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UPLIFT FORCES ON FOUNDATIONS IN FROST HEAVING SOILS

BY

EDWARD PENNER

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Uplift Forces on Foundations in Frost Heaving Soils

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Field studies of uplift forces by frost heaving are described for columns of various types and sizes and for a block concrete wall. The changing ground surface heave pattern around the block wall was used to predict the maximum heaving force which compared favorably with the measured value.

Unit adfreeze strengths and maximum uplift forces were highest for steel columns, followed by concrete and wood; the lowest values were for the block concrete wall. In general, unit adfreeze strengths were highest for the small diameter columns and lowest on the largest columns. Differences are ascribed to the response of the various materials to air temperatures and to the shape and size of the structure.

L'auteur décrit des études sur place des forces de soulèvement dues au gel relativement à divers types de poteaux de différentes dimensions et à un mur de blocs de béton. Les variations de soulèvement du sol naturel autour du mur de blocs servent à prédire la force de soulèvement maximale, celle-ci étant assez rapprochée de la valeur mesurée.

Pour ce qui est de la résistance unitaire en adhérence de la glace et des forces de soulèvement maximales, les poteaux d'acier présentent les valeurs les plus élevées, suivis des poteaux de béton et de bois; le mur de blocs de béton produit les valeurs les plus faibles. La résistance en adhérence de la glace est généralement plus élevée pour les poteaux de moindre diamètre et plus faible pour les poteaux plus larges. On attribue ces différences à l'effet de la température de l'air sur les matériaux ainsi qu'à la forme et aux dimensions de la construction.

Vertical displacement of foundations in seasonal frost areas is a common occurrence where the soils are frost susceptible. Placing footings below the depth of frost penetration does not necessarily protect foundation structures from heaving unless adfreezing of the soil to the structure is prevented or the load on the structure exceeds the maximum uplift forces.

Uplift in frost-susceptible soils resulting from adfreezing is a serious stability problem for some types of transmission towers, utility poles for telephone and power lines, transformer and distribution station structures, and unheated building foundations. Relatively few studies related to this problem, however, appear in the literature.

Crory and Reed (1965) and Vialov (1959) have shown the uplift forces to be substantial in the active layer of permafrost regions. Tsytovich *et al.* (1959) and Saltykov (1944) have studied some aspects of the problem in areas of seasonal frost in the U.S.S.R. The early work of Trow (1955) is well known in Canada as is the work of Kinoshita and Ono (1963) that was carried out in Japan.

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The Division of Building Research has investigated and published results on various aspects of the uplift problem in the field due to frost heaving. The initial paper (Penner and Irwin 1969) was concerned with measured uplift forces due to adfreezing on small diameter steel piles; in a second paper (Penner and Gold 1971) uplift forces were compared between small diameter wood, concrete, and steel columns.

The objective of the work reported in this paper was to determine the influence of column diameter on uplift force and adfreeze strength for the three commonly used foundation materials, wood, concrete, and steel. A study of a block concrete wall, more complete than was described earlier (Penner and Gold 1971), it is also included. Special attention is given to the ground surface deformation around different structures. The heave deformation pattern is discussed in some detail and a method of calculating uplift forces on the foundation wall from the heave pattern is given.

All the studies referred to were carried out in Ottawa on the same site. Adfreeze uplift forces, however, are known to be influenced by climate and soil type. Studies similar to those discussed here are at present underway at Thompson, Manitoba, to obtain more detailed information on this point.

Uplift Forces by Adfreezing

Vertical displacement of foundation structures in frost-susceptible soil occurs because the wet soil freezes to the below-ground portion of the foundation within the frozen layer. Ice lensing, the cause of frost heaving, at the frozen–unfrozen ground boundary lifts structures embedded in the frozen layer unless special precautions are taken to prevent movement. When the structure is rigidly fixed so that uplift is prevented the heaving soil imposes maximum forces on the foundation and characteristic ground heave patterns result.

Evidence presented previously (Penner and Gold 1971) proved that the shape and size of the foundation unit influenced the heave deflection pattern of the ground in its vicinity. The heave deflection pattern observed at the ground surface around field structures is thought to be a direct reflection of the amount that the heave rate is modified at the freezing plane by the resisting forces of the fixed structure to which the soil is frozen. When such a pattern develops the amount of heave reduction decreases with distance from the column.

The rate of relative movement between a fixed structure and the soil, under field conditions, is dependent on the rate of ice lens growth. Ice lens growth in turn is dependent on moisture availability, the general frost susceptibility characteristics of the soil, and temperature conditions. For example, during warming trends in winter the temperature of the frozen soil rises and the apparent adfreeze strength is reduced (Saltykov 1944). In addition, the rate of ice lensing decreases (Penner 1960) because the thermal gradient is reduced. The frozen layer and the embedded structure, therefore, are subjected to uplift rates controlled by the temperature fluctuations in the weather.

As a result of temperature gradient fluctuations the frozen layer under natural conditions in the field is usually nonhomogeneous with respect to ice content. During periods of rapid heat withdrawal from the soil the ice lenses are numerous and closely spaced; during periods of low heat extraction the lenses tend to be greater in thickness and less numerous (Penner 1960). Also, the ice lensing process, the cause of uplift, only occurs when heat is withdrawn from the soil and it is not possible, therefore, to have a constant and uniform temperature in the frozen layer while forces are developing. It is not surprising, considering the continually changing and nonhomogeneous conditions with respect to the material and temperature of the frozen layer, that a rigorous viscoelastic theory has not been developed for the behavior of the seasonal adfreeze problem on foundation structures.

Complex thermal patterns are sometimes induced in the soil by the structure when it is exposed above the ground surface. The thermal influence on the soil is relatively large for steel structures, because of the differences in thermal conductivity, is much less for concrete, and is relatively negligible for wood structures as will be shown by the results of this study. This further complication is partly due to rapidly changing temperatures that cause continuing changes in the strength of frozen soils.

TABLE 1. Column diameters (in.)[1]

Nominal size (in.)	Average of measured diameter (in.) for each pair					
	Wood		Steel		Concrete	
3	W-3	3.42	S-3	3.50	C-3	3.45
6	W-6	6.01	S-6	6.63	C-6	5.98
12	W-12	11.00	S-12	12.75	C-12	12.00

[1] 1 in. = 2.54 cm.

In addition, ice lenses form normal to the direction of heat flow and the resultant forces are in the direction of heat flow. Complex thermal patterns, therefore, result in complex force fields and this inhibits the development of analytical or theoretical solutions to the problem as noted above.

Methods and Materials

Column and Block Concrete Wall Construction and Installation

Wood, concrete, and steel columns, 3, 6, and 12 in. (7.6, 15.2, and 30.5 cm) in diameter were used in this present study. Two of each material and size were installed randomly on the site; the results reported are based on averages.

The 3- and 6-in. (7.6- and 15.2-cm) diameter wood (cedar) columns were turned from solid stock obtained locally but the 12-in. (30.5-cm) columns were turned from laminated stock made from four 6 × 6-in. (15.2 × 15.2-cm) timbers. The surfaces of the wood columns at the time of installation were smooth, untreated, and unweathered.

The concrete columns were made from locally purchased ready-mix concrete. For the 3-in. (7.6-cm) diameter columns the concrete was placed inside a plastic pipe form; the 6- and 12-in. (15.2- and 30.5-cm) diameter columns were formed in sonotubes. A reinforcing rod was placed down the center line of all the concrete columns to facilitate handling and installation. Column surfaces were smooth with little evidence of air entrapment at the interface between the concrete and form.

The steel columns consisted of rolled steel pipes. The manufacturer's surface coating was removed with a solvent and the final treatment was to wire brush the surface until it was clean and relatively smooth. One-inch (2.5-cm) thick boiler plates were welded to both ends of the steel pipes to provide a substantial bearing surface for the force gauge at the upper end and a watertight seal at the lower end. Boiler plates were also placed on the upper ends of both the concrete and wood columns. These were seated with a neat cement–water mixture to provide a stable bearing surface for the force gauges and to distribute the load uniformly over the column ends. The measured diameters of the various column types and sizes are given in Table 1.

Thermocouples were installed at 1-ft (0.3-m) intervals on one of each column type and size with the exception of the 3-in. (7.6-cm) diameter wood and concrete columns. For those, soil temperature profiles measured at two locations on the site were used to estimate the length of column exposed to the frozen layer for adfreeze calculations. All columns were 6 ft (1.8 m) in length and embedded in the soil to a depth of 5 ft (1.5 m). Columns were placed in augered holes 6 in. (15.2 cm) larger than the column diameter and backfilled immediately with the same soil, then compacted to approximately the original density.

The block concrete wall was constructed in a trench 2 ft (0.6 m) wide, 5 ft (1.5 m) long, and 5 ft (1.5 m) deep. The wall, 8 in. (20.3 cm) wide and 4 ft (1.2 m) long, extended about 8 in. (20.3 cm) above the ground surface after completion. A 6 I 12 1/2 steel beam was placed on the block concrete wall to distribute the load uniformly across the top of the wall.

Temperature Measurements on the Site

Ground temperatures were measured at two locations on the snow cleared test site well away from snowbanks around the perimeter of the site. Twenty-gauge copper–constantan thermocouples were attached to 1-in. (2.5-cm) diameter wooden dowels at 6-in. (15.2-cm) intervals to a depth of 4.5 ft (2.7 m). Eighteen inches (45.7 cm) of the thermocouple lead were wrapped around the dowel at each thermocouple location to prevent errors due to heat flow along the wire. Both ground and column temperatures were recorded daily at about 0830 h with a digital data acquisition system.

Surveys

A rock anchored, 0.75-in. (1.9-cm) high tension steel rock bolt was used as a bench mark for level surveys. Weekly surveys were carried out in the top surface of all columns and on the center point of the reaction frames. The survey points on the structures were ⅜-in. (1-cm) self tapping screws.

The ground surface deflection pattern was also determined weekly from level surveys on lag bolts set into the asphalt surface at 0.5, 1, 2, 3, 4, 5, 6, and 7 ft (0.15, 0.3, 0.6, 0.9, 1.2, 1.5, 1.8, and 2.1 m) from the embedded steel columns and at the same distance from the sides and ends of the concrete block wall. Two lines of markers were used at the columns and four lines for the concrete wall. In the latter case, two lines were set out perpendicular to the long dimension of the wall and one from each end. The heave data given in the paper are the

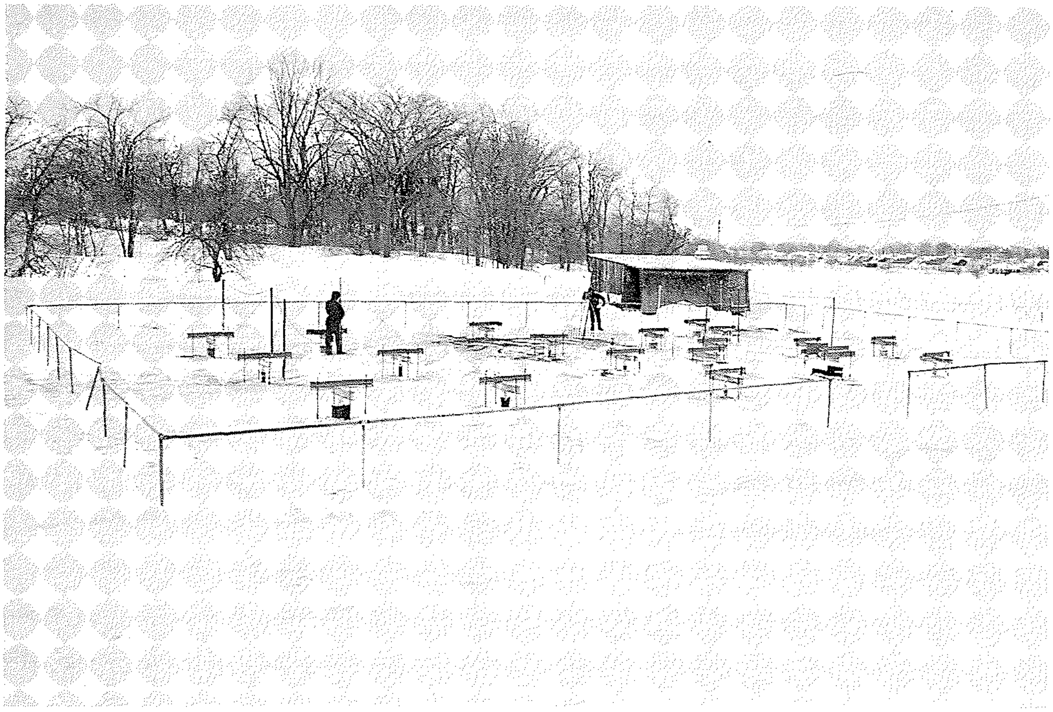


FIG. 1. Overall view of test site, its surroundings, and the test installations.

average of surveys on the two lines of surface markers.

Soil and Site Conditions

The test site, approximately 72 × 106 ft (21.9 × 32.3 m) in size, was located on National Research Council of Canada property on the Montreal Road toward the eastern city limits of Ottawa, Ontario. A detailed description of the soil deposit is given elsewhere (Crawford 1961). The moisture content was about 44% in the autumn and the average particle size analyses showed the soil to consist of about 70% clay size particles and 30% silt size. A working surface for the construction phase was provided by removing the grass sod and placing a 1.5- to 3-in. (3.8- to 7.6-cm) thick gravel pad and a 1.5-in. (3.8-cm) overlay of asphaltic concrete. Bedrock at the site, which was between 11 and 20 ft (3.3 and 6.1 m) below the ground surface, provided a convenient means of anchoring the reaction frames.

A view of the site, its surroundings, and the test installations are shown in an early winter view in Fig. 1. The test area was snow cleared whenever necessary. The building behind the test site is a temperature controlled instrument hut used for the temperature measuring data acquisition system and other instrumentation. A Stevenson screen located to the left of the instrument hut was used to measure air temperatures for freezing index calculations.

Design of Reaction Frames for Columns and Foundation Wall

The reaction frames shown in Fig. 1 were anchored 18 in. (45.7 cm) below bedrock surface with 0.75-in. (1.9-cm) high tension rock bolts and 1.25-in. (3.2-cm) expansion shells at the four corners of the frame. The design and construction are described in detail in a previous paper (Penner and Gold 1971) dealing with a comparison of adfreeze strength on small diameter columns.

Force Measurements – Dillon Gauges

The uplift forces on the 3-in. (7.6-cm) diameter columns were measured with 10-kip (454-kg) capacity force gauges, with 25-kip (11 350-kg) gauges for the 6-in. (15.2 cm) columns and with 50-kip (22 700-kg) gauges for the 12-in. (30.5-cm) diameter and the block concrete wall. The gauges were centered between the ends of the columns and the bottom of the reaction frame. For the wall, the uplift force was measured by using a Dillon gauge and a dummy gauge having similar deformation characteristics. They were placed at opposite ends of the structure between the wall and the reaction frame. The uplift force was taken to be twice the force measured on the Dillon gauge. Force readings were carried out daily starting at about 0830 h.

Experimental Results and Discussion

Block Concrete Wall

Heave Force, Adfreeze Strength, and Ground Surface Deformation

The measured uplift forces and calculated adfreeze strengths for this installation were given in a previous paper for the winter of

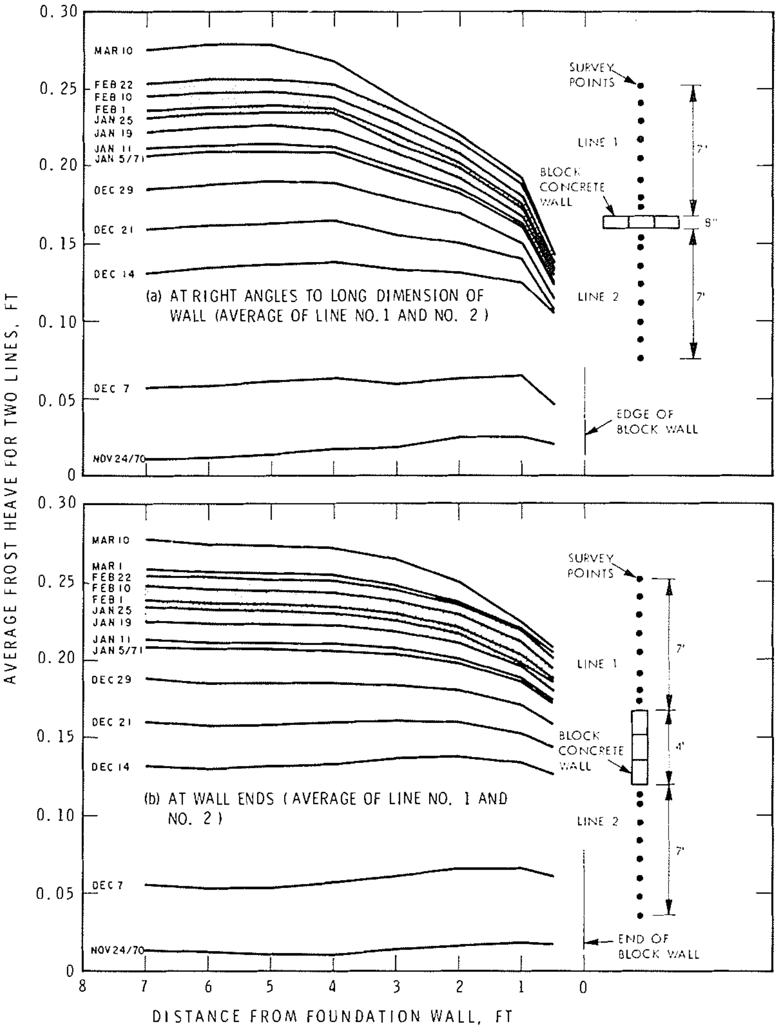


FIG. 2. Ground surface heave at ends of 4-ft (1.2-m) long concrete wall and at right angle to long dimension of wall, 1970–1971.

1969–70. The ground deformation measurements around the structures, later found to be necessary, were not made until the 1970–71 winter period and are reported here.

The ground surface deflection pattern based on weekly surveys is quite different at the ends of the wall from that at the sides (Fig. 2). The surface deflection pattern shows that the adfreezing of the soil suppresses the heave rate in the vicinity of the wall and this provides a novel method of calculating uplift forces. The daily force measurements, adfreeze strengths based on the area of the wall exposed to the frozen layer, and vertical movements of the wall due to the strain in the reaction assembly and gauges, are given in Fig. 3.

Predicting Total Uplift Force from the Ground Surface Deflection Pattern

The ground surface heave pattern was used previously (Penner 1970) and was shown to give reasonable estimates of the heave forces developed at the freezing plane. In this case the structure was a rigidly held plate at the ground surface. The same approach is used in the present study to estimate the total vertical force on the block concrete wall by adfreezing. The important assumptions are that, (*a*) the

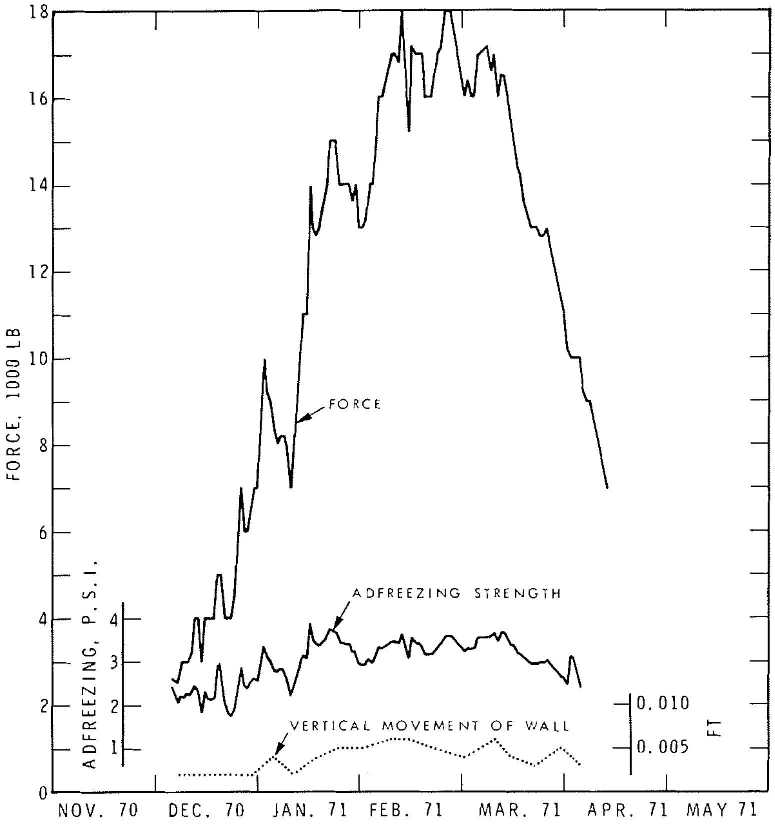


FIG. 3. Force measurements, calculated adfreeze strengths, and vertical movement of block wall during heaving period, 1970–1971.

main heaving forces are developed at the bottom of the frozen layer, and (*b*) the ground surface heave pattern results from the resisting forces of the adfreeze to the wall. Both are considered to be reasonable assumptions. Some redistribution of unfrozen water has been shown to occur within the frozen layer under laboratory conditions but from field measurements of ground heaving at various depths it appears this can be neglected. The deformation behavior of ice sheets around structures (Lofquist 1944) is thought to validate the second assumption although less well documented for soils (Saltykov 1944). This resistance to heave extends out from the wall and reduces the rate of heave at the freezing plane as shown by the heave pattern given in Fig. 2.

A solution can be developed if the influence of load on the heave rate is known for the soil in question. It was shown by Linell and Kaplar (1959) that heave rate R can be expressed by the following equation:

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

where: R_0 = heave rate at frost line, but not influenced by pile;
R = heave rate at pressure P;
P = applied pressure; and
a = constant for a given soil type (negative value).

The value of a for Leda clay at this particular site, shown previously to give reasonable values of P (Penner 1970), was −0.126. The R_0 value is the heave rate taken a distance of 7 ft (2.1 m) from the pile. At this distance, the influence of the piles on the ground heaving is not measurable.

The overburden due to the weight of the frozen layer is the same at all points away from the wall and hence does not enter into the calculations. P is, therefore, the pressure at the

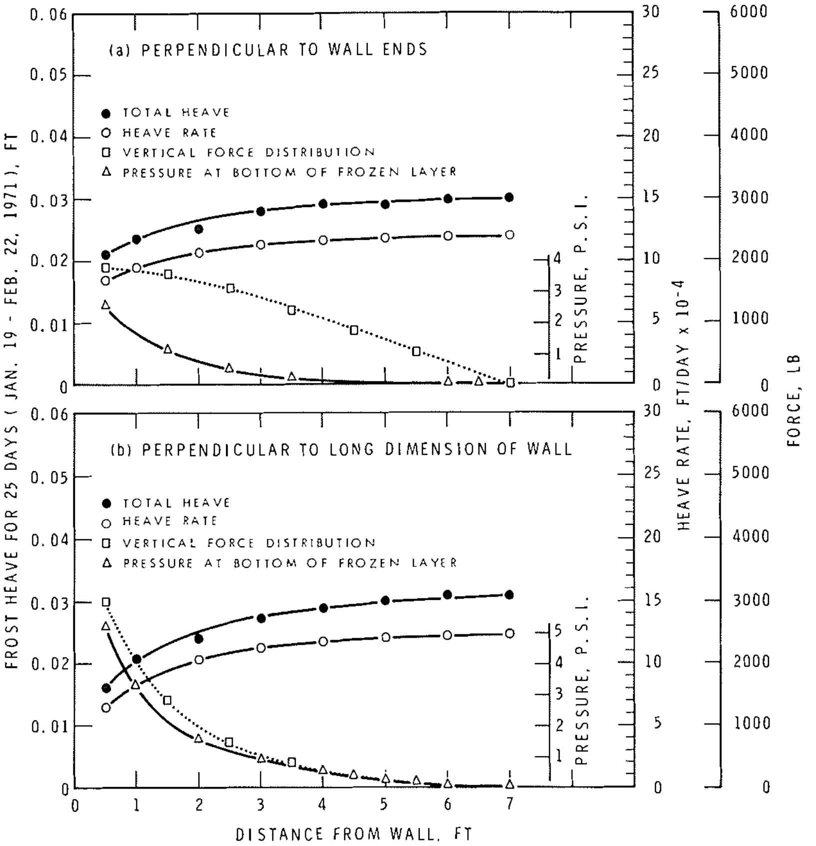


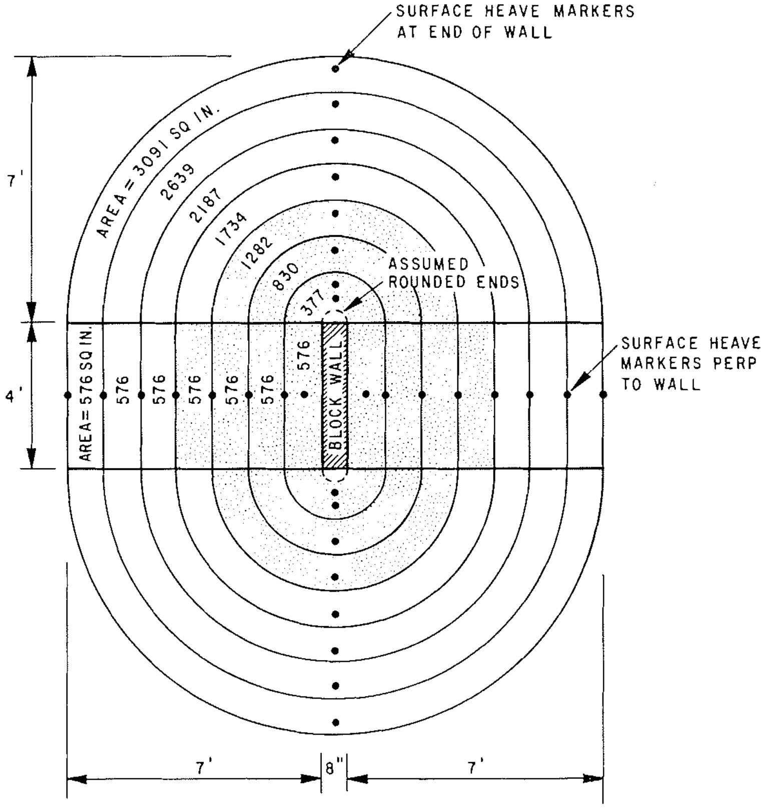
FIG. 4. Total heave, heave rate, vertical pressure, and force distribution at bottom of frozen layer as a function of distance from wall. Period Jan. 19–Feb. 22, 1971.

freezing front resulting from the resistance to heave imposed by adfreezing of the frozen soil layer to the fixed wall.

The maximum or near maximum uplift forces were developed during the period from January 19 to February 22, 1971 as shown by the shaded portions in Fig. 2. The heave rates were then calculated at distances from the wall of from 0.5 to 7 ft (0.15 to 2.1 m) at both the ends and the sides (Fig. 4). These rates were then used in Eq. [1] to calculate the pressure and finally the uplift forces in 1 ft (0.3 m) increments from the pile, in the area pattern shown in Fig. 5. The pressures calculated were divided by the particular area to which it applied (see Figs. 2 and 5) and the force calculated was plotted at the center of the given area *e.g.* the force between 1 and 2 ft (0.3 and 0.6 m) from the pile was plotted at a distance of 1.5 ft (0.46 m) from the pile (Fig. 4). Summing the upward force at the ends of the wall gives a value of 10 400 lb (4680 kg) and for the sides 11 900 lb (5355 kg) giving a total uplift force of 22 300 lb (10 035 kg). The measured maximum uplift force for the wall was 18 000 lb (8100 kg) (Fig. 3).

The agreement found between calculated and measured forces supports the validity of the heave and load transfer mechanism proposed. It was assumed, however, that there was no interaction between the different rates of heaving at the ends and sides. The heave boundaries between the sides and ends are not thought to be as sharply defined as those used in the calculations but no appropriate method was found to allow for the interaction.

The rationale on which the analytical approach is based is reasonable because the heaving phenomenon involved is well understood. The upward force is a direct result of



NOTE: DOTTED AREA SHOWS GREATEST DEFORMATION

FIG. 5. Pattern of areas involved for calculation of total force.

ice lens growth and the force generated is transmitted to the fixed wall. The differential heave pattern measured could only result from interference with ice lens growth.

Uplift Forces on Embedded Columns

The adfreeze studies for the wood and concrete columns extended over two consecutive winters, 1970–71, and 1971–72. Steel columns were added to the later study. The actual diameters of the columns were somewhat different from the nominal values and are given in Table 1. The symbol W is used to identify the wood columns, C the concrete, and S the steel, each accompanied by the nominal diameter, *e.g.* C-3 is a 3-in. (7.6-cm) diameter concrete column.

The time–depth relationship of the 0 °C isotherm measured at two locations on the site (not influenced by columns) and those for the various columns are given in Fig. 6 for the 1970–71 winter and in Fig. 7[1] for the 1971–72 winter. The column lengths over which the temperature was below 0 °C, and the average temperature, were much different for the steel columns than for the wood and concrete columns as would be expected. Figure 8 gives comparisons of the temperature profile on the 12-in. (30.5-cm) diameter columns for three arbitrarily selected days during the 1971–72 winter and Fig. 9 shows the influence of the column diameter on the column temperature profile. The temperature profiles for the wood column were almost the same as the ground temperature profile. The 12-in. (30.5-cm) diameter concrete column had temperatures a little lower than the ground at the same depth

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[1] The depth scale has been offset for each curve in the graphs (Figs. 6 and 7) to avoid the confusion of overlapping lines but the same scale has been maintained throughout as indicated.

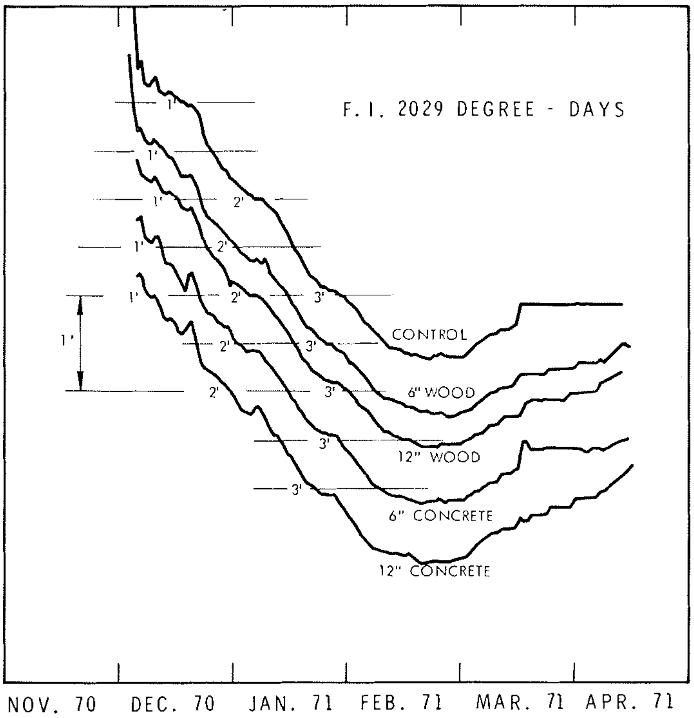

FIG. 6. Depth of 0 °C isotherm, 1970–1971.

but the 6-in. (15.2-cm) column had a temperature profile very similar to that for the ground. Large divergences from the ground temperature profile are very evident on the steel column and, as may be seen, this effect increases with column diameter.

The column area used to calculate adfreeze strengths was based on the depths of the 0 °C isotherm measured directly on the columns except for the 3-in. (7.6-cm) wood and concrete columns. These columns were not instrumented for temperature measurements and the depth of the 0 °C isotherm was assumed to be that given by the soil temperature profile. The error introduced in this way is not thought to be significant because the dependence of the depth of the 0 °C isotherm for the 6-in. (15.2-cm) wood and concrete columns was found to be almost the same as for the undisturbed ground.

Some movement of the columns, although small compared with the total heave, was unavoidable. The vertical movements ranged between 0.005 and 0.020 ft (0.0015 and 0.0061 m) depending on the force imposed on the pile. These movements were due to the compression of the force gauge and slight adjustments in the reaction frame and rock bolt assembly as the load increased.

Steel Columns

The average ground surface heave patterns established from weekly level surveys on two radial lines of markers for each column are given in Fig. 10. These heave patterns display the same general characteristics as those for the ends and sides of the concrete wall. The greatest suppression of heave in the surrounding soil was around the 12-in. (30.5-cm) diameter column and the least around the 3-in. (7.6-cm) column, in fact, the ground around the 3-in. (7.6-cm) column showed little evidence of heave suppression.

Figure 11 gives daily force measurements, calculated adfreeze values, and column strain based on the average for two 12-in. (30.5-cm) diameter steel columns. The area of the column within the frozen zone for adfreeze calculation was based on the daily position of the 0 °C isotherm on the soil – steel column interface. Graphs similar to Fig. 11 were prepared for all columns but the results will be presented in

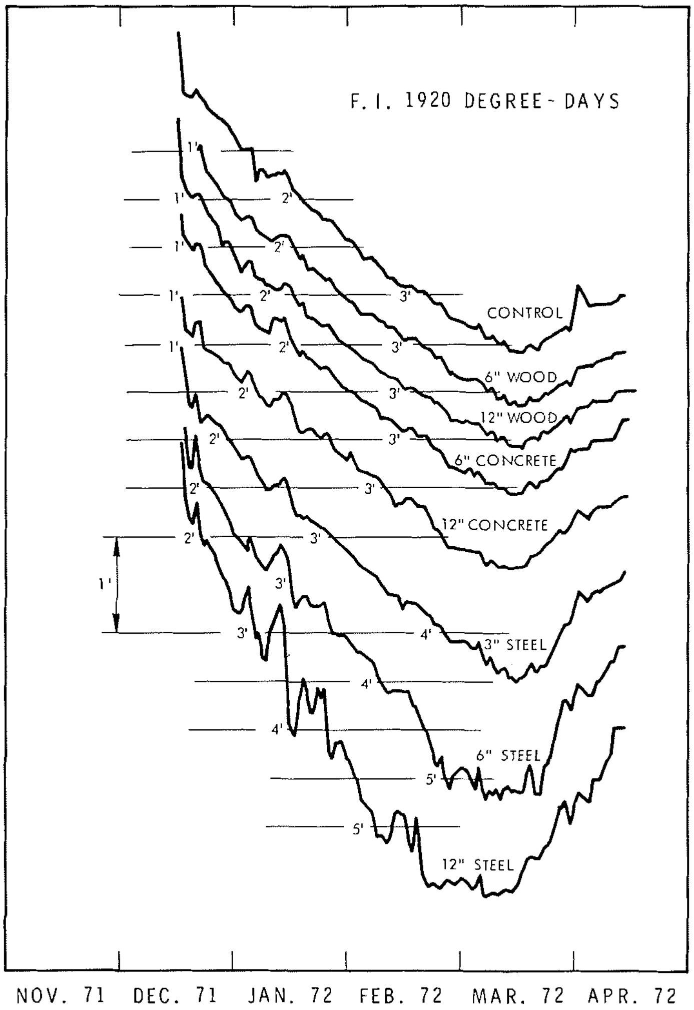

FIG. 7. Depth of 0 °C isotherm, 1971–1972.

tabular form only to conserve space. The detailed field results for one pair of columns (12-in. (30.5-cm) diameter) are given here to show the pattern of the total force and adfreeze values during one winter period to draw attention to the daily variations that occur during naturally varying climate conditions. These variations are a direct reflection of the response of the ground temperature and ground temperature gradients to changes in air temperature. Adfreeze strengths are temperature dependent and ground thermal gradients are of paramount importance in establishing heave rates and hence displacement rates in the soil surrounding the columns. Both are involved in the transfer mechanism of uplift forces from frozen soil to column.

Adfreeze strength comparisons between column type and diameter are made on the basis of peak values for the month and average monthly means (Table 2). Adfreeze strengths for the steel columns are highest for the smallest column (3-in. (7.6-cm)), intermediate for the 6-in. (15.2-cm), and lowest for the 12-in. (30.5-cm) diameter column. This is the order in which the results would be expected to fall based on the predicted values for the block wall ends and sides. It is also in agreement with the analysis of Lofquist (1944) for uplift forces by ice covers on structures when the

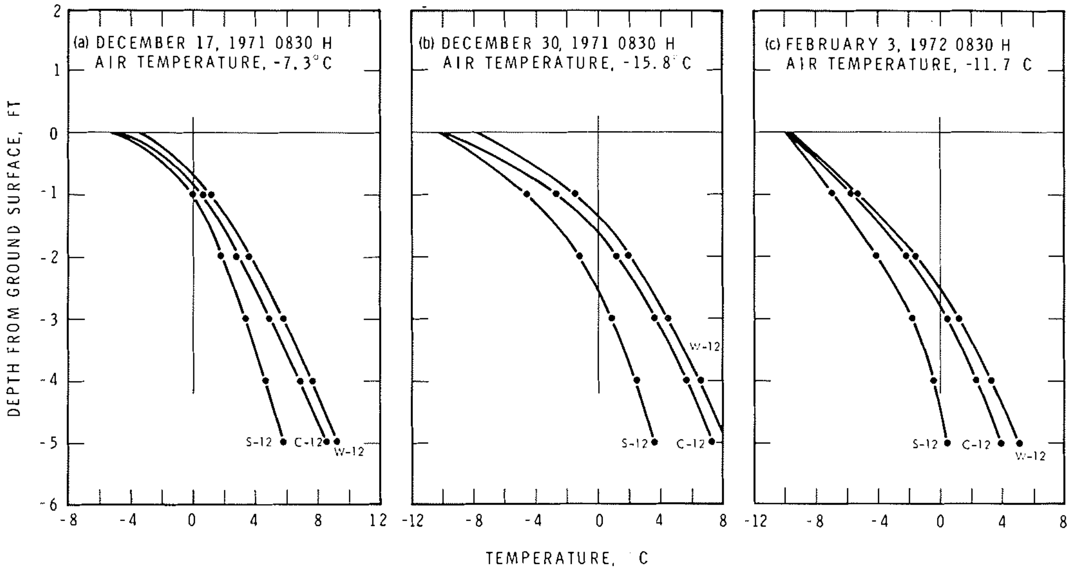

FIG. 8. Comparison of temperature profiles on the large diameter steel, wood, and concrete piles at various times during the winter. Note: (1) Piles were exposed 1 ft (0.3 m) above ground surface, snow cleared area. (2) Ground temperature profile similar to that of wood pile.

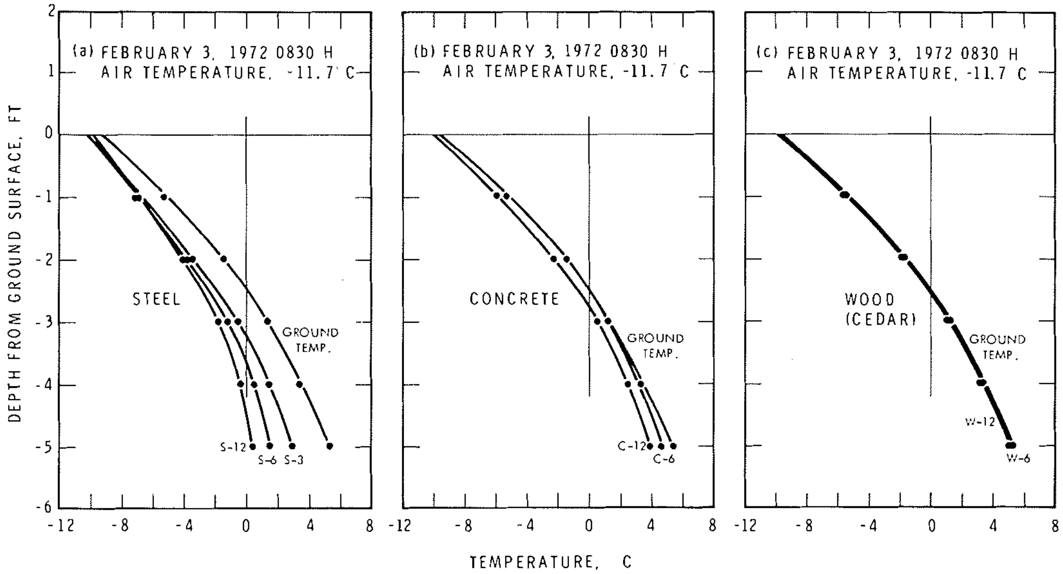

FIG. 9. Comparison of temperature profiles on piles of various sizes and materials in relation to the ground temperature profile on the site. Note: Broad line in part (C) includes the temperature profile for wood-12, -6, and natural ground, snow cleared area.

water level rises, a problem that has many similarities to the adfreezing uplift forces on structures in frost-susceptible soils (Penner and Gold 1971).

While weekly or monthly adfreeze values are thought to be useful for comparisons between column material and size, damage to the structure may occur unless peak adfreeze values resulting from rapid changes in the ground temperature are known. These are also given in Table 2 for all the foundation structures involved in the present study: 2 years of observa-

TABLE 2. Monthly mean, peak adfreeze, and peak force values for columns and the block concrete wall

	December			January			February			March			Season average		
Steel columns 1971–72 freezing index 1920 degree-days															
	S-3	S-6	S-12	S-3	S-6	S-12	S-3	S-6	S-12	S-3	S-6	S-12	S-3	S-6	S-12
Peak adfreeze (p.s.i.)[1]	37.0	29.4	25.0	25.6	19.7	13.9	16.0	15.4	11.1	14.8	13.6	11.4			
Avg. adfreeze (p.s.i.)	25.3	20.0	15.3	12.7	11.0	9.4	12.9	12.8	9.1	10.2	10.6	10.5	15.3	13.6	11.1
Peak force (kips)[2]	8.7	13.6	23.0	7.5	12.3	18.5	8.2	15.6	28.0	8.2	17.7	31.0			
Concrete columns 1970–71 freezing index 2029 degree-days															
	C-3	C-6	C-12	C-3	C-6	C-12	C-3	C-6	C-12	C-3	C-6	C-12	C-3	C-6	C-12
Peak adfreeze (p.s.i.)	16.5	21.8	17.3	16.2	21.5	16.6	14.7	16.0	14.1	7.5	10.0	9.0			
Avg. adfreeze (p.s.i.)	13.1	18.9	14.8	11.5	15.5	13.4	10.0	13.8	12.0	5.6	7.4	6.1	10.1	13.9	11.6
Peak force (kips)	3.9	9.3	14.4	6.0	11.6	20.6	6.6	12.4	23.0	3.5	8.0	13.5			
Concrete columns 1971–72 freezing index 1920 degree-days															
Peak adfreeze (p.s.i.)	27.9	36.1	20.4	12.8	16.3	12.0	10.9	13.2	9.1	7.5	8.9	7.0			
Avg. adfreeze (p.s.i.)	12.3	19.7	14.3	7.7	11.5	8.1	7.4	9.7	8.3	5.5	6.6	6.6	8.2	11.9	9.3
Peak force (kips)	3.6	8.1	12.8	3.4	7.5	10.1	3.9	8.0	11.9	3.4	6.7	11.8			
Wood columns 1970–71 freezing index 2029 degree-days															
	W-3	W-6	W-12	W-3	W-6	W-12	W-3	W-6	W-12	W-3	W-6	W-12	W-3	W-6	W-12
Peak adfreeze (p.s.i.)	16.8	25.7	20.2	14.0	16.4	13.3	10.8	12.7	10.4	4.0	7.6	7.1			
Avg. adfreeze (p.s.i.)	12.0	16.9	14.4	10.0	12.1	10.0	7.5	9.8	8.6	2.7	5.0	5.8	8.1	11.0	9.7
Peak force (kips)	3.1	7.3	10.0	4.9	9.3	12.3	5.0	9.7	13.9	2.0	6.2	10.1			
Wood columns 1971–72 freezing index 1920 degree-days															
Peak adfreeze (p.s.i.)	19.0	32.8	35.3	11.1	15.2	12.3	10.7	12.0	10.2	7.5	8.9	7.9			
Avg. adfreeze (p.s.i.)	11.0	17.0	15.3	7.1	10.0	8.4	6.9	8.8	7.4	4.8	6.3	8.3	7.5	10.5	9.4
Peak force (kips)	2.4	7.3	14.1	2.8	6.6	9.8	3.7	7.3	11.5	3.2	6.7	11.3			
Block concrete wall 1969–70 freezing index 2039 degree-days															
Peak adfreeze (p.s.i.)		11.4			7.3			6.5			6.5				
Avg. adfreeze (p.s.i.)		6.8			6.5			6.3			4.2			6.0	
Peak force (kips)		16.0			27.0			30.8			31.0				
Block concrete wall 1970–71 freezing index 2029 degree-days															
Peak adfreeze (p.s.i.)		3.0			3.9			3.7			3.7				
Avg. adfreeze (p.s.i.)		2.6			3.1			3.4			3.2			3.1	
Peak force (kips)		7.3			15.0			18.0			17.2				

[1] 1 p.s.i. = 0.07 kg/cm^2.

[2] 1 kip = 454 kg.

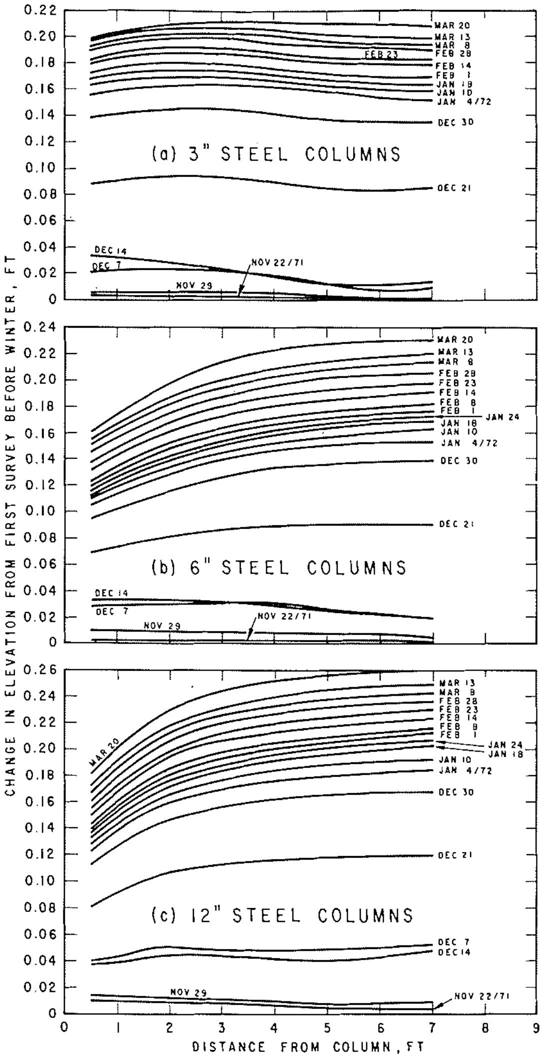

FIG. 10. Ground surface heave pattern around 3-, 6-, and 12-in. (7.6-, 15.2-, and 30.5-cm) steel columns, 1971–1972.

tions on the block concrete wall, 1969–70 and 1970–71; 2 years on the wood and concrete columns, 1970–71 and 1971–72; and 1 year on the steel columns 1971–72.

The temperature at the bottom of the 6- and 12-in. (15.2- and 30.5-cm) steel columns which were embedded to a depth of 5 ft (1.5 m) dropped below 0 °C at the end of February 1972 (Fig. 7). This did not occur on any of the other columns. The maximum force shown in Fig. 11 (12-in. (30.5-cm) steel columns) may be high by 3000–4000 lb (1350–1800 kg) because of basal heaving. It should be noted, however, that the heave forces and direction of heat flow at the freezing point are always normal to the freezing plane (Fig. 12) which probably accounts for the relatively small contribution to the total force after the frost line penetrated beyond the end of the column. Only the vertical components of the force contribute to uplift.

The rates of vertical movement of the frozen soil (heave rate) relative to the steel columns and adfreeze strengths on a weekly basis are given in Fig. 13. At the beginning of the winter when the frost penetration rates and frost heave rates were at their highest the adfreeze strength was also high. The rate of relative displacement between soil and column appears to influence the apparent adfreeze strength which is described in Soviet literature and more recently by Johnston and Ladanyi (1972).

Calculation of the total uplift force from the heaving pattern around the steel piles, as was carried out for the block concrete wall, was not possible. As the maximum forces were being approached the frost line had advanced beyond the base of the two larger columns (6- and 12-in. (15.2- and 30.5-cm) diameter) hence the uplift forces could not be assigned to adfreeze only.

Wood and Concrete Columns

The adfreeze measurements on steel columns discussed previously were for one winter only, 1971–72. The same measurements for wood and concrete columns were carried out for two consecutive winters, 1970–71 and 1971–72 (Table 2). The general pattern of adfreeze and total uplift forces was similar to the steel columns. The exception was that the lowest adfreeze values were obtained on the 3-in. (7.6-cm) diameter columns for both materials and both winter periods. The order for the 6- and 12-in. (15.2- and 30.5-cm) diameter columns was the same as for the steel columns, *i.e.* the higher adfreeze values occurred on the 6-in. (15.2-cm) diameter columns. The reason for the anomaly regarding the 3-in. (7.6-cm) diameter columns remains unexplained although one possibility is that the stress and the associated strain of the soil around small diameter wood and concrete columns were sufficiently high to cause yielding.

Peak adfreeze values tended to be the highest

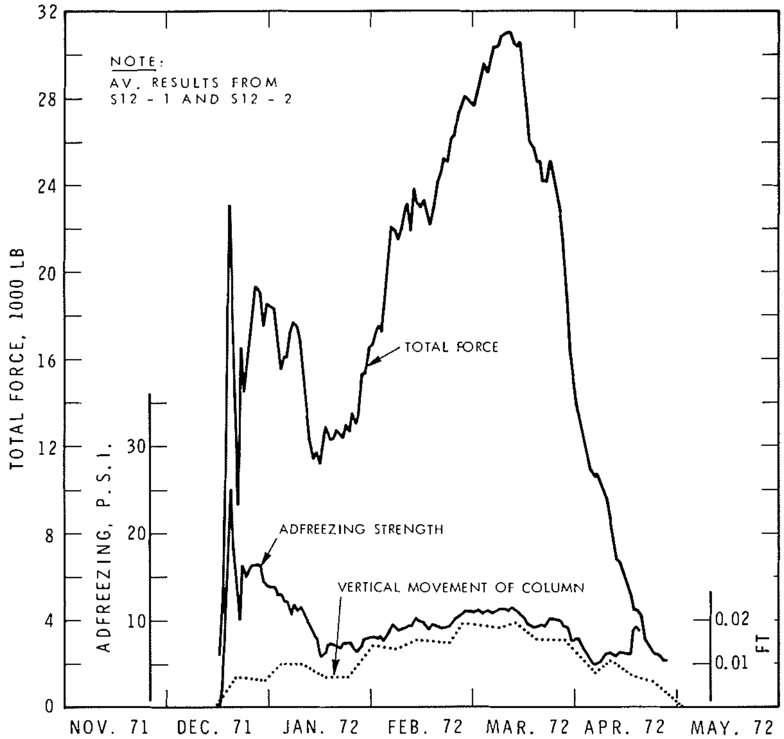

FIG. 11. Total force, adfreeze strength for 12-in. (15.2-cm) diameter steel pile, 1971–1972.

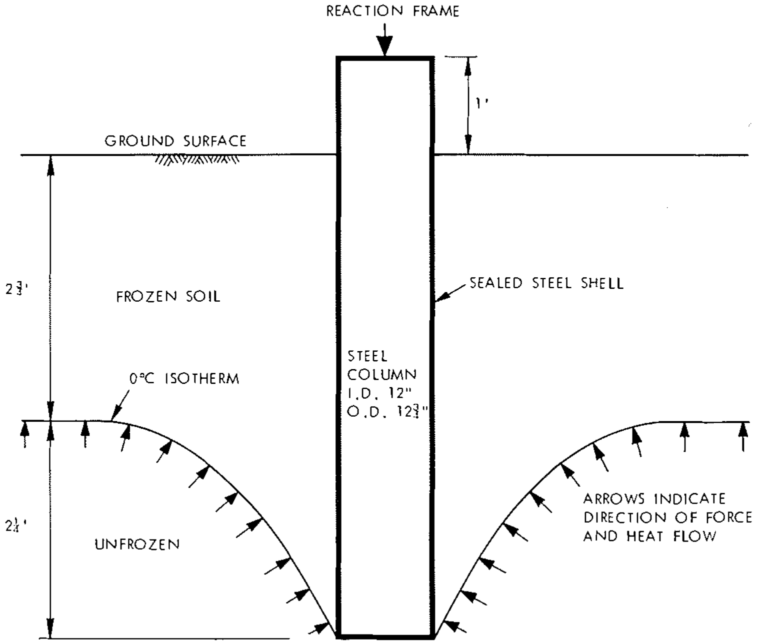

FIG. 12. Schematic of direction of heat flow and force as freezing front approaches bottom of 12-in. (15.2-cm) steel column.

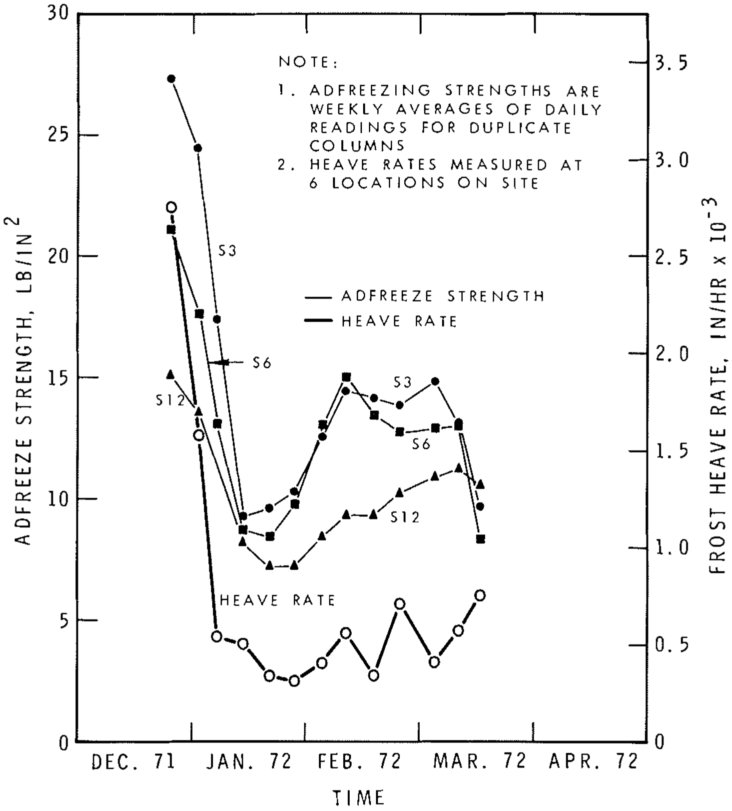

FIG. 13. Unimpeded frost heave rate on small footings site *versus* steel column adfreeze strength, 1971–1972.

at the onset of cold weather in the fall, although the maximum total uplift force on the pile occurred much later in the winter. Similar results were obtained for the steel piles.

Summary

Adfreeze strengths may vary from year to year as evidenced by the 1970–71, 1971–72 results for wood and concrete columns, and the concrete block wall results for 1969–70, 1970–71 (Table 2). While the overall severity of the winters based on the freezing index was similar, the differences may be attributable to other climatic influences such as changes in the moisture regime or the pattern of cold and warm periods during the winter.

The adfreeze strengths were highest for steel followed by concrete and wood. This is attributed mostly to the influence of temperature on adfreeze strength. The steel columns were normally colder than the wood and concrete columns. Saltykov (1944) and Tsytovich *et al.* (1959) have both shown the increase in adfreeze strength as the temperature decreases.

The maximum uplift forces were also higher on the steel columns. This is partly accounted for by the higher adfreeze strengths and the longer column length over which the adfreeze force was acting (Figs. 8 and 9). Extreme values in adfreeze strength differ by about a factor of two for the different materials studied, but for some periods the range is much less. Adfreeze strengths for the block wall are again much less than for any of the columns studied (Table 2).

Adfreeze strengths were highest for the smallest steel columns (3-in. (7.6-cm) diameter) followed by lower values for the 6-in. (15.2-cm) columns and lowest for the 12-in. (30.5-cm) columns. The results for the 3-in. (7.6-cm) diameter wood and concrete columns do not fall into this pattern but the 6- and 12-in. (15.2- and 30.5-cm) diameter columns followed the pattern for steel columns.

The deformation characteristics of ground heaving around columns appears to be related to column diameter (Fig. 10). A similar pattern was also evident between the side and ends of the concrete wall (Fig. 2).

The suppression of ground heaving by the fixed concrete block foundation wall and the resultant deformation pattern was used to predict the maximum total uplift force using Eq. [1] which was in reasonable agreement with the measured value. The mechanism of uplift envisaged, therefore, appears to be supported.

Peak values of adfreeze strength occur during the early freezing period when heaving rates are high, but maximum uplift forces often occur near the time of maximum frost penetration late in the winter season. The maximum uplift forces were highest for the steel columns followed by concrete and wood.

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