Adfreezing of Leda clay to anchored footing columns

Penner, E.; Irwin, W. W.

Canadian Geotechnical Journal, 6, 3, pp. 327-337, 1969-07-01

NATIONAL RESEARCH COUNCIL OF CANADA
CONSEIL NATIONAL DE RECHERCHES DU CANADA

ADFREEZING OF LEDA CLAY TO ANCHORED FOOTING COLUMNS

BY

E. PENNER AND W. W. IRWIN

Reprinted from
CANADIAN GEOTECHNICAL JOURNAL
VOL. VI, NO. 3, 1969
P. 327

RESEARCH PAPER NO. 405
OF THE
DIVISION OF BUILDING RESEARCH

OTTAWA
July 1969

PRICE 25 cents NRC 10834

This publication is being distributed by the Division of Building Research of the National Research Council of Canada. It should not be reproduced in whole or in part without permission of the original publisher. The Division would be glad to be of assistance in obtaining such permission.

Publications of the Division may be obtained by mailing the appropriate remittance (a Bank, E[illegible]ble at par in Ottawa, to the Re[illegible]ch Council of Canada, Ottaw[illegible]

A li[illegible]ined from the Publications [illegible]l of Canada, Ottawa 7, Canad[illegible]

ADFREEZING OF LEDA CLAY TO ANCHORED FOOTING COLUMNS[1]

E. PENNER and W. W. IRWIN[2] *Soil Mechanics Section, Division of Building Research, National Research Council of Canada, Ottawa, Canada*

The heaving force transmitted to 3½-in. (7.6-cm) diameter steel pipes by adfreezing in Leda clay was measured in the field for two consecutive winters. The maximum uplift force was approximately 6000 lb (2700 kg), which corresponds to an apparent adfreeze strength of about 12.5 p.s.i. ($\approx$ 0.9 kg/cm^2). It developed gradually during prolonged periods of cold weather, but dropped off rapidly during warming trends, although the whole soil profile remained below 0 °C. Adfreezing did not retard frost heave in the soil in the vicinity of the steel pipes.

Agreement between experimental values for maximum uplift forces by adfreezing and values predicted by Dalmotov's equation suggests that such predictions can be used as a guide for design purposes if no other information is available.

Les auteurs ont mesuré au cour de deux hivers consécutifs la force de soulèvement transmise à des colonnes d'acier de 3 po. (7.6 cm) et demi de diamètre par une argile à Leda y adhérant par gel. L'effort maximal dirigé de bas en haut atteignait une valeur de 6000 livres (2700 kg) correspondant à une force d'adhérence de 12.5 livres/po^2 ($\approx$ 0.9 kg/cm^2). Cette force de soulèvement s'est accrue graduellement au cours des longues périodes de temps froid, mais a diminué rapidement pendant les périodes de réchauffement, bien que l'ensemble du profil de sol se soit maintenu en dessous de 0 °C. Ces phénomènes d'adhérence n'ont pas retardé le soulèvement du sol par gel au voisinage des colonnes d'acier.

L'accord observé entre les valeurs expérimentales des forces maximales de soulèvement par le gel et les valeurs calculées au moyen de l'équation de Dalmatov indique que cette relation peut servir de guide pour les calculs lorsqu'aucune autre donné n'est disponible.

INTRODUCTION

Placing foundation footings below the depth of frost penetration in frost-susceptible soils does not necessarily prevent heaving damage. Movements resulting from ice lens growth in the soil may be transmitted to the structure by "frost-grip" if wet soil is allowed to freeze to foundation walls or supporting columns. This study was designed to measure the magnitude and variation of uplift forces induced by frost heaving and to determine whether frost heaving of soil is impeded in the vicinity of an anchored structure. A preliminary field installation was made to allow measurement of the heaving force transmitted to small-diameter vertical steel pipes in Leda clay as a guide to more comprehensive investigation of the adfreezing problem in frost-heaving soils.

[1]NRCC 10834.
[2]Present address: M. M. Dillon Limited, Ottawa, Canada.

Canadian Geotechnical Journal, 6, 327 (1969).

There is extensive literature on the mechanical behavior of frozen soil in both the laboratory and the field where structures are founded on piles in permanently frozen ground. Current Russian literature recognizes the similarity between strength properties of frozen soils and the adfreezing strength properties between soils and other materials. This background information can be applied usefully to the problem of adfreezing.

Frost-grip, or adfreezing strength, at the foundation wall or footing column depends on such variables as foundation material, the nature of the soil, moisture and temperature conditions—factors similar to those considered in evaluating the load-carrying capacity of pile foundations in permanently frozen ground. It differs in that the adhesion influence is seasonal, the bond interface is near the ground surface where temperature fluctuations are extreme, the rate of strain is controlled by the rate of heaving of the soil under the particular moisture availability characteristics, and other variables related to climate. The problem of seasonal adfreezing, however, exists also in the active layer in permafrost areas and is an important consideration in pile foundation design.

PHENOMENA OF ADFREEZING

When wet frost-susceptible soils freeze in contact with foundation units, two significant processes occur simultaneously. Phase transformation of water to ice not only increases the strength and changes the strength characteristics of the soil, but is also responsible for the strong bond of adhesion between the foundation unit and the soil. A second process creates an upward thrust of frost heaving in the surrounding soil. As ice lenses form normal to the direction of heat flow, most of the volume change in the frozen layer results in upward displacement. Ice lens growth is most active at the interface between the frozen and unfrozen soil. As the frozen layer heaves, it attempts to carry with it any structure embedded in the frozen mass and places stresses on columns or walls in the direction of heaving.

The strength of the bond formed by adfreezing between a structure and the soil depends on many factors, but only a cursory review is within the scope of this paper. The most important factors are soil type and water content, the nature of the material in the structure—wood, concrete, or steel—and the method used to place the foundation. The strength behavior of the bond depends also on the load imposed and its duration. Quick strength tests cannot be applied directly to situations where the strain rate is slow (Vialov, 1959). In the present study, movements between a structure and adjacent frozen soil result from ice lens growth. The total relative movement depends on heaving characteristics of the soil and displacement of the foundation.

Early Russian workers referred to by Saltykov (1944) assumed that a completely rigid bond formed between an anchored structure and the soil, and that consequently no displacement occurred between the soil and structure until the bond was ruptured. A similar assumption is made in the analysis used by Trow (1955). More recent studies (Saltykov 1944; Tsytovich 1959; Vialov 1959) and the results presented in this paper indicate that an anchored structure does not reduce the amount of heave in the soil next to it. Whether all heaving soils are similar in this respect is not known.

For any given soil, both the adfreeze strength characteristics of the bond and the heave that mobilizes the adfreeze strength are strongly influenced by the thermal regime. Vialov (1959) gave the temperature dependence of adfreeze strength or shear strength of frozen soil for temperature-controlled experiments as follows:

$$[1] \qquad \tau = \tau_0 + a\sqrt{|t|}$$

where τ_0 is the adfreeze strength at a given temperature, a is a parameter dependent on soil type and moisture content, and t is the temperature in C degrees. Vialov showed experimentally that a drop in t from −0.4 °C to −3.5 °C increases the adfreeze strength by a factor of approximately 2.5 to 3.5.

Tsytovich (1959) gave Dalmatov's equation, which was confirmed by field experiments, for maximum heaving forces on a structure by adfreezing. This relation is said to hold for temperatures between 0 and −12 °C, and as follows:

$$[2] \qquad T = \mu h_a (c - 0.5\, b\, t_s)$$

where T = total upward force due to frost heaving (kg)
μ = perimeter of foundation in contact with soil (cm)
t_s = surface temperature (°C)
h_a = thickness of frozen zone (cm)
b and c = parameters determined experimentally.

METHODS AND MATERIALS

Soil Conditions

The experimental plot is located on National Research Council of Canada property in Ottawa. The soil is a post-glacial clay of marine origin, commonly referred to as Leda clay (Crawford 1961). Depth to bedrock varies from 11 to 20 ft (3.4 to 6.1 m) because of a steep bedrock slope from south to north. The surface of the ground at the site slopes gently in the same direction, providing good surface drainage. Frost heaving at the site is approximately 3 to 4 in. (7.6–10.2 cm) every winter on snow-cleared areas. The average water content between 1 and 6 ft (.3 and 1.8 m) was about 44%, based on measurements taken during the autumn.

The soil consists of about 70% clay-size particles, with the remaining 30% in the silt-size range.

Site Preparation

The experimental site (40 by 50 ft (12.2 by 15.2 m)) on which the footings were located is shown in Fig. 1A. In preparing the experimental plot the sod was removed and the site was levelled and covered with a 3-in. (7.6-cm) layer of crushed rock and 1½-in. (3.8-cm) thick asphaltic concrete surface.

Design and Installation of Anchored Footing Columns

Heaving forces were measured on 3½-in. (8.9-cm) OD, 3-in. (7.6-cm) ID, steel pipes installed to a depth of 5 ft (1.5 m). A reaction frame was fixed to the top of the pipe and the whole assembly was anchored to rock with a ¾-in. (1.9-cm) diameter rock bolt running down the center of the grease-filled pipe (Figs. 1B and 2). A 5000-lb (2268-kg) capacity Dillon mechanical force gauge was used to measure the tension developed between the pipe and the center

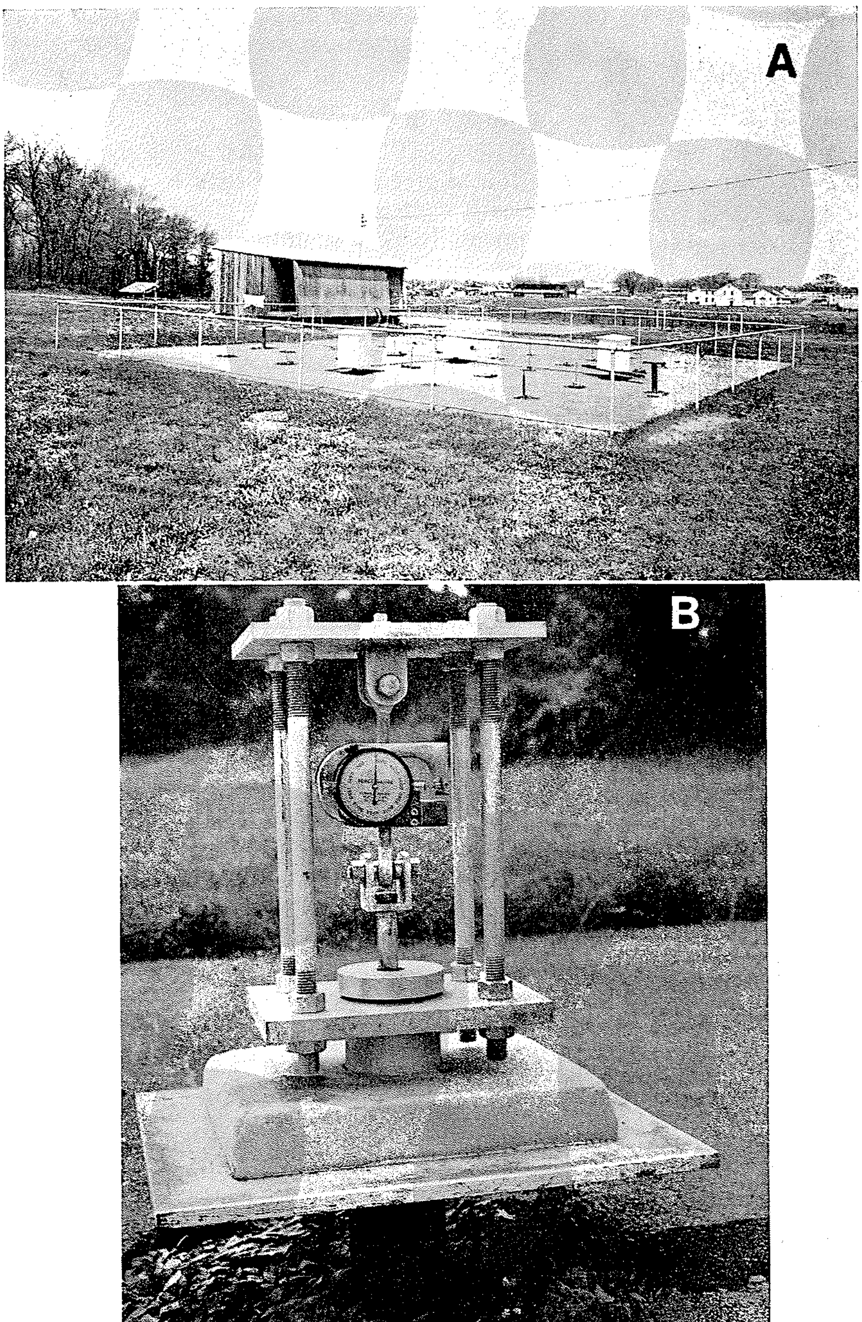

Fig. 1. A, Site of experimental small footings. B, Reaction frame.

rod by heaving of the soil. The rock anchor was a $1\frac{1}{4}$-in. (3.2-cm) expansion shell and $\frac{3}{4}$-in. (1.9-cm) rock bolt, with an assembly breaking load of 35 000 lb (15 876 kg). The expansion shell was anchored 18 in. (45.7 cm) below the surface of the limestone bedrock. Steel pipes were lowered in 6-in. (15.2-cm)

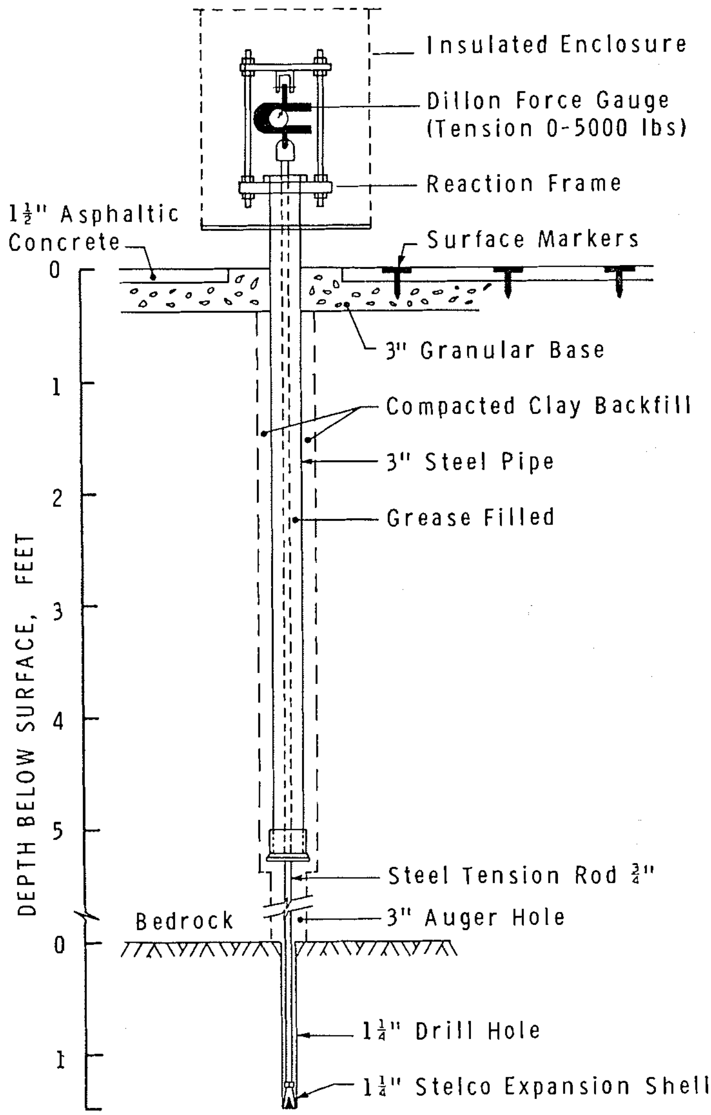

FIG. 2. Force-measuring footing column.

diameter augered holes and backfilled with the previously removed soil. The reaction frame was protected from rain, snow, and rapid temperature changes by an insulated plywood box (Fig. 1A).

Temperature Measurements

Copper–constantan thermocouples were attached to 1½-in. (3.8-cm) wooden dowels and installed next to the steel footing columns in 1¼-in. (3.2-cm) augered holes to ensure good thermal contact. Weekly readings were used to estimate the progress of the frost line. Thermocouples were located at the 3-in. (7.6-cm), 12-in. (30.5-cm), 18-in. (45.7-cm), 24-in. (61-cm), 36-in. (91.4-cm), 48-in. (122-cm), and 60-in. (152.4-cm) levels.

Force Measurements

The Dillon mechanical force gauge is a U-shaped alloy-steel bar with the force measurement indicated on a precision dial indicator. Approximate strain for full-scale deflection is 0.04 in. (.10 cm). During the winter of 1966–67 only one of the three steel columns had a 5000-lb (2268-kg) capacity gauge; another had a 2500-lb (1134-kg) capacity gauge and the third, a 1000-lb (454-kg) gauge. The last two were shown to have insufficient capacity for peak force measurements, so that during the second winter all three columns had 5000-lb (2268-kg) gauges, although one of the installations malfunctioned and thus only two columns provided reliable data.

Readings were taken at the same time of day—0830 hours—although diurnal variations were normally small. The manufacturer's calibrations were checked in the laboratory and found satisfactory for field measurements.

Surface Heave Measurements

To determine the frost-heaving behavior of the ground surface on the site near the anchored columns, surface reference markers were embedded in the asphaltic concrete. These consisted of 3-in. (7.6-cm) diameter steel disks, ¼ in. (.6 cm) thick, welded to a sharpened steel pin 1½ in. (3.8 cm) in diameter and 5 in. (12.7 cm) long. The markers were placed in the hot asphalt so that the top of the disk was flush with the asphalt surface. Duplicate lines of markers were installed at right angles to each other at distances of 1, 2, and 3 ft (.3, .6, and .9 m) from one anchored footing and 1 and 2 ft (.3 and .6 m) from a second footing. Heaving behavior of the site was established with similar surface markers, some 9 ft (2.7 m) away from the anchored footings. Precise level surveys, referenced to a stable bench mark at the corner of the site, were carried out semi-monthly to follow the progress of heaving. The stability of the bench mark was occasionally checked against a previously well-established bench mark during the first winter of the experiment.

EXPERIMENTAL RESULTS

Results of Surface Heave Measurements

The area was kept cleared of snow for the entire winter period. Figures 3 and 4 show the results of two winters' precise level surveys in the vicinity of one of the anchored footings. Because the pattern of heaving was similar around the other anchored column the results are not shown. The closest marker was 1 ft (.3 m) from one of the anchored columns. No elevations were established within this first foot, but visual observation indicated no noticeable change in the heaving pattern from that established by precise levelling. Figure 5 compares the average heave within 3 ft (.9 m) of the anchored columns with that of a surface marker 9 ft (2.7 m) from them during two winters. Heaving is shown to be similar, and it is concluded that the anchored columns did not impede frost heave of the soil. It is important to know this for a realistic assessment of the adfreezing phenomenon of soils to foundation elements.

Adfreezing Results and Thermal Conditions

The results of force measurements and related temperature measurements are given in Fig. 6A for the winter of 1966–67 and in Fig. 6B for the winter of 1967–68. The maximum total force transmitted from the heaving soil to the

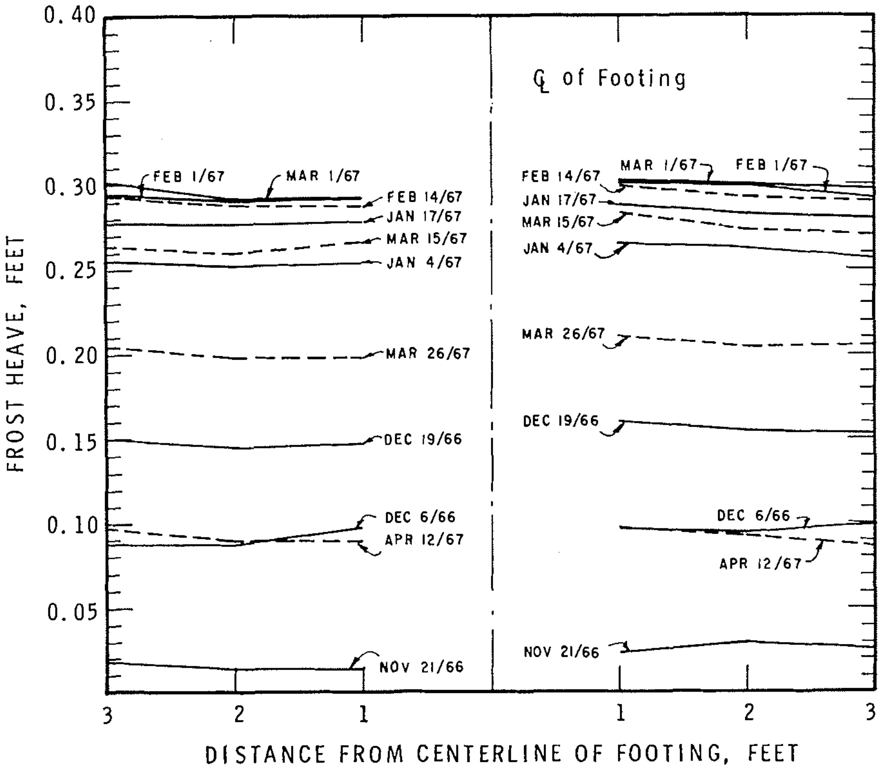

FIG. 3. Surface heave around anchored column for 1966–67.

3½-in. (8.9-cm) anchored steel column was approximately 6000 lb (2722 kg) for the first winter and approximately 5000 lb (2268 kg) for the second. It may be seen that the increase of force to these maxima occurred during a prolonged period of cold weather and continued to rise until the weather moderated (compare (b) and (c) in Fig. 6A and (b) and (c) in Fig. 6B). For both years the maxima appeared after substantial frost penetration had taken place.

The close relation between weather conditions and total generated force is evident. For both winters the temperatures at the 3-in. (7.6 cm) depth are given to show that reduction in total force occurs before the soil temperature rises above 0 °C as the weather moderates.

The apparent adfreeze strength plotted in Figs. 6A(a) and 6B(a) was calculated by dividing the force measured by the area of the column in contact with the frozen soil. The maximum apparent adfreeze strength calculated in this way was approximately 12 p.s.i. (.84 kg/cm^2). Figures 6A(d, e) and 6B(d, e) give the degree–day curve, freezing index, temperature at 3-in. (7.6 cm) depth and depth of frost for both winters.

Discussion of Results

The principal objectives of this research were:

(1) to observe the displacement of the ground around anchored footings in order to select the most realistic method of calculating adfreeze strengths;

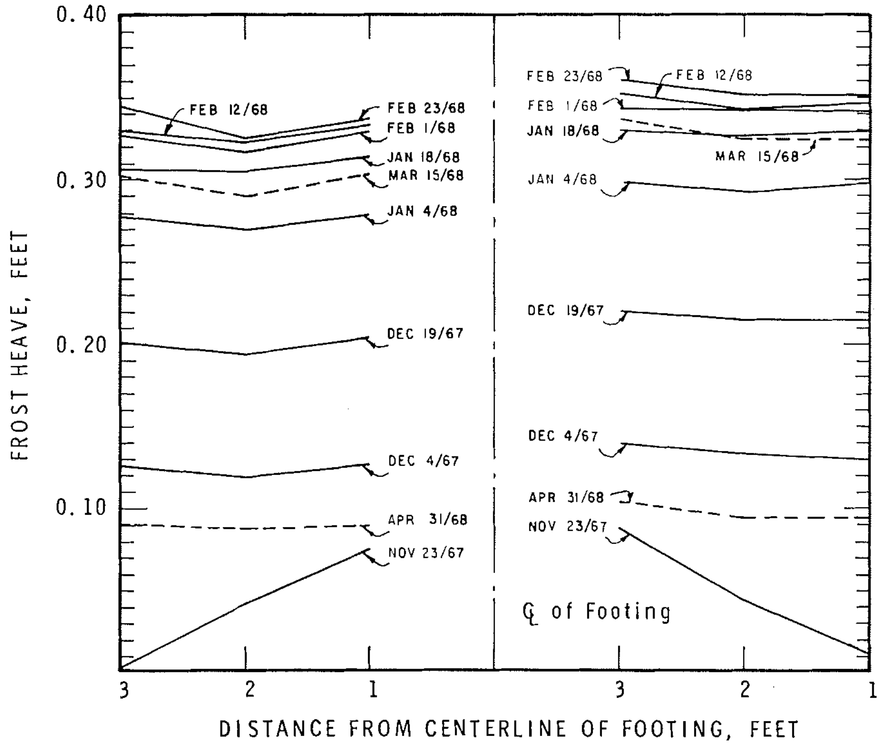

FIG. 4. Surface heave around anchored column for 1967–68.

(2) to determine experimentally the magnitude and variation of frost-heaving forces on small footing columns in Leda clay under natural conditions in the field.

The results of the experiments indicate that when a frost-heaving soil such as Leda clay adfreezes to an anchored structure it does not become rigidly bonded, but that continued strain or plastic flow occurs immediately adjacent to the structure to accommodate the natural rate of heaving of the surrounding area. This observation is supported by Russian studies (Saltykov 1944) showing that the heave characteristics of the surrounding soil are unimpeded by adfreezing except within a 1-cm layer of the structure.

Computations using Dalmatov's (1957) formula (Eq. [2]) and coefficients for predicting the maximum heaving force transmitted to the structure for both seasons are in agreement with the measurements presented in Figs. 6A(c) and 6B(c). Dalmatov's constants ($c = 0.4$, $b = 0.1$), are based, however, on experiments in a silty clay loam and for wooden piles. Agreement may be fortuitous, to some extent, since the total force is partly dependent on soil type and the type of adfreezing material of the structure. According to Kinoshita and Ono (1963) the maximum adfreezing strength on iron pipes is 2.1 kg/cm^2, on vinyl pipe 1.65 kg/cm^2, on concrete pipe 1.16 kg/cm^2, and on concrete pipe coated with epoxy-resin paint 0.52 kg/cm^2. The results of the present study show an apparent adfreeze strength of less than 1 kg/cm^2 (12.5 p.s.i.) on a steel pipe. These differences indicate that the value of the

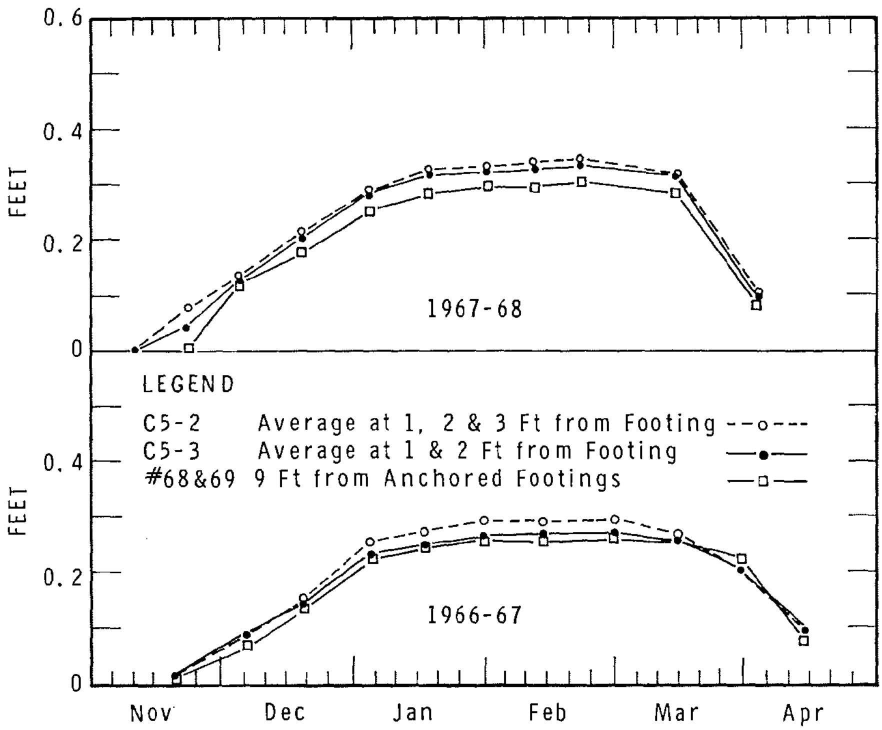

FIG. 5. Surface heave near anchored footing and at a distance.

constant determined by Dalmatov (1957) for wood is not completely valid for other structural materials.

The experiments show that build-up of heave forces to a high value of adfreezing occurs during a period of prolonged cold weather. The forces, however, respond very rapidly to a warm spell. Although the ground remains frozen, Figs. 6A(c, d), 6B(c, d), the forces drop off sharply owing to a reduction in the adfreezing strength and heave rate of the soil.

As the measured adfreezing strength becomes evident only when strain is produced by the frost heaving process, it is more correctly called "apparent adfreezing strength."

CONCLUSIONS

It has been demonstrated under field conditions that uplift forces by adfreezing in Leda clay can be as high as 6000 lb (2722 kg) on $3\frac{1}{2}$-in. (8.9-cm) diameter steel pipes. This corresponds to an apparent adfreezing strength in excess of 12.5 p.s.i. ($\approx$0.9 kg/cm^2). Hence, placing foundation footings below the depth of frost penetration does not ensure stability of a structure against frost heaving if the soil is allowed to freeze to the foundation wall or column.

Adfreezing does not appear to impede ground heaving next to an anchored footing column. This observation is in agreement with recent Russian literature on the subject. It is concluded that a practical method of calculating adfreezing strength is to divide the total heaving force by the area of contact between the frozen soil and the column or foundation wall, as opposed to the analyses used by Trow (1955). Variation of the total heaving force is strongly dependent on soil

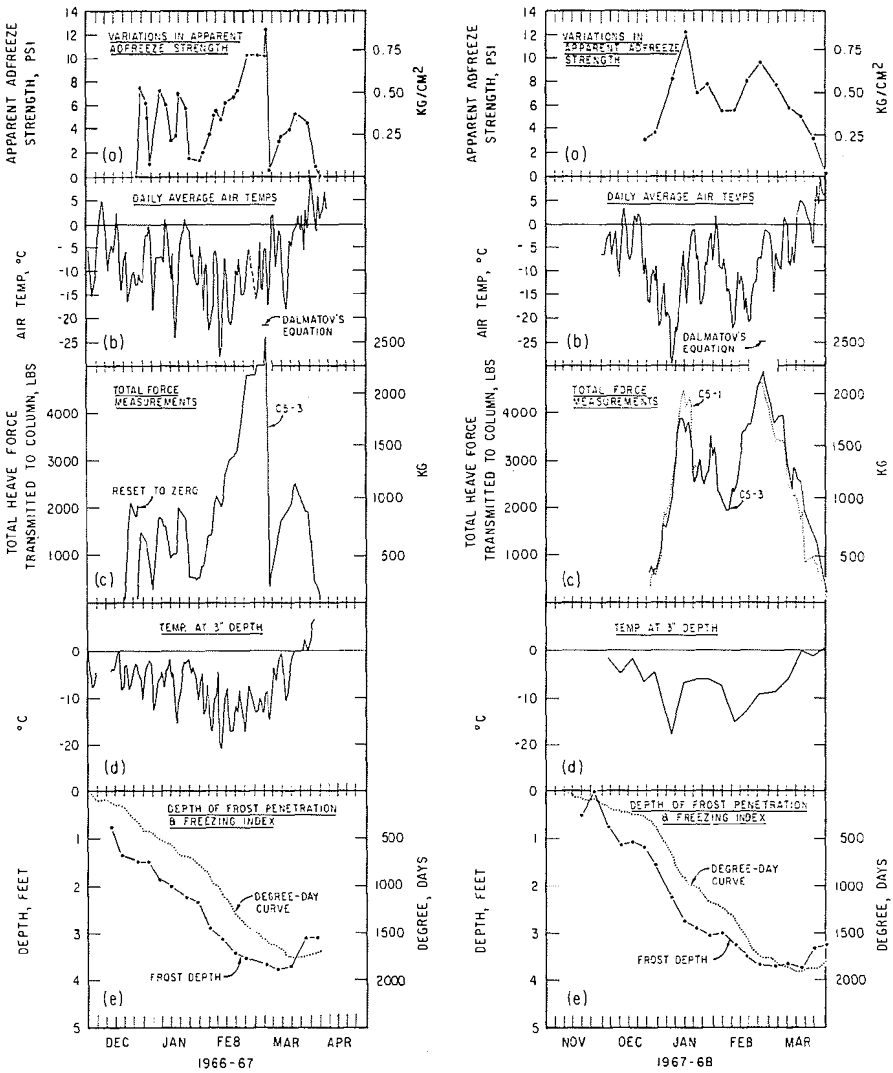

FIG. 6. Force, adfreeze strength, and temperature conditions.

temperature. Prolonged cold periods result in large forces. Warming periods have the opposite effect, and it is generally more immediate.

For designers faced with the need to assign values of total uplift by adfreezing resulting from frost action, Dalmatov's equation is a reasonable guide. In the meantime, further field studies on apparent adfreeze strength and heave force are in progress at the Division of Building Research of the National Research Council of Canada.

ACKNOWLEDGMENTS

The authors wish to express their appreciation to members of the Soil Mechanics Section of the Division of Building Research, National Research

Council of Canada, for their assistance with the studies, in particular Mr. D. Eldred.

This paper is a contribution from the Division of Building Research, National Research Council of Canada, and is published with the approval of the Director of the Division.

REFERENCES

CRAWFORD, C. B. 1961. Engineering studies of Leda clay soils in Canada. Roy. Soc. Can., Spec. Publ. No. 3, Univ. Toronto Press, Toronto. (Revised 1965.)

DALMATOV, B. I. 1957. Effect of frost heaving on foundations of structures. Gosizd literatuy po stroitch stuv i arkhitekture. Leningrad, Moscow.

KINOSHITA, S. and ONO, T. 1963. Heaving forces of frozen ground. I. Mainly on the results of field research. Low Temperature Science Laboratory, Teron Kagaku, Serial A, **21**, pp. 117–139. (Translation on file, Nat. Sci. Library, Nat. Res. Council Can., Ottawa, TT 1246, 1966.)

SALTYKOV, N. I. 1944. Calculating frost heaving forces on foundations. Izvestiia Akademii Nauk SSSR, Otdelenie Tekhnickeskikh Nauk, No. 6, pp. 305–412. (Translation 46 by Jaroslov J. Peel, Sipre Bibliography Project, Library of Congress, Washington.)

TROW, W. A. 1955. Frost action on small footings. Highway Research Board, Washington, Bulletin 100, pp. 22–27.

TSYTOVICH, N. A. 1959. Principles of geocryology; Part II, Engineering geocryology; Chapter III, Basic mechanics of freezing, frozen and thawing soils. pp. 28–79. Tech. Transl. 1239, Div. Building Res., Nat. Res. Council Can., Ottawa, 1966.

VIALOV, S. S. 1959. Reologicheskie Sovvistva i nesushchara sposobnost merzliykh gruntov. Izdatel' stov Akademii Nauk SSSR, Moscow. (Reological properties and bearing capacity of frozen soils.) Transl. 74, U.S. Army Materiel Command, CRREL, Hanover, September 1965.