THE UNIVERSITY OF MANITOBA

FROST HEAVE FORCES ON STRUCTURAL MEMBERS

by

YASUO TANAKA

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SUMMARY

A study of frost heave forces acting on structural members embedded in, or resting on a Lake Agassiz silt is presented in this thesis. The investigation was made using a full scale model in the laboratory. The apparatus consisted of a large tank equipped with a freezing unit which provided unidirectional freezing of the soil.

A series of six tests were run, and the frost heave forces were studied under constant rates of frost penetration. Soil temperatures, frost heave forces on the structural members, surface heave of unrestrained ground, and surface heave around an embedded structural member were observed during the tests.

The surface heave results of unrestrained ground indicated that the higher the rate of frost penetration, the larger the initial rate of heave. The relationship obtained was in good agreement with results obtained by other researchers. The surface heave of the soil seemed to be influenced by the load acting on frost front. The test results showed that the surface heave decreased rapidly after the overburden pressure at the frost front exceeded approximately 110 lb/ft^2.

The surface heave was impeded by the embedded member, and the radius of the influence was approximately 18 inches.

There was no apparent effect of the rate of frost penetration on the frost heave forces acting on the embedded members. The adfreeze stress which was calculated on the basis of the uplift force and the depth of frost penetration, increased approximately linearly with a decrease in the average frozen soil temperature. The unit adfreeze stress was expressed as a function of frozen soil temperature by the following equation for a temperature range of 29.5°F to -13.0°F:

$$\tau = 53.1 - 1.8\ t$$

where τ : Unit adfreeze stress (psi)

t : Frozen soil temperature (F°)

The frost heave force on a structural member resting on the soil surface, increased approximately linearly with an increase in the depth of frost penetration. The uplift force was influenced by the rate of frost penetration, and the results indicated that the faster the rate of frost penetration, the lesser the frost heave force.

CHAPTER 1

INTRODUCTION

Frost heave of the ground surface commonly occurs in a region where there is seasonal freezing and thawing of the soil. The expansion of moisture in the soil pores during freezing or the formation of an ice lens at the frost line results in a volume increase of the soil. Studies of frost heave have been made by such investigators as Casagrande[1] 1932, Beskow[2] 1935, Linell[3] 1959. Frequently the relationship between frost heave and particle size of the soil was studied in order to determine the frost susceptibility of the soil.

Frost heave of soil may generate an enormous uplift force on structures resting on, or embedded in the soil, causing undesirable vertical movements and damage to the structures. In the case of embedded structures, the upward movement of soil is transmitted to the structure by means of an "adfreeze stress" between the structure surface and the frozen soil. Kinoshita[4] studied the frost heave force on buried pipes in the field. In his study, three pipes of different materials were used; plastic, steel, and concrete. Penner [5,6,7] recently conducted experiments in the field which dealt with the frost heave forces on a surface plate, on buried pipes, and on walls. The primary objectives were to establish field measurements of the frost heave forces exerted on surface or embedded structures. Since these studies were conducted in the field, environmental conditions such as rate of frost penetration and moisture in the soil were not controlled.

A full scale model research project dealing with the frost heave forces on structural members located on or within frozen soil has been underway at the University of Manitoba, Civil Engineering Department, for the past three years. The experiment was undertaken in the laboratory by utilizing a large tank equipped with a freezing unit in order to create unidirectional freezing of the soil within the tank. Instrumentation was provided to measure soil and air temperatures, frost heave and uplift forces developed on structural members. The objectives were to measure the frost heave forces under different rates of freezing. A series of six tests were run with the rate of frost penetration varying from 0.5 inches to 3.0 inches per day.

In this thesis a summary of the test results is presented along with correlation studies of the results.

CHAPTER 2

FROST ACTION OF SOILS

In this chapter, a review is made of research pertaining to the mechanism of soil freezing, magnitude of frost heave, and the frost heave forces acting on surface or embedded structures.

Mechanism of Soil Freezing

When heat extraction occurs below freezing temperatures and supplies of water are provided in the soil, ice crystallization occurs in the soil pores. The formation of crystals may occur on the basis of both heterogeneous and homogeneous nucleation, heterogeneous nucleation being the initiation of growth or formation of an ice crystal by a foreign substance, and homogeneous nucleation being initial growth on the basis of a bud of crystallization formed within the water phase.

The nucleation starts at a somewhat lower temperature than the freezing point. Linell's investigation(3) showed that the nucleation temperature could be as low as 25^{o}F depending on the soil type. This extra cooling to initiate the nucleation is called "super cooling". Also the presence of solutes such as salts in pore water can lower the freezing temperature.

The mode of frost propagation depends on the soil type. Yong and Warkentin(8) illustrate two different types of frost propagation, the first type of which is shown in the following schematic diagram, Figure 1.

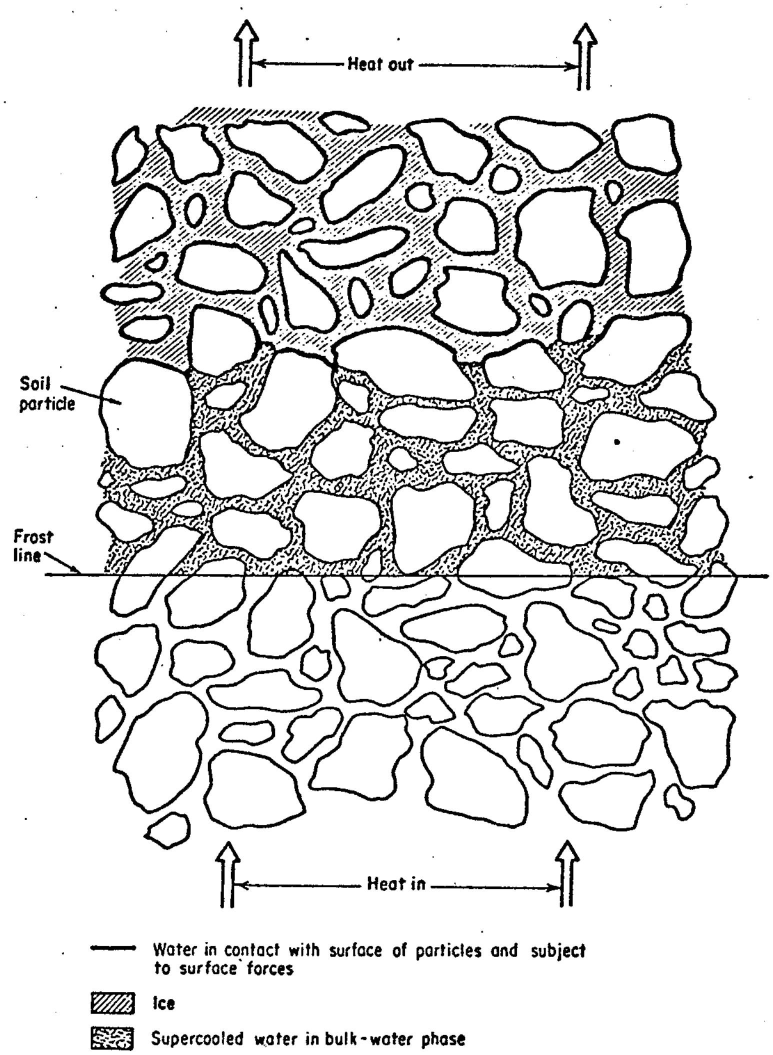
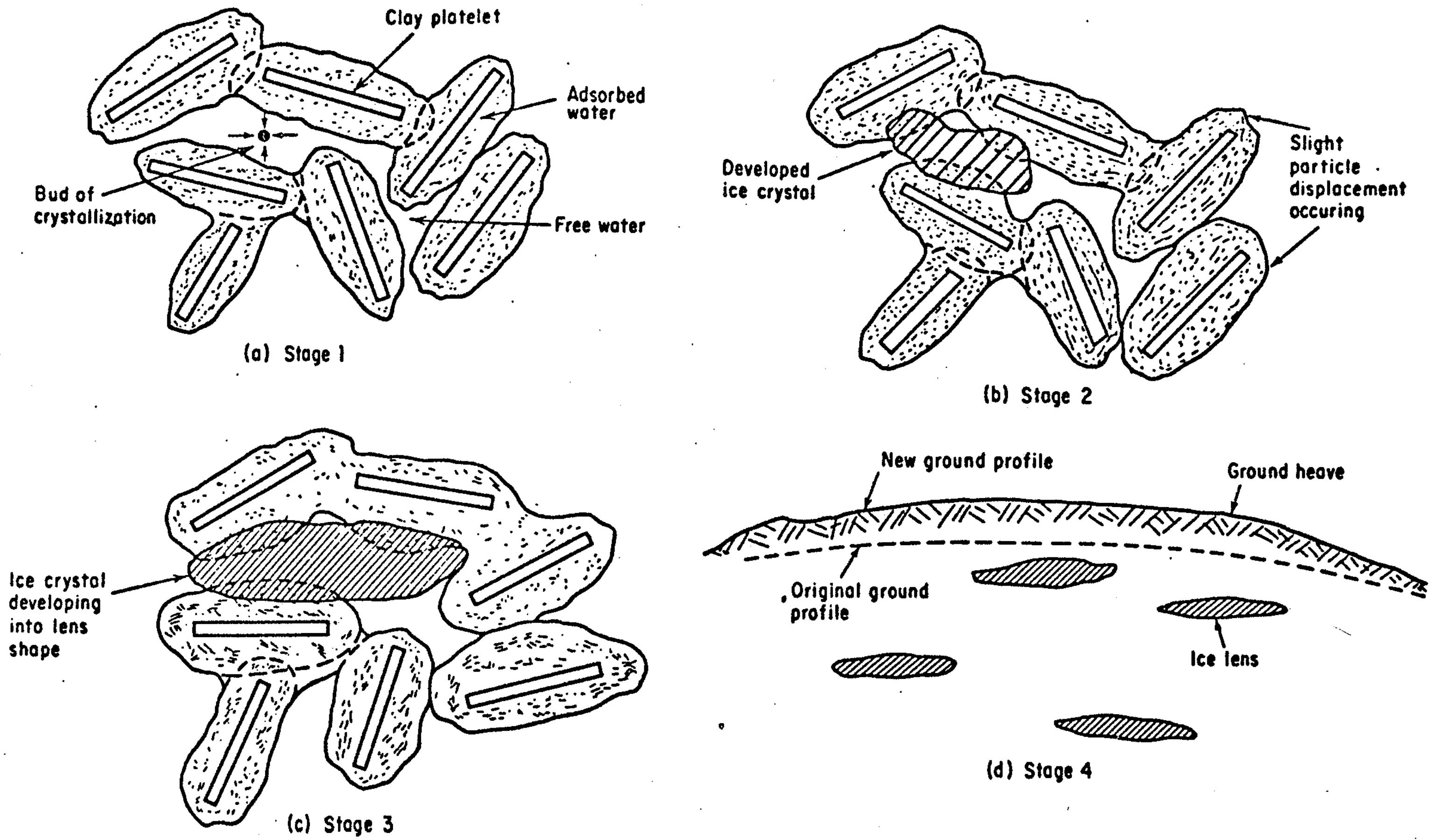


Figure 1. Schematic View of Soil Freezing in Coarse-Grained Soils, after Yong and Warkentin(8)

Coarse grained soils have large pores and large soil particles, therefore the pore water can flow freely through the voids, and gravity is the most dominant force acting on both pore water and soil particles. Consequently the pore water changes to ice progressively from one void to the next as the frost front progresses, and the ice formation takes place without significant movement of water to the point of ice crystallization. Thus there is no significant increase in volume during the freezing of coarse grained soils.

In fine grained soils, because of the small size of both soil particles and pores, the electro-potential and the surface force are the most dominant forces acting on the soil particles and the pore water. The pore water exists in two ways, free water and adsorbed water. In fine grained soils, the formation of ice starts within the free water rather than the adsorbed water. After ice crystallization of the free water has been made in the void, further growth of ice can take place by migration of water up to the point of ice crystallization. This process of ice lens formation takes place until the energy required to supply the water for ice growth becomes too large. Then other ice lenses may be formed further downward where the temperature may be lowered within the nucleation temperature range. This process is shown in Figure 2.



Stages in Growth of Ice Lenses. (a) Free Water Being Used in Immediate Pore Space for Growth of Ice Crystal. (b) Free Water Being Drawn from Neighboring Pores and Some Adsorbed Water Being Used to Further Crystal Growth. (c) Free Water Being Drawn in from Pore Spaces Further Away, and More Adsorbed Water in the Immediate Pore Space Being Used Up; Particle Displacement Occurs Because of Growth of Crystals into Lens Shape. (d) Macroscopic View of Formation of Ice Lenses in Subsoil Due to Progress of Frost Line and Depletion of Water Supply Around Crystal Growth

Figure 2 Schematic View of Soil Freezing in Fine-Grained Soils. After Yong and Warkentin(8).

As the ice lenses propagate into the soil pores, a force develops at the ice-water interface along the curvature of the soil pores. This force is called heaving pressure. A theoretical analysis made by Everett and Haynes[9] led to the following equations for the heaving pressure with a close-pack array of spherical particles of uniform size;

$$P = \frac{2\,\sigma_{iw}}{r_i} + \frac{2}{r}\,(\sigma_{is} - \sigma_{ws}) \quad ....(1)$$

where P : heaving pressure

σ_{iw}: ice-water interfacial energy

σ_{is} : ice-solid interfacial energy

σ_{ws}: water-solid interfacial energy

r_i : radius of pore

r : radius of sphere

applying the Young-Dupre equation;

$$\sigma_{is} - \sigma_{ws} = \sigma_{iw} \cos\theta$$

where θ is the contact angle between ice-water and water-solid surface.

and defining B' as $r/r_i \cos\theta$;

$$P = \frac{2\,\sigma_{iw} \cos\theta\,(1+B')}{r} \quad .... (2)$$

It is not within the scope of this thesis to discuss the details of this equation, however, the following implications from the theory should be recognized;

i) a maximum heaving pressure is attained when the ice is about to penetrate through the foramina of soil structures.

ii) the equation implies that the smaller the pore size, the greater the heaving pressure generated.

Frost Heave

Early investigations of frost heave have been undertaken by such investigators as Casagrande(1) 1932, or Beskow(2) 1935. For the frost susceptibility of soils, studies regarding the effects of soil type or texture on frost heave have been carried out by Cathy(10) 1962, and Linell(3) of U.S. Arctic Construction and Frost Effects Laboratory (ACFEL) 1959. The ACFEL standardized their frost heave tests as follows; six inch high cylindrical samples are frozen at a rate of frost penetration of 3/4 to 1/2 inches per day. The frost susceptibility criteria prepared by the ACFEL, which is based on the rate of heave of the soil, is presented in Figure 3.

It has been well established through these investigations that a soil consisting of intermediate grained particles such as silt or clayey silt is most frost susceptible in

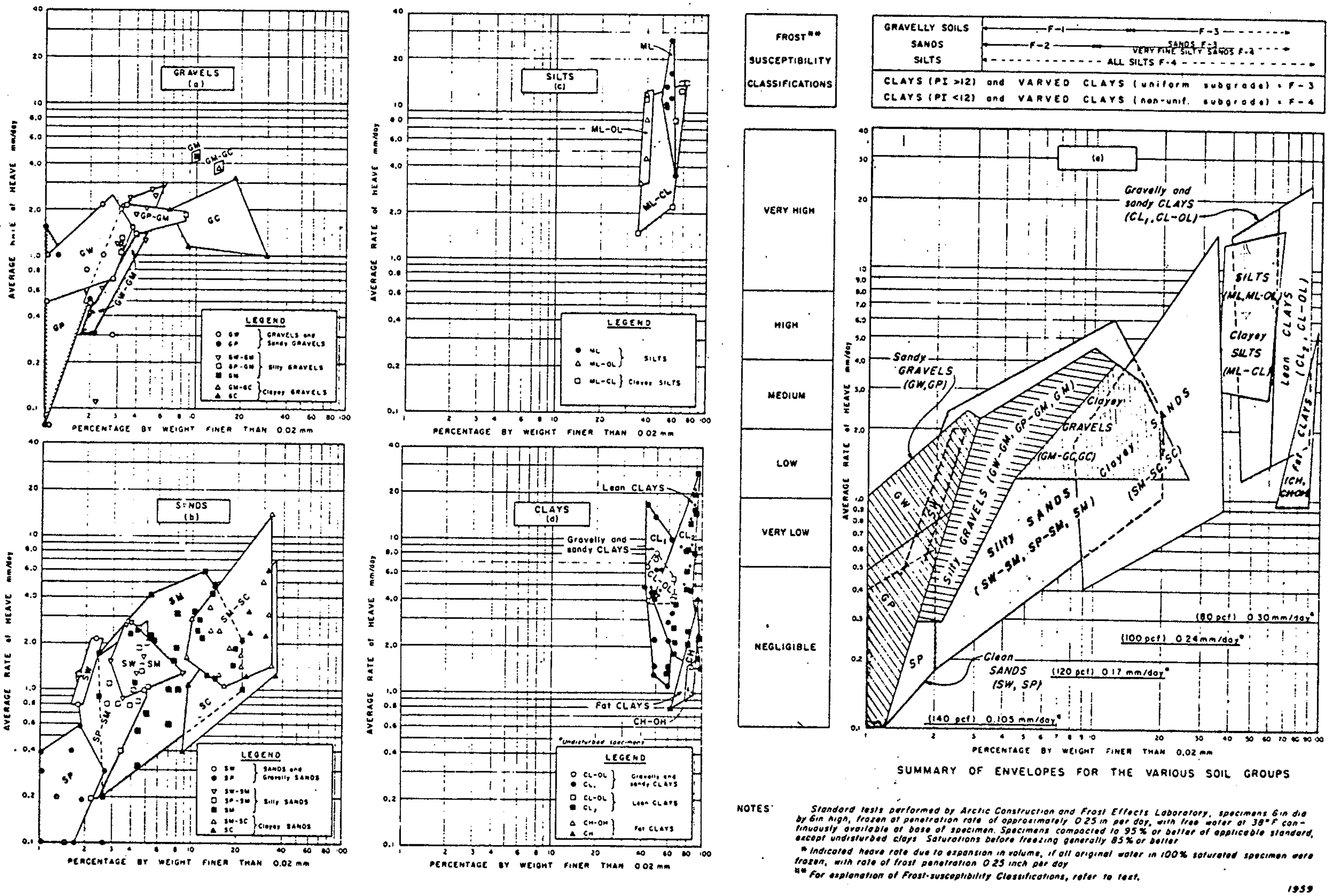


Figure 3. Frost Susceptibility Criteria Prepared by the ACFEL after Linell(3).

terms of frost heave. Terzaghi and Peck[11] gave the following reasoning for the frost heave of such soil;

> "the tendency of ice lenses to develop and grow increases rapidly with decreasing grain size. On the other hand the rate at which the water flows in an open system toward the zone of freezing, decreases with decreasing grain size. Hence it is reasonable to expect that the worst-heave conditions would be encountered in soils having an intermediate grain size."

The frost heave of soil is known to be influenced by two factors other than soil type, one being the load on the frost line and the other being the rate of heat extraction. Kapler[12], using a freezing test on small cylindrical samples similar to the ACFEL samples showed that frost heave decreased with increasing load on the frost line. Osler[13] also pointed out the importance of the load, showing that the frost heave in natural grounds would vary with depth of frozen soil, and, therefore, should be examined in terms of the particle size of the soil and the depth of frozen soil.

The rate of heat extraction, which is in turn related to the rate of frost penetration, influences the frost heave.

Kapler's[12] and Penner's[14] laboratory investigations showed that the higher the rate of frost penetration, the greater the initial rate of frost heave. Penner[15] further showed that increasing the rate of heat removal from the freezing plane, increased the rate of migration of moisture to the frost front, and consequently increased the heaving rate.

Frost Heave Force on Surface or Embedded Structures

The ice lenses propagating into the soil pores generate a force called the heaving pressure at the ice/water interface, and the theory accounting for this phenomena was presented in the preceeding section of this chapter. In case of freezing of natural grounds, the heaving pressure continues to develop at the frost front as the ice lenses grow, and this force can be transmitted to the structures if the surface heave is restrained by the structure.

Penner[5] made an investigation of the frost heave force on a restrained surface plate in the field, and found the following general trends for the frost heave force;

1. The variation of the frost heave force was closely associated with weather conditions.
2. Cold weather resulted in an increase of the force, and

periods of moderating weather reduced the force value.

3. Generally the frost heave force increased as the frost depth increased.

Since the heaving pressure develops in the same direction as the heat flow, it is possible that the frost heave force acts laterally if the ground freezing takes place laterally such as in case of vertical cuts of the ground. McRostie and Schriever(16) showed an example of such a frost heave force developed on the tie-back plates in vertical cuts.

Unfortunately few investigation have been made of the frost heave force on surface structures, and the subject has not been fully explored.

Frost heave forces can also act on embedded structures. When the soil is frozen to an embedded structure, a bond or adhesive force develops at the interface between the frozen soil and the structure. This process is called adfreezing. Thus frost heaving of soil may cause an uplift force on the embedded structure by way of the adfreezing phenomena.

Penner(6,7) and Kinoshita(4) investigated the frost heave force on embedded structures in the field. Kinoshita's study indicated that the material of the embedded pipes influenced the frost heave force. His test results showed that steel pipe gave the largest heave force, followed by plastic pipe, and then concrete pipe. Russian researchers, Dalmatov[17] and Vyalov[18], studied the adfreeze strength in relation to frozen soil temperature. Their studies were based in laboratory investigations using a slow rate of shear and they found that the adfreeze strength increased with a lowering of the temperature of the frozen soil. Ness[19] studied adfreeze strength by a model test. The adfreeze strength obtained varied from 40 psi to 75 psi with frozen soil temperatures ranging between 18°F to 25°F.

These adfreeze strength were considerably higher than those reported by Penner[6,7]. Because the approach taken by Nees was to measure the maximum shear resistance of the frozen bond under rapid loading, it may not represent the same phenomena that take place in the seasonal freezing of the ground.

CHAPTER 3

EXPERIMENTAL INVESTIGATION

This chapter deals with the test apparatus, soil properties, test programme, and procedure.

Test Apparatus

A large tank equipped with a freezing unit was used to create unidirectional freezing of the soil within the tank as shown in Figure 4. The soil was made up of upper silt layer and lower sand layer. The depth of the silt was 68 inches. Water was supplied to the soil from the bottom of the tank. The phreatic level was kept at 35 to 37 inches below the soil surface using an outside resevoir attached as shown in Figure 4.

Two vertical members consisting of 3" x 3" structural steel angles, embedded in the soil as shown in Figure 4, were used for the adfreeze study. The embedment depths of the vertical members were 45.5 and 55 inches. A proving ring and a load cell were placed between the vertical members and an overhead floor beam to measure the uplift forces on the vertical members. The loading capacities of the proving ring and the load cell were 11.5 kips and 20 kips respectively.

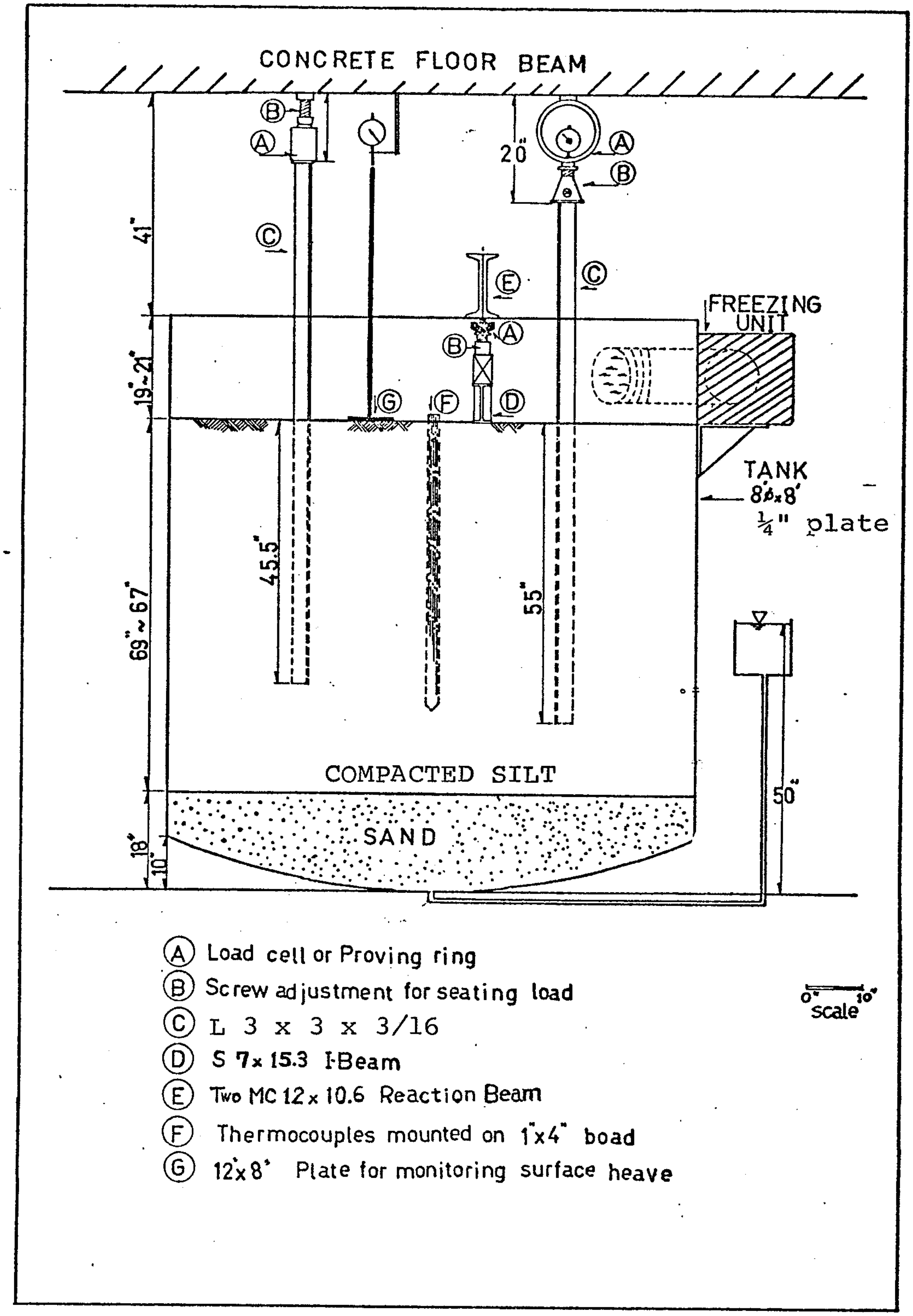


Figure 4. Instrumentation

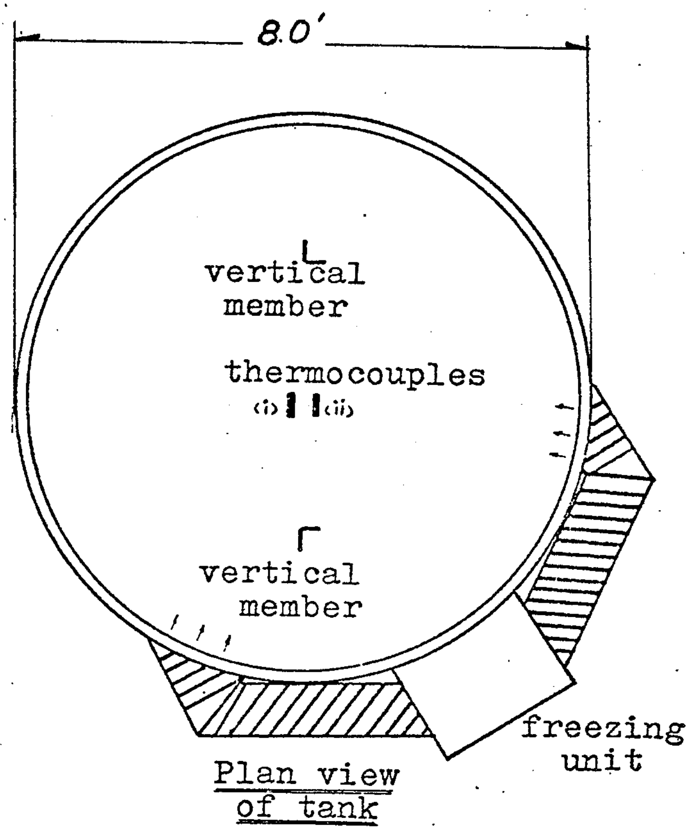
A horizontal member which was a 32-inch long S-7x15.3 I-Beam, was placed on the soil surface, and upward movement of the horizontal member was restrained by a reaction beam. A load cell was placed between the horizontal member and the reaction beam to measure the uplift force. The capacity of the load cell was 200 kips.

Thermocouples to monitor the soil temperature were mounted on a wooden strap (1" x 4") and buried in the soil near the centre of the tank as shown in Figure 5.

A surface steel plate 12" x 8" x ½" was used to monitor the unrestricted surface heave of the soil. A surface heave measurement assembly, as shown in Figure 6, was used to monitor the surface heave of the soil in the vicinity of a vertical member.

Soil Properties

Silt from the Lake Agassiz basin was used for the investigation. The gradation of the soil is given in Figure 7. The envelope in the figure shows the range of the grain size distribution obtained from four tests. The silt was predominantly inorganic and light brown in colour. The Liquid Limit ranged from 23.0 to 23.8, and the Plasticity Index ranged from 4.4 to 5.0. The compaction moisture content of the soil ranged between 15 and 25 percent varying



Depth of Thermocouple

Thermocouple set	Thermocouple No.	Depth below Soil Surface (inches)
i	1	0.0 (air)
	2	0.5
	3 to 26 inclusive	1.5 to 36.0 at 1.5" interval
ii	27 to 39 inclusive	33.0 to 51.0 at 1.5" interval

Figure 5. Location of Thermocouple in Freezing Tank.

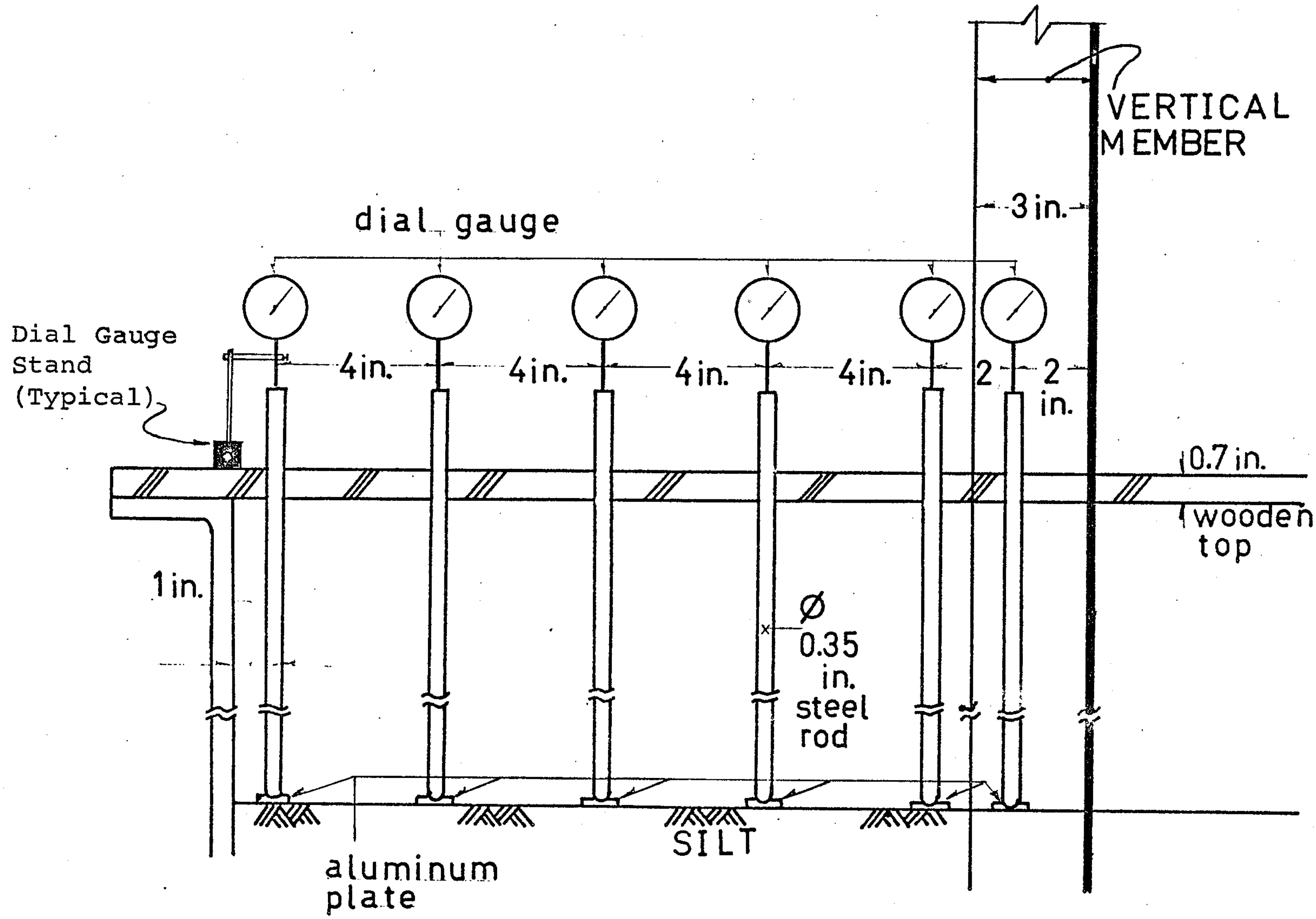


Figure 6. Surface Heave Measurement Assembly.

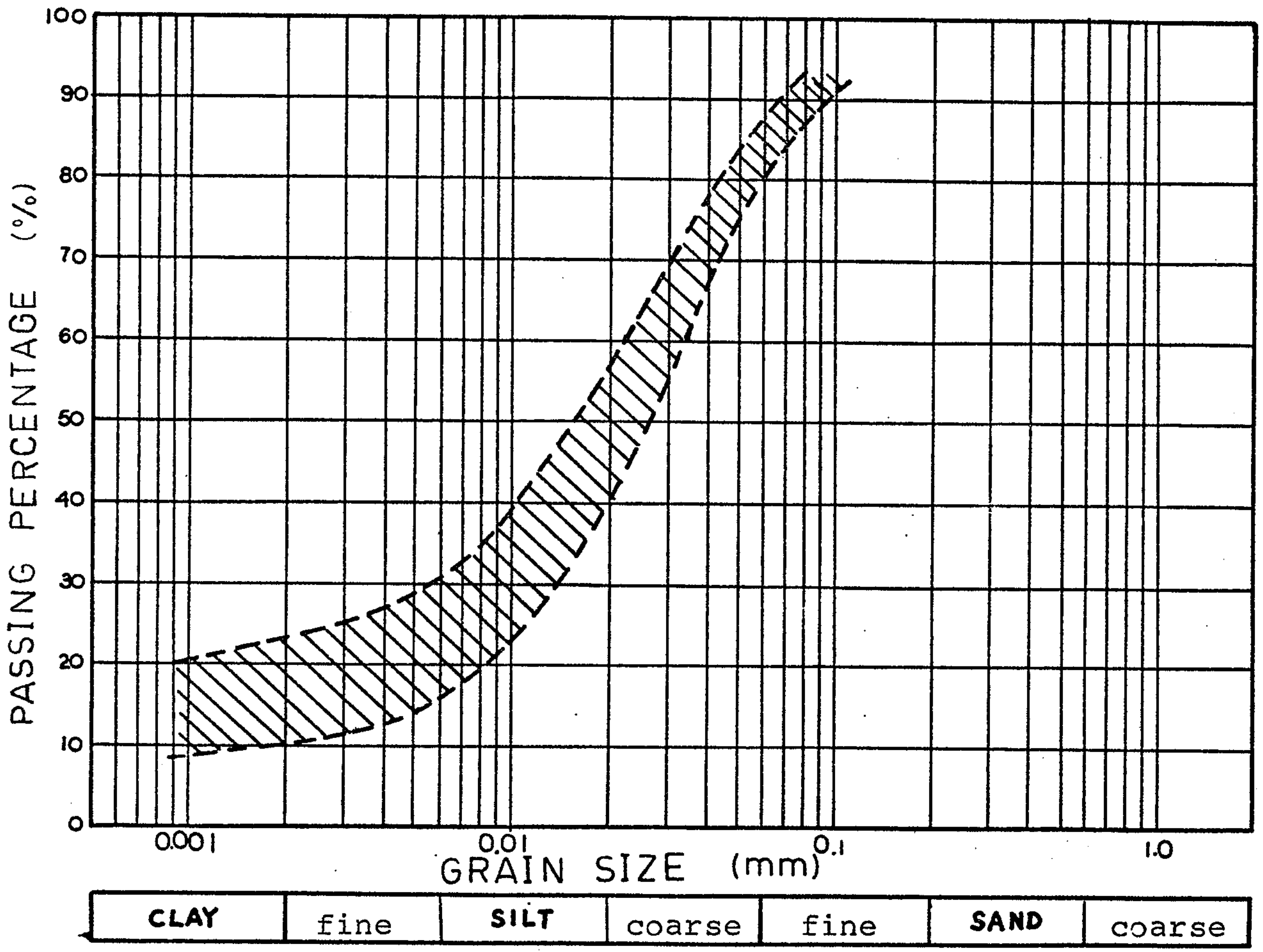


Figure 7. Envelope of Grain Size Distribution Curves.

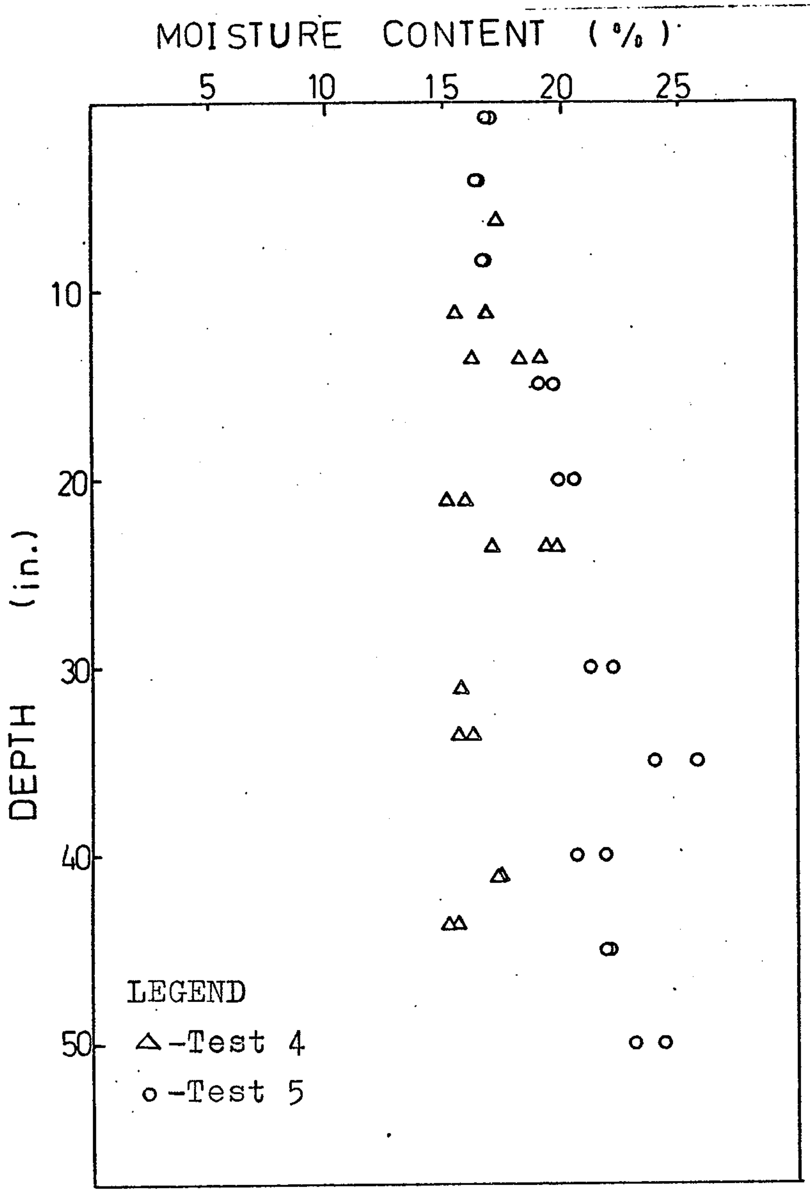


Figure 8. Compaction Water Content Distribution With Depth.

with depth as shown in Figure 8. The silt was compacted by hand tamping to dry densities ranging between 108 and 118 lb/ft^3.

Test Programme and Procedure

A series of six tests were performed to investigate the frost heave forces. A summary of the six tests is given in Table 1. The first test was run with an attempt to maintain a constant boundary freezing temperature. The remainder of the tests were run with an attempt to maintain the rate of frost penetration constant during each test. The rate of frost penetration was varied from 0.5 inch to 3.0 inches per day. The rate of frost penetration was controlled by carefully monitoring the soil temperatures in the tank, and the boundary freezing temperature was adjusted by manual operation of the thermostat on the freezing unit as required.

Measurements of the air and soil temperatures, surface heave, and the frost heave forces on vertical and horizontal members were taken at intervals of 1 to 2 hours during the day. The freezing phase of the test was continued until the frost penetration exceeded the depth of the vertical members. Observations were continued during the thawing phase of the test.

Table 1

Details of Test Programme

Test No.	Duration of Test (days)		Observation					Frost Condition
	freezing	thawing	A	B	C	D	E	
No.1	78	18	x	–	x	x	–	Constant boundary temperature
No.2	22	14	x	–	x	x	–	dz/dt=1.0 inches/day (unsuccessful)
No.3	24	—	x	–	x	x	–	dz/dt=2.0 inches/day
No.4	102	22	x	x	x	x	–	dz/dt=0.5 inches/day
No.5	51	19	x	x	x	x	x	dz/dt=3.0 inches/day
No.6	28	16	x	x	x	x	x	dz/dt=1.0 inches/day

Note A – Frost heave force on the vertical member
B – Frost heave force on the horizontal member
C – Soil Temperature
D – Surface heave
E – Surface heave in the vicinity of a vertical member
dz/dt – Rate of frost penetration

CHAPTER 4

TEST RESULTS AND ANALYSES

This chapter deals with the results and analyses of the six tests performed according to the test programme outlined in Table 1. Six comprehensive reports[20,21,22,23,24,25] containing the details of the individual tests and the results, have been previously prepared. The reports contain test data on soil temperature, frost heave, uplift thrust on buried vertical members, and uplift thrust on a surface horizontal member. In the following sections, the results and correlation studies of the six tests are presented according to subject matter.

Soil Temperature and Frost Penetration

Using soil temperature readings, the depth of the 32^{o}F. isotherm was established and was assumed to be the depth of frost penetration. The location of the 32^{o}F. isotherm was determined by either using polynomial curve fitting or by using linear interpolation between two thermocouple readings that were above and below 32 degrees Fahrenheit. In most cases, the polynomial curve fitting was used. The details of the two methods are as follows:

For polynomial curve fitting, a fourth degree polynomial was fitted to the soil temperature distribution. The coefficients of the polynomial were calculated applying the Least Squares Method. Figure 9 shows a typical temperature distribution and its representation by a fourth degree polynomial. The depth corresponding to the $32^{o}F$. isotherm was determined by the Half Interval Search Method. The error in temperature approximation for this numerical method was set as $\pm$ $0.05^{o}F$.. An example of the calculation is given in the Appendix.

Linear interpolation was employed where the polynomial curve fitting was not satisfactory because of a large variance in soil temperature. The data were examined and the two thermocouple readings which straddled the $32^{o}F$. isotherm were selected. A linear variation of temperature with depth was assumed between the two thermocouples and the location of the $32^{o}F$. isotherm was thus located.

Using the above procedures for locating the $32^{o}F$. isotherm, frost penetration as a function of time is shown in Figure 10 for the six tests. As can be seen from Figure 10, in four tests, (Test No.3 through No.6), a constant rate of frost penetration was achieved. The achieved rates were 2 inches per day, 0.5 inch per day, 1 inch per day and 3 inches per day for Test Nos.3,4,5 and 6 respectively. The rates of frost penetration in Test No.1 and No.2 varied during the test.

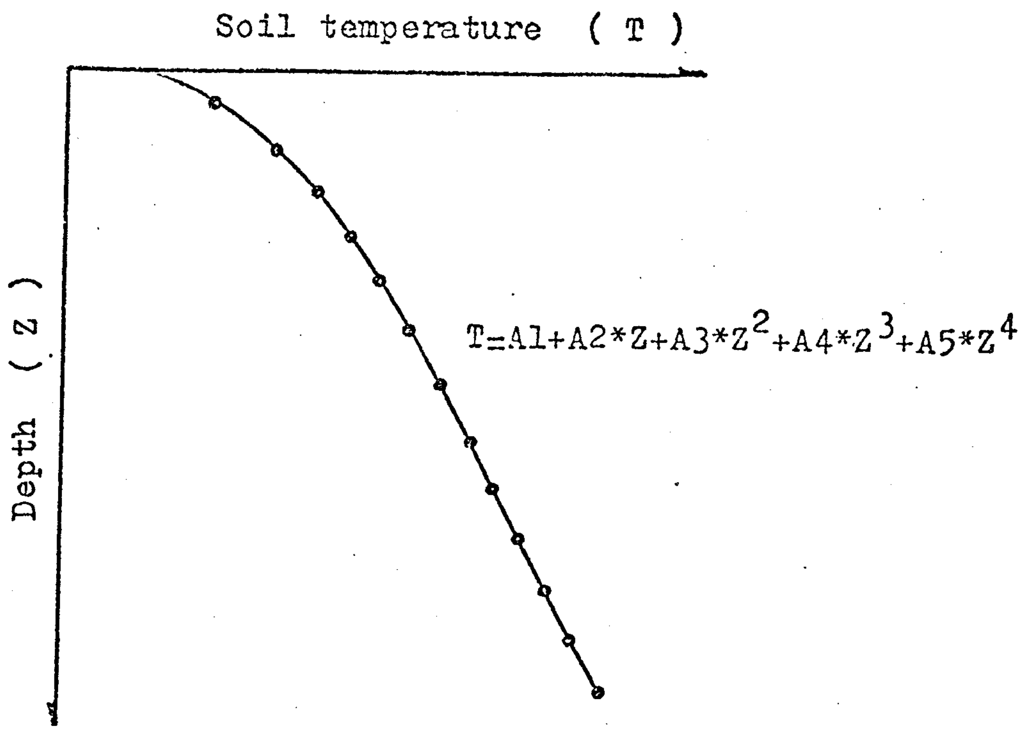


Figure 9. Typical relationships between soil temperature and depth.

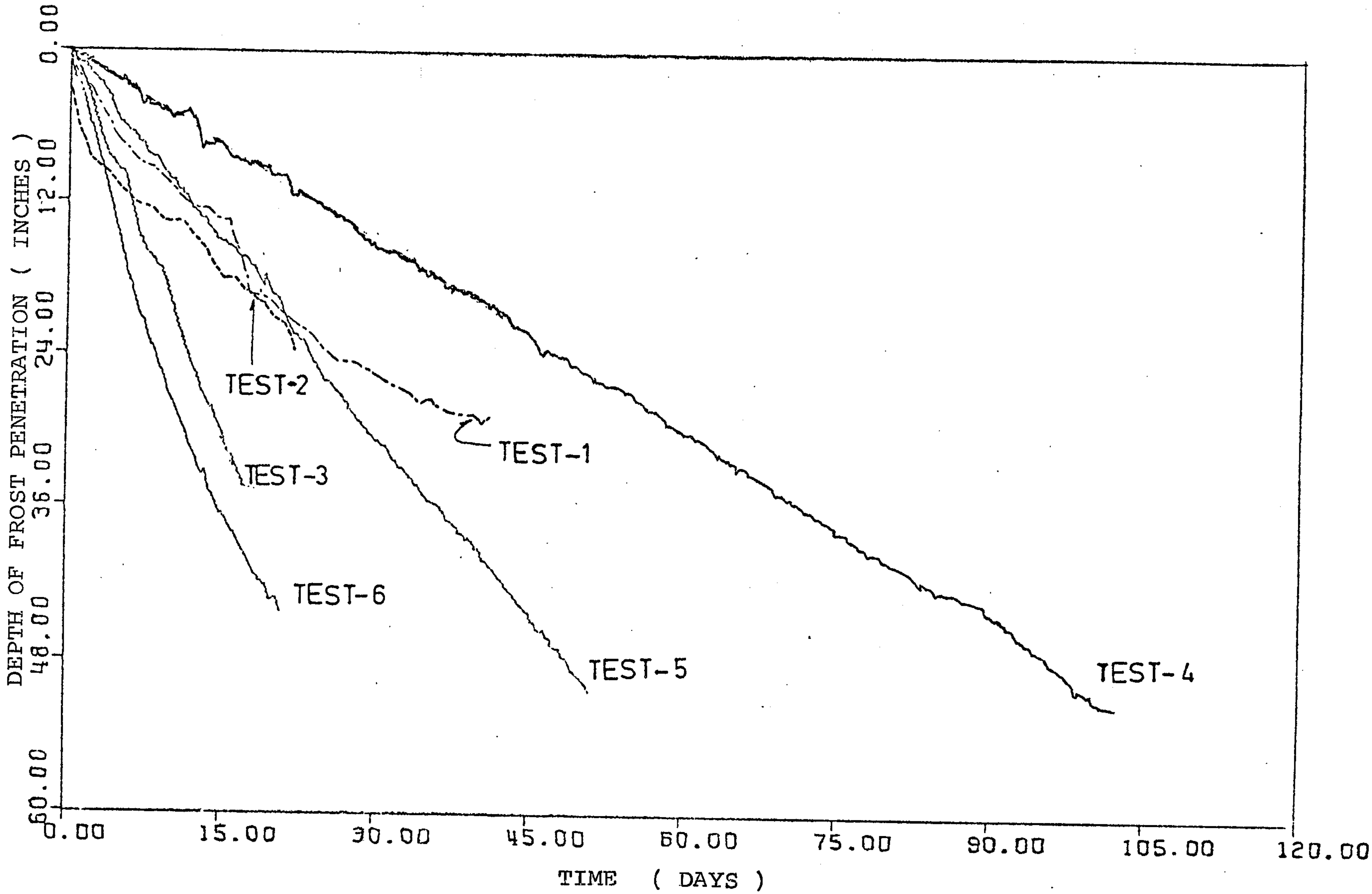
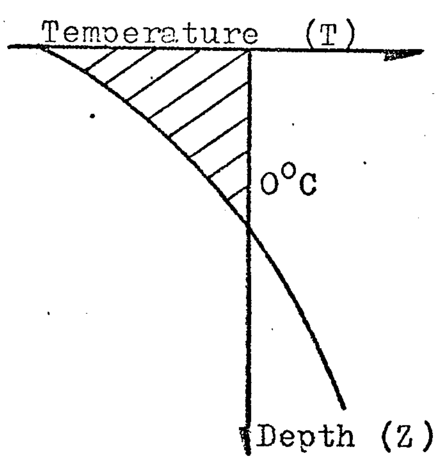


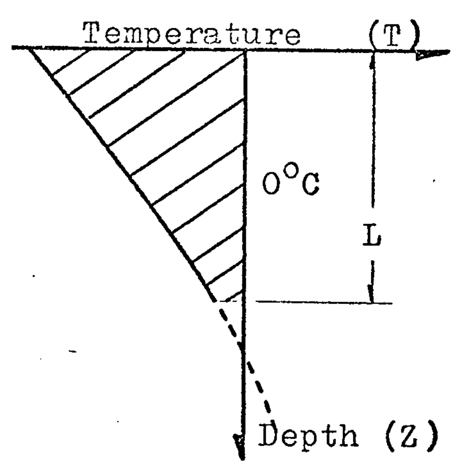
Figure 10. Depth of frost penetration versus time for different rates of frost penetration.

Using the polynomial equations the depths corresponding to different isotherms were also determined. A typical plot of soil temperature isotherms as a function of time during the freezing phase is shown in Figure 11. As can be seen from Figure 11, the soil temperature at any depth generally decreased with time. A significant time lag existed between changes in surface temperature and temperature change in the vicinity of the frost front. The time lag ranged from 1 to 2 days which made the controlling of the rate of frost penetration somewhat difficult.

The average soil temperature in the frozen zone was determined as follows. Using the polynomials, the area representing the product of depth and temperature as shown in sketch (a) below, was computed by integration, and the average frozen soil temperature was obtained by dividing the area by the depth of frozen soil.



(a)



(b)

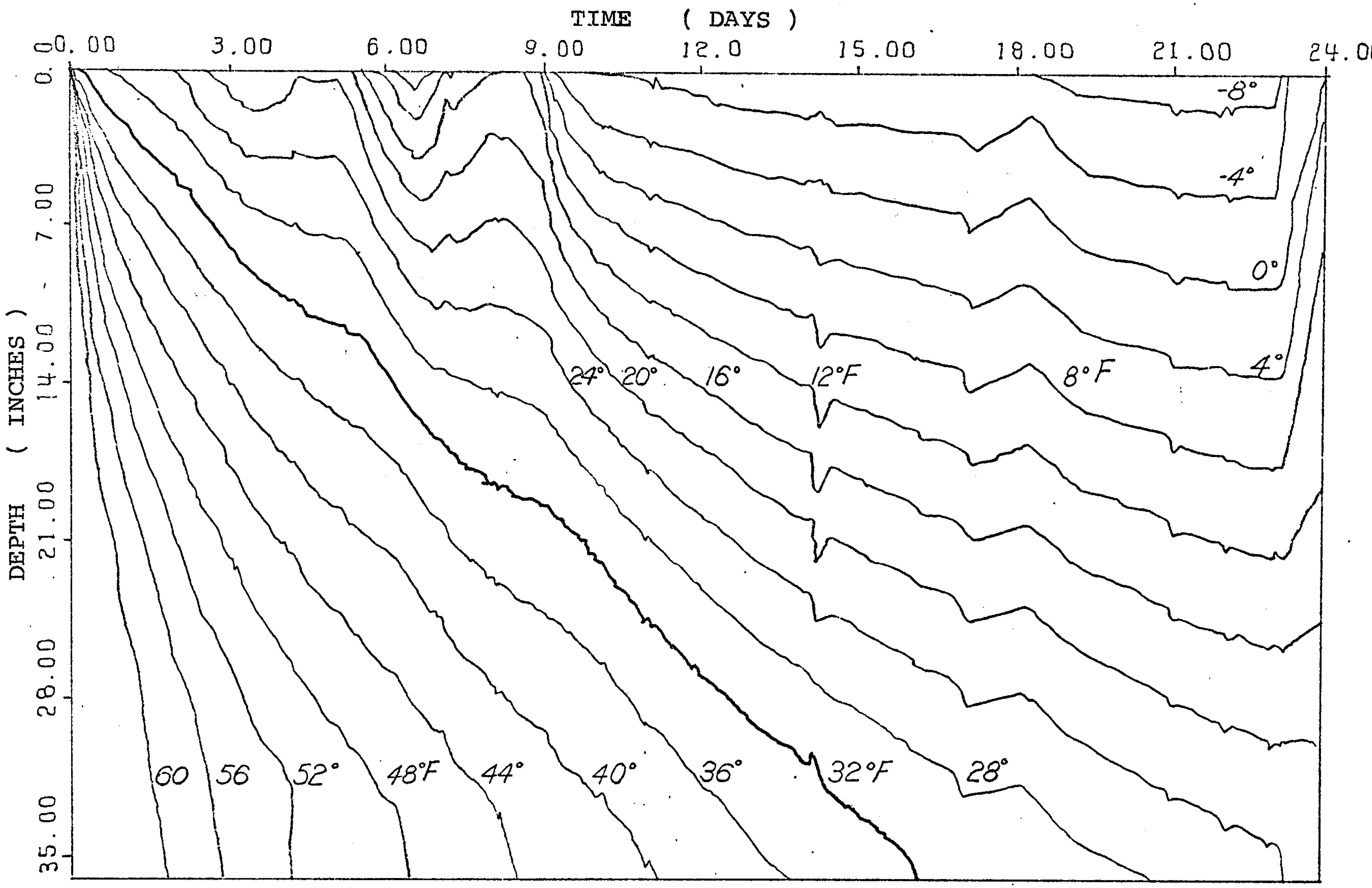


Figure 11. Locations of different isotherms as a function of time; Test No.3

When the depth of frost penetration exceeded the length of one of the vertical members, the average soil temperature within the depth of the vertical member was computed as shown in sketch (b) by dividing the shaded area by the length, L, of the vertical member. The above procedure was used when the temperature distribution was represented by a polynomial. When polynomial curve fitting was unsatisfactory, a numerical integration by Gregory's formula or Simpson's rule was used to compute the shaded area.

The average frozen soil temperature is presented as a function of the depth of frost penetration in Figure 12. As can be seen from Figure 12, the average frozen soil temperature generally decreased as the depth of frost penetration increased, but there was no relationship between the average frozen soil temperature and the depth of frost penetration, and no identifiable interrelationship between the average frozen soil temperature, the depth of frost penetration, and the rate of frost penetration.

Surface Heave of Unrestrained Ground

The surface heave of unrestrained ground monitored by the surface plate is presented as a function of depth of frost penetration in Figure 13 for all six tests. The

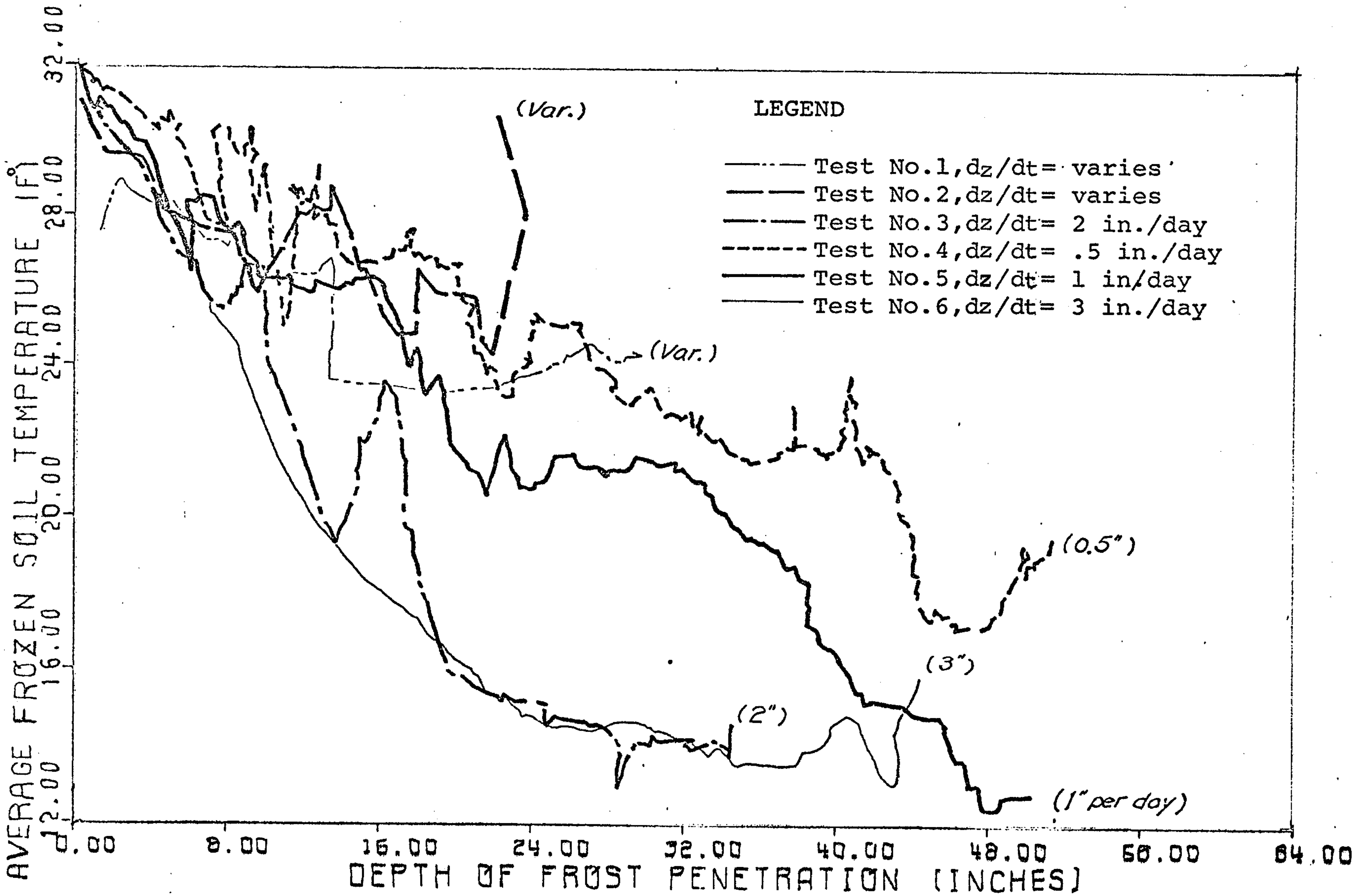


Figure 12. Average frozen soil temperature versus depth of frost penetration for different rates of frost penetration.

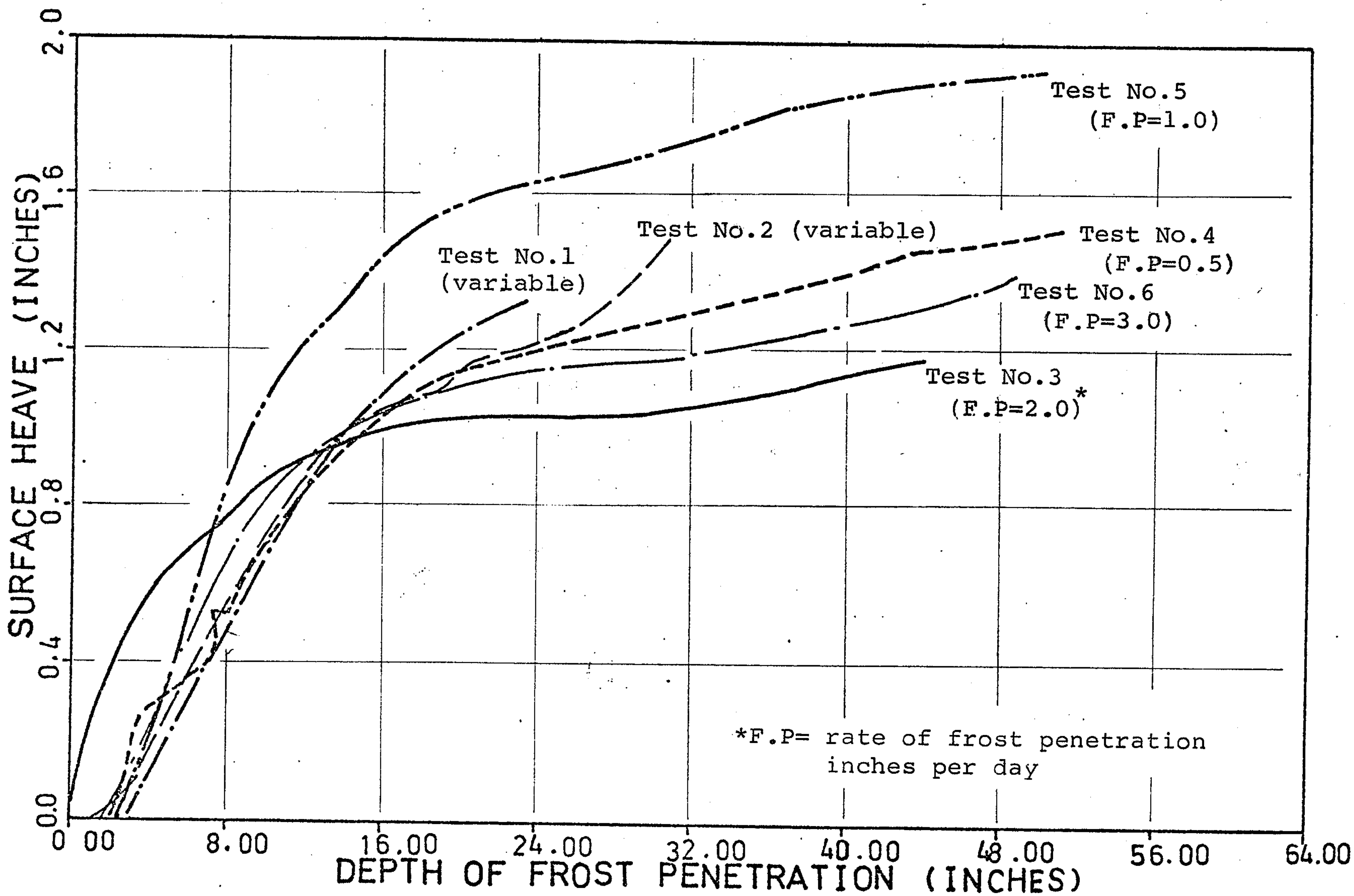


Figure 13. Surface heave versus depth of frost penetration for different rates of frost penetration.

surface heave continued throughout the freezing phase with the rate of heave generally decreasing with an increase in the depth of frozen soil. The observed maximum heave was 1.95 inches at a depth of frost penetration of 51 inches (Test No.5).

As can be seen from Figure 13, there was no definitive correlation between the amount of surface heave and the rate of frost penetration.

An attempt was made to correlate the maximum heaving rate of the six tests with the different rates of frost penetration. Surface heave increased rapidly at the beginning of each test and continued thereafter at a decreasing rate for the duration of the freezing phase. The maximum rate of heave, therefore, corresponds to the initial tangential slope of "the heave versus time" curve, as shown in Figure 14. The maximum rates of heave and the corresponding rates of frost penetration are presented in Figure 15 and Table 2. Also shown in Figure 15 is the computed heave rate based on expansion of pore water assuming the soil to be saturated and no inflow of moisture.

A comparison of the writer's results with those obtained by Penner(14) is seen in Figure 15. As can be seen from Figure 15, the ralationship between the maximum rate of heave and the rate of frost penetration agrees with the

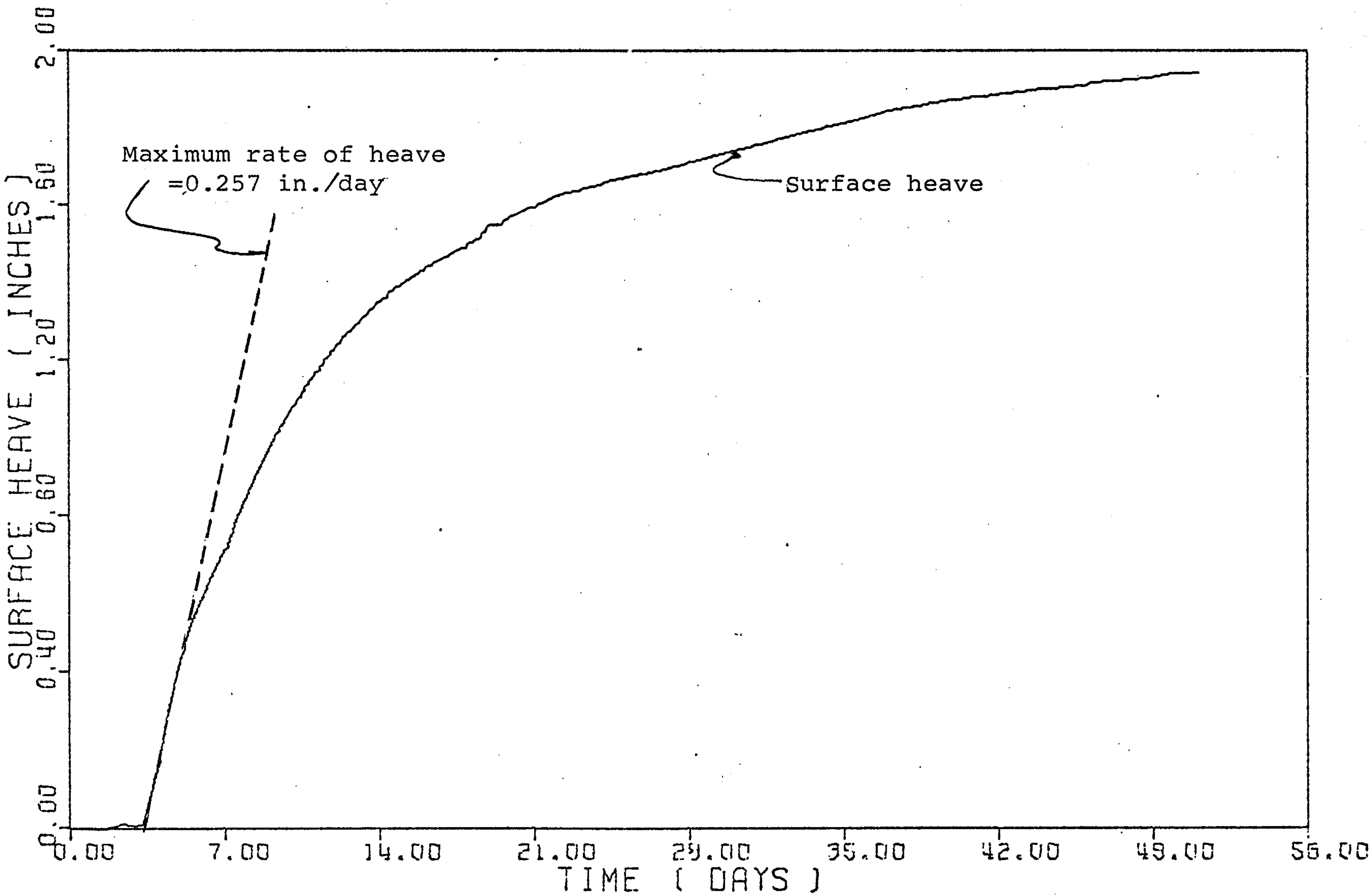


Figure 14. Surface Heave Versus Time; Test No.5.

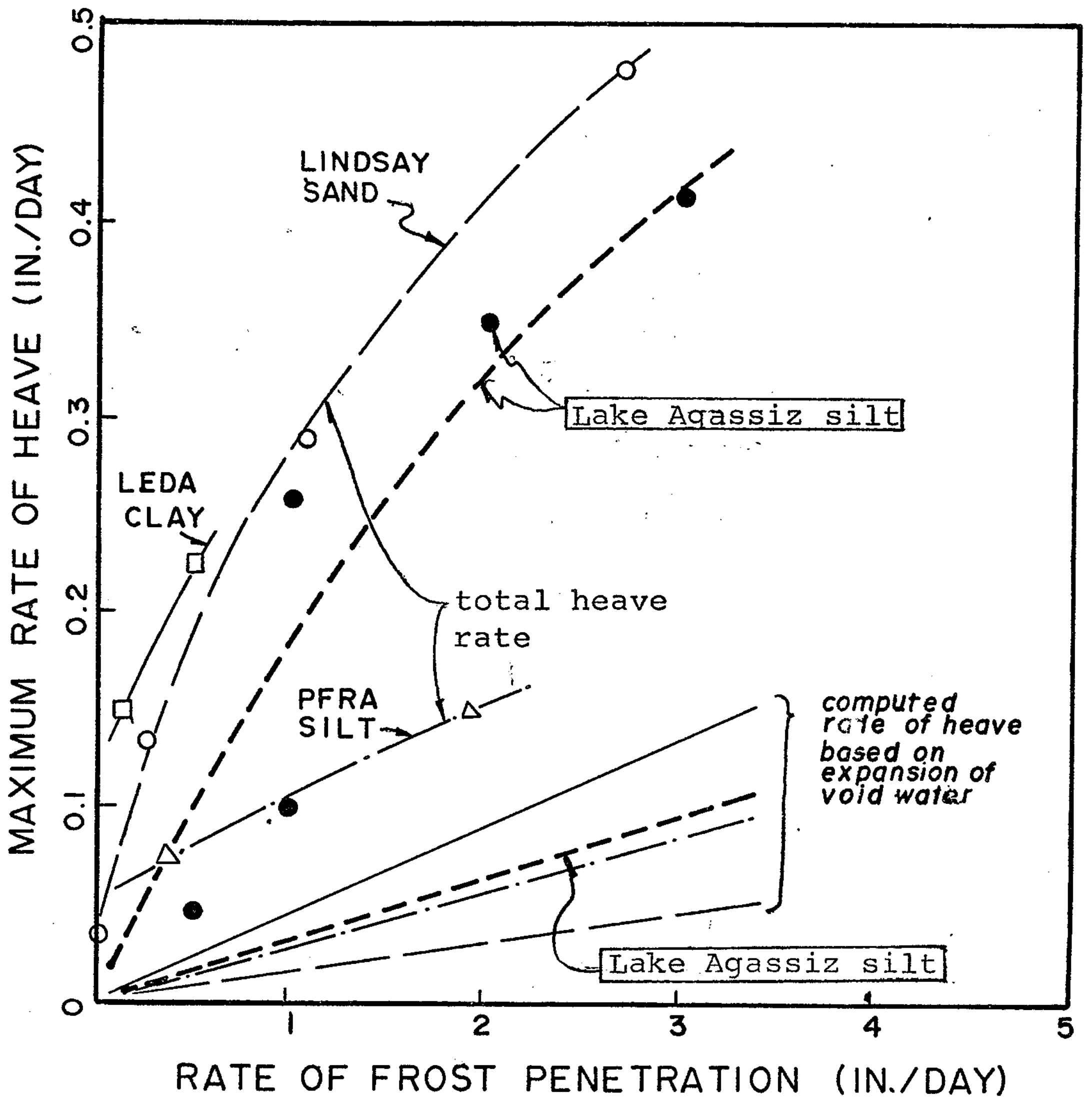


Figure 15. Heave Rate Versus Frost Penetration Rate, after Penner[14].

Table 2.

Maximum Rate of Heave and
Frost Penetration Rate.

TEST No.	MAXIMUM RATE OF HEAVE	CORRESPONDING RATE OF FROST PENETRATION
1	0.10 (in./day)	1.0 (in./day)
2	----	---
3	0.348 (in./day)	2.0 (in./day)
4	0.048 (in./day)	0.5 (in./day)
5	0.257 (in./day)	1.0 (in./day)
6	0.410 (in./day)	3.0 (in./day)

results obtained by Penner.

Although the ralationship between the maximum rate of heave and the rate of frost penetration shows good agreement with Penner's result, the trend of surface heave increase with frost penetration differed. In the writer's investigation, as the depth of frost penetration increased, the rate of surface heave decreased, whereas the experiment conducted by Penner showed almost a linear increase of surface heave with frost penetration. The difference may be attributed to the much larger depth of frost penetration in the writer's study. Consideration of this is presented in the next section.

It has been noted by various investigators, Beskow[2] and Kaplar[12] , that a load placed on a specimen undergoing freezing reduces the rate of heaving. This is explained by the following energy concept. In the heaving process, work is performed in lifting a load above the freezing front and in raising water up to the freezing front. If the load is increased then the amount of energy available for raising the load is expended on lifting it a somewhat shorter distance than if the load had not been present.

In the freezing of soil, the frozen soil above the freezing front acts as a surcharge load. A correlation study was made between the magnitude of heave and the depth of frost penetration. The ratio of surface heave (H) to depth of frozen soil (Z) is plotted on Figure 16 against the depth of frozen soil (Z). Also the overburden pressures corresponding to the depth of frozen soil are shown in the figure. As can be seen from Figure 16, with the exception of one test, the heave ratio increased to a magnitude of 7% to 12% at a depth of frost penetration of about 10 inches which corresponds to about 110 psf overburden pressure, and decreased thereafter, to a magnitude of about 3% to 5%.

Therefore it may be concluded that the magnitude of surface heave is impeded by the overburden pressures in excess of 110 psf.

The effect of the rate of frost penetration on the heave ratio-overburden pressure relationship appears to be insignificant as can be seen in Figure 16.

<u>Surface Heave in The Vicinity of The Vertical Member</u>

The vertical ground movements around the vertical member were measured in Test No.5 and No.6, and the observations are shown in Figures 17 through 20. Figures 17 and 18

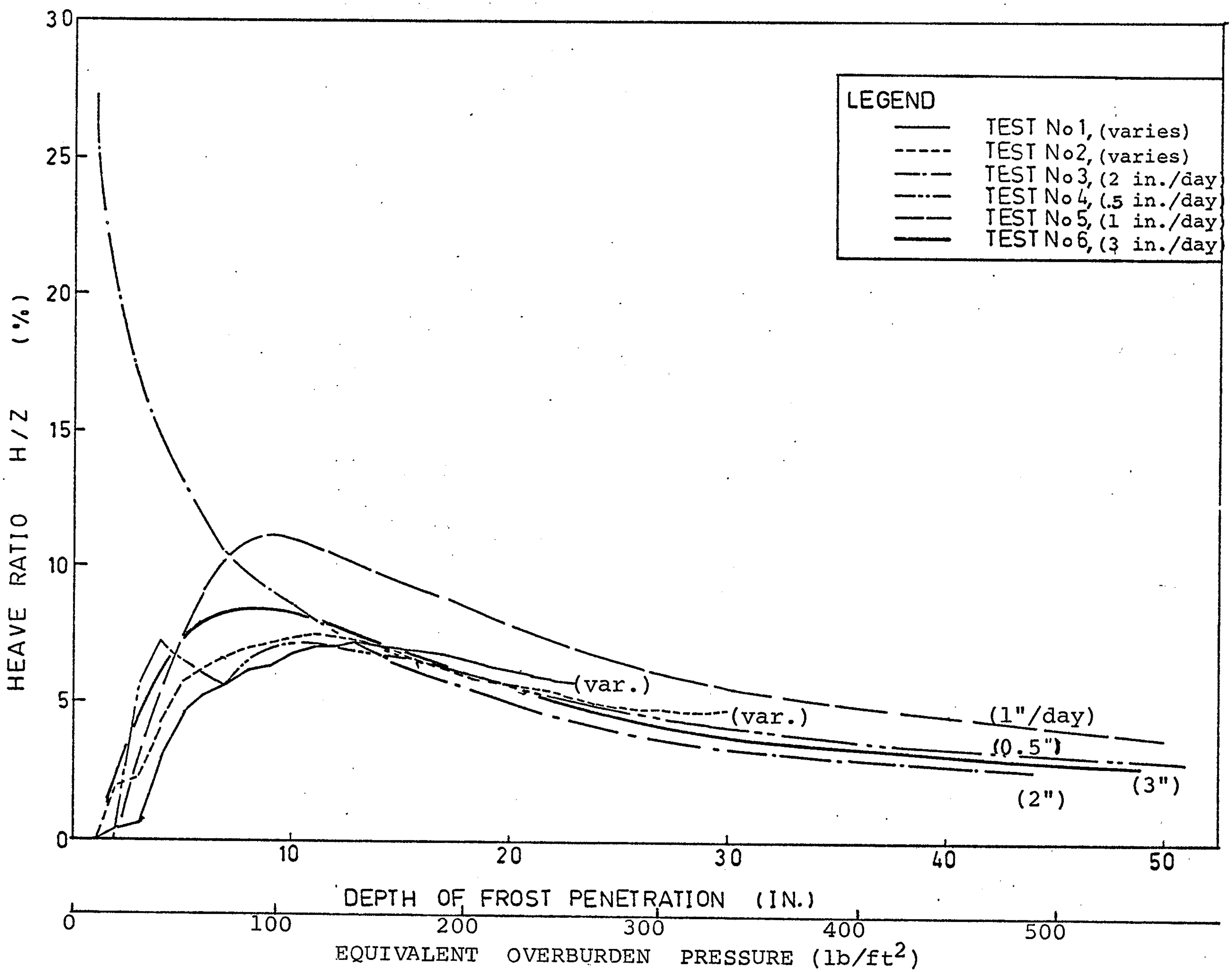


Figure 16. Heave ratio versus depth of frost penetration for different rates of frost penetration.

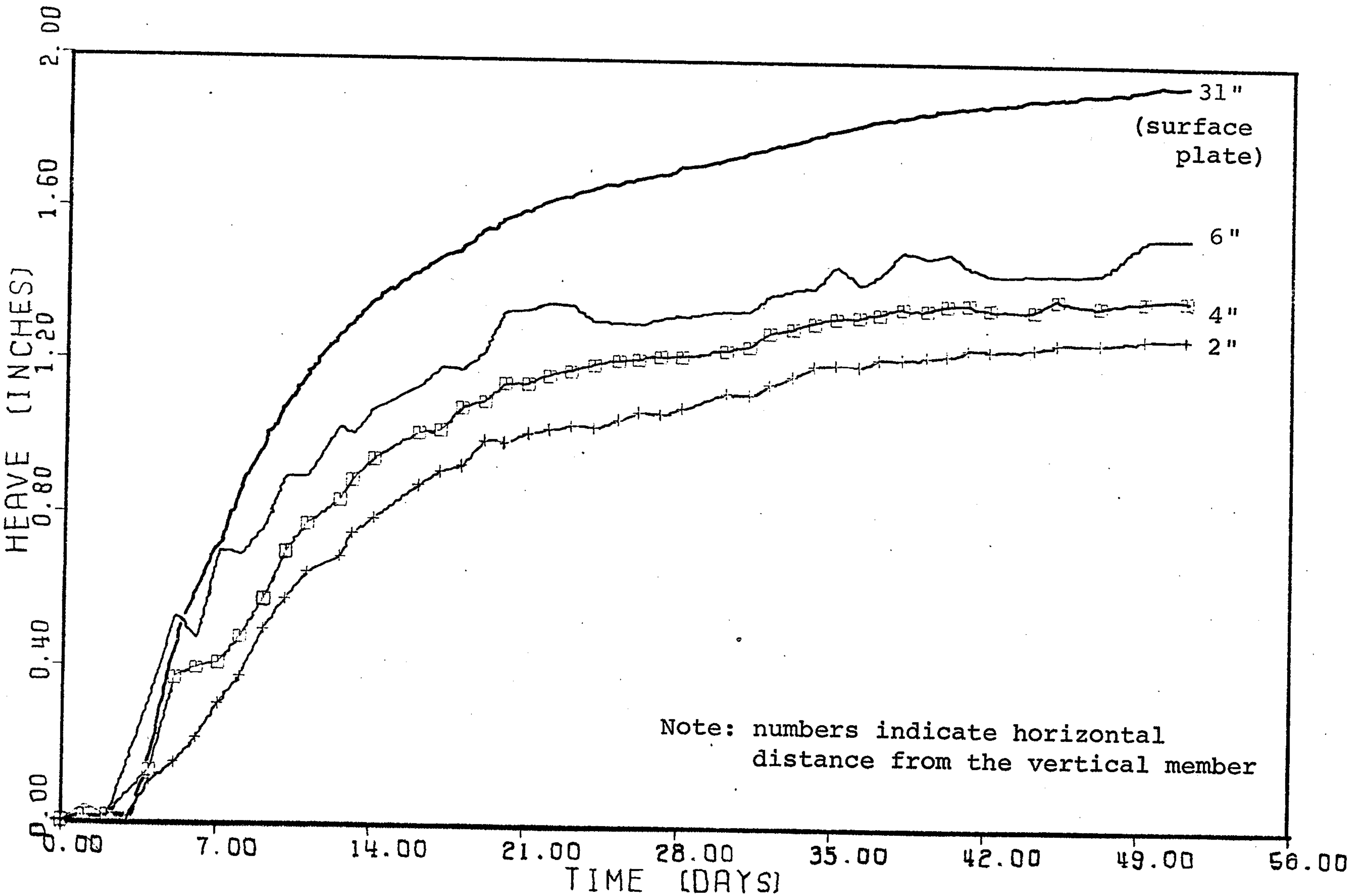


Figure 17. Surface heave in the vicinity of a vertical member; Test No.5

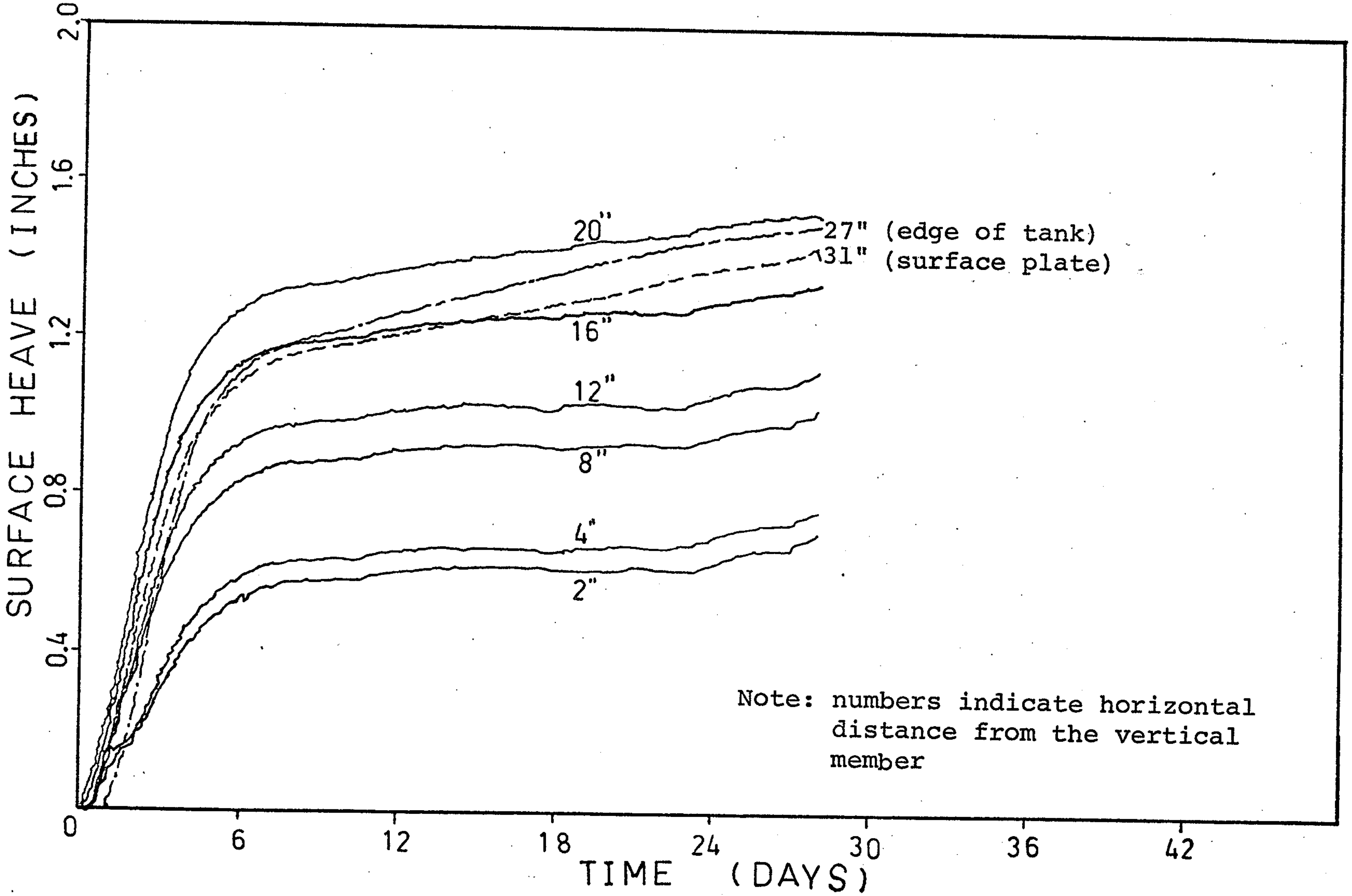


Figure 18. Surface heave in the vicinity of a vertical member; Test No.6

present the ground movements at various distances from the vertical member as a function of time. From Figures 17 and 18, it is evident that the presence of the stationary vertical member had an influence on the surface heave of the soil adjacent to it. The radius of influence of the vertical member would appear to be about 16 to 20 inches as indicated in Figure 18, in which the surface heave at distances greater than 16 inches is relatively constant in magnitude.

In Figures 19 and 20, the variation in surface heave with distance from the member is shown for different elapsed times. The figures indicate that the pattern of heave versus distance is consistent with time. Although no surface heave measurements were taken at the member-soil interface, observations at the end of the test indicated that there was a continuous displacement between the vertical member and the contact soil.

The above results indicated that some plastic flow occurred along the interface of the vertical member throughout the test and that the vertical member impeded the frost heave within a distance of about 16 to 20 inches from the vertical member. These findings disagree somewhat with other researchers' observations[26],[7]. Saltykov[26] conducted a laboratory test and also a field test to study

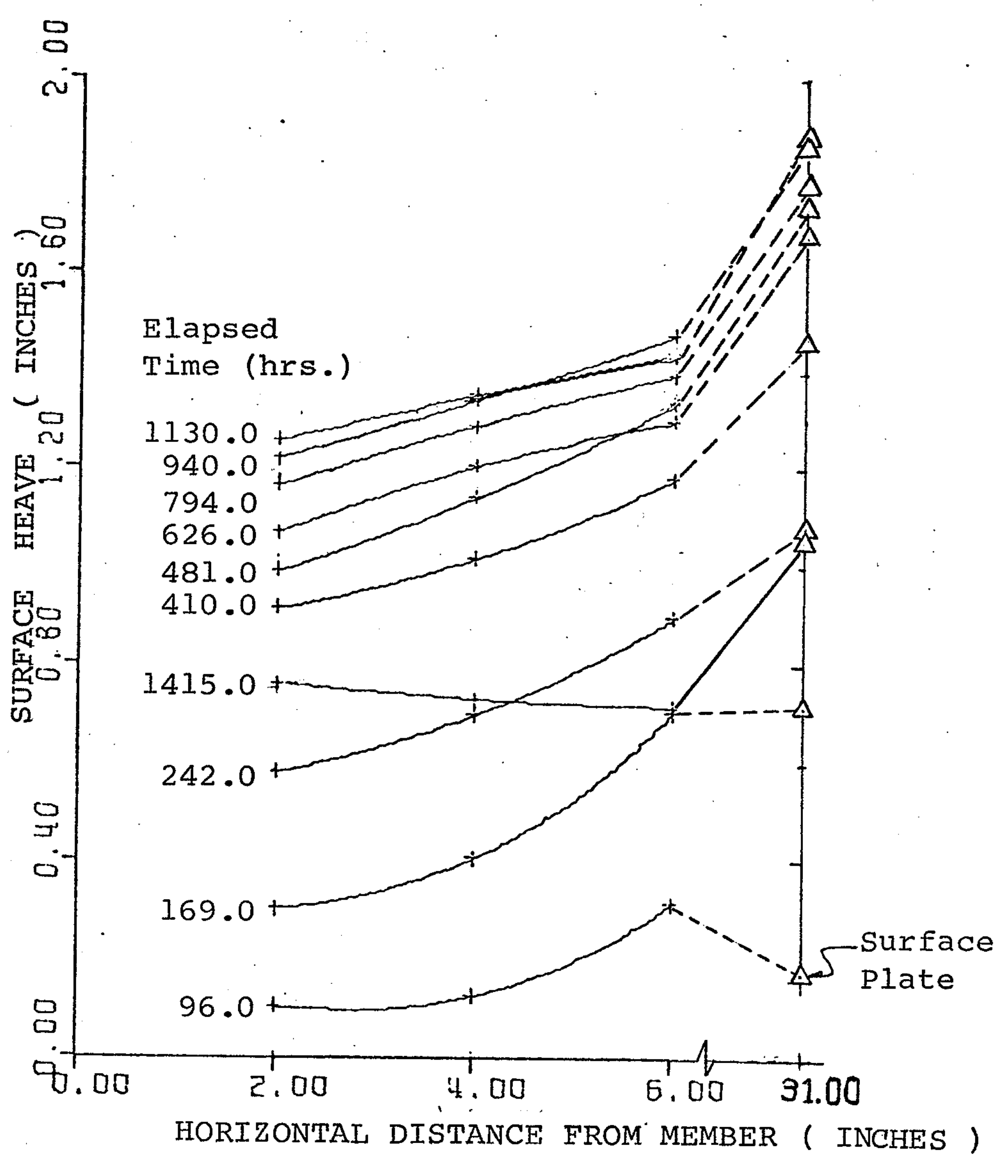


Figure19. Surface profile in the vicinity of a vertical member at various time intervals; Test No.5

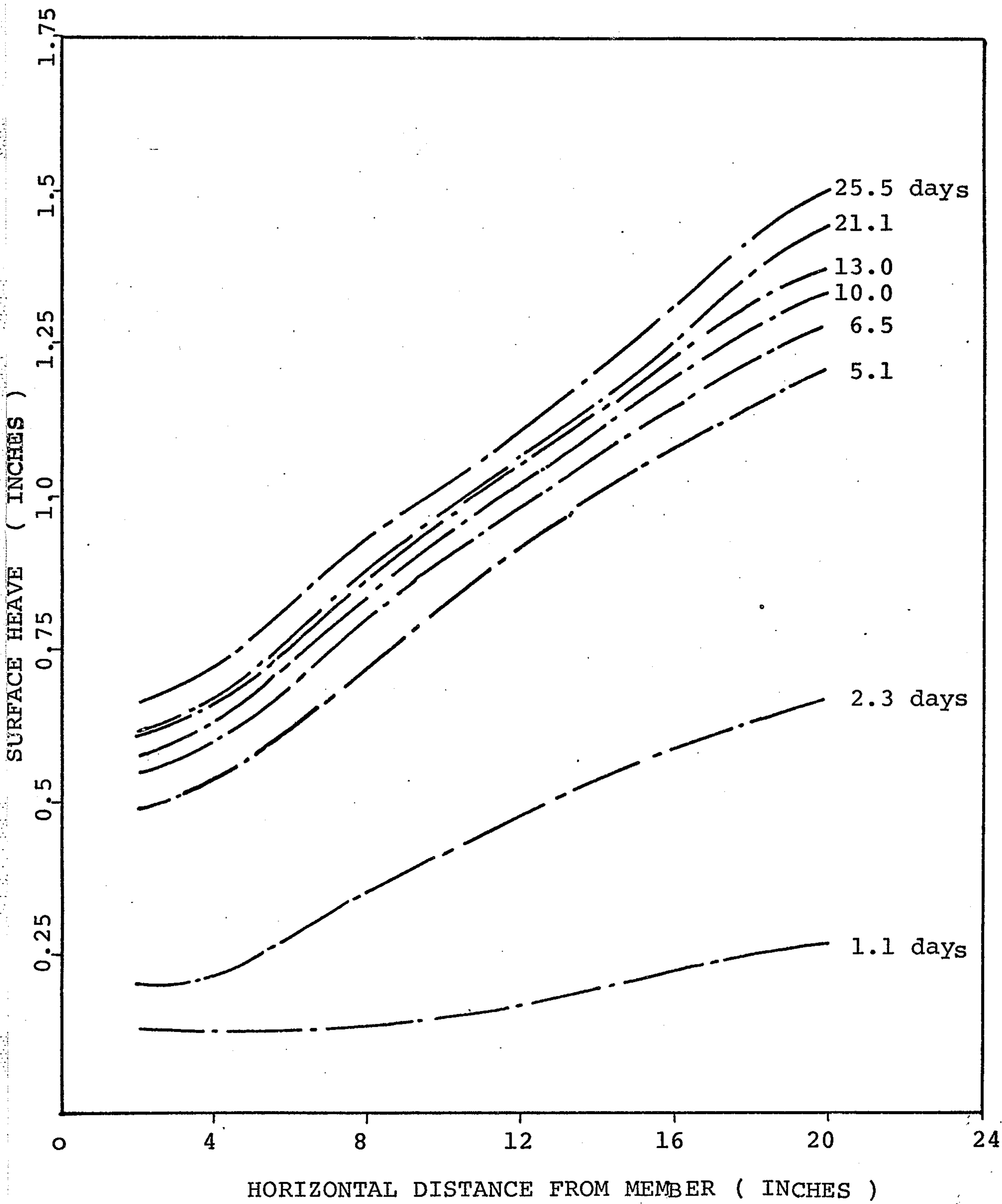


Figure 20. Surface profile after various days of freezing; Test No.6

frost heave in the vicinity of an isolated stationary pipe. He reported that, in the laboratory test in which a 5 cm diameter wooden post was used, plastic deformation of the soil was observed within 1 cm radius of the post and free frost heave occurred beyond that. Penner's[6] observations were made under field conditions with an embedded 3.5 inch diameter steel pipe. Based on the measurement of ground heave around the pipe at radii of 1 ft, 2 ft, 3 ft and 9 ft, he found that there was no impediment of frost heave by the embedded steel pipe. However, Penner[7] observed a difference in heave pattern due to geometrical differences in foundation structures. He found that the impediment of frost heave in the case of a long wall was as much as 7 feet.

An attempt was made to present the nature of the displacement adjacent to the vertical member. Figure 21 depicts the relative heave of soil adjacent to the vertical member as a function of the depth of frost penetration. The relative heave is expressed as a ratio between the frost heave at a distance of 2 inches from the member and the heave of the surface plate. The two-inch distance was chosen because it represented the frost heave measurement nearest to the vertical member. As can be seen from Figure 21,

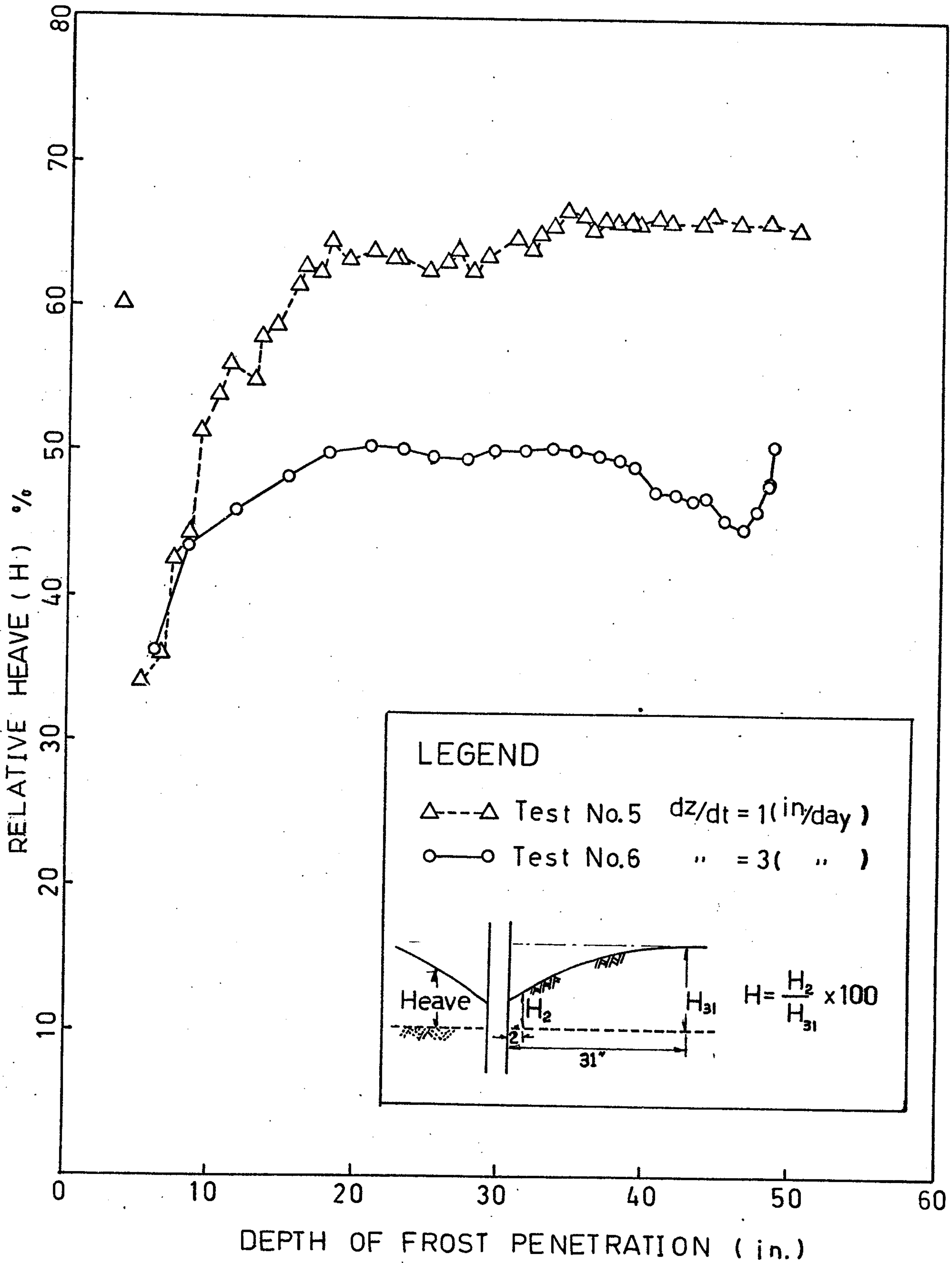


Figure 21. Relative movement of soil adjacent to the vertical member as a function of frost depth.

both curves indicate an increase in the relative heave up to a depth of frost penetration of about 20 inches and thereafter the relative heave reaches a constant. This indicates that the impediment to frost heave by the vertical member is greatest at a shallow frost penetration then decreases to a constant value at a depth of frost penetration of about 20 inches.

The relative heave in Test No.5 was larger than that in Test No.6. However, there was insufficient test data to draw any valid conclusions regarding the effects of rate of frost penetration on relative heave.

The results of "relative heave" and corresponding depth of frost penetration are given in Tables 3 and 4 of the Appendix.

Adfreeze Stress

In this section, the measured uplift thrust and the calculated adfreeze stress on the vertical members are analyzed.

The maximum and average uplift thrust on the vertical members are presented as a function of the depth of frost penetration in Figures 22 and 23 for the six tests. The test number and rate of frost penetration are indicated

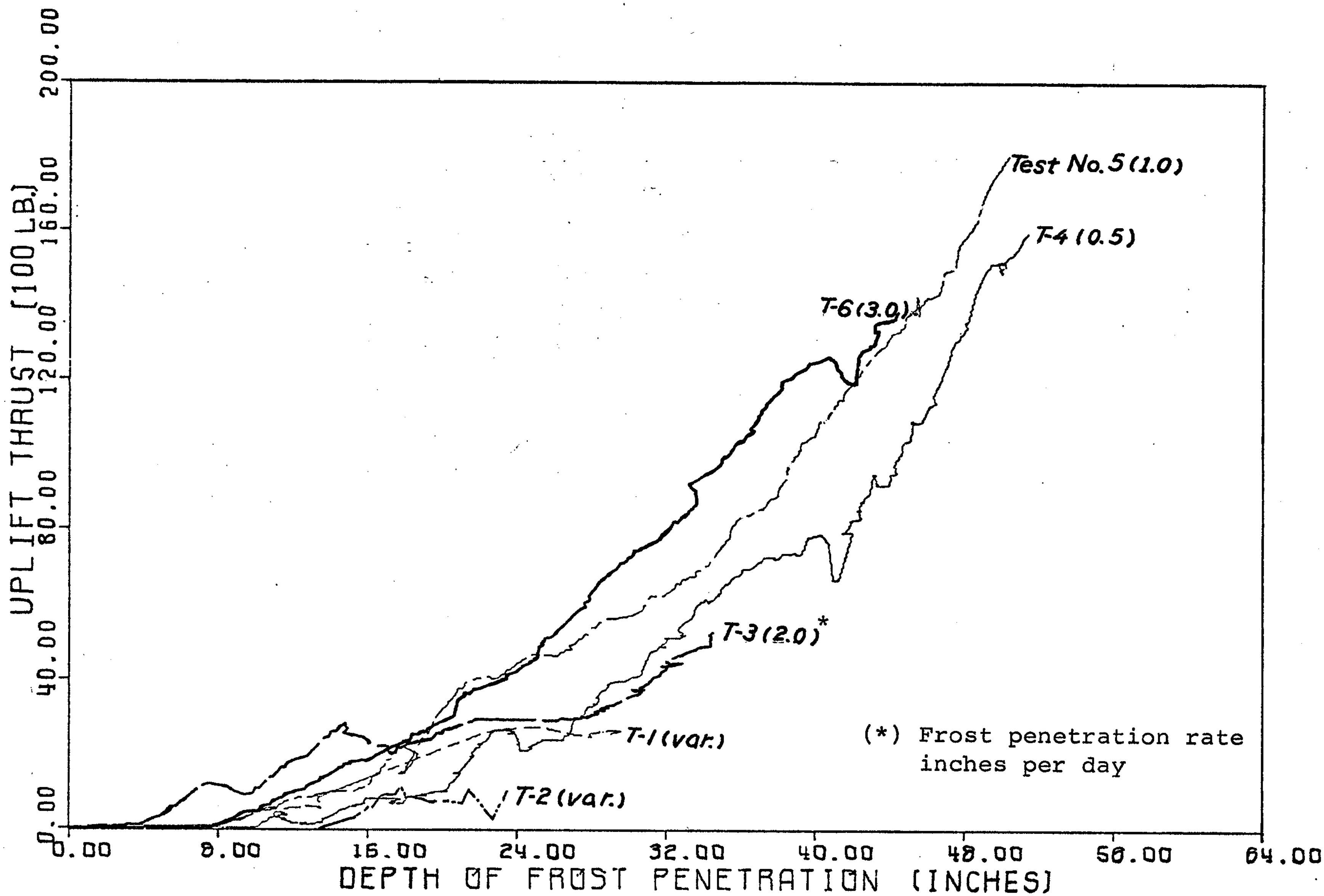


Figure 22. Maximum uplift thrust versus depth of frost penetration for different rates of frost penetration.

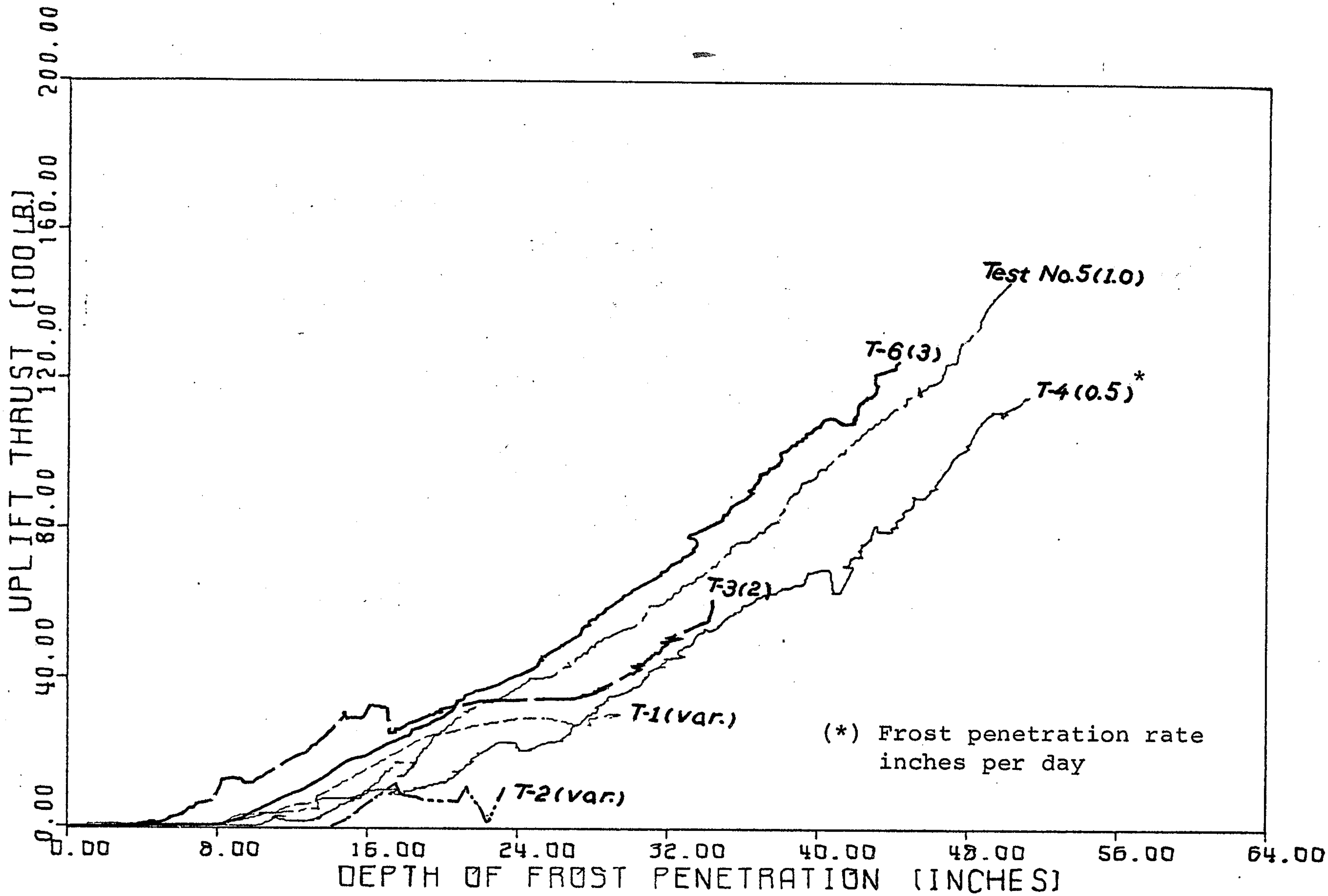


Figure 23. Average uplift thrust versus depth of frost penetration for different rates of frost penetration.

on the curve to which they correspond.

As can be seen in the figures, the uplift thrust increased with the depth of frost penetration during the freezing period as would be expected. The maximum uplift thrust occurred in Test No.5 and was 18 kips with a corresponding depth of frost penetration of 51 inches.

In general the following observations were made regarding the results:

1) the uplift thrust started after a depth of frost penetration of about eight inches.
2) the relationship between the uplift thrust and the depth of frost penetration was not linear. The rate of uplift force increased with an increase in the depth of frost penetration.
3) there was no definitive relationship between the uplift thrust and the rate of frost penetration.

The adfreeze stress was obtained by dividing the uplift thrust by the area of contact between the member and the frozen soil. The maximum and average stresses for the two vertical members are presented as a function of the depth of frost penetration in Figures 24 and 25 respectively. The test number and rate of frost penetration are indicated on the curve to which they correspond. The maximum adfreeze stress was

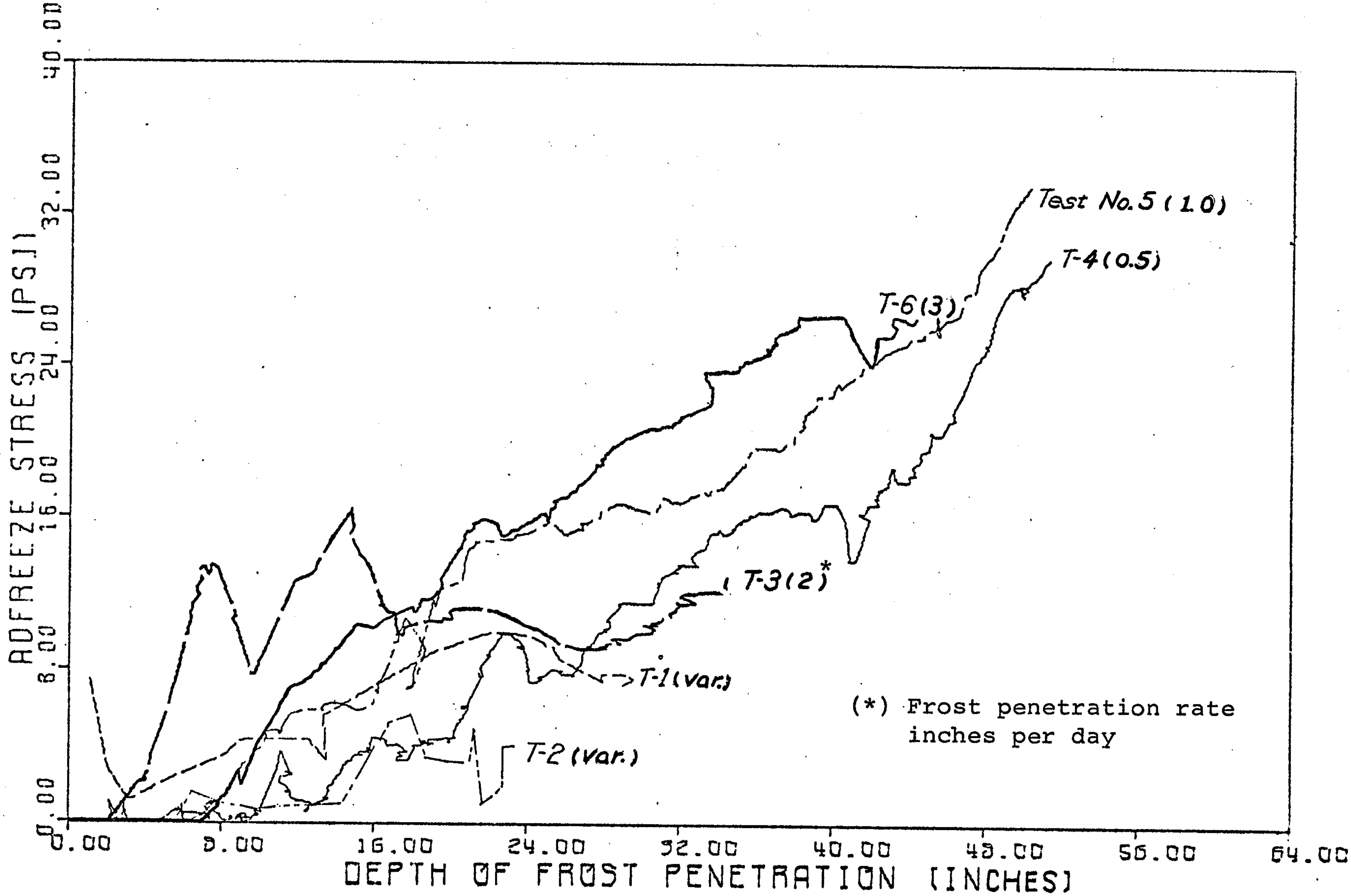


Figure 24. Maximum adfreeze stress versus depth of frost penetration for different rates of frost penetration.

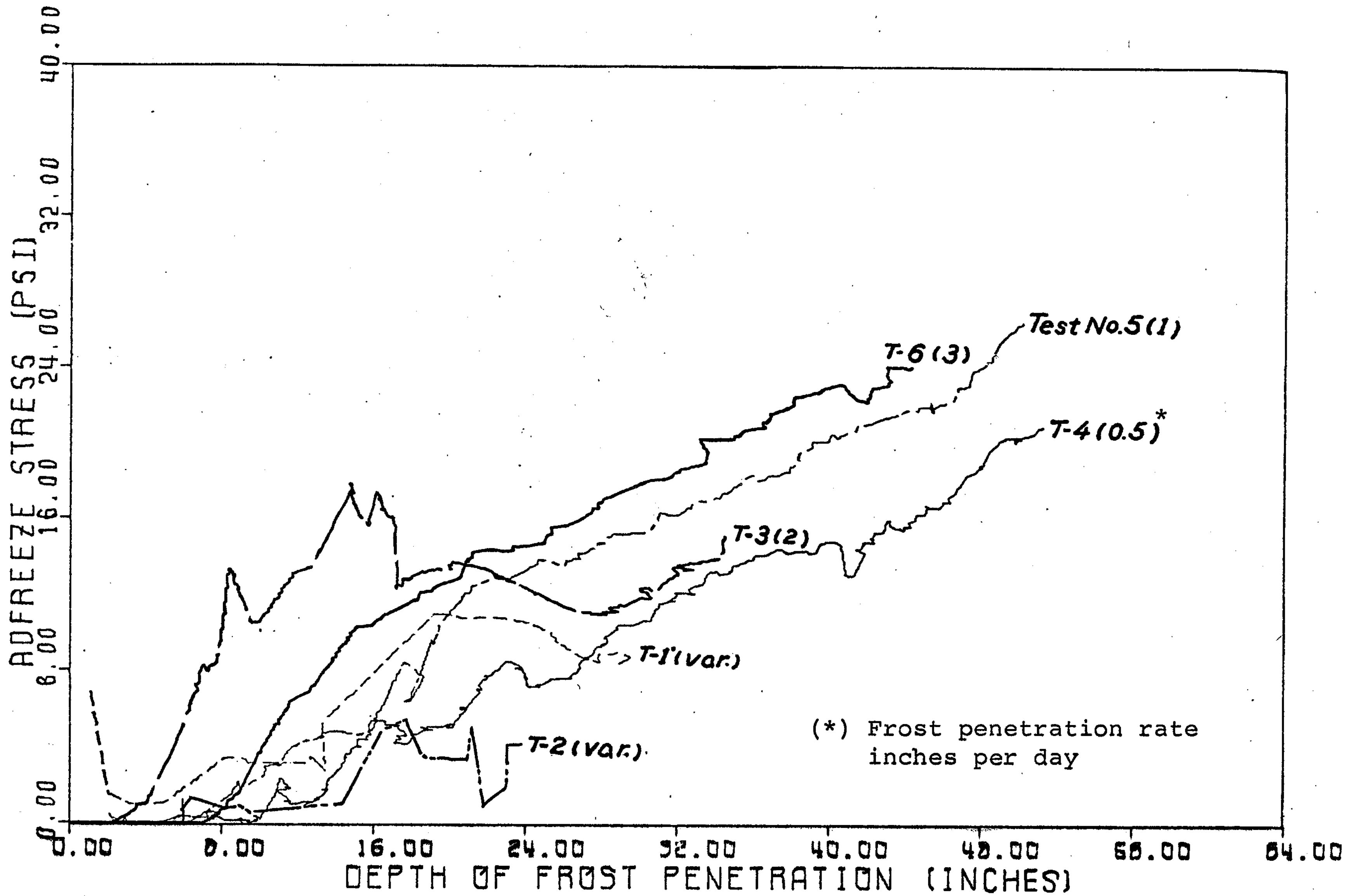


Figure 25. Average adfreeze stress versus depth of frost penetration for different rates of frost penetration.

33 psi. which occured in Test No.5.

In general the following observations were made regarding the results:

1) the adfreeze stress generally increased as the freezing phase progressed, but there were short-term deviations from this trend.
2) the different rates of frost penetration had no definitive effect on the adfreeze stress.

It is known that the mechanical properties of frozen soil are highly dependent on the temperature of the soil. Russian researchers, Vyalov(18) and Dalmatov(17), studied the effect of temperature on the shear strength of frozen soils. Both researchers found that there was an increase in shear strength with a lowering of the soil temperature.

Adfreeze stress is a measure of the creep strength of frozen soil, since it is generated by plastic flow at the interface between the member and the frozen soil. The relationship between the adfreeze stress and the average temperature of frozen soil was investigated. For this correlation study the data corresponding to the vertical member having the larger magnitude of adfreeze stress was used, rather than the average of the two members. Figure 26 shows the correlation between the adfreeze stress and the average temperature of

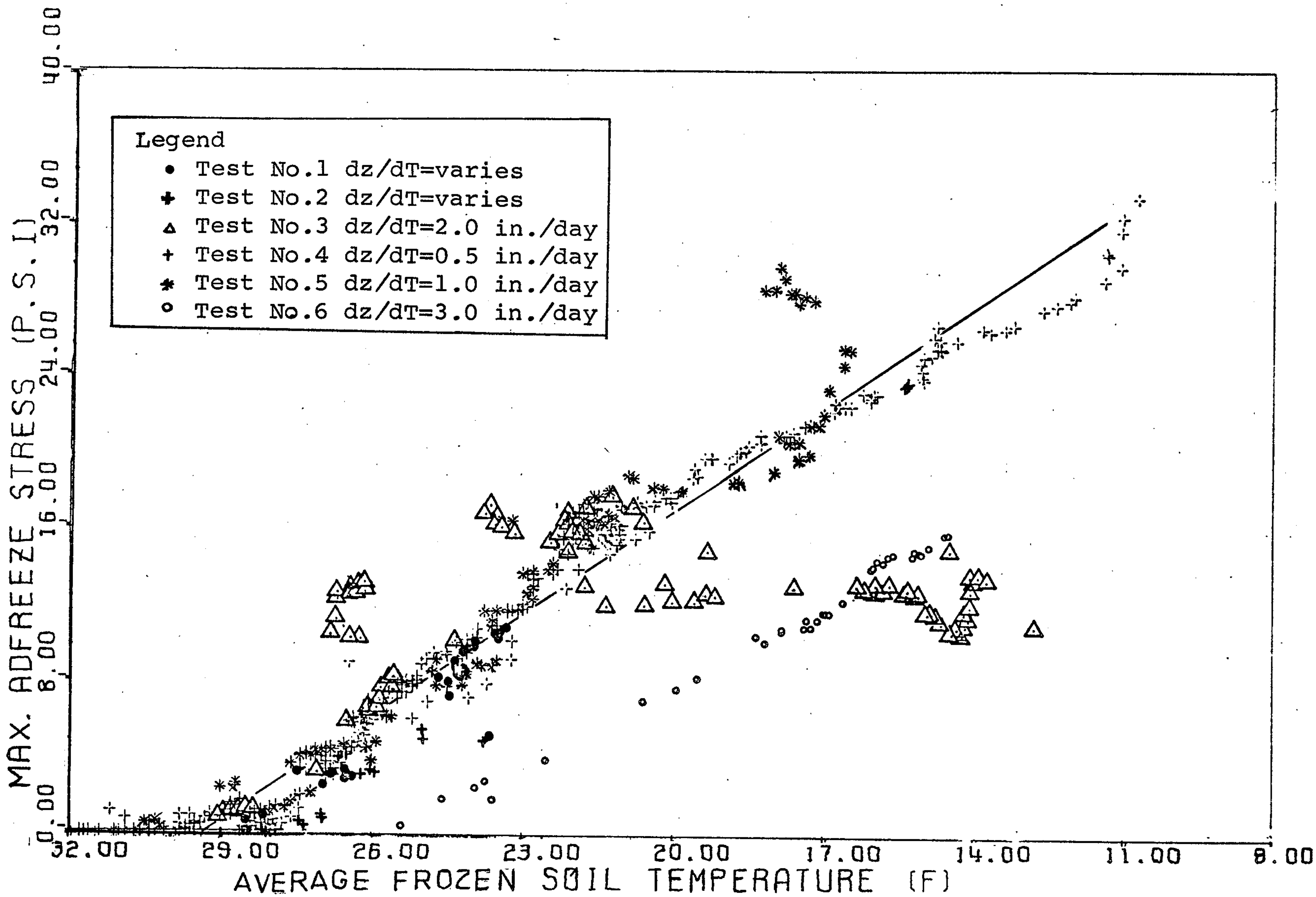


Figure 26. Average frozen soil temperature versus adfreeze stress; vertical member having the larger magnitude of adfreeze stress.

the frozen soil. As can be seen from Figure 26, the adfreeze stress generally increased with a decrease in average frozen soil temperature and the ralationship was approximated by a straight line. The results of Test No.3 deviated considerably from the linear relationship shown, and the results indicated that the adfreeze stress was essentially independent of the average temperature of the frozen soil. The linear relationship is represented by the following equation;

$$\tau_{max} = 1.8 \times (29.5 - t_{ave}) \qquad \text{for } 29.5^{o}F > t_{ave} > 11^{o}F$$

where τ_{max} : Maximum adfreeze stress (psi)

t_{ave} : Average frozen soil temperature (F^{o})

It should be noted here that the adfreeze stress presented in the writer's investigation is based on the assumption of uniform distribution of stress along the interface. Since there is considerable variation in the frozen soil temperature along the interface, there is probably a variation in the adfreeze stress since it is temperature dependent.

An analysis of the unit adfreeze stress distribution was made using the results of the writer's investigation and the relationship between the frozen soil temperature and the bond strength of frozen soil, as determined by Dalmatov(17) and Vyalov(18).

Dalmatov suggested a linear variation of adfreeze strength with frozen soil temperature, and gave the following equation;

$$S = c - b.t$$

where S : Adfreeze strength (kg/cm^2)

c,b: Parameters dependent on soil type, determined experimentally

t : Frozen soil temperature (C^o)

However Vyalov suggested a non-linear variation of adfreeze strength with frozen soil temperature, expressed by the following relationship;

$$S = S_o + a\sqrt{t}$$

where S : Adfreeze strength (kg/cm^2)

S_o : Adfreeze strength at 0^oC soil temperature (kg/cm^2)

a : A parameter dependent on soil type, determined experimentally

t : Frozen soil temperature (C^o)

Both investigators obtained their equation from temperature controlled laboratory tests.

It was demonstrated in the writer's investigation that the adfreeze stress was temperature dependent and the relationship was approximately linear. Thus the results support the linear relationship suggested by Dalmatov. The linear relationship obtained from the writer's investigation gives the following equation for average unit adfreeze stress as a function of soil temperature;

$$\tau = 53.1 - 1.8\ t \qquad \ldots\ldots\ (1)$$

where τ : Unit adfreeze stress (psi)

t : Soil temperature (F^o)

The distribution of unit adfreeze stress along the interface is thereby obtained using equation (1) and the soil temperature distribution within frozen zone. The temperature distribution was expressed as a function of depth by means of a fourth degree polynomial;

$$t = A_1 + A_2Z + A_3Z^2 + A_4Z^3 + A_5Z^4$$

Therefore the relationship between unit adfreeze stress and depth is given by;

$$\tau = 53.1 - 1.8\ (A_1 + A_2Z + A_3Z^2 + A_4Z^3 + A_5Z^4)$$

where τ shall be positive, or zero.

Typical examples of unit adfreeze stress distribution along the interface are depicted in Figure 27 and 28.

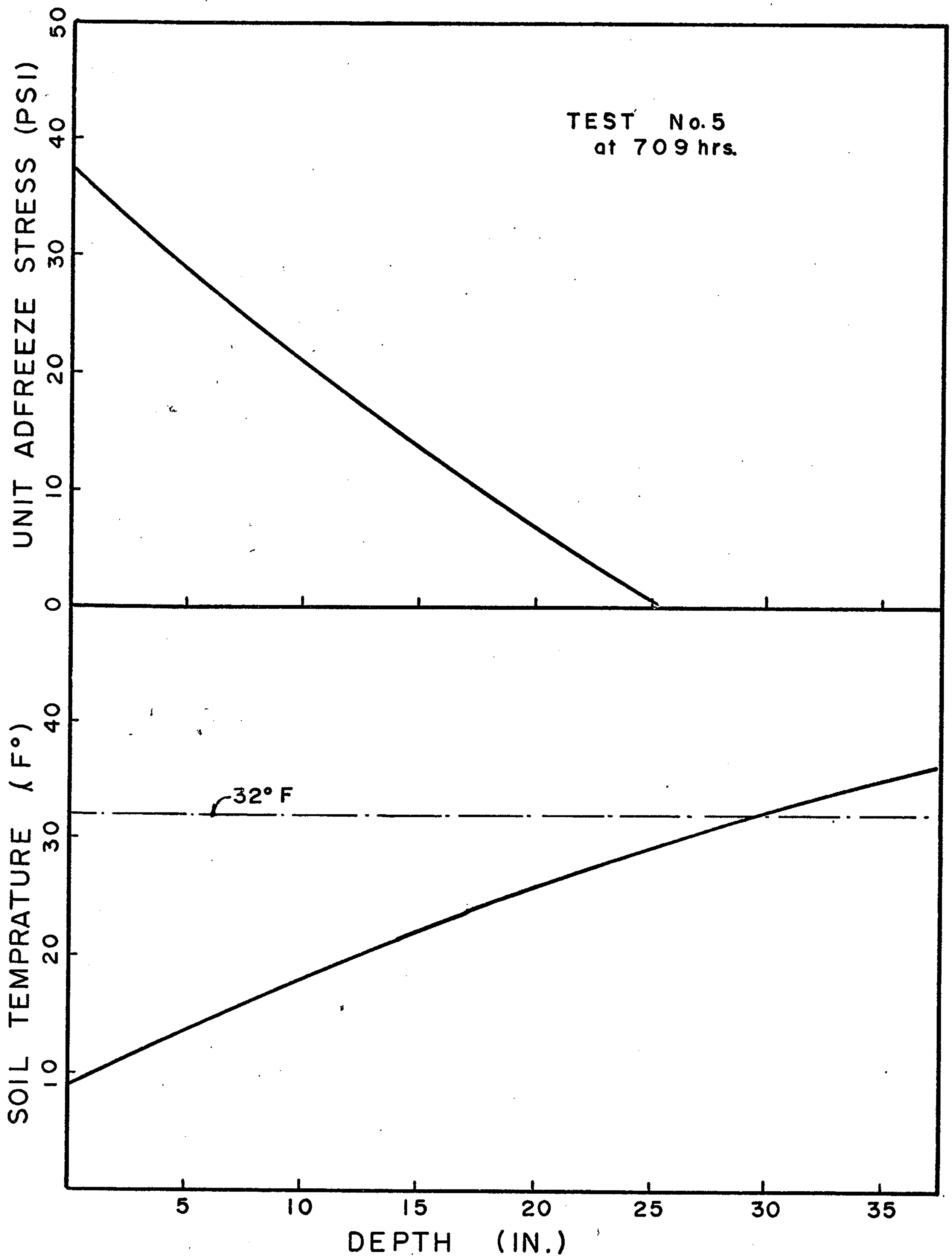


Figure 27. Computed variation of unit adfreeze stress with depth, and soil temperature distribution; Test No.5, at 709 hrs.

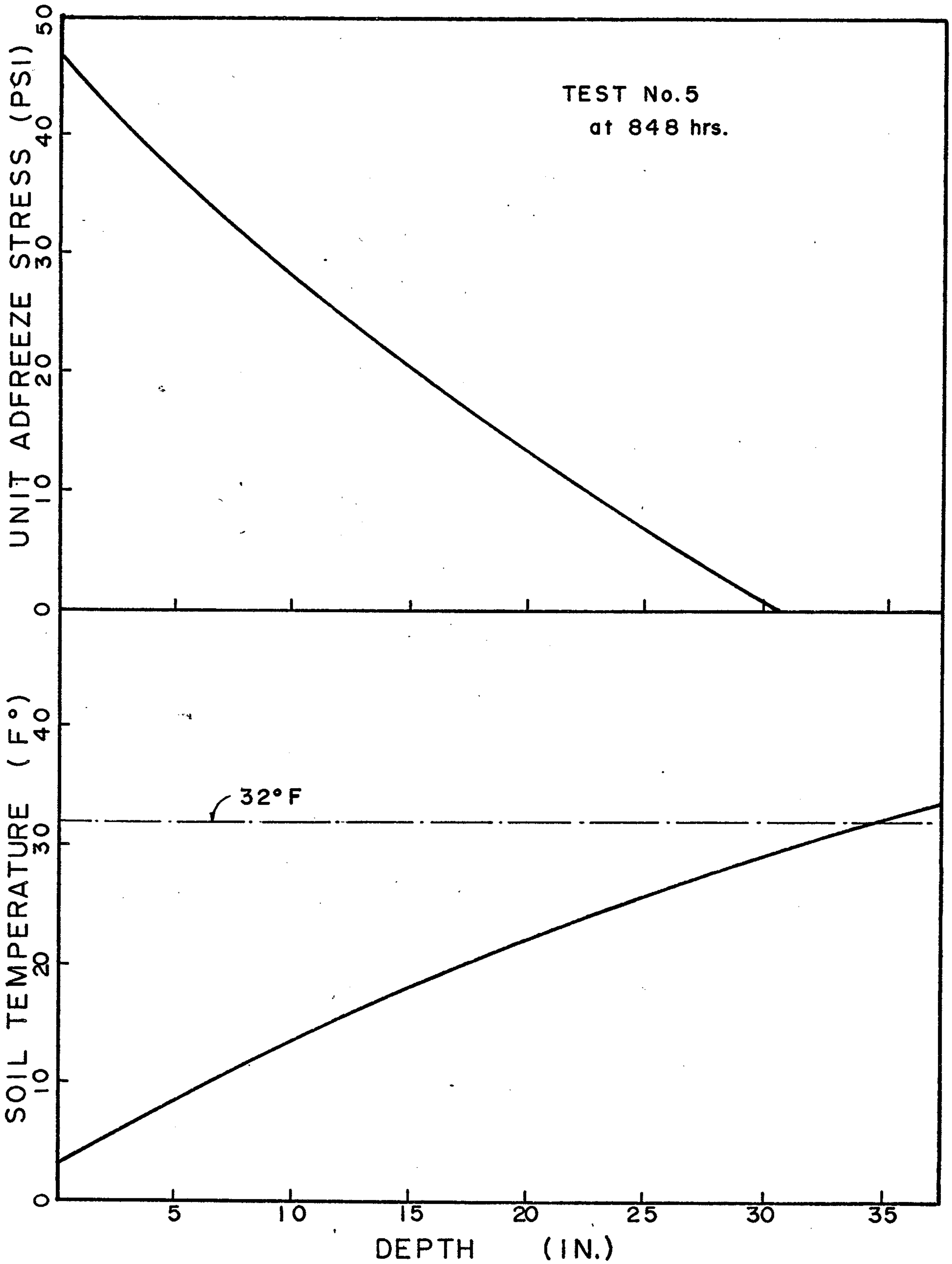


Figure 28. Computed variation of unit adfreeze stress with depth, and soil temperature distribution; Test No.5, at 848 hrs.

Uplift Thrust on The Horizontal Member

The uplift thrust exerted on the horizontal member is presented in terms of a frost heave pressure which represents the unit stress acting on the base of the horizontal member. The frost heave pressures are presented as a function of the depth of frost penetration in Figure 29. The test number and rate of frost penetration is indicated on each curve.

The maximum heave pressure observed was 352 p.s.i. which occurred in Test No.4. However, this does not necessarily represent the maximum value of frost heave pressure generated in Test No.4 because the thrust exceeded the capacity of the load cell, and the readings beyond the capacity were discounted because they could not be converted to load with any reliability.

As can be seen in Figure 29, it is clearly demonstrated that;

1) the frost heave pressure did not level off during the freezing phase.

2) there was almost a linear relationship between the depth of frost penetration and the frost heave pressure.

3) the difference in the rate of frost penetration seemed to have an effect on the uplift thrust. Within the limited number of tests conducted, the slower the rate

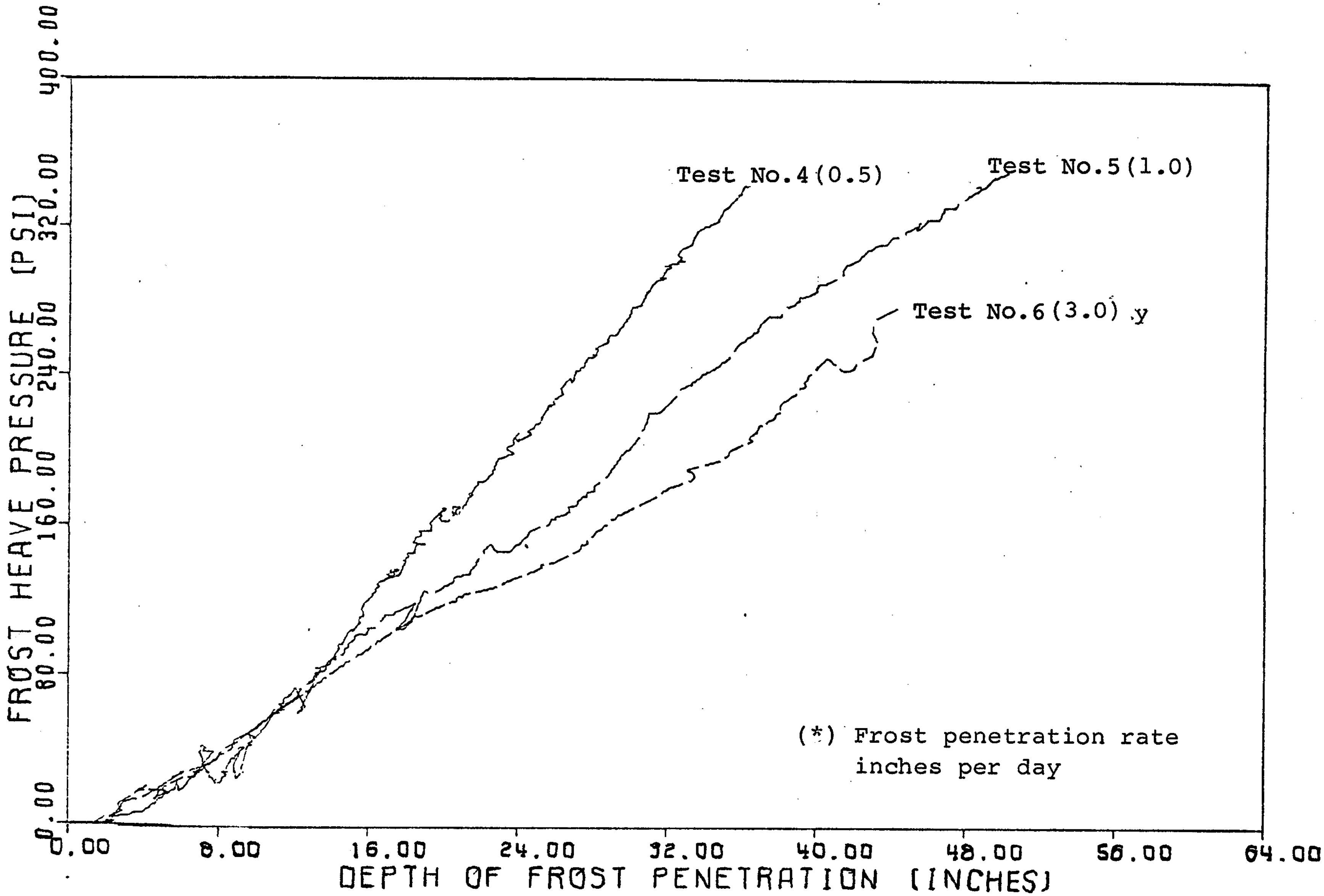


Figure 29. Frost heave pressure on horizontal member versus depth of frost penetration for different rates of frost penetration.

of frost penetration, the larger was the uplift thrust for a given depth of frost penetration.

A linear relationship between the depth of frost penetration and the contact pressure indicates that uplift thrust on a horizontal member is more closely related to the depth of frost penetration than to the surface heave. This is demonstrated in Figure 30 which shows the surface heave force in relation to the depth of frost penetration and also to the surface heave. As can be seen in the figure, the surface heave force increased almost linearly with the depth of frost penetration, but it did not show the same trend when compared with the surface heave.

The observation that the slower the rate of frost penetration, the larger the uplift thrust for a given depth of frost penetration may be explained from the view point of ice lense activity at the frost front.

Penner[27] conducted an experiment of ice lense activity and he concluded that "the maximum heaving pressure develops after the period of active frost penetration and rises to this maximum when the ice-water interface is essentially stationary." The "heaving pressure" represents the pressure generated by the expansion of ice lenses at the frost front. This experimental observation by Penner conforms

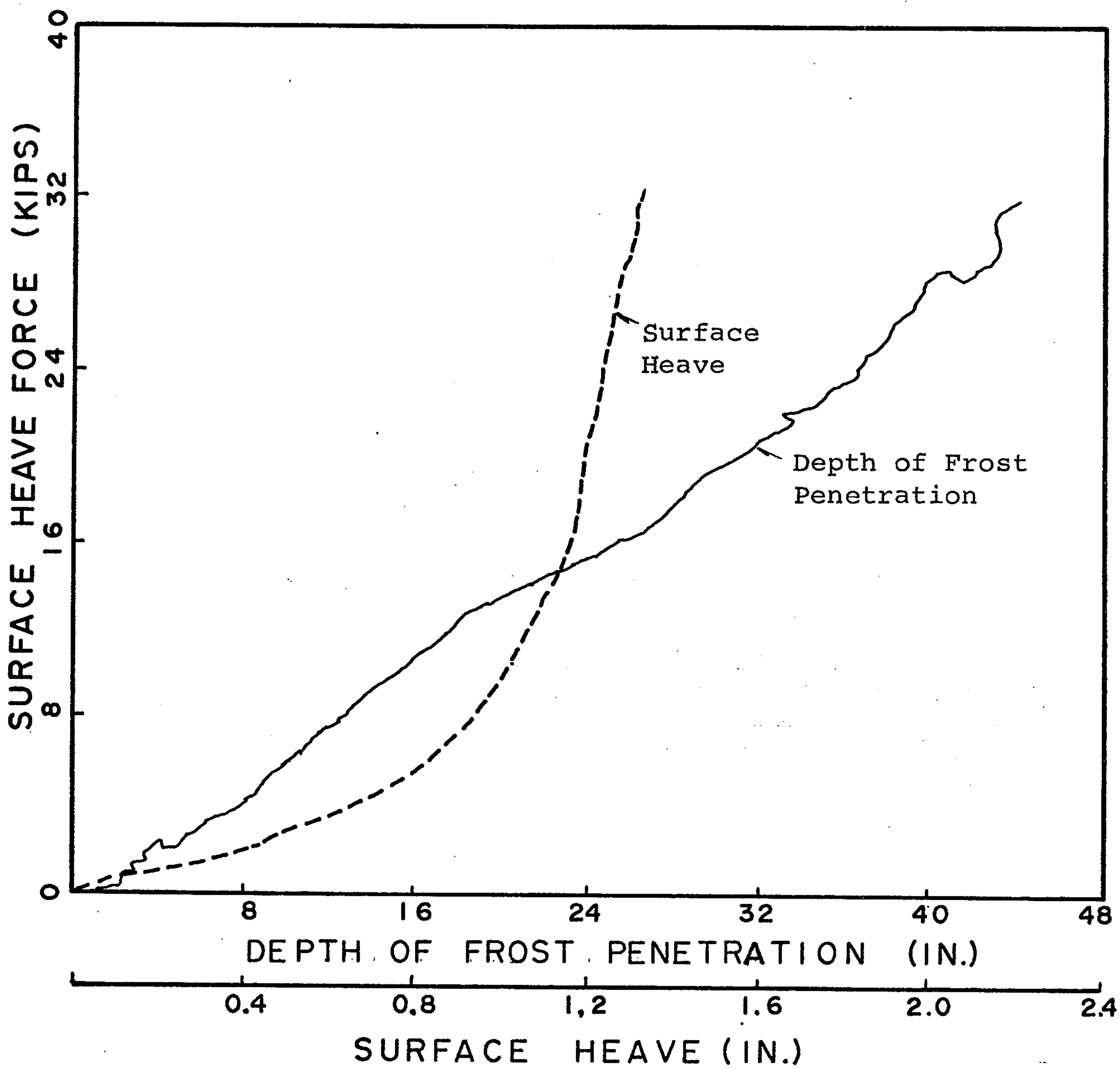


Figure 30. The relationship between depth of frost penetration, surface heave, and surface heave force on the Horizontal Member; Test No.6.

with the Everett's theory for porus media. Everett's[9] theory says that the heaving pressure is generated by the ice lense propagation into the pore, and that the equilibrium at ice-water interface is necessary to attain the maximum heaving pressure. This suggests that, when there is a constant downward penetration of the freezing front, equilibrium at the ice-water interface cannot be achieved and therefore the maximum heaving pressure cannot be attained. Furthermore it may be that the faster the rate of frost penetration, the further the conditions at the ice-water interface are from equilibrium which may explain the trend between the uplift thrust and the rate of frost penetration observed in the writer's investigation. The lack of an observed maximum heave pressure may also be explained on the basis of continual frost penetration.

CHAPTER 5

CONCLUSIONS AND FURTHER RECOMMENDATION

The research project described herein was primarily designed to investigate the factors that affect the adfreeze and frost heave forces. In this chapter the findings are summarized and recommendations for further study are presented.

Conclusions

1) The distribution of temperature with depth in the soil for a constant rate of frost penetration during the freezing phase was nonlinear and was best represented by a fourth degree polynomial.

2) Surface heave continued throughout the freezing phase with the rate of heave generally decreasing with an increase in the depth of frozen soil.

3) Overburden pressure appeared to effect the surface heave. The general trend was that the expansion of soil due to freezing was largely impeded by overburden pressures in excess of about 110 lb/ft^2.

4) The maximum rate of heave increased as the rate of frost penetration increased, which was similar to the trend found in Penner's investigation.

5) Surface heave was influenced by the presence of the buried structural member with the radius of influence being about 16 to 20 inches.

6) The adfreeze stress was best correlated with average temperature of the frozen soil. The unit adfreeze stress increased linearly with a decrease in the frozen soil temperature according to the following equation:

$$\tau = 53.1 - 1.8\ t \quad \text{for } 29.5^{o}F \geq t > -13.0^{o}F$$

where τ : Unit adfreeze stress (psi)

t : Frozen soil temperature (F^{o}).

7) The uplift thrust on a horizontal member increased throughout the freezing phase of the test. There was almost a linear relationship between the depth of frost penetration and the uplift thrust.

8) There was no correlation between heave of the soil surface and the uplift thrust on the horizontal member.

9) The rate of frost penetration appeared to have an effect on the uplift thrust on the horizontal member. The trend observed was that the slower the rate of frost penetration, the larger the uplift thrust for a given depth of frost penetration.

Recommendations for Further Study

1) The maximum uplift thrust on a horizontal member should be determined with a stationary frost front. This study should include the effect of the size of the horizontal member on the unit uplift thrust.

2) A theoretical study of ice lense activity at the frost front should be continued in order to have a clear understanding of the mechanism of frost heave forces. In particular the effects of the rate of frost penetration on the heaving pressure at the frost front should be studied.

3) The relationship between the frozen soil temperature and the unit adfreeze stress should be studied further. Attention should be given to the distribution of the adfreeze stress with depth.

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A P P E N D I X

Table 3.
Relative Surface Heave Adjacent to a Vertical Member; Test No.5

Time(hr.)	Surface Heave(in.) at 2 in. (A)	at 31 in. (B)	A/B (%)	Depth of frost penetration(in.)
96.0	0.106	0.177	59.9	3.7
122.0	0.151	0.447	33.8	5.1
146.0	0.216	0.606	35.7	6.5
169.0	0.304	0.717	42.4	7.4
194.0	0.378	0.860	44.0	8.4
218.0	0.501	0.980	51.1	9.2
242.0	0.581	1.081	53.7	10.3
266.0	0.651	1.166	55.8	11.2
300.0	0.694	1.267	54.8	12.8
314.0	0.751	1.301	57.7	13.4
338.0	0.792	1.352	58.6	14.3
387.0	0.881	1.436	61.3	15.8
410.0	0.918	1.467	62.6	16.4
434.0	0.933	1.501	62.2	17.3
458.0	0.998	1.549	64.4	18.1
481.0	0.993	1.573	63.1	19.4
506.0	1.015	1.597	63.7	21.1
530.0	1.027	1.624	63.3	22.5
553.0	1.036	1.637	63.3	23.1
578.0	1.031	1.656	62.4	24.9
604.0	1.054	1.671	63.1	26.1
626.0	1.072	1.682	63.8	26.9
650.0	1.068	1.694	62.4	27.8
674.0	1.086	1.710	63.5	28.9
722.0	1.124	1.739	64.7	30.9
748.0	1.119	1.756	63.8	32.0
770.0	1.148	1.770	64.9	32.5
794.0	1.169	1.785	65.5	33.5
818.0	1.197	1.799	66.6	34.4
842.0	1.200	1.812	66.2	35.5

Table 3.

(continued)

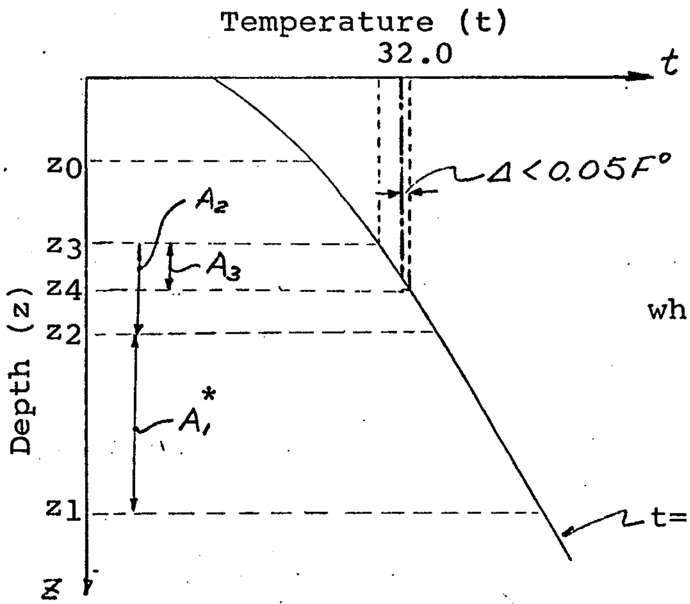
Time(hr.)	Surface Heave(in.)			Depth of frost penetration(in.)
	at 2 in. (A)	at 31 in. (B)	A/B (%)	
867.0	1.197	1.836	65.3	36.1
889.0	1.216	1.842	66.0	37.0
914.0	1.216	1.853	65.7	37.8
940.0	1.226	1.863	65.8	38.8
962.0	1.230	1.872	65.7	39.4
986.0	1.243	1.880	66.2	40.6
1010.0	1.241	1.886	65.9	41.6
1058.0	1.248	1.899	65.8	43.7
1083.0	1.262	1.905	66.3	44.4
1130.0	1.261	1.918	65.8	46.3
1180.0	1.271	1.932	65.8	48.4
1225.0	1.271	1.946	65.3	50.4

Table 4.
Relative Surface Heave Adjacent to a Vertical Member;Test No.6

Time(hr.)	Surface Heave(in.)			Depth of frost penetration(in.)
	at 2 in. (A)	at 31 in. (B)	A/B (%)	
24.0	0.1410	0.0921	153.0	3.0
48.0	0.1578	0.4358	36.2	6.0
73.0	0.3125	0.7199	43.4	8.4
97.0	0.4185	0.9109	45.9	11.6
121.5	0.4909	1.0177	48.2	15.2
144.0	0.5413	1.0841	49.9	18.0
168.0	0.5660	1.1251	50.3	20.8
192.0	0.5767	1.1518	50.1	23.1
216.0	0.5789	1.1670	49.6	25.2
240.0	0.5828	1.1777	49.5	27.5
266.0	0.5970	1.1923	50.1	29.4
288.0	0.6038	1.2049	50.1	31.5
312.0	0.6125	1.2178	50.3	33.3
338.0	0.6180	1.2319	50.1	35.0
360.0	0.6205	1.2430	49.8	36.6
383.5	0.6212	1.2554	49.5	38.0
407.0	0.6210	1.2691	49.0	39.0
430.0	0.6070	1.2832	47.3	40.5
459.0	0.6105	1.2979	47.1	41.9
480.0	0.6110	1.3078	46.7	43.1
504.0	0.6230	1.3258	47.0	44.0
528.0	0.6100	1.3438	45.3	45.3
552.0	0.6100	1.3615	44.8	46.7
576.0	0.6320	1.3720	46.1	47.5
599.0	0.6565	1.3843	47.8	47.8
623.0	0.6690	1.3935	48.0	48.0
648.0	0.6728	1.4064	47.8	48.6
672.0	0.7120	1.4100	50.5	48.7

Half Interval Search Method

Since there is no solution available for a high degrees of polynomial equation, the solution can be obtained by successive trial error procedure. The Half Interval Search Method is illustrated as follows;



where

$A_1 = (z_0 + z_1)/2$

$A_2 = (z_1 + z_2)/2$

....

etc.

$t = A_1 + A_2z + A_3z + A_4z + A_5z$

Z_0, Z_1, ... are successive trial values of depth, and the above procedure will be repeated until the descrepancy becomes less than the specified error (0.05 F^{o}).