

Frost heave forces on embedded structural units

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Large-scale model studies of frost heave forces acting on horizontal, vertical, and inclined members embedded in a silt were carried out under frost penetration rates ranging from about 4 to 75 mm per day.

Maximum adfreeze stresses in the range of 150 to 350 kPa under varying rates of frost penetration were measured on steel structural angles embedded vertically in the soil. A limiting value of 350 kPa was attained at a freezing rate of 4 mm per day.

Maximum basal heave pressures in the range of 1900 to 2500 kPa were measured on a short steel structural member placed horizontally on the surface of the soil. No limiting value of basal heave pressure was attained under the test conditions used.

Limiting resultant vertical pressures ranging from 350 to 1300 kPa were measured on steel structural members embedded at an inclination of 45 degrees.

A graph of frost heave pressure *versus* member inclination was prepared on the basis of the study, which should serve as a guide for the design of structural units embedded in frost-susceptible soils.

Des études de modèles à grande échelle concernant les forces de soulèvement par le gel agissant sur des éléments horizontaux, verticaux et inclinés plantés dans du limon, ont été faites pour des vitesses de pénétration du gel allant d'environ 4 mm par jour à 75 mm par jour.

Des contraintes maximales dues à la prise par le gel, allant de 150 kPa à 350 kPa pour diverses vitesses de pénétration du gel, ont été mesurées sur des cornières d'acier plantées verticalement dans le sol. Une valeur limite de 350 kPa fut obtenue pour une vitesse de congélation de 4 mm par jour.

Des pressions maximales de soulèvement à la base, dans la gamme de 1900 kPa à 2500 kPa, furent mesurées sur un élément de charpente en acier court placé horizontalement à la surface du sol. Aucune valeur limite de la pression de soulèvement à la base ne fut obtenue dans les conditions d'essai utilisées.

Des pressions résultantes verticales limites entre 350 kPa et 1300 kPa furent mesurées sur des éléments de charpente en acier plantés à un angle de 45 degrés.

Une courbe de la pression de soulèvement due au gel en fonction de l'angle d'inclinaison de l'élément fut tracée à l'aide des résultats de l'étude, et cette courbe devrait servir de guide pour la conception d'unités structurales plantées dans des sols gélifs.

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Introduction

Structural units embedded in frost-susceptible soils may be subjected to significant forces associated with the freezing of the soil. The forces are generally manifested in one of two ways. If the soil beneath the unit freezes and expands, it exerts an upward pressure on the base of the unit. This pressure is referred to as *basal heave pressure* and has been investigated by

Domaschuk (1980), Kinoshita *et al.* (1963, 1967, 1978), Penner (1970, 1974), Sutherland and Gaskin (1973), Yong and Osler (1971), as well as several Russian investigators as reported by Tsytoovich (1975). The investigations included field tests, laboratory tests on small specimens, and model tests on a variety of soils (Table 1). The maximum pressures varied from 226 to 3035 kPa and appear to be affected more by method of test than by soil type.

TABLE 1. Maximum measured basal heave pressures

Soil type	Investigators	Method of test	Max. basal pressure (kPa)
silty clay loam	Kinoshita & Ono (1963)	field test, steel plate	2873
silty clay loam	Kinoshita (1967)	field test plate diam. = 0.3 m plate diam. = 0.12 m	1200 2950
clay (Leda)	Penner (1974)	field test, steel plate	1867
kaolin	Sutherland & Gaskin (1973)	lab test on cylindrical specimens	797
silt	Domaschuk (1980)	large model test	2400
sandy silt	Yong & Osler (1971)	lab test on cylindrical specimens	435
silty sand	Yong & Osler (1971)	lab test on cylindrical specimens	226
silty sand	Kinoshita <i>et al.</i> (1978)	field test, steel plate	3035

In the other manifestation of frost heave force, the soil freezes to the sides of the unit and as the soil expands it exerts an upward drag on the unit. The tangential stress generated at the soil-structure interface is referred to as *adfreeze stress*. Studies of adfreeze stress have been conducted by Russian investigators dating back to the 1930's as reported by Tsytoich (1975). Other investigators were Crory and Reed (1965), Domaschuk (1980), Johnston and Ladanyi (1972), Kinoshita and Ono (1963), Penner and Gold (1971), and Trow (1955). A variety of test methods were used some of which were determining the bond strength between a member and the frozen soil by loading the member; determining the bond strength between frozen soil and the sides of a container in which the soil was frozen; extracting structural members from frozen soil; laboratory model tests; and field tests in which members embedded in soil were prevented from moving upward as the surrounding soil froze and heaved (Table 2). The table indicates maximum adfreeze stresses ranging from 116 to 2756 kPa, and the wide range of these values can be attributed primarily to variations in test methods.

The method of test should simulate the field problem as much as possible. In this respect, tests in which the member is restrained while the soil in which it is embedded, freezes, provides the best measure of basal heave pressures and adfreeze stresses.

The basal heave pressure and adfreeze stresses reported in Tables 1 and 2 are applicable to horizontal and vertical surfaces only. There are instances in which structural members with *inclined* surfaces are embedded in soils which undergo freezing. Of particular interest to the writer, were the foundation units used to support the central mast of guyed towers used by Manitoba Hydro along a 900-kilometre DC line. The foundation unit (Figure 1) consisted of four inclined structural angles bolted to a welded cap at the top and to a steel grillage at the bottom thus forming a truncated pyramid.

The structural angles were inclined at an angle of 13 degrees from the vertical. The foundation units were approximately 2.3 m high and were installed with the top approximately 0.3 m above ground surface. Much of the soil along the hydro line consisted of a silt till. The groundwater table was at, or near, ground surface at many of the installations. Frost heave forces caused structural failure of a large number of these units a few years after their installation. The failures were in the form of caps splitting along the welds, shearing of bolts connecting the structural angles to the cap and the grillage, and bending and twisting of the inclined angles. One unit, which was in the process of being replaced when photographed, shows the extent of damage (Figure 2). It was apparent that frost heave forces in excess of those associated with adfreeze forces caused the unit to fail. The

TABLE 2. Maximum measured adfreeze stresses

Soil type	Investigators	Method of test	Max. adfreeze stress (kPa)
silty clay loam	Kinoshita & Ono (1963)	field test, members, restrained, iron pipe	210
		vinyl pipe	165
		concrete pipe	116
clay	Penner and Gold (1971)	field tests: concrete block wall	45-62
		steel column	96-114
		concrete column	90-134
		wood column	62-90
varved clay (permafrost)	Johnston & Ladanyi (1972)	field test, rod anchors extracted: Thompson, Man. Gillam, Man.	147-231 118-249
clay	Tsytoich (1975)	lab tests, breaking bond between wood stakes and frozen soil by loading the stakes	286-1834
silt	Crory and Reed (1965)	field test, piles restrained	275
silt	Domaschuk (1980)	large model studies, steel members restrained	234
Ottawa sand	Parameswaran (<i>Pers. commun.</i> 1979)	small model, piles extracted, wood	1220-2420
		steel	1146
		concrete	1611
sand	Tsytoich (1975)	lab tests, breaking bond between wood stakes and frozen soil by loading the stakes	128-2702
	Trow (1955)	lab tests, breaking bond between frozen soil and concrete container	2756

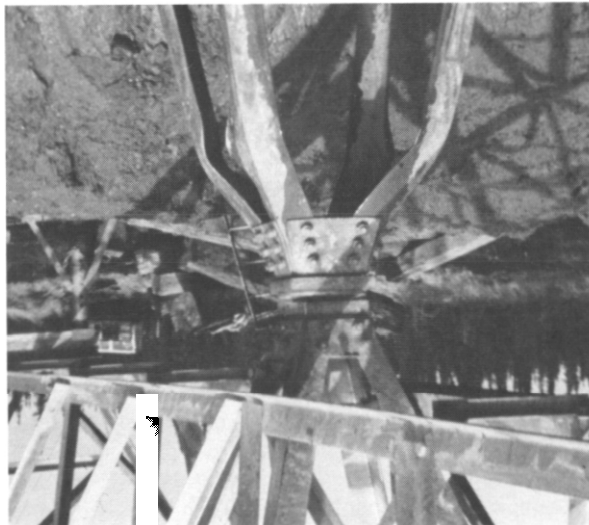


FIGURE 2. Failure of a transmission tower foundation by frost heave forces.

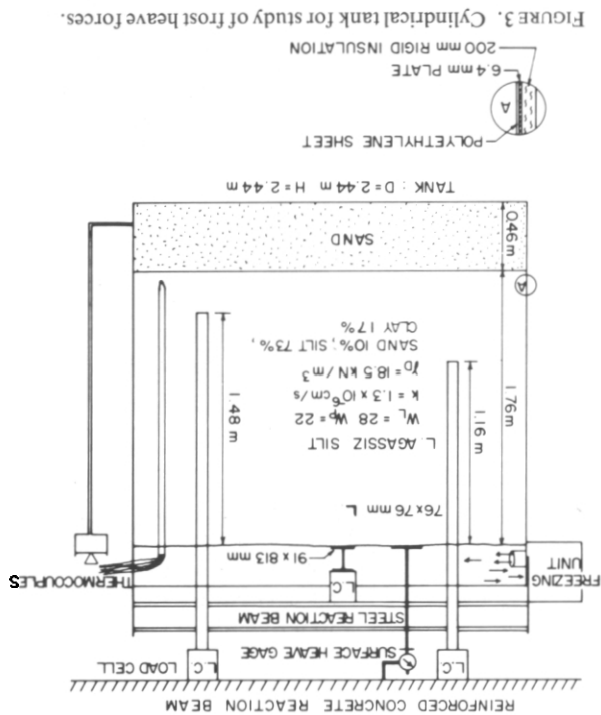


FIGURE 3. Cylindrical tank for study of frost heave forces.

tank was fibreglass-lined on the inside and was insulated on the outside. A sheet of polyethylene was placed between the wall of the tank and the soil to prevent the soil from freezing to the side of the tank. A layer of sand, 0.64 m thick, was placed in the bottom of the tank and 1.7 m of silt was placed over the sand. Water from an external source was supplied to the sand throughout the tests. The silt, commonly

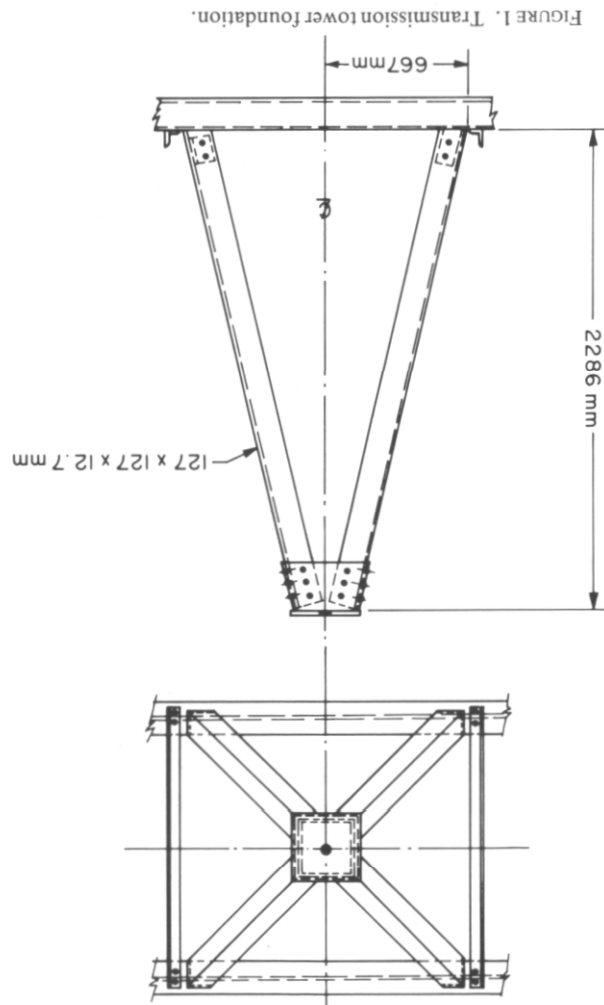


FIGURE 1. Transmission tower foundation.

Three adfreeze tests were carried out in a steel cylindrical tank, 2.44 m in diameter, 2.44 m in height, and filled with soil (Figure 3). The tank was constructed of 6.4 mm plate and consisted of two cylindrical halves joined by a circumferential flange 152 mm in width which provided lateral rigidity. The

Adfreeze Stresses

Equipment and Procedure

failures indicated the need for design information on the magnitude of frost heave forces on inclined members, information which was lacking at the time the units were designed. Consequently, with financial assistance from Manitoba Hydro, a research program was initiated at the University of Manitoba in which frost heave forces acting on vertical, horizontal, and inclined members were investigated. The results of the research are presented in this paper.

encountered in the soils of the Winnipeg area, and referred to as Agassiz silt, was an ML silt. Some of its properties are listed in Figure 3.

The refrigeration equipment used to freeze the soil, consisted of an evaporator with an electric fan and defrost mounted on the side of the tank, a water-cooled condenser, and a compressor. The capacity of the unit was one-half ton and the lowest air temperature attainable in the tank was -30°C . The air was blown across the surface of the soil, thus providing unidirectional freezing of the soil.

The adfreeze stress was investigated by measuring the vertical thrust exerted on two steel angles, 76.2×76.2 mm, embedded vertically in the soil to depths of 1.16 and 1.40 m. The vertical movement of a steel plate, 305×203 mm, with an attached rod, placed on the surface of the soil was used as a measure of the frost heave. Thermocouples mounted at 50.8-mm spacing on a wood strap embedded in the soil were used to monitor soil temperatures.

The tests were conducted using frost penetration rates of approximately 12, 25, and 75 mm per day.

A fourth test was later performed on the same soil in an improved testing facility and at a variable rate of frost penetration. The facility (Figure 4) consisted of a pit 2.44 m square and 1.83 m deep constructed of reinforced concrete, with prefabricated steel bin wall sections used above basement floor level to

extend the height of the pit. A layer of Agassiz silt approximately one metre thick, was placed over a thin layer of sand. Water was fed to the sand in a manner similar to that used in the cylindrical tank. The same refrigeration unit previously described was used and boundary temperatures of -3 to -5°C were used to achieve a slow rate of frost penetration. Initially the rate of frost penetration was approximately 28 mm per day, then decreased to a rate of about 4 mm per day at a frost depth of 0.4 m, and remained essentially constant thereafter. The rate indicated on subsequent figures is the latter constant rate. Soil temperatures and surface heave were monitored in the same manner as previously described. Adfreeze stress was determined by measuring the vertical thrust exerted on a structural steel angle, 89×89 mm, embedded vertically in the soil.

Test Results

The test results are presented as plots of surface heave, average temperature of the frozen soil, and average adfreeze stress, as a function of the depth of frost penetration. Surface heave occurred in each of four tests as the frost depth increased (Figure 5). For three tests, conducted at constant rates of frost penetration throughout the test, most of the surface heave occurred during the first half-metre of frost penetration. The heave continued throughout each test at a decreasing rate. The maximum heave for the three tests ranged from 35 to 50 mm with no consistent relationship between the maximum heave and the rate

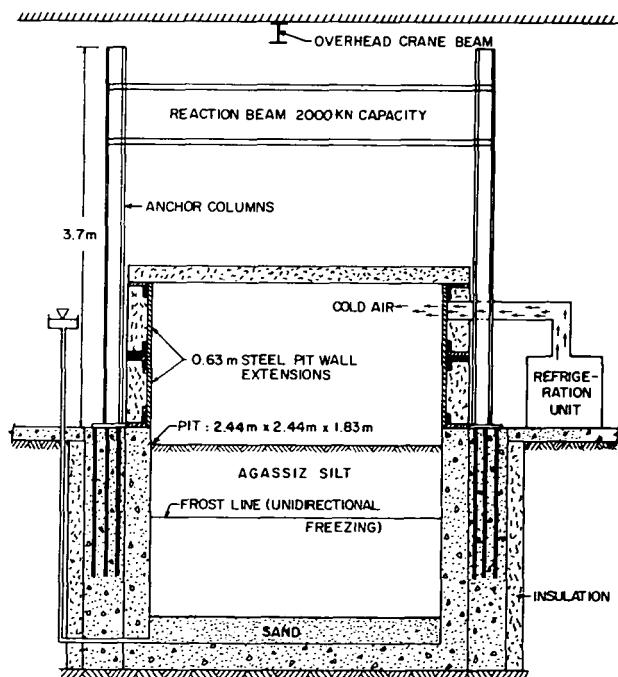


FIGURE 4. Test pit for study of frost heave forces.

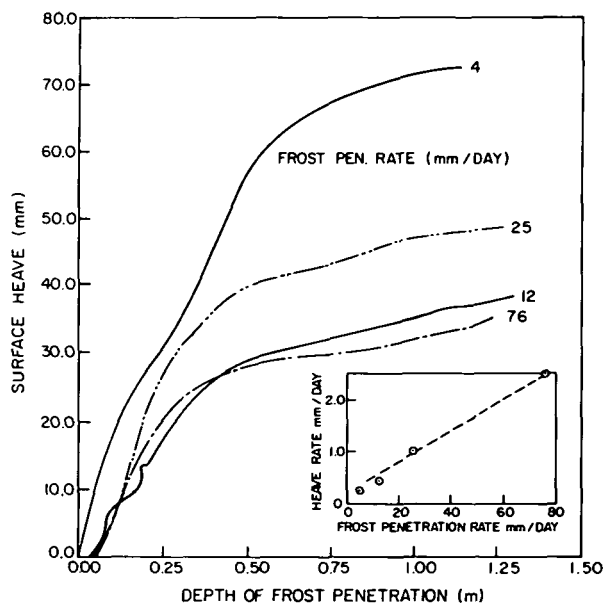


FIGURE 5. Surface heave versus frost depth.

of frost penetration. In the fourth test, which had a decreasing rate of frost penetration for the first 0.4 m of frost depth and a very slow rate thereafter, the surface heave was much higher. Considering the results of the four tests collectively, the test with the 12 mm/day freezing rate appears to be anomalous. The maximum rate of heave increased with an increase in the rate of frost penetration as indicated in the inset. This supports the finding of Penner (1972).

The average temperature of the frozen soil decreased as the depth of frost penetration increased in the three tests conducted at constant frost penetration rates (Figure 6). The frozen soil temperature was also affected by the rate of frost penetration with the highest frost penetration rate associated with the lowest soil temperature at any given frost penetration depth. Frozen soil temperatures ranged between 0 and -10°C for the three tests. In the other test the temperature of the frozen soil remained relatively constant, ranging between -1.8 and -2.6°C throughout most of the test.

Adfreeze stress was calculated on the basis of the measured uplift thrust and the circumferential area of the structural angle within the frozen zone. The results are plotted in Figure 7. The adfreeze stresses shown for the constant frost penetration rate tests, represent the averages for the two angles used in the test. For those tests, the adfreeze stress increased approximately linearly with frost depth and, for a given frost depth, the adfreeze stress increased with an increase in rate of frost penetration. In the fourth test, the adfreeze stress increased substantially during the period of the very slow frost penetration rate, attaining a limiting value of about 350 kPa. The maximum adfreeze stresses determined in the tests, are of the same order of magnitude as the field test values obtained by Crory and Reed (1965) and Kinoshita and Ono (1963) for silty soils.

The factors affecting adfreeze stress for a given soil and a given structural member are first, the rate of surface heave; secondly, the magnitude of surface heave; and thirdly, the temperature of a frozen soil.

The rate of surface heave may be considered to be a rate of shear deformation at the soil-structure interface and, for rheological materials such as frozen soil, the higher the rate of shear deformation, the larger the adfreeze stress, a correlation suggested by Johnston and Ladanyi (1972) and Penner (1974).

The magnitude of heave is a measure of the magnitude of shear deformation and, the larger the magnitude of shear deformation, the higher the adfreeze stress, providing the peak value has not been attained.

Adfreeze stress increases with a decrease in frozen

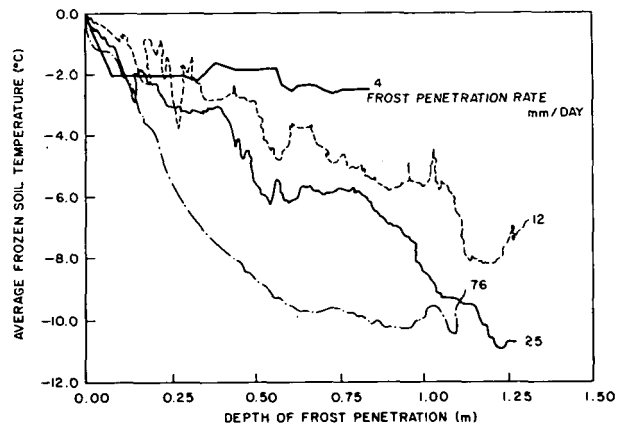


FIGURE 6. Temperature of frozen soil versus frost depth.

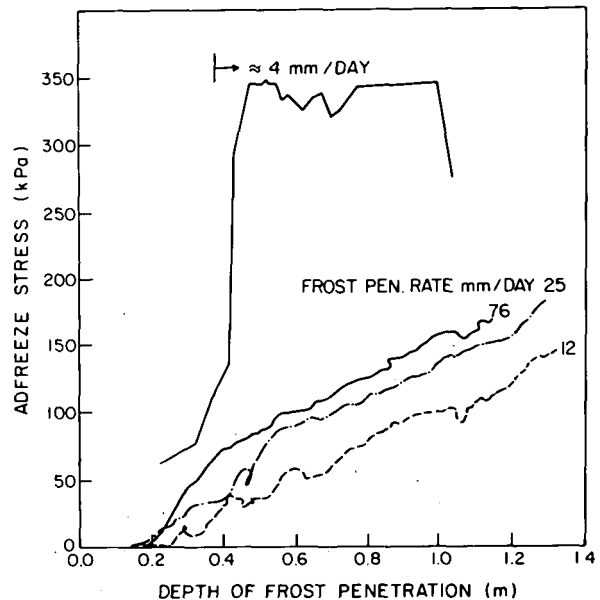


FIGURE 7. Adfreeze stress versus frost penetration.

soil temperature due to the associated increase in the strength of the soil. The dependence of the strength of frozen soils on soil temperature is well documented in the literature.

The effects of the three factors mentioned on the adfreeze stresses are difficult to separate and quantify because they are not independent variables. Moreover, the freezing rate does not have a single effect on the adfreeze stress since it affects the three aforementioned factors differently. For example, increasing the freezing rate is associated with a higher rate of heave, a lower frozen soil temperature, and a lower magnitude of surface heave. The first two factors have the effect of increasing the adfreeze stress

whereas the third factor has the effect of decreasing the adfreeze stress. Thus, it is difficult to predict what the effect of increasing the rate of frost penetration will have on the adfreeze stress. For these reasons there was no rational pattern to the relative positions of the adfreeze stress curves (see Figure 7).

To attain a limiting value of adfreeze stress, the heave rate must become zero or the temperature of the frozen soil must become constant or increase. In the three constant frost penetration rate tests, as the frost depth increased the heave rate decreased but remained greater than zero, and the temperature of the soil decreased. This accounted for the continued increase in adfreeze stress with frost penetration. In the fourth test, the temperature of the soil and the rate of surface heave became essentially constant with time, and a limiting adfreeze stress for that temperature and rate of heave was attained.

Basal Heave Pressures

Equipment and Procedure

Basal heave pressures were investigated concurrently with the adfreeze stress studies. A short section of a structural member was placed on the surface of the soil and the force required to prevent upward movement of the member was measured. An 813-mm length of a 57×15.3 I-beam, was used in the three tests performed at constant rates of frost penetration in the cylindrical tank, and a 914-mm length of a square tubing, 101.6×101.6 mm, was used in the test carried out in the test pit.

Test Results

The basal heave pressures computed on the basis of the uplift thrust and the base area of the member are shown as a function of frost depth (Figure 8). The heave pressures increased almost linearly with frost

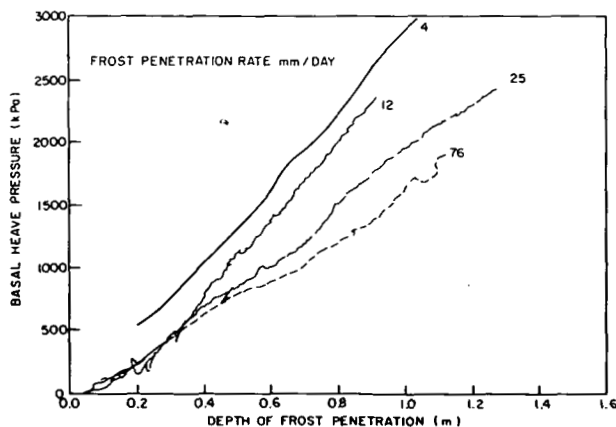


FIGURE 8. Basal heave pressure versus frost depth.

depth. The maximum values measured were of the order of 2000 to 3000 kPa which compare favourably with values determined by field tests conducted by Kinoshita *et al.* (1963, 1967), for silty soils.

The factors affecting basal heave pressures are the heaving rate, the temperature of the frozen soil, the magnitude of surface heave and the depth of frost penetration. The effects of the first three factors on basal heave pressures are the same as those on adfreeze stress, previously discussed. The effect of frost depth on basal heave pressures can be rationalized by considering the problem to be one of pressures generated at the frost front being transmitted to the member at ground surface. The area in the plane of the frost front that contributes to the uplift force exerted on the member may be thought of as the base of a truncated pyramid emanating from the member. Thus, as the frost depth increases, the base of the truncated pyramid increases and the force exerted on the member increases providing the pressure at the frost front remains constant. However, the pressure transmitted upward from the frost front does not remain constant with frost depth and, at some depth, begins to decrease. Thus, the net effect of frost depth on the uplift force is difficult to define.

The relative positions of the curves (see Figure 8) indicate that, for a given frost depth, the slowest rate of frost penetration, which was associated with the maximum magnitude of surface heave, resulted in the maximum basal heave pressure.

To attain a limiting value of the basal heave pressure the surface of the soil would have to stop heaving or the limiting strength of the soil would have to be attained. Since neither of these conditions was met in any of the tests, the basal heave pressure continued to increase with frost penetration.

Forces on Inclined Members

Equipment and Procedure

A total of four tests were run to investigate frost heave forces exerted on inclined members embedded in soil. The facilities used for the adfreeze and basal heave pressure tests were also used for the tests on inclined members. Two tests were performed in the cylindrical tank and two tests were performed in the test pit.

The inclined member consisted of two legs welded together to form a 90-degree angle. Each leg was made up of two C12 \times 25 channel members separated by a steel plate 25 mm thick. The width and depth of the bearing surface of each leg was 180×1219 mm (Figure 9). The member was positioned symmetrically in the soil so that horizontal forces

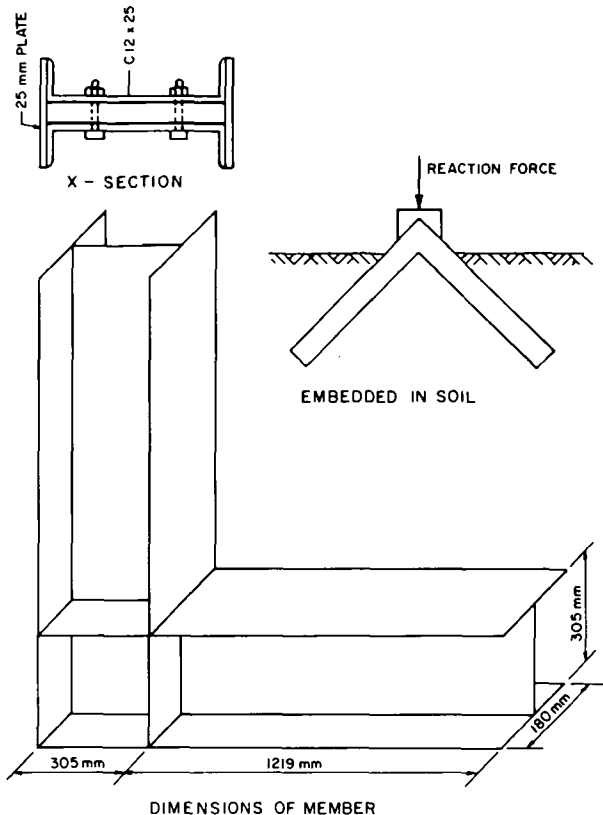


FIGURE 9. Details of inclined member.

exerted on the two legs would counteract each other. A load cell was placed between the top of the member and a reaction beam. Surface heave and soil temperatures were monitored as in previous tests.

The first test was performed at a constant frost penetration rate of about 28.4 mm per day. The subsequent tests were run at slower, variable frost penetration rates. For these latter tests a boundary temperature was applied and maintained constant until the frost depth became constant, then the boundary temperature was lowered and kept constant until the frost depth again became constant. The procedure was repeated until the desired frost depth was reached. This procedure generally resulted in rates that initially decreased with time, but became fairly constant for prolonged periods of time. Rates as low as 3.5 mm per day were achieved in this manner.

Test Results

Plots of frost penetration, surface heave, and the vertical thrust exerted on the member are shown as a function of time for the four tests (Figures 10, 11, 12, and 13). The resultant vertical stress acting on the base of the inclined member was computed on the

basis of the measured vertical thrust and the base area of the member within the frozen zone. The vertical stresses thus computed are also included in the figures.

Test No. 1 was carried out for 38 days. The rate of frost penetration was relatively constant at approximately 28.4 mm per day. The surface heave increased at a decreasing rate and became essentially constant after a frost depth of about 0.82 m. The frost heave force on the member increased at a fairly constant rate to this depth, and increased very little beyond this depth. The associated vertical stress increased to a maximum of about 220 kPa when the frost depth was 0.5 m, remained essentially constant until the frost depth was 0.82 m, then decreased.

Test No. 2 was carried out for 27 days with a maximum frost depth of 0.72 m. For the first 0.4 m of frost depth the soil was frozen at a rapid rate of about 67.5 mm per day, then the rate was decreased to an average rate of about 14.5 mm per day. The frost depth remained constant for periods of several days during the latter portion of the test. Surface heave continued throughout the test, whereas the frost heave force fluctuated, particularly during periods of stationary frost front.

Test No. 3 was carried out for 152 days to a maximum frost depth of 0.74 m at frost penetration rates of 5.7 to 3.6 mm per day. The frost depth fluctuated with time because of the very slow rates. The surface heaved at a relatively constant rate throughout the test. The frost heave force increased throughout the test with some minor fluctuations. Due to malfunction of a Data Logger, the force was not recorded during the 41- to 76-day time interval. For calculating vertical stress, a frost depth was used which was based on average rates of frost penetration, shown by the broken lines. The vertical stress thus calculated, attained a limiting value of approximately 1240 kPa.

Test No. 4 had a duration of 102 days and a maximum frost penetration of 1.05 m. The frost penetration rate was approximately 28 mm per day for the first 0.5 m of frost depth and approximately 3.8 mm per day thereafter. The surface heave rate was relatively constant after the first five days and the frost heave force reached a maximum when the frost depth was approximately 0.7 m. The vertical stress attained a limiting value of approximately 1380 kPa when the frost depth was approximately 0.7 m.

Thus, maximum vertical stresses ranging from 220 to 1380 kPa were measured for the tests performed at different frost penetration rates.

The factors affecting the resultant vertical stress exerted on an inclined member are the same as those affecting basal heave pressure, namely magnitude of

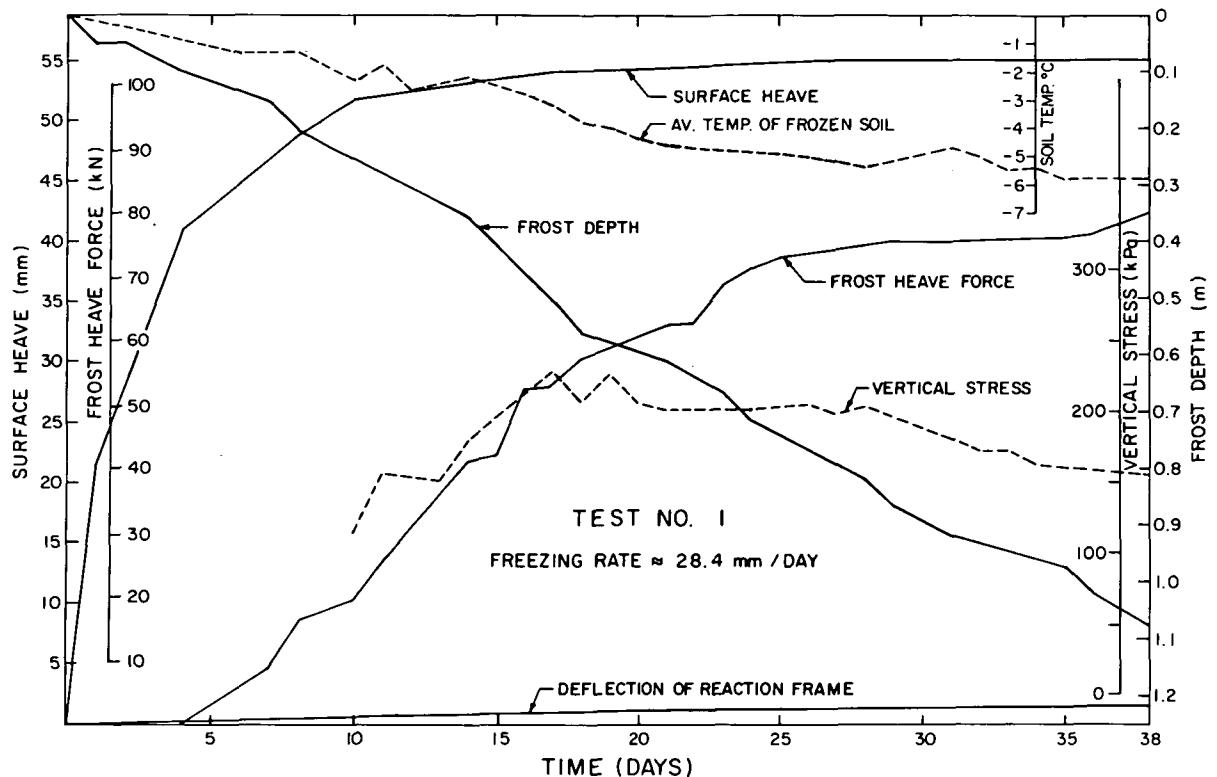


FIGURE 10. Results of Test No. 1 on inclined member.

surface heave, rate of surface heave, frozen soil temperature, and frost depth. To separate and quantify the effects individually was impossible. For comparative purposes the resultant vertical stress was plotted *versus* frost depth for each test in Figure 14. The relative positions of the individual curves suggest that the rate of frost penetration may serve as the best parameter for quantifying the vertical stress exerted on an

inclined member. The inset in Figure 12 is the plot of maximum vertical stress attained in each test *versus* the corresponding rate of frost penetration, dz/dt (see inset in Figure 12), and indicates a consistent trend of an increase in vertical stress with a decrease in the rate of frost penetration for the range of frost penetration rates investigated.

Frost Heave Forces *versus* Member Inclination

The results of the investigation of frost heave forces exerted on vertical, horizontal, and inclined members are shown on a common plot of vertical stress *versus* member inclination (Figure 15). The vertical stress represents the adfreeze stress, the basal heave pressure, and the resultant vertical stress on the inclined member, for the three aforementioned studies. The stresses at the one-metre frost depth were taken as the basis for comparison. The results indicate a substantial decrease in vertical stress exerted on an inclined member as the angle of inclination, *measured from the frost plane*, increases. It is important to make the distinction between the frost plane and a horizontal plane, as the two do not always coincide. From the information presented in Figure 15 it is possible to determine the normal and the tangential stresses acting on an inclined member.

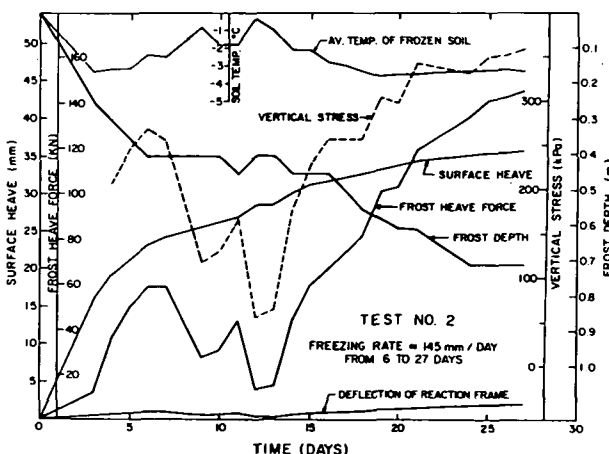


FIGURE 11. Results of Test No. 2 on inclined member.

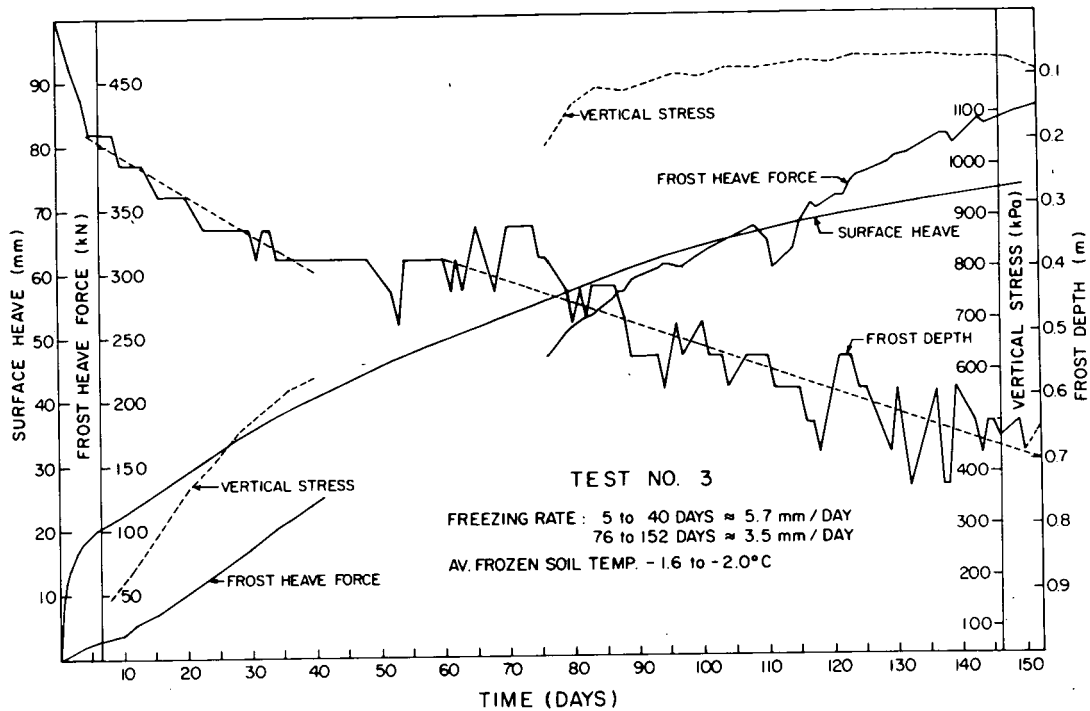


FIGURE 12. Results of Test No. 3 on inclined member.

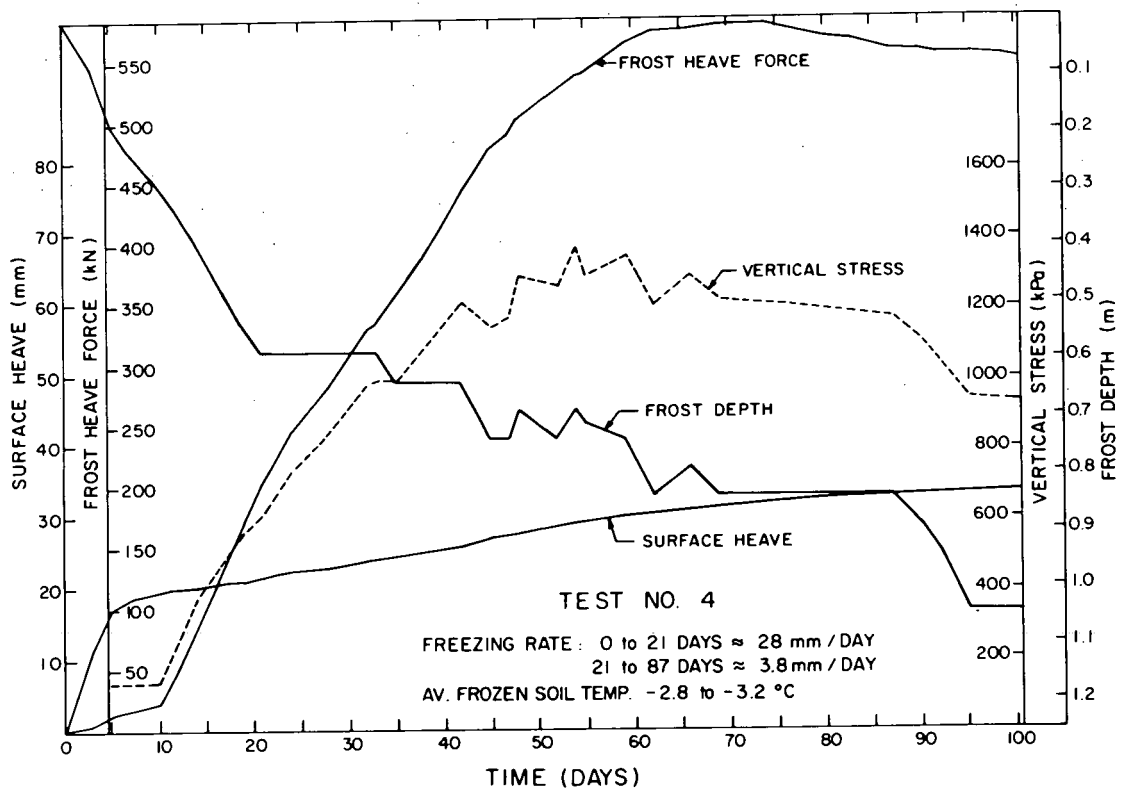


FIGURE 13. Results of Test No. 4 on inclined member.

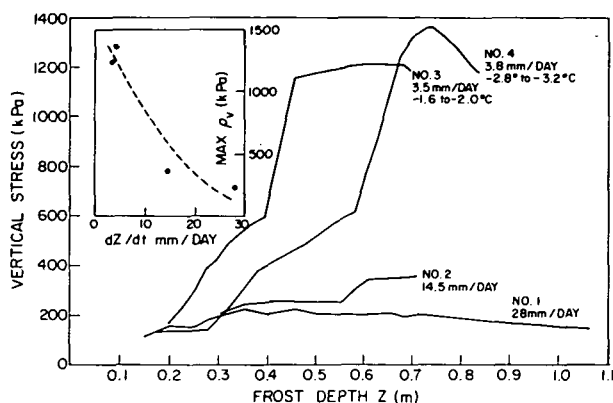


FIGURE 14. Vertical stress on inclined member versus frost depth.

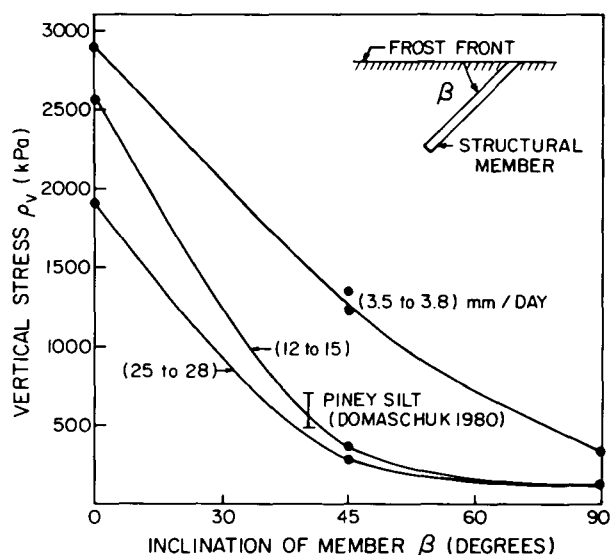


FIGURE 15. Relationship between vertical stress and member inclination.

The results of an investigation by Domaschuk (1980) of the frost heave forces acting on an inclined member embedded in a non-plastic silt (Piney silt) are included (see Figure 15). The tests were carried out using small models and frost penetration rates ranging between 15 and 25 mm per day. The results are in good agreement with those obtained for Agassiz silt using larger models.

Conclusions

1. Adfreeze stresses for an ML silt were found to be affected by soil temperature, and the rate and magnitude of surface heave. The maximum adfreeze stress between a structural steel angle and the silt was 350 kPa.

2. Basal heave pressures for the ML silt were affected by rate and magnitude of surface heave, soil temperature, and depth of frost. Rate of frost penetration and depth of frost appeared to be the principal factors. The maximum basal pressure measured was 3000 kPa.

3. Resultant vertical stresses exerted on a structural member inclined at 45 degrees to the frost line, were found to increase with frost depth to limiting values, which depended on the rate of frost penetration. Limiting values ranged from 220 kPa for a frost penetration rate of 28 mm per day, to 1310 kPa for a frost penetration rate of 3.8 mm per day.

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