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HEAVING PRESSURE IN SOILS DURING UNIDIRECTIONAL FREEZING

E. PENNER *Soil Mechanics Section, Division of Building Research, National Research Council, Ottawa*

Ice lenses in natural soil are normally formed in a thermal gradient regime, and this permits the development of an undulating frost line if a range of pore sizes exists. Evidence is presented that suggests that the undulating nature of the ice-water interface permits the ice lens to form over the smaller pores of the system. Although fractions with only a limited particle size range have been studied, the results support the use of particle size as a valid basis for assessing frost susceptibility.

Les lentilles de glace dans les sols se développent ordinairement en présence d'un gradient thermique, ce qui produit la formation d'une ligne de gel de forme ondulante lorsqu'il existe une gamme de variations dans les grosseurs des pores. Cet article présente une certaine évidence tendant à suggérer que la nature ondulatoire de l'inter-face glace-eau rend possible la formation de lentilles de glace au-dessus des plus petits pores du système. Quoique la présente étude air porté sur une variation limitée de dimensions de particules, les résultats obtenus constituent un témoignage en faveur de l'emploi de la grosseur des particules comme base valable pour évaluer la gélivité des sols.

It is most important that potentially frost-susceptible soils can be easily and accurately indentified from readily determined properties or behaviour characteristics without laborious freezing tests. Where wet conditions normally prevail, silty soils are highly frost-susceptible and no special tests are required to establish this. On the other hand, soil materials consisting of sands and gravels are clearly not frost-susceptible. The difficulty arises in assessing "borderline" soils that may be coarse-grained but contain small amounts of contaminating fines.

The most common basis for establishing frost susceptibility for engineering purposes is the grain size distribution curve, in which assessment is made of the percentage of finer-than-silt-size particles and the over-all grading of the material. The present research concerns the behaviour of the ice-water interface of the ice lens in relation to the pore and particle dimensions of the soil.

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Its purpose is to evaluate the usefulness of grain size as a satisfactory basis for assessing potential frost susceptibility. Recent investigations (Everett 1961, Everett and Hanyes 1965, and Penner 1966) have led to a better understanding of heaving pressure—an important phenomenon in ice lens formation—in compacts of uniform spherical particles of known size. Naturally occurring soil materials usually consist of non-spherical particles of various sizes. The present work is concerned with this more complex system.

CONDITIONS OF ICE LENS GROWTH IN SOIL

Thermal conditions

The initiation of an ice lens occurs and its growth is sustained because the ice propagation phenomenon through a saturated porous material is temperature-dependent (Sill and Skapski 1956) as shown by the following equation:

$$T - T_m = \Delta T = \frac{-2T_m \sigma_{iw}}{Q_F \rho_i r_i}\,; \tag{1}$$

r_i = radius of curvature of the ice-water interface and of pore radius,

ρ_i = density of the ice,

Q_F = latent heat of fusion,

T_m = temperature of melting at zero curvature of the solid-liquid interface at standard pressure,

T = temperature at which freezing takes place with radius of curvature r_i in contact with water,

σ_{iw} = ice-water interfacial energy.

Pores in all natural soils, however, cover a considerable size range and the freezing front cannot advance uniformly even when one-dimensional heat flow is imposed on the system as a whole. On the cold side of the freezing front a part of the adsorbed water on the particles changes to ice. The film is then recharged from below. This will begin to occur slightly below the freezing point of free water provided that ice crystallization has occurred. The ice cannot propagate through the porous system at any local site until the conditions of equation (1) are satisfied.

Continuation of ice growth at the face of the lens can only be sustained in the presence of a temperature gradient. The heat flow away from the lens must exceed the heat supply to the lens in order to accommodate the latent heat released. It is important to understand that the formation and growth of the lens is in a thermal gradient regime and that it is of special significance when the porous material contains a range of pore sizes. It is suggested that the underside of the ice water interface boundary positions itself everywhere within the porous body in a condition of non-propagation when the maximum pressure by ice lens growth is attained. To the unaided observer it appears as a plane located normal to the direction of heat flow, but on a microscopic scale the underside of the face is envisaged as shown in Figure 1.

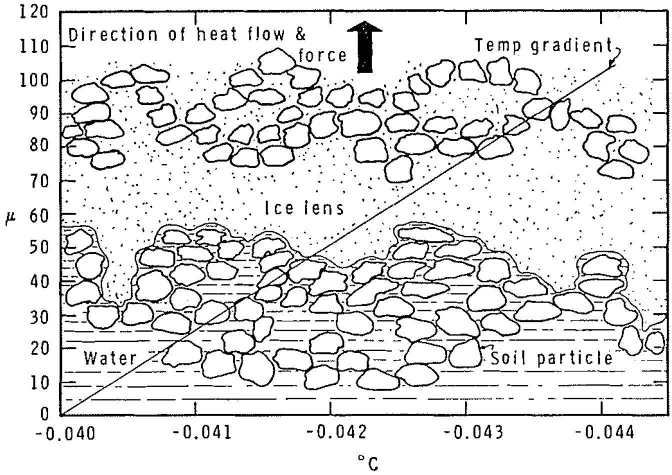

FIGURE 1. Schematic diagram of the ice-water interface at maximum pressure development

The exact position of the freezing plane in a porous material of complex internal geometry cannot be predicted easily. Even if it were possible, the temperature sensing devices for direct measurement are not small enough to sense the freezing plane temperature with reliable accuracy. Estimations of the freezing plane temperature are usually made from a knowledge of the thermal conductivity of the frozen and unfrozen portions, the over-all thermal gradient, and the thickness of the layers involved.

INDUCED SUCTION AND HEAVING PRESSURE IN SOIL

The maximum pressure produced by a growing ice lens depends on the internal pore geometry of the porous material. In the absence of overburden pressures a suction will be induced, if no additional water is permitted to enter the sample, again depending on the internal pore geometry (Penner 1957). When a load is imposed on the heaving system, the maximum suction that will be induced is less. The maximum heaving pressure for a given porous material is developed in an open system (Penner 1958, and Everett 1961), i.e., free excess of water permitted during ice lens development.

Attempts have been made to characterize the potential frost susceptibility of soil, based on the magnitude of the induced heaving pressure and experimentally determined moisture release curve (Hoekstra *et al.* 1965). With recently improved experimental techniques the heaving pressure predictions of Everett and Haynes (1965), based on particle size, have agreed with experimental values. According to Everett and Haynes, the maximum pressure produced by a continuous ice lens in a close-pack array of spheres of uniform size consists of two components: the first and most important is equivalent to the pressure drop across the curved ice-water interface just before it penetrates the pore, and the second is the flotation effect.

$$\Delta p = \frac{2\sigma_{iw}}{r_i} + \frac{2}{r}(\sigma_{is} - \sigma_{ws}); \tag{2}$$

r_i = pore radius,

r = particle radius,

σ_{iw} = ice-water interfacial energy,

σ_{is} = ice-solid interfacial energy,

σ_{ws} = water-solid interfacial energy.

Introducing the Young-Dupré equation

$$\sigma_{is} = \sigma_{ws} - \sigma_{iw} \cos\theta. \tag{3}$$

and defining

$$B' \text{ as } r/r_i \cos\theta, \tag{4}$$

then

$$\Delta p = \frac{2\sigma_{iw}\cos\theta(1 + B')}{r}. \tag{5}$$

Experimental agreement has greatly increased confidence in the approach suggested in the theory of ice lens growth. The use of equation (5) however, is restricted because it applies to a close-pack array of spherical particles of uniform size. For this particular case, B' is known and the effective area is about πr^2 for each sphere. The second component of pressure on equation (2) is small compared with the first. As no precise solution has yet been found for a porous media of complex internal geometry, the equation below is used for calculating the effective radius of the pores at the maximum pressure measured, omitting the flotation effect:

$$\Delta p = 2_{\sigma}{}_{iw}/r_i. \tag{6}$$

This equation is applicable to a continuous ice lens over small cylindrical openings, but no accurate area correction is possible such as that for small uniform-size glass heads in close pack geometry.

EXPERIMENTAL

Material

Commercially available potter's flint, which is actually angular fragments of flint, was separated into five particle-size fractions by continuous elutriation. Each fraction contained a fairly narrow range of particles sizes, as determined from photomicrographs of smears of the particles on glass slides. Fraction 1 had particle diameters ranging from about 60 microns to 100 microns; fraction 2, from 35 to 70 microns; fraction 3, from 30 to 60 microns; fraction 4, from 20 to 50 microns; and fraction 5, from 10 to 30 microns.

The experiment did not require complete uniformity of size. It was desirable, however, that the moisture release curves should have characteristic breaks in the curves relating to pore drainage so that the heaving pressure measurements could be related, at least, to distinctive portions of the curve. The fractions were essentially free from any contaminating fines and elutriation was continued until this had been achieved.

Apparatus and method

Compacts were prepared from water slurries of the various fractions after the particles had been cleaned with sulphuric acid-chromate solutions. Densification was carried out by jarring and tamping. Excess water was removed with blotting paper, and jarring was continued until maximum density had been obtained. The method was shown to give reproducible results. For the freezing experiments the samples were prepared by this method in the sample holder of freezing apparatus; for suction experiments the suction sample holder was used.

The apparatus used to measure heaving forces is shown in Figures 2 and 3. The upper cell is the cold side and is held in a fixed position. The lower cell (warm side) rests on a sensitive force transducer fixed to the lower plate. The upper and lower plates at the extremities of the cells are held together with four invar rods 1.27 cm in diameter. Fluctuations in room temperature (± 1 C deg.) that could cause dimensional changes in the apparatus were avoided by circulating temperature-controlled liquid through the hollow invar rods and end plates.

The sample holder containing the compact was placed between the two cells (Figure 2(b)) in the centre section so that it was in direct contact with the finned metal heat exchangers. Temperature-controlled glycol solutions circulating inside the two finned heat exchangers imposed the desired temperature gradient across the sample.

The sample holder had a small porous plate at the lower end for water transmission to the specimen and an external water level kept the specimen water-saturated during the growth of the ice lens. Temperatures that were monitored continuously at the ends of the specimen showed less than ± 0.005 C deg. fluctuation over periods of several days; during shorter periods, variations were considerably less. Temperature variations at the freezing front were imperceptible, as indicated by the constancy of heaving pressures at equilibrium.

The experimental procedure for freezing was as follows. The specimen holder containing the sample was inserted between the two cells and a thermal gradient established, with the lower side slightly above 0 °C and the upper side about -0.26 °C. Freezing was initiated by seeding the cold side with a frosted wire. After about a day, while the pressure was increasing, the freezing plane became stationary within the specimen. The temperature gradient, 0.376×10^{-4} C deg./micron, was kept the same for all trials. Upon stabilization, the pressures were reduced to zero by adjustment of the nuts holding the upper and lower cells in position. The procedure was repeated several times until the ice lenses were estimated to be about 2 mm thick. Maximum forces in the vertical

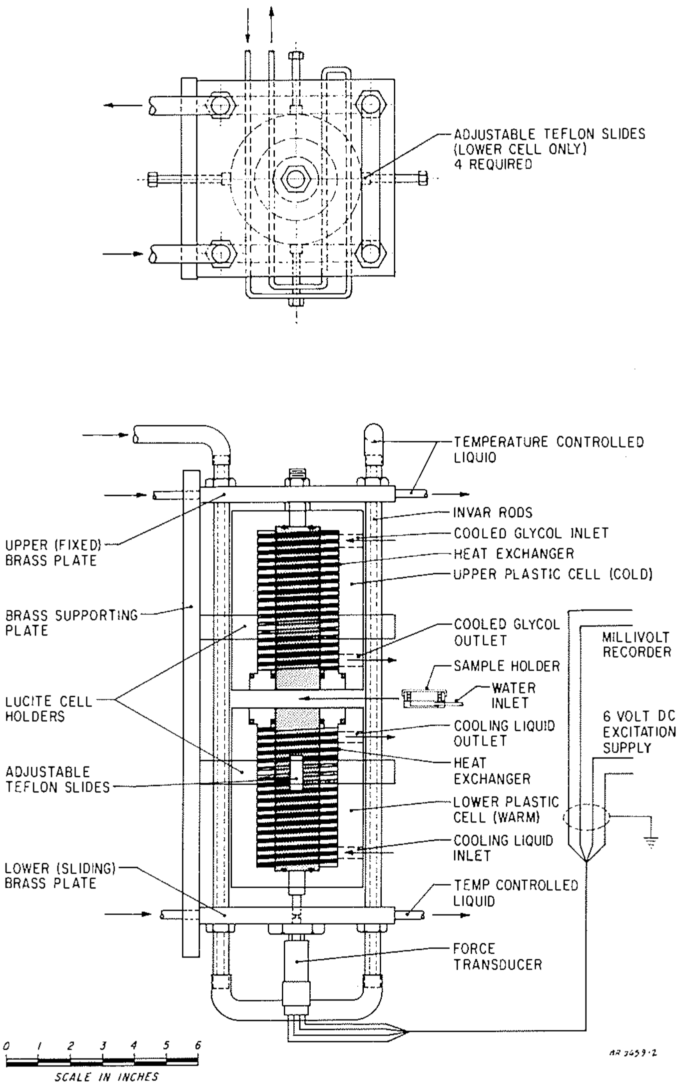

FIGURE 2. Heave pressure cell

direction were then allowed to develop and were monitored on a millivolt recorder from the output of the calibrated force transducer. During final pressure build-up the temperature at each end of the specimen was not permitted to vary so that the force measured would originate only at the ice-water interface below the ice lens and not as a result of expansion from additional freezing in the frozen layer behind the ice lens of the sample. Each run was repeated at least twice and averaged.

Water retention curves were determined with the well-known suction apparatus that uses a filter membrane instead of a porous plate. The change in moisture content was measured by volume in a calibrated capillary tube. At

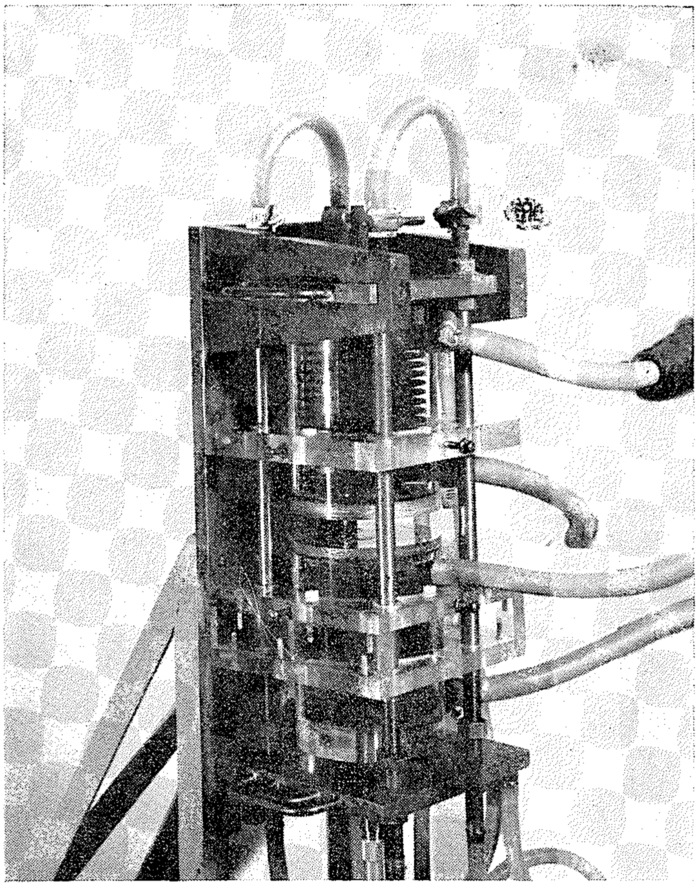

FIGURE 3. Heave pressure apparatus

higher pressures, when appreciable air diffused across the membrane, the volume of air was measured and subtracted from that of water. Air pressures were measured with a calibrated pressure transducer. In the freezing experiments, the particles were pre-treated with a sulphuric acid–chromate solution before each run and washed free of the cleaning solution with distilled water.

RESULTS AND DISCUSSION

Figure 4 shows the moisture release curves in terms of pore radius, using 72 ergs/cm$_2$ for the air-water interfacial energy. This value should be reasonably accurate for clean distilled water on freshly cleaned flint-particles. The vertical lines on each curve give the radius of pores effective in producing the heaving pressure measured, using a value of 35 for σ_{iw} (Penner 1966) in equation (6).

These results suggest that the larger pores are not involved in producing the maximum heaving pressures. The interpretation is that the ice at the ice-water interface near the final equilibrium position propagates through the larger pores, terminating when smaller pores are encountered. For the largest fraction,

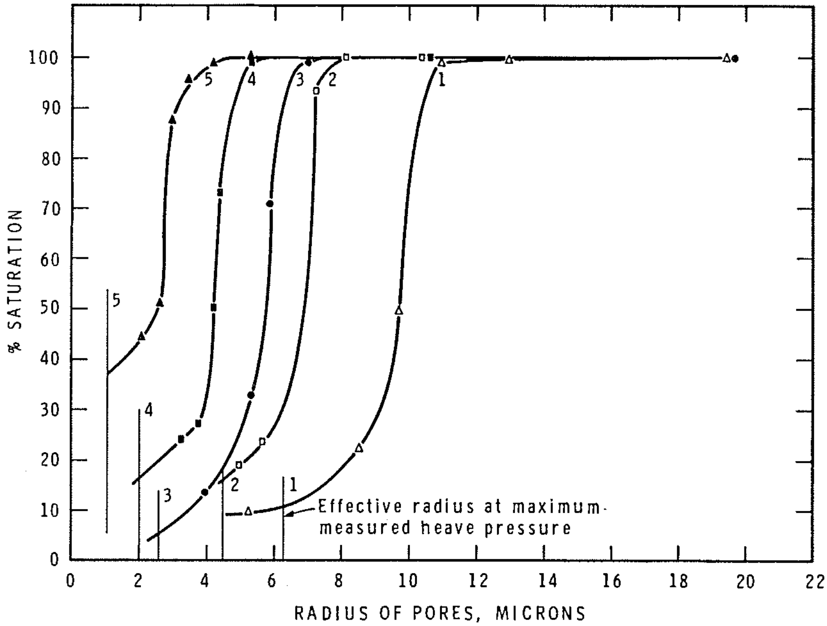

FIGURE 4. Pore radius–per cent saturation curves for fractionated potter's flint

which has some pores as large as 13 microns, the effective pore radius creating the maximum pressure was 6.3 microns. For the smallest fraction, the largest pores are shown to be about 5 microns, with the effective radius causing maximum heave of pressures of about 1 micron. The percentages of the total water at saturation occupying pores smaller than the effective heaving radius was 10 per cent for the largest fraction. For the No. 2 fraction it was 17.5 per cent, for No. 3, 5 per cent, for No. 4, 16 per cent, and for No. 5, 37.5 per cent.

When a large pore located near the equilibrium ice-water interface position is encountered, the ice advances through it until the smaller pores stop propagation. The lowest possible temperatures necessary for full pressure development may not be reached. This situation exists because the propagation of ice is toward the warm side.

The temperature gradient used in the experiments here described is shown in Figure 1. An example will illustrate the effect on the temperature variation along an undulating interface. Pores of 1 micron in size stop ice propagation at temperatures higher than −0.045 °C (equation (1)). If a pore 10 microns in size is encountered and ice propagates through it as a result of the macroscopic temperature gradient, the temperature at this position is 0.000376 C deg. higher. It may be seen from this that considerable undulation is possible without a large increase in temperature and a correspondingly lower pressure, because the temperature gradient is small compared with the pore and particle dimensions. This interpretation is probably somewhat oversimplified because the macroscopic thermal gradient in a porous material does not necessarily apply strictly to a microscopic scale because of the differences in thermal conductivity between solids particles and liquid filled pores. It is not possible to state how this influences the frost heaving experiments just described.

The major finding in these experiments is that the radius of the pores calculated from the measured heaving pressures corresponds not to the size of the pores on the moisture release curves where most of the water is held but to the smaller pore sizes below this. Table I shows the variation in particle size and

TABLE I

Comparison of predicted and measured radius of pores in compacts of fragmental particles

Sample no.	(1) Approx. range of particle diameter (micron)	(2) Average particle radius (micron)	(3) Average pore radius*	(4) Average pore radius†
1	60–100	40	7·14	6·3
2	35– 70	26	4·64	4·49
3	30– 60	22	3·92	2·56
4	20– 50	17	3·03	1·99
5	10– 30	10	1·78	1·1

*Calculation based on close-pack array of spheres where radius of particle (column 2) equals 5.6 × radius of pore.

†Calculated from heaving pressure measurements using $r_i = 2\sigma_{iw}/\Delta p$, equation (6).

the average particle radius for the various fractions. In the column second from the right the pore radius has been calculated assuming spherical particles of average size in close-pack geometry and a factor of 5.60 between radius of particle and the pore radius. The last column on the right gives the pore radius calculated from the heaving pressure. These results lend weight to the proposal of the undulating ice-water interface and that the final position is such that the interface rests on the smaller pore sizes rather than on larger pores of the system. This can be achieved only by assuming an undulating frost line. The results given in the table also support the view that the influence of particle size on pore size is a significant criterion in estimating potential frost susceptibility.

The measured heaving pressures are plotted as a function of average particle diameter of each fraction in Figure 5. With increasing diameter, the heaving pressure decreases but does not fall to zero abruptly. This supports the view that there is no sharp dividing line between susceptibility and non-susceptibility to frost. The theoretical relation is plotted using equation (6), with a value of 35 for σ_{iw} and a value of 5.6 for r/r_i, the ratio of particle size to pore size (Everett and Haynes 1965). The Everett and Haynes relation equation (5) is also plotted, using area corrections.

These studies support the use of grain size distribution curves of soils materials as a valid basis for assessing potential frost susceptibility. It must be remembered, however, that frost action in the field depends on factors such as the moisture environment, the thermal regime, overburden pressures, and permeability. The final assessment should take into consideration all these factors in relation to the type of engineering structure involved.

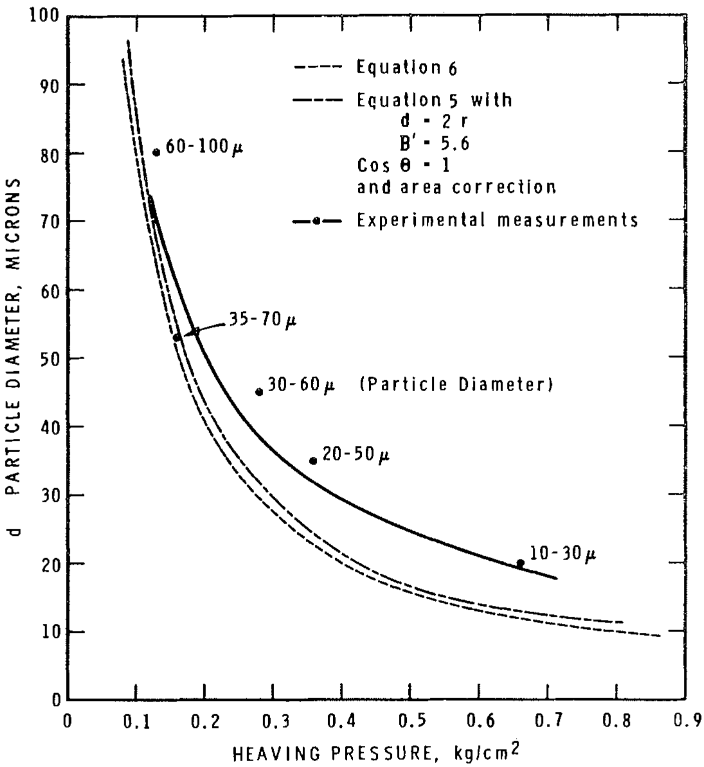

FIGURE 5. Relation between heaving pressures and average diameter of fractions

CONCLUSIONS

Pore dimensions calculated from heave pressure measurements for the various fractions of potter's flint indicate that the smaller pores of the system are involved in the development of heaving pressures.

Moisture release curves showed that the systems have a large range in pore size. To account for the magnitude of the heaving pressures, an undulating ice-water interface is assumed to be as shown in Figure 1. An undulating ice-water interface is possible because the freezing plane is in a thermal gradient regime, a necessary feature of ice lensing, and the ice advances through the larger pores until minimum pore restrictions, compatible with equation (1), prevent further ice propagation at equilibrium.

There is no abrupt dividing line between soils that are susceptible and those that are non-susceptible to frost. Experimental results in Figure 5 follow the calculated relation between average grain size and heaving pressures.

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