PARTICLE SIZE AS A BASIS FOR PREDICTING FROST ACTION IN SOILS

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SYNOPSIS

Maximum heaving pressures caused by ice lens growth were determined experimentally for saturated specimens consisting of fragmental particles in several size ranges. Theoretical predictions show that the pores produced by the smaller particles in the system are responsible for the maximum heaving pressures measured. The suggestion is that the ice-water interface assumes an undulating configuration over the smaller pores when ice proliferation stops, and hence heaving pressures rise to a maximum.

Particle size seems to be an adequate basis for predicting frost susceptibility in practice although the exact amounts and size limits permissible have not been evaluated.

The nature of the failure caused by frost action is not the same for all engineering structures. Failures by "rate of heave" and "heaving pressure" should both be considered if the possibility of frost damage exists. The results substantiate earlier conclusions that there is no sharp dividing line between frost-heaving and nonfrost-heaving soils.

Recent studies by the author have shown that the theory of Everett (2) and Everett and Haynes (3) provides a realistic basis for the growth of ice lenses from pure water in porous systems of simple and uniform geometry. Difficulties arise when the theory is applied to soils which have a more complex porous structure because a grain size, and hence a pore size, distribution exists. For a porous system of this complexity, the theory as it stands is not adequate for prediction, since little is known about the size of pores, in a given pore size range, that determine the heaving pressure characteristics.

The two laboratory approaches for assessing frost susceptibility ("rate of heave" and "heaving pressure") are not entirely compatible, but it is clear and consistent that soils which are not frost-susceptible should not exhibit any measurable heaving pressure or rate of heave. Soils that have a low heaving pressure may show a considerable rate of heave under little or no

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restraint. On the other hand, some soils that exhibit a high heaving pressure from ice lens growth, such as dense clays, may due to permeability limitations have a sufficiently low heaving rate to be acceptable for some engineering structures subject to freezing conditions, (Fig. 1).

Fig. 1. Schematic representation of relationship between heaving rate, heaving pressure and particle size resulting from ice lens growth

The trend in soil engineering has been to predict the frost susceptibility of a soil from its particle size characteristics through relationships determined by "rate of heaving" experiments. Many organizations have carried out such tests but there are no generally-accepted limits to particle size or percentage of fines which determine frost susceptibility.

In this paper an attempt is made to elucidate further the mechanism of heaving, particularly the development of "heaving pressures" by ice lens formation in relation to the particle size distribution of the sample. It will be shown that from measurements of heaving pressure it is possible to obtain an estimate of the sizes of particles which are responsible.

REVIEW OF PREVIOUS WORK

Experimental studies (5) with simple porous systems of uniform glass beads have shown that the predictions of particle size or pore size from heaving pressure measurements are satisfactory using the equation of Everett and Haynes (3). These research workers believed that the validity of the equation extends to pores down to $1/10\mu$ in size and that this is a limiting feature when soils containing clays are being considered (4).

In the equation of Everett and Haynes (3) the heaving pressure of a continuous ice lens, Δp , is given by the following for a close pack array of uniform beads:

$$\Delta p = \frac{2\sigma_{iw}}{r_i} + \frac{2}{r}(\sigma_{is} - \sigma_{ws}) \dots \dots \dots (1)$$

where

- σ_{iw} = ice-water interfacial energy
- σ_{is} = ice-particle interfacial energy
- σ_{ws} = water-particle interfacial energy
- r_i = radius of pore
- r = radius of particle

The first component on the right hand side is equal to the pressure drop across the curved ice-water interface on the pore; the second is referred to as the flotation effect as demonstrated by Corte (1).

The equation can be simplified by applying the Young-Dupre equation

$$\sigma_{is} - \sigma_{ws} = \sigma_{iw} \cos \theta \dots \dots \dots (2)$$

where θ is the contact angle between the ice/water and water/solid surfaces. Equation (1) can be simplified further in terms of the radii used by defining B' as the ratio of r/r_i and the cosine of the contact angle as follows:

$$B' = r/r_i \cos \theta \dots \dots \dots (3)$$

Applying Eqs. (2) and (3), Eq. (1) may then be rewritten

$$\Delta p = \frac{2\sigma_{iw} \cos \theta (1 + B')}{r} \dots \dots \dots (4)$$

B' equals 5.6 for a close-pack array of uniform spherical beads and a value of 35 ergs/cm² was used for σ_{iw} ; $\cos \theta$ is given a value of 1.

Recent studies (6) on samples with a pore geometry of greater complexity than uniform glass beads show that the measured heaving pressures correspond to the smaller pores of the system, but the relationship to the size of the particles was not investigated. Suction determinations were carried out with water to ascertain the pore size distribution of the different sized fractions of fragmented particles of potters flint.

The strong influence of the smaller pores is possible because during frost action in nature the ice lenses grow in a thermal gradient regime. When a pore size distribution exists in the soil, the bottom of the ice lens is thought to take on an undulating configuration, with the ice advancing further into the system (toward the warm side) where larger pores are encountered and being held back above the smaller pores. At equilibrium, when the maximum heaving pressure is attained, the radius of the ice-water

curvature in the pores between the lower face of the ice lens and the porous bed must be consistent everywhere with the temperature as given by Eq. (5).

$$T - T_m = \Delta T = \frac{-2T_m\sigma_{iw}}{Q_F\rho_i r_i} \dots\dots\dots (5)$$

where

- r_i = radius of curvature of the ice-water interface and of pore radius
- ρ_i = density of ice
- Q_F = latent heat of fusion
- T_m = absolute temperature of melting at zero curvature of the ice-water interface at standard pressure
- T = absolute temperature at which freezing takes place
- ΔT = freezing point depression
- σ_{iw} = ice-water interfacial energy

At the attainment of the maximum heaving pressure, the ice front is stable: the rate of melting is equal to the rate of freezing.

METHODS AND MATERIALS

The particle size fractions studied were from a silty soil obtained from an excavation at a building site. The various fractions were prepared by elutriation at various flow rates until the effluent was clear. The actual particle size distribution in the fractions was determined by taking photomicrographs of smears of the particles on glass slides and, in most cases, measuring over 500 particles. Each particle diameter consisted of the average of the largest and smallest dimensions of the fragments. These measured diameters were then arranged in size groups and plotted in the usual way. The particle size curve for the natural soil (Curve 7, Fig. 2) from which the fractions were removed was determined by sedimentation using a standard hydrometer technique.

The samples were densified in the sample holder and frozen using an average thermal gradient of 0.376×10^{-4} C/micron as previously described (5). Heaving pressures were measured with a calibrated pressure transducer in a freezing apparatus also described in previous publications (5) (6). Ice lenses were allowed to grow at low stresses until the ice lens was several millimeters in thickness. At this stage the framework holding the sample was made rigid and pressures were allowed to develop to the maximum with only a few thousandths of an inch of strain. All growth conditions were under fully saturated conditions using distilled water. The heaving pressure measurements for some of the fractions were repeated up to 9 times and averages taken, until confidence in the measurements was established. Suction curves were determined on two of the fractions using the now well-known porous plate technique. Instead of using suction directly for plotting purposes, the

suction parameter is expressed in terms of the equivalent radius of the pore by using the capillary equation

$$\Delta s = \frac{2\sigma_{aw}}{r_i} \dots\dots\dots (6)$$

where Δs is the suction, σ_{aw} is the air/water interfacial energy and r_i is the pore radius. The suction curves represent the equilibrium conditions at increasing suctions.

EXPERIMENTAL RESULTS

The particle size distribution for each of the fractions and the parent material are given in Fig. 2. Figure 3 gives the particle size distribution

Fig. 2. Measured heaving pressures resulting from ice lens growth in relation to particle size distribution

Fig. 3. Heaving pressure in relation to pore size and particle size distribution

of fractions 1 and 2 as well as the suction curves for these two fractions. The measured maximum heaving pressures were substituted into Eq. (4) to find the equivalent diameter of the particles of a bed of close-pack spherical beads which corresponded to these pressures. The vertical arrows on the curves in Figs. 2 and 3 point to this calculated equivalent diameter. The inset table on Fig. 2 gives the numerical values of the measured maximum pressures when the growth of the ice lens ceased.

DISCUSSION OF RESULTS

It is immediately evident (Fig. 2) that the smaller the average size of the particles contained in the sample, the higher the heaving pressure as predicted by Eqs. (1) and (4). This has been generally understood and is alluded to in recent frost action literature. Of special interest is the magnitude of the heaving pressure in relation to the particle sizes contained in the various fractions. In all cases the calculated equivalent diameter of particles responsible for the heaving pressure measured corresponds to the smaller size portion of the particular fraction. It is recognized, however, that the equation used is based on a particular geometry a close-pack array of spherical particles.

With fragmental particles such as were used here, it is difficult to predict the pore size distribution that would exist in a sample made from any particular fraction. The pore size distributions determined experimentally by the suction technique for fractions 1 and 2 are given in Fig. 3 along with the particle size distributions. Again, as pointed out in a previous paper (6), it may be seen that the pore size calculated from the heaving pressures corresponds to the finer pores in the system. In fraction 1, only about 8% of the total pore volume was smaller than the size of pores instrumental in producing the measured heaving pressures; in fraction 2 the figure is about 10%.

It appears, therefore, that the fine portion of any soil subjected to freezing is of great significance in the growth of ice lenses. Further, this finding supports the view that on a microscopic scale the underface of the ice lens has an undulating topography such that in the final position of non-propagation and maximum uplift, the ice lens everywhere faces the smaller pores of the system. To obtain further supporting evidence for this view, fraction 1 and fraction 2 were mixed in equal quantities to give fraction 3 which is also shown in Fig. 2. Fraction 1 produced a heaving pressure of 0.22 kg/cm^2 , fraction 2 a pressure of 0.37 kg/cm^2 . With the mixture of 1 and 2, the pressure was 0.40 kg/cm^2 , a value very close to that of the finer material, fraction 2.

Based on the heaving pressures measured and taking an average wet density of 2.12 g/cm^3 for the soil, the growth of ice lenses in fraction 1 would lift a layer of soil 1.04 m in thickness-No. 2, 1.76 m; No. 3, 1.90 m; No. 4, 2.0 m;

No. 5, 3.14 m; No. 6, 5.38 m; No. 7, 6.81 m. These uplift pressures are formidable for such relatively coarse-grained particles and should be borne in mind in assessing possible heaving when freezing is permitted under building foundations.

The heaving pressures would be reduced if the water table is below the position of the ice lens inducing a suction in the pore water. For the simple geometry of a capillary tube opening Everett's equation (2) is

$$\Delta p - \Delta s = \frac{2\sigma_{iw}}{r_i} \dots\dots\dots(7)$$

where Δp is the heaving pressure, Δs is the suction in the pore water (negative quantity) and r_i is the radius of the opening. If suction pressures are allowed to develop by the ice lens instead of a heaving pressure other influences are involved. Equation (6) indicates the equivalence of the maximum suction in the absence of any overburden pressure and the maximum heaving pressure in a system where saturation is maintained. Porous systems containing a pore size distribution will probably partially desaturate before the maximum suction is attained; this reduces the permeability, so that the point at which equilibrium is reached is difficult to evaluate.

Penner (7) attempted to evaluate Δp and Δs experimentally, using potters flint with a limited range of particle sizes. In general, a 2:1 ratio was found between the maximum heaving pressure and the maximum suction; for example, in a sample which produced a heaving pressure of 1000 g/cm² with no suction in the pore water, the same sample with no overburden restraint produced only a maximum suction of 500 cm of water. The difference between Everett's predictions (Eq. (6)) and Penner's experimental values may be explained by partial desaturation and difficulty with estimating the equilibrium suction. In addition, after partial desaturation, the continuity of the ice-water interface is probably destroyed. Everett's theory requires that the system remain saturated, which is probably not physically possible if a pore size distribution exists. The exact numerical relationship between Δp and Δs may be in doubt but the trend indicated by experiment and theory is thought to be correct; that is, any suction in the pore water of the porous system reduces the maximum heaving pressure attainable.

CONCLUSIONS

1. The size of the smaller particles in the soil for the range of particle size studied determines the magnitude of the heaving pressure developed because of their influence on the dimensions of the porous system. Linking the relationship between particle size and heaving pressure leads to the conclusion that in ice lens growth frost action criteria based on particle size appears to be an adequate basis for predicting frost susceptibility.

2. The maximum heaving pressure develops *after* the period of active frost penetration and rises to this maximum when the ice-water interface is essentially stationary.

3. There does not appear to be an abrupt dividing line based on particle or pore size that separates frost-heaving soils from nonfrost-heaving soils.

4. The pores lying in a plane taken normal to the direction of heat flow would have all pore sizes represented. The experimental observation that the smaller sizes are more influential in determining the maximum heaving pressure indicates that on a microscopic scale an undulating ice-water interface exists. The undulating feature of the ice lens is possible in a porous system of varying pore sizes exposed to a thermal gradient regime. Both are essential features of the mechanism of ice lensing in nature and also simulated in these experiments.

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NOTATION

- Δp = heaving pressure
- Q_F = latent heat of fusion
- r_i = radius of pore
- r = radius of particle
- Δs = pore water suction or tension
- T = absolute temperature of melting of ice crystals with radius of curvature of r_i at standard pressure
- T_m = absolute temperature of melting of ice with zero curvature at standard pressure
- ΔT = freezing point depression
- θ = contact angle between the ice/water and water/solid surfaces
- ρ_i = density of ice
- σ_{iw} = ice-water interfacial energy
- σ_{is} = ice/solid interfacial energy
- σ_{ws} = water/solid interfacial energy
- σ_{aw} = air/water interfacial energy

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