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FROST HEAVING FORCES IN LEDA CLAY

BY

E. PENNER

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Frost heaving forces in Leda Clay[1]

E. PENNER

Division of Building Research, National Research Council of Canada, Ottawa 7, Canada

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The frost heaving forces developed under a 1 ft (30.5 cm) diameter steel plate were measured in the field throughout one winter. The steel plate was fixed at the ground surface with a rock-anchored reaction frame. Heave gauges and thermocouples were installed at various depths to determine the position and temperature of the active heaving zone.

The general trend was for the surface force to increase as the winter progressed. When the frostline approached maximum depth the force was in excess of 30 000 lb (13 608 kg). Estimates of the heaving pressure at the frostline ranged from 7 to 12 psi (0.49 to 0.84 kg/cm^2) during this period.

The variation of surface heaving force was closely associated with weather conditions. Warming trends resulting in a temperature increase of the frozen layer caused the forces to decline.

Les forces de soulèvement dues au gel qui se sont produites sous une plaque d'acier de la pied (30.5 cm) de diamètre ont été mesurées en nature durant un hiver. La plaque d'acier était fixée à la surface du sol ou moyen d'un cadre ancré au roc. Des jauges de soulèvement et des thermocouples furent installés à différentes profondeurs pour déterminer la position et la profondeur de la zone active de soulèvement.

En général, la force de soulèvement à la surface tendait à s'accroître au cours de l'hiver. Lorsque la ligne de gel atteignit la profondeur maximum, la force de soulèvement dépassait 30 000 lb (13 608 kg). Durant cette période, la pression de soulèvement au niveau de la ligne de gel a été estimée à des valeurs comprises entre 7 et 10 p.s.i. (0.49 à 0.84 kg/cm^2).

La variation de la force de soulèvement à la surface a suivi de près les conditions climatiques. Durant les périodes moins froides la température s'est élevée dans la zone de gel et les forces de soulèvement ont diminué.

Introduction

An important engineering aspect of the frost action problem concerns the large forces that are sometimes associated with the heaving phenomenon in frost-susceptible soils. Each winter, frost heaving damage to permanent structures results in maintenance expenditures that could have been avoided by adequate consideration of the frost problem. In the case of temporary soil-bracing structures that are left exposed to freezing conditions, such forces must either be taken into consideration in the design or prevented by heated enclosures or insulation (McRostie and Schriever 1967; Pappas and Sexsmith 1968). In a recent paper, numerous examples are given of frost heaving that has displaced foundation units not adequately protected during winter construction (Crawford 1968).

The field study described in this paper was undertaken to measure the heaving force developed against a fixed plate at the ground surface and to estimate the heaving pressures (vertical stresses) developed at the frost line. A similar experiment, carried out previously in Japan (Kinosita 1967), was useful in planning the present study.

The need for these experiments arises because it is still not possible to reliably predict heaving forces from soil properties, although some advances in this respect have been made recently. These results should give designers an appreciation for the magnitude of the forces that can be generated by frost heaving, and a decision can then be made whether to take them into account in design or to avoid such hazards by preventing the soil from freezing (i.e., insulating or heating).

Heaving Forces and Ice Lensing

Frost heaving in freezing soils is attributable mostly to the freezing of water that migrates to the freezing plane[2] and freezes in the form of an ice lens. Ice lensing activity and the associated heave are thought to be greatest at the freezing plane, although in clays some water

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[1] NRCC 11131.

[2] The freezing plane normally refers to the location which separates the unfrozen soil from the partially frozen soil.

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may move from the unfrozen soil into the frozen soil well beyond the freezing plane.

The water may originate from an outside source (high water table), or it may be supplied by decreasing the moisture content of the unfrozen soil; the actual situation may lie somewhere in between. If the second alternative occurs, shrinkage may result in some soils. In such cases the total thickness of the ice lenses would be greater than the observed heaving at the ground surface.

It is well known that the ice-water ratio of so-called frozen soils is temperature dependent. Under normal climatic conditions in the field, the temperature of the frozen layer is lowered as the average daily air temperatures decrease. This results in an increase of the ice phase and a decrease of the water phase in the "frozen" layer, which also adds to the amount of heave observed. These aspects are noted here to draw attention to the complexity of the frozen soil system. It is thought, nonetheless, that the main cause of heaving pressures and frost-heave displacement is the formation of ice or ice lenses at the freezing plane.

The direction of displacement and heaving pressure is parallel to the direction of heat flow. For example, where the freezing plane progresses laterally in a vertical wall of an excavation, the movement induced by ice lens formation is also in the lateral direction. If the heat flow pattern can be anticipated for a particular situation, the direction of heaving and the associated forces can be reliably predicted.

On the other hand, the magnitude of the heaving pressures at the freezing plane cannot be reliably predicted for most natural soils, although the particle size distribution is a useful guide. Under similar conditions of temperature and moisture availability, the pressure developed by ice lens growth is known to be related inversely to particle size. Pressures are low for fine sands, intermediate for silts, and high for clay soils.

Heaving pressures can be predicted from theory (Everett and Haynes 1965) for laboratory prepared specimens of uniform-sized spherical particles with a given packing array. Such a prediction is not possible when the particle size varies, although recent studies (Penner 1968) show that the smaller-sized fraction has a strong influence on the maximum heaving pressures attainable. The theory of Everett and Haynes is based on the capillary phenomena at the ice–water interface within the porous medium. When most of the water is surface-adsorbed water, as might be the case in some clays, predictions are not possible on this basis. A further complication arises in the field due to lack of homogeneity along the freezing plane, caused by the natural structure of the soil. Ice may penetrate along fissures and channels instead of through the porous system, and much lower stresses would result. In the laboratory, maximum values are obtained when the soil is thoroughly mixed or remoulded to destroy the macrostructure, with the result that the frost line is held relatively stationary.

Methods and Materials

Reaction Frame for Force Measurements

An H-shaped frame, consisting of twin 6 I 12½ steel beams, was designed for the superstructure of the reaction frame (Figs. 1 and 2). The frame was anchored to bedrock at the corners using ¾ in. (1.9 cm) rock bolts with 1¼ in. (3.2 cm) expansion shells. Competent limestone bedrock is located at a depth of about 12 ft (3.7 m) from the ground surface and the expansion shells were installed 18 in. (45.7 cm) below the bedrock surface. The reliability of the rock anchor assembly installations was tested separately by applying a tension of 25 000 lb (11 340 kg) to the rock bolts for several hours.

A 50 000 lb (22 680 kg) Dillon mechanical compression gauge was used for force measurements. It was covered with a plastic enclosure for protection from rain and snow. The surface plate, which was a 1 in. (2.54 cm) thick, 12 in. (30.5 cm) diameter circular steel plate, was welded to a 3½ in. (8.89 cm) steel pipe. The force gauge was located between the pipe and the reaction frame. In order to position the surface plate correctly in contact with the thin

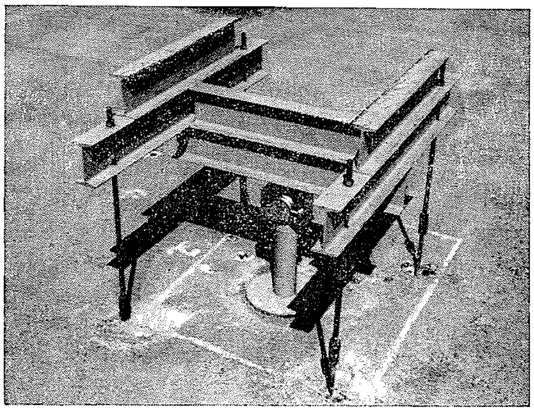
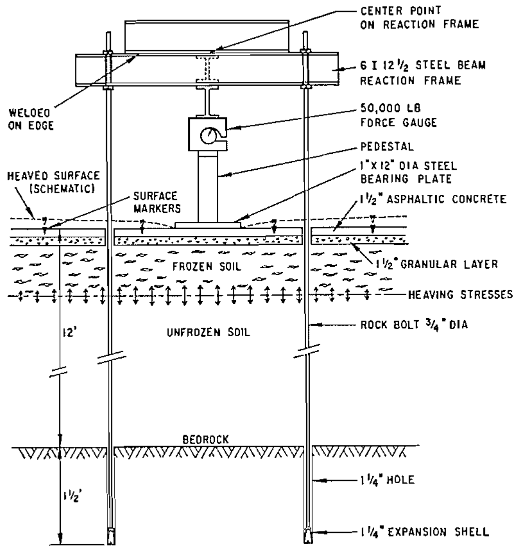
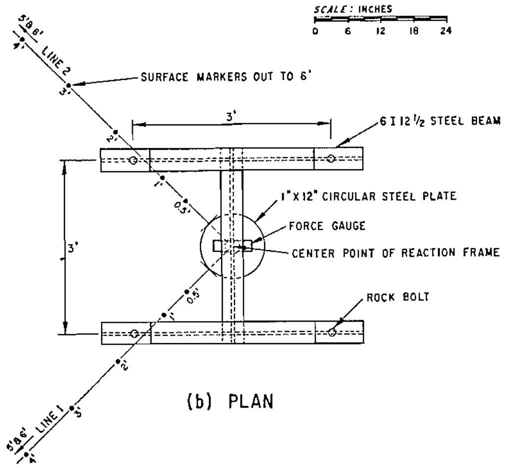


FIG. 1. Reaction frame and bearing plate.



(a) SECTION



(b) PLAN

FIG. 2. Reaction frame.

asphaltic concrete layer, it was possible to adjust the frame levels at all four corners just prior to the onset of ground freezing. Two sets of surface markers were positioned radially at distances of ½, 1, 2, 3, 4, 5, and 6 ft (0.15, 0.30, 0.60, 0.91, 1.26, 1.52, and 1.83 m) out from the rim of the surface plate for heave measurements. The markers were 3 in. × ⅜ in. (7.62 × 0.95 cm) lag screws installed flush with the asphalt surface using an impact wrench.

Heave Gauges and Temperature Measurements

Heave and temperature measurements at various depths were made at two locations on the snow-cleared site, at a distance of 18 and 30 ft (4.5 and 8.1 m) from the reaction frame. The results given later in the paper are averages for the two locations.

The heave gauges (Fig. 3) were installed at ½ ft (0.15 m) intervals from the surface of the soil to a depth of 4½ ft (1.37 m). The stainless steel base plate (4 × 4 × ⅛ in.) (10.2 × 10.2 × 0.32 cm) was attached to a ½ in. (1.27 cm) diameter steel rod. Adfreezing to the rod was avoided with a grease-filled protective steel pipe sleeve. The movement measured at the top of the rod was equal to the amount of heave at the base plates.

Twenty-gauge copper-constantan thermocouples attached to a wooden dowel were used to measure the soil temperatures at ½ ft (0.15 m) intervals corresponding to the depths of the heave location gauges. Eighteen inches (0.46 m) of the thermocouple cable was rolled around the dowel at each level to reduce errors due to conduction of heat along the cables to the thermocouple union.

The base plates of the heave gauges were driven into the walls of a narrow trench, which was backfilled with the excavated soil close to the original density. With this instrumentation it was possible to relate the zero degree isotherm position with the position of the active heaving zone as indicated by the heave gauges.

Soil and Site Conditions

The site is located on National Research Council of Canada property on the Montreal Road near the eastern city limits of Ottawa. The natural grass sod was removed and replaced with a working surface consisting of a 1½ in. (3.81 cm) layer of gravel and a 1½ in. (3.81 cm) layer of asphaltic concrete. As is normal for this area, the ground water-table was near the ground surface before the first freeze occurred. The soil at the site is a post-glacial clay of marine origin (Crawford 1961). It is reasonably uniform with depth, and consists of 70% clay-sized and 30% silt-sized particles. The average moisture content in the autumn is about 44%.

Measurement Methods

Soil temperatures were measured daily at 0830 hours with a data acquisition system. Air temperature measurements were obtained from a meteorological station located a few hundred yards from the site. The Dillon force gauge was read daily at 0830 hrs. Occasional spot checks at other times of the day showed that the diurnal variation was small. A calibration check prior to installation showed the accuracy of the gauge to be better than 1% of the full range.

Level surveys, referenced to a stable bench mark, were carried out weekly to follow the progress of heaving for both surface and heave-position gauges. Level surveys were done also on the center and corners of the reaction frame as a check on its stability.

Results and Discussion

The average daily temperatures, the daily force readings and the estimated frost penetration depth (0 °C) are given in Fig. 4. These results are shown together on the same graph so that comparisons can be made easily. The

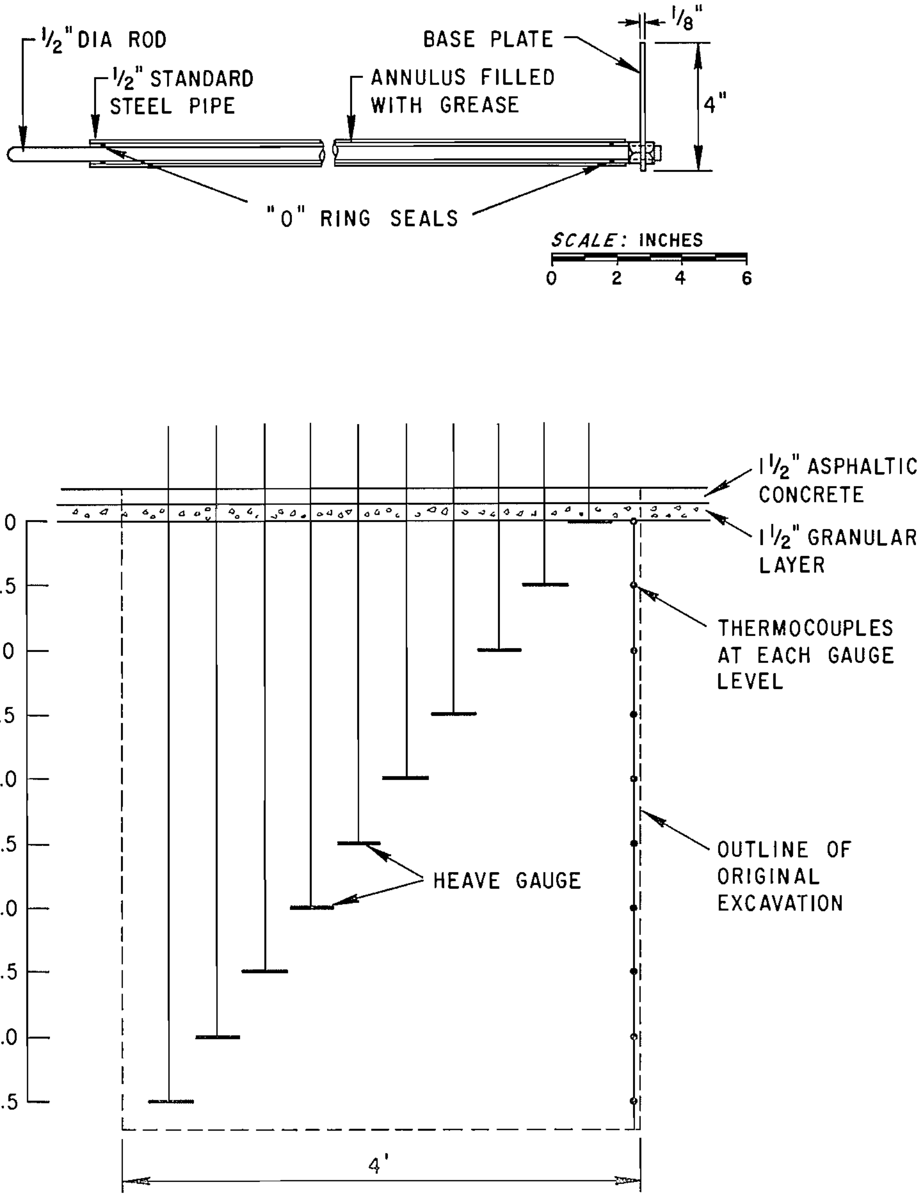


FIG. 3. Heave gauges and thermocouple locations.

maximum heave force measured with the 12 in. (30.5 cm) diameter surface plate was 30 000 lb (13 608 kg). It reached this value on 14 February 1969, after a period of prolonged cold weather and active heaving. Periods of moderating weather reduced the force values; only when frost heaving was actively taking place did the total force increase. The center position on the frame moved 0.020 in. (0.05 cm) at maximum force. This was fully recovered after the frame was unloaded (Fig. 4).

The vertical movement of the heave gauges are given in Fig. 5. These results show that the initial gauge movement corresponded closely to the time the 0 °C isotherm intercepted the gauge. The frost line position was determined daily, but heave movement readings were taken only once a week. Because of this, the exact

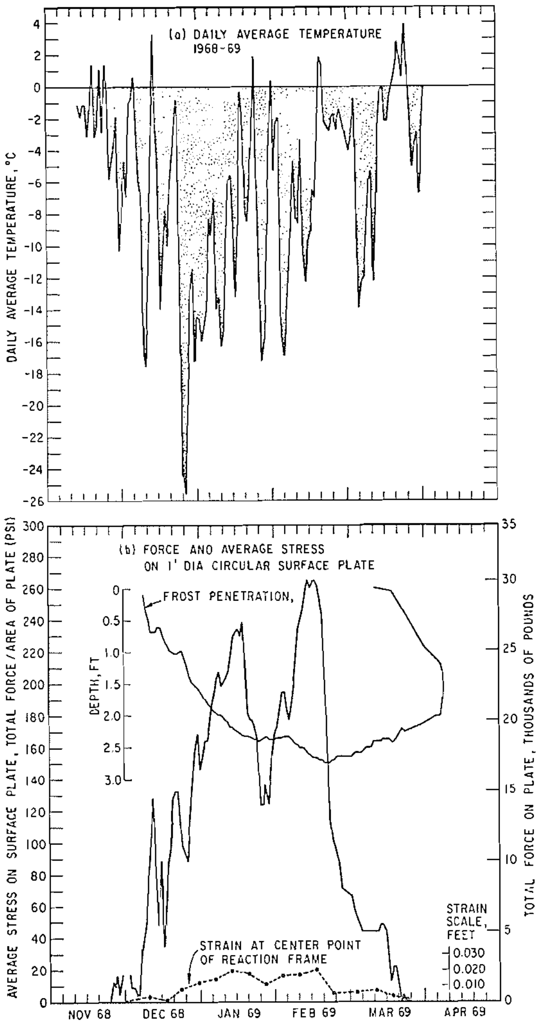


FIG. 4. Temperature, force, and frost depth results.

day when each gauge started moving is not known.

The vertical distance between gauges remained almost constant after the frost line passed their position. Slight increases in these distances indicate some further lensing activity within the "frozen" soil, but it can be concluded that the main heaving activity was at the freezing plane which corresponded closely with the 0 °C isotherm.

Figure 6 shows the results of the heave measurements along the two lines of surface markers radiating out from the surface plate. The shape of the curves shows the manner in which frost heaving was impeded near the plate. The rate of heave calculated from the shaded portions on the graphs (heave between 3 to 10 February 1969) was used as one of the methods to estimate the vertical stress distribution on the horizontal freezing plane. The particular time interval (shaded area) was selected because the surface heaving was approaching a maximum (Fig. 4), but the heave rate was still substantial under a slow rate of frost penetration.

Estimation of Average Surface Stress at Frost Line

The force measurements show a general increase as the winter progressed (Fig. 4). Variations from this appear to be a gradual response to changing air temperatures and the resultant changes in ground temperatures. The force on the surface plate is thought to reflect a *balance* between creep of the frozen soil under stress (Vialov 1965) and rate of heave. When the rate of creep exceeds the heave rate the force measured at the surface reduces. A warming trend during the winter reduces the heave rate, at the same time the rise in temperature of the frozen layer causes the creep rate to increase. As would be expected, there is a time lag between the change in force and the associated change in air temperatures.

Figure 7*a* gives the average surface stress on the plate as a function of frost depth. The trend is a general increase in surface stress with depth of frost line, but responses to thermal conditions are also clearly evident.

An attempt was made to estimate the vertical stress at the frost line by using the Boussinesq elastic theory of stress distribution, taking into account all the assumptions this implies, including a uniform contact stress at the surface plate. The results of the calculations are plotted in Fig. 7 as a function of frost depth. The elastic modulus of the frozen layer, E_f, and that of the unfrozen soil beneath, E_u, are not known. E_f, which is probably temperature-dependent because of the presence of ice and the fact that the ratio of ice to water varies with temperature, is greater than E_u. Figure 7*b* presents the stress obtained assuming $E_f = E_u$. The stress obtained using Burmister's (1958) graphs for E_f/E_u equal to 5 and 10 is plotted in Figs. 7*c* and 7*d* respectively. The tendency is for the load to spread and the stress at the freezing

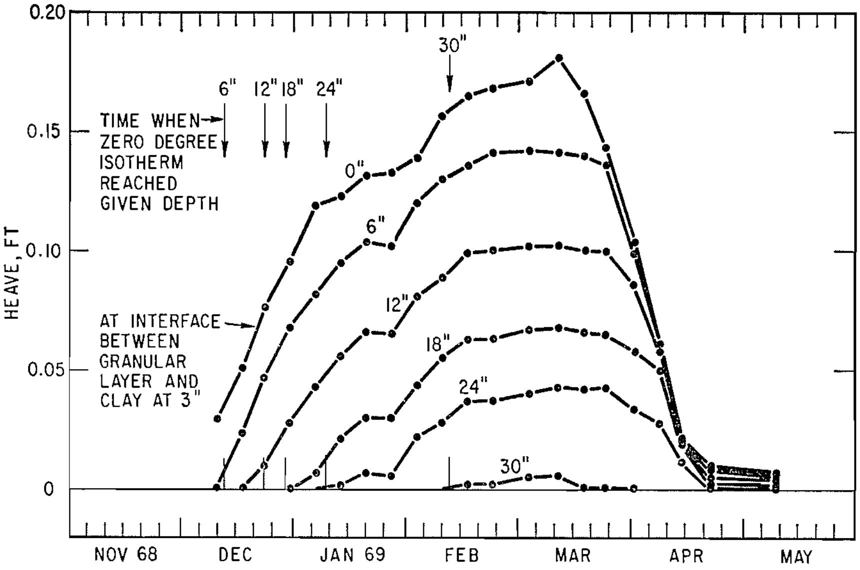


FIG. 5. Vertical heave and settlements at 6 in. (15 cm) depth intervals in the soil profile near reaction frame.

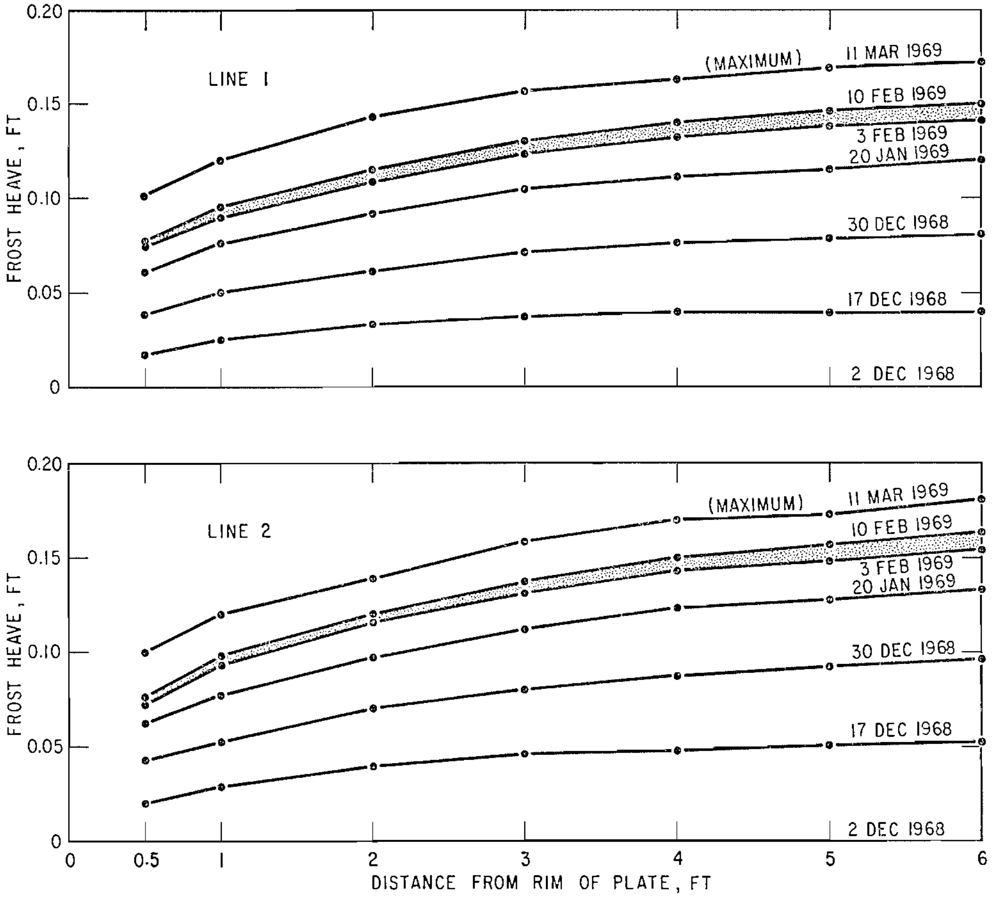


FIG. 6. Frost heave at ground surface near surface plate.

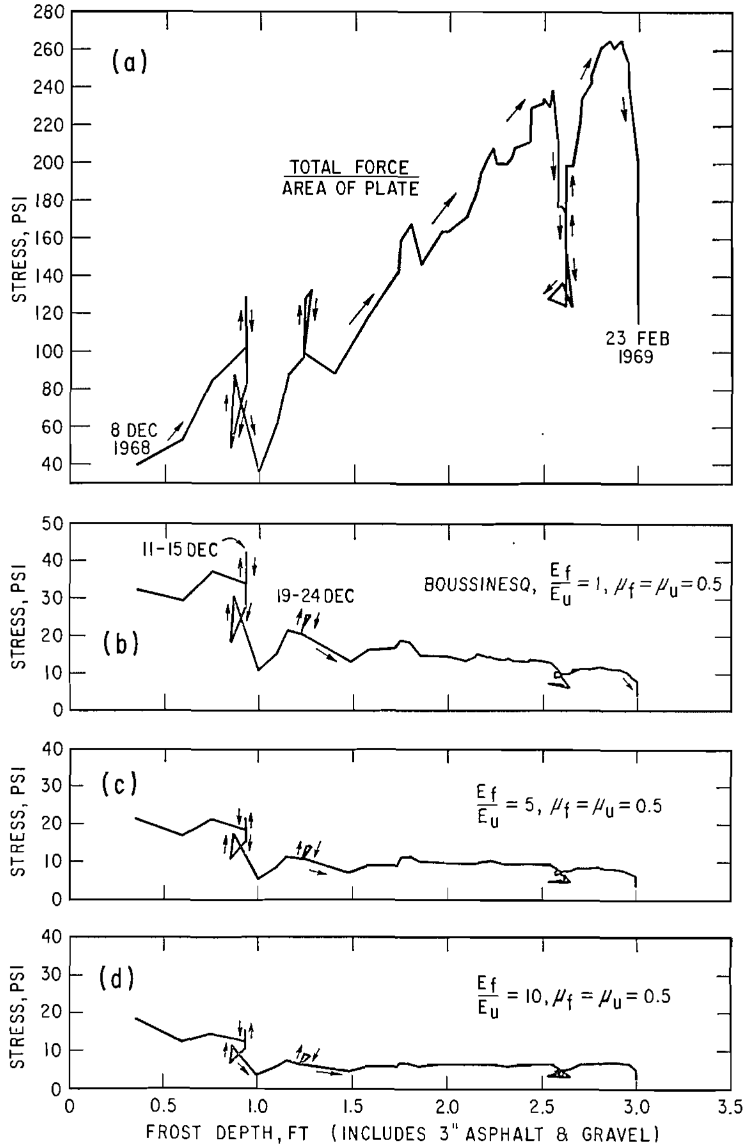


FIG. 7. Average stress at surface and estimated stresses on centerline of plate at frost line. (f = frozen, u = unfrozen).

plane to decrease as the ratio increases. The stress at the freezing plane also tends to decrease as the frost depth increases. These calculations show that the stress at the freezing plane is largest early in the season before the maximum heaving force has been developed. Values of the maximum in Figs. 7*b* to *d* range from 35 psi to 15 psi (2.46 kg/cm^2 to 1.05 kg/cm^2) (frost depth 0.75 ft (22.9 cm)). Just prior to spring break up, when the total force measured was highest ($\approx$30 000 lb (13 608 kg)), the values range from 12 psi to 7 psi (0.84 to 0.49 kg/cm^2). These field values are lower than might be expected for this type of soil from theory (Penner 1968).

Vertical Stress Distribution on the Horizontal Plane at Frost Line

The dependence of frost heave at the surface on distance from the fixed plate (Fig. 6) pro-

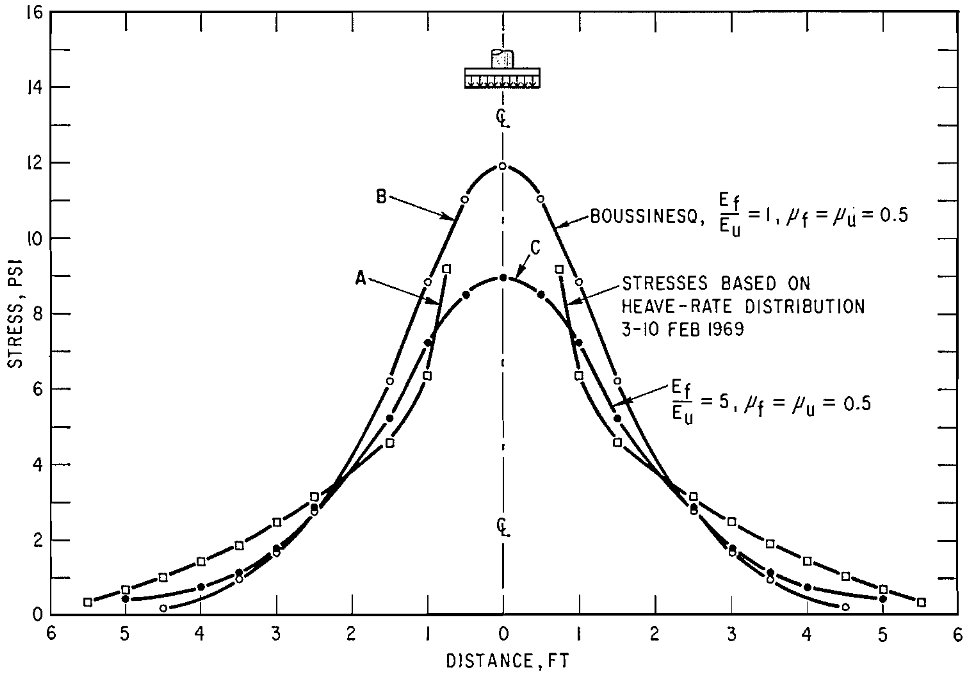


FIG. 8. Vertical stress distribution on horizontal plane at frozen-unfrozen interface (depth 2.75 ft, 0.836 m).

vided a novel approach for assessing heaving pressures at the frost line. It is commonly known that the heaving rate of soil, as determined in the laboratory, is inversely related to the pressure applied to the freezing plane. The results given by Linell and Kaplar (1959) for several soils conform to the following equation:

[1] $$R = R_0 e^{aP}$$

where R_0 = heave rate at zero pressure
a = constant for given soil type (negative value)
P = applied pressure
R = heave rate at pressure P

The dependence of rate of heave on pressure at the freezing plane is not known for Leda clay; hence the value of "a" was taken from a similar soil that had been studied by Linell and Kaplar.

The heave rate was calculated from the average of the movements of the two sets of surface markers as a function of distance from the plate for the period 3 to 10 February 1969 (shaded area in Fig. 6) when the force on the surface plate was near a maximum. Equation [1] was then used to calculate the pressure at the freezing plane. This is shown in Fig. 8 plotted against distance from the plate (curve A). The value used for R_0, the heaving rate at zero pressure, was taken at a point some 7 ft (1.8 m) away from the reaction frame not influenced by the fixed surface plate. The main assumption in this calculation is that the pressure at the freezing plane is related by Eq. [1] to the heaving rate observed at the surface of the ground directly above it.

Curve B in Fig. 8 is the Boussinesq vertical stress distribution on a horizontal plane at a depth of 2.75 ft (0.84 m), using the Newmark influence charts and Poisson's ratio of 0.5. Curve C was obtained by using Burmister's (1957) distribution when E_f/E_u, the frozen-unfrozen elastic moduli ratio, is 5. The curves B and C are very similar except for the position directly below the center of the surface plate. This agreement indicates that at a depth of 2.75 ft (0.84 m) (5.5 × plate radius) the differences involved in applying incorrect elastic moduli ratios are relatively unimportant. The stress distribution calculated from heaving rates (curve A) tends to indicate a greater spreading of the surface force. Since the method depends on rate of heave, the stress on the center line of the fixed plate could not be evaluated.

Conclusions

The results lead to the following conclusions:

1. The main heaving activity is thought to be mainly associated with the freezing plane—the interface between the frozen and unfrozen soil. The heaving activity within the frozen mass is shown by the results to be relatively small.
2. The maximum heaving force measured at the surface is unexpectedly high, although the estimates of the vertical stresses at the freezing plane (heaving pressure due to ice lens growth) are relatively small considering the texture of Leda clay. In natural Leda clay under field conditions, ice propagation probably occurs along fissures and channels; this would tend to reduce the heaving pressures that are possible if ice propagation took place through all the pores of the soil.
3. Although the vertical stresses calculated are estimates, the agreement between the several methods used suggest they are of the right order.
4. The variation of the surface heaving force on a fixed plate is closely associated with weather conditions. Warming trends that increase the temperature of the frozen layer reduce the temperature gradients and hence the heaving rate, which results in a decline of the surface force.
5. The general trend is for the surface heaving force to increase as the winter progresses and the frost depth increases. As the thickness of the frozen layer increases, the heaving pressure at the frost line decreases, but as the frost depth increases the surface heaving force increases. This is attributed to the increasing area of influence at the freezing plane.

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