 1). The size distribution of the pores in a soil provides a schematic model of its structure which can be used in studying water and air movement.

There is one difficulty in using a water content - tension curve. The curve exhibits hysteresis and differs whether the process involved is wetting or drying. The question then arises of which side of the hysteresis to select for measuring size distribution of pores. The entry of ice in the pores is a desaturation process; water is replaced by ice instead of by air. Therefore, to develop a relationship between heaving pressure and pore size, the desaturation side of the hysteresis is preferred.

Experimental method and apparatus

The apparatus as shown in Figure 2 is a stainless steel cylinder, 4 in. in diameter and 4 1/2 in. in depth, tapered* and coated on the inside with Teflon. To the bottom is attached a stainless steel base plate housing a porous stone, the plate being sealed to the mold by an "O" ring. A Peltier battery† is attached to the cold plate at the top of the mold. The cold plate is sealed against the mold by a "U" cup. Above and taking the thrust of the cold plate is a Baldwin load cell which in turn bears against the reaction frame.

By tapering and coating the inside of the cylinder, frictional forces are minimized. The "U" cup also minimizes heat transfer between the cold plate and the cylinder. It is possible to measure the flow of moisture to and from the cylinder.

A thermoelectric element having a cooling capacity of 54 Btu/hr was used to insure unidirectional freezing and to obtain proper control of frost penetration. By adjusting the current supply and the cooling fluid for the hot chamber, the desired

* Tapered design adopted from cylinders used by C. W. Kaplar
† Peltier battery type PT47/5, Ferroxcube Corporation of America.
rate of penetration could be obtained. A low-voltage d-c power supply was used to provide the power requirements of the thermoelectric element.

The pressure obtained upon freezing a sample was measured by means of a Baldwin SR-4 load cell. Several load cells of different capacities were used to fit the requirements of the soils tested. Power was supplied to the load cell by a low-voltage d-c power supply, the output being recorded on a Leeds and Northrup millivolt recorder. The output was also measured and the recorder calibrated by means of a Keithley differential voltmeter.

The frost penetration was measured by thermistors placed at 1-in. intervals of depth and recorded on the Leeds and Northrup millivolt recorder using the method described in the Technical Note by Hoekstra and Anderson (1964).

Samples were compacted and saturated in the sample mold. Compaction was accomplished using a Proctor compaction hammer weighing 5 lb and having a 12-in. drop; 25 blows were applied to each of three layers. The sample was then de-aired under vacuum and saturated with de-aired distilled water.

The tests were conducted in a cold room with an ambient temperature ranging from 40 to 42°F. The rate of penetration was maintained at approximately 2 in./day for normal runs. When testing for the effect of rate of penetration on the heave pressure, the rate was increased to as much as 20 in./day. Water was supplied to the sample at a constant head, at a pressure equal to the height of the sample. While freezing, water was free to move into or out of the test sample. The normal test duration was 24 hr. Upon completion of a test the sample was thawed and sampled for determination of its soil moisture characteristics.

Permeability tests were run on similarly prepared samples.

Results and discussion

On several soils the heaving pressure, the moisture content versus tension curves, and the saturated permeabilities were measured in the laboratory.

The first experiments were designed to test the surface energy concept of ice entry into soil pores.

In the first place, if the pressure that develops upon freezing a soil is the pressure required for ice to proliferate through the pores, then this pressure should originate at the freezing front. To verify this, a layered sample of silt
and sand was frozen in the test chamber. When the frost line penetrated from the sand into the silt layer, there was a marked change in the rate of increase in pressure (Fig. 3). This can be explained as follows. The sand has larger pores than the silt. Hence, when the frost line moves from the sand to the silt a larger pressure is required for ice entry. The reverse is also true, e.g., when the frost line moves from the silt to the sand a smaller pressure is required for ice proliferation. This demonstrates that the observed pressure originates at the freezing front which is consistent with the concept that the pressure is associated with the ice-water interface.

Secondly, the surface energy concept is based solely on the pore geometry of the soil. Thus, it should be valid for any solid-liquid interface used in the soil matrix. When a soil was saturated with benzene and then cooled in the test chamber, the benzene solidified and a solid-liquid benzene interface, completely analogous to an ice-water interface, was formed in the soil. The pressure that developed was the result of the surface energy between liquid and solid benzene. Figure 4 illustrates the results of two tests on Richfield silt, one saturated with benzene, the other with water. The curves are similar in shape, but the pressure developed for the benzene system is less, the surface energy for solid-liquid benzene being also less.

The benzene test demonstrates another important point. Since unfrozen water in soil has been shown to freeze gradually as the temperature is lowered, it might be that the expansion upon freezing of unfrozen water is the primary source of the pressure. The experiment with benzene refutes this idea, since benzene contracts upon freezing. However, the freezing of trapped, unfrozen water upon further cooling adds to the pressure produced at the interface.

This is illustrated in Figure 5. A sample of Fairbanks Silt was prepared in the normal manner and frozen from the top down under restraint. It was then allowed to come to an equilibrium temperature of approximately -1.0°C. It was further cooled from the top down and the pressure was measured. The pressure resulting from further cooling was about 10%.

The pressures, in general, were reproducible. The variation from the mean value for the pressure after 24 hr was within 8% for all tests with one exception. The increase in pressure with time can be described by the relation

\[ y = A \left[ 1 - \exp(-a \sqrt{t}) \right]. \tag{6} \]

where

- \( y \) = pressure at any time \( t \)
- \( A \) and \( a \) = constants
- \( t \) = time.

This relation can be written in the form

\[ \ln(A - y) = \ln A - a \sqrt{t}. \tag{7} \]
When \( t \to \infty \), \( \exp \sqrt{t} \to 0 \), and the pressure, \( y \), approaches the maximum pressure \( A \). The maximum pressure, \( A_{\text{est}} \), can be estimated from Figure 6. The estimated value, \( A_{\text{est}} \), can be put into eq 7 in the form

\[
\ln \left( A_{\text{est}} - y \right) = \ln A - a \sqrt{t}.
\]  

(8)

This relation is plotted for several soils in Figure 7. This figure shows that eq 8 adequately describes the increase in pressure with time. From the intercept at time zero, \( \ln A \) is obtained. If \( A \) differs from \( A_{\text{est}} \), \( A \) and \( A_{\text{est}} \) can be made to coincide by successive approximations. It was found, however, that near agreement was obtained on the first approximation. The pressure increases at a decreasing rate for a considerable length of time. To verify the existence of a maximum pressure, an initial load, higher than the maximum load obtained from extrapolation, was applied to a soil sample. Figure 8 shows that Augrey Sand never exceeded the initial load of 20 psi; the maximum extrapolated load was 18 psi. This experiment justifies extrapolation to a maximum load.

The pressures measured for a 24-hr period and the extrapolated values are given in Table I. As can be seen, each soil has a characteristic value. The rate of pressure development curves (Fig. 6) show characteristic slopes for each soil type.

The method employing the pressure plate and the pressure membrane (Richards, 1949) was used to determine moisture retention. Much difficulty was encountered in obtaining dependable results, and the data show considerable
Figure 6. Pressure vs time for soils tested.

Figure 7. Pressure vs time for soils tested.

Figure 8. Pressure vs time for normal and pre-loaded tests.

Figure 9. Tension vs per cent saturation for soils tested.
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Table 1

<table>
<thead>
<tr>
<th>Soil</th>
<th>24-hr pressure (psi)</th>
<th>Maximum pressure (extrapolated) (psi)</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Lebanon Clay</td>
<td>132</td>
<td>146</td>
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<tr>
<td>Richfield Silt</td>
<td>65</td>
<td>61</td>
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<tr>
<td>New Hampshire Silt</td>
<td>28</td>
<td>27</td>
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<tr>
<td>Augrey Sand</td>
<td>13</td>
<td>15</td>
</tr>
<tr>
<td>Hutchinson's Pit Gravel</td>
<td>12</td>
<td>14</td>
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scattering. Tests of this nature require practice and experience. A method was developed which proved to be more reliable. The samples were contained in a metal ring by filter paper and reweighed after every pressure increase. Thus the same sample was carried throughout the test. A limitation of this method was that the wet filter paper added additional weight to the sample. The percent saturation versus tension curves are given in Figure 9.

An empirical criterion has to be established in order to correlate the pressure developed with the water content versus tension curve of the soil. The following reasoning was used. The maximum pressure will be developed in order for the ice interface to proliferate through the smallest pores. However, it is clear that this cannot be the only criterion; the number of small pores present is another. If there were only a few pores of a small size present, the freezing front could bypass them. The amount of water held in pores of a particular size range is given by the slope of the curves in Figure 9. The tension at the point where the slope of the line decreases rapidly, as indicated in Figure 9, is plotted versus the pressure developed (Fig. 10).

Many investigators have presented criteria for determining the frost susceptibility of soils. These criteria relate a percent by weight finer than a given fraction to degree of frost susceptibility.

A close look at the frost heaving process reveals that pore size distribution could be a more fundamental criterion. Water must flow through the soil in order for ice lenses to form and heaving to take place. This process is limited by the permeability, which is determined by pore size and can be calculated (Marshall, 1958) from the pore size distribution.

It was shown that the pressure developed upon freezing a soil is apparently determined by pore size. That grain size can be partly successful in predicting frost susceptibility is due to the fact that grain size and pore size are related. However, this relationship is obscured by factors such as gradation and particle shape. This is illustrated by the grain size characteristics of

![Figure 10. Pressure vs tension for soils tested.](image-url)
Richfield Silt and Augrey Sand (Fig. 11). The Unified Soil Classification System (Linell and Kaplar, 1958) classifies both soils as S. M. (silty sands). However, Richfield Silt is well graded and, therefore, has smaller pores than Augrey Sand which is poorly graded. As a result, there is a large difference in heaving pressure.

The measurement of heaving pressures upon freezing a soil was shown to be an overall indication of pore size. Moreover, these measurements are simpler than the determination of the moisture retention curves. That this pressure is related to important soil parameters is illustrated in Figures 10 and 12.

Figure 11. Grain size chart.

Figure 12. Pressure vs permeability.
The pressure varies from approximately 10 psi to 80 psi for frost susceptible soils so that a subclassification according to degree of frost susceptibility is possible using this system. The degree of frost susceptibility depends on permeability and the tension a soil can develop upon being frozen. More data should be collected to explore the possibility of establishing a classification system for frost susceptibility based on pore size.

GLOSSARY

1. Soil moisture tension or soil suction - the tension that would develop in a column of water in contact with soil at one end when sufficient suction was placed on the water to prevent its transfer into or out of the soil. (Taylor, 1961)

2. Frost susceptibility - that property of a soil that allows detrimental ice segregation to occur under optimum conditions of temperature and water supply. (H. R. B., 1955)

3. Heaving pressure - the pressure a soil develops upon unidirectional freezing when it is restrained to heave.

LITERATURE CITED


Beskow, Gunnar (1935) Soil freezing and frost heaving with special application to roads and railroads, Swedish Road Institute, Stockholm. Translated by J. O. Osterberg, Published by the Technological Institute, Northwestern University, 1947, 145 p.


Croney, D. (1949) Some cases of frost damage to roads, Road Research Laboratory, Department of Scientific and Industrial Research (London), Road Note no. 8.


and Bridge, Pamela M. (1952) The suction of moisture held in soil and other porous materials, Road Research Laboratory (London), Technical Paper no. 24, 42 p.


LITERATURE CITED (Cont'd)


Penner, Edward (1958) Pressures developed in a porous granular system as a result of ice segregation, Highway Research Board Special Report 40, p. 191-199.


Taber, Stephen (1918) Ice forming in clay soils will lift surface weights, Engineering News Record, vol. 80, p. 262-263.


--- (1930) Freezing and thawing of soils as factors in the destruction of road pavements, Public Roads, vol. 11, no. 6, p. 113-132.


Williams, P. J. (1964) Unfrozen water content of frozen soils and soil moisture suction, Geotechnique, vol. 5, p. 231.

Upon freezing a saturated soil in an open system from the top down, a considerable pressure develops. The pressure is the result of the surface energy of a curved ice-water interface. The curvature of the interface is necessary for ice to proliferate through the soil pores. The curvature is related to the pore size distribution of the soil. The test chamber is designed to minimize the friction of the soil with the wall. An accurate control of heat removal is obtained by thermoelectric cooling. A load cell placed on top of the sample is used to measure the pressure developed and at the same time prevents heaving of the sample. By measuring the pressure on a layered sample, it can be shown that the pressure develops at the freezing front. The results on several soils indicate that the maximum pressure that develops has a characteristic value for each soil. For each soil used, the water content versus tension curve is given and the maximum pressure is related to this curve.
### KEY WORDS

- Soil freezing
- Frost heaving models
- Heaving pressure
- Frost-susceptibility criteria
- Pore size
- Surface energy concept

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