Frost Action Theories Compared with Field Observations

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Recent investigations of the mechanism of frost action in soils have increased the understanding of the basic nature of this mechanism. Two recent studies have related the heat flow through the soil system to the moisture migration and the resulting frost heave. Both investigators obtained good correlation between theory and laboratory experimental results, but arrived at somewhat different conclusions.

This paper reports some results of field observations on suitably prepared field observation plots. Although these observations were made with a view toward exploring several aspects of frost action, only the relationship of the heat balance to heaving and penetration is discussed. Measured heave rates were compared with estimated heat flow rates for the condition of zero penetration rate. Although there are variations in the behavior of the four soils evaluated and variations between seasons, field observations agree well with theoretical predictions. For the case of a penetrating frost line, neither of the conflicting concepts can be verified completely. On the basis of the limited data available, it appears that the validity of either concept depends on the soil type.

•RECENT INVESTIGATIONS of the mechanism of frost action in soils have increased understanding of the basic nature of this mechanism. Certain of these studies have related the heat flow through the soil system to the moisture migration and the resulting frost heave. Two of these researchers, Higashi (1) and Penner (2), in particular have produced excellent results. Both studies were conducted in the laboratory, and the investigators obtained rather good correlation between experimental results and theory. These investigators reached somewhat different conclusions, however, with respect to the relationship between the rate of penetration of the frost line and the rate of heaving.

It is of considerable interest that these investigators reached differing conclusions in view of the fact that they used similar concepts. Both concerned themselves with the difference in heat conduction between the frozen and unfrozen zones. Higashi concluded that for the case of a nonadvancing frost line, the heave rate is proportional to this heat conduction difference up to some critical cooling rate. Beyond this critical cooling rate, the heaving rate decreases as the rate of frost line penetration increases.

Penner conducted laboratory experiments in which the heat flow through both the unfrozen and frozen zones was directly measured. He did not specifically consider the case of a nonadvancing frost line, and concluded that the rate of frost heaving increased as the rate of frost penetration increased.

Due to the difference in the conclusions reached, it is pertinent to determine how well these concepts apply to natural conditions of freezing in the field. It is the purpose of this paper to report on some results of field observations that will aid in the evaluation of these concepts and lead to their effective extension to field conditions. These observations were made on suitably prepared observation plots at the Keweenaw Field Station (KFS) of the U. S. Army Cold Regions Research and Engineering Laboratory (CRREL) located at Houghton, Mich.

Heaving rates were compared with estimated heat flow rates for the condition of zero frost penetration rate. The field observations agree fairly well with the theoretical predictions. The agreement is better for certain soils than for others, and the agreement is better for a season of moderate temperature fluctuations than for a season of sharp temperature fluctuations. Although the field data do not fit the theoretical relationship as well as the results of laboratory investigations, due in large measure to the comparative difficulties of field studies, it is believed that they are significant.

The relationship between heave rate and penetration rate for the condition of rapid frost penetration was also studied. The field data do not form a well-defined general relationship for this case, so neither of the theories applying to this condition can be verified with certainty from the field observations. Some tentative relationships for specific conditions are indicated from the limited data available. However, it should be pointed out that the field freezing took place with the distance to water table progressively decreasing from about 3 to 0 ft, with the thickness of overburden progressively increasing from 0 to about 3 ft. These conditions were different from those of either of the laboratory investigations mentioned above.

DESCRIPTION OF STUDY

Field Observation Plots

Four soils were used in the field observation plots, ranging from a fat clay to a sand with fines. A water-resistant basin was constructed in such a manner than a nearby reservoir would control the water level in the basin. A graded filter was placed in the bottom of the basin, and the selected soils placed over the filter. These soils were placed on lifts about 6 in. high and compacted by field methods. The depth of test soil over the filter is about 46 in. (see Fig. 1).

The test plots were instrumented with thermocouples for measuring temperatures at suitable depth increments, heave plates for determining the heaving at various levels, and frost tubes for a direct indication of the frost penetration during the freezing-down period. In the late autumn of 1959 this instrumentation was supplemented by the addition of moisture tensiometers.

To obtain the maximum freezing effect and permit ready sampling of the soils, no pavement was placed over the soils. Snow was cleared from the site to eliminate the insulating effect of a snow cover.

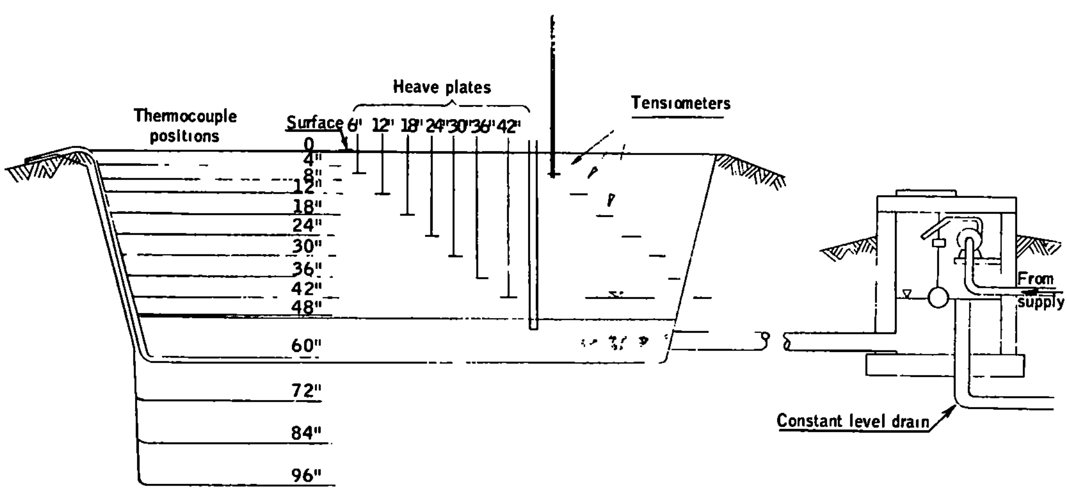

Figure 1. Cross-section of field observation plot (not to scale).

Data Obtained

With the advent of freezing conditions, the thermocouples were read to determine the temperature gradients, and the heave plates were read periodically with an engineer's level and rod to determine the heave at the various levels. The slurry frost tubes also were read at periodic intervals, thus obtaining a direct indication of the frost line. These observations were continued throughout the freezing season.

The depth of frost penetration was determined by a comparison of three kinds of data or indications. The primary method was to determine the break in the temperature gradient which occurs at the frost line. This break is caused by the difference in thermal conductivity between frozen and unfrozen soil.

The position of the frost line as determined by this method was then checked by comparing it with the location of heaving as indicated by the several heave plates at their respective depths (see Fig. 2). The time when a given heave plate first showed vertical movement was taken as the time the frost line reached that given level. Finally, the data from the slurry frost tubes were considered. All three indicators agreed quite closely.

RESULTS OF OBSERVATIONS

Surface heave and the penetration of the frost line were plotted against time for each of the four soils studied, for the three seasons of record. The surface heave for all soils was considerably smaller for the first season following construction than for the two succeeding seasons. This first season was quite severe (2,200 degree-days) compared to the two following seasons, 1,780 and 1,650 degree-days, respectively.

The surface heave rate was not constant at all times, but varied somewhat, including some periods when the rate was essentially zero. The changes in heaving rate, or breaks in the plot of accumulated heave against time, were quite definite.

Likewise, the rate of frost penetration was not constant with time but showed considerable variation For certain soils and specific temperature conditions, the frost line remained constant at a given level for several days before further penetration occurred. The results of these observations of heave and penetration are summarized in Figures 3 to 6.

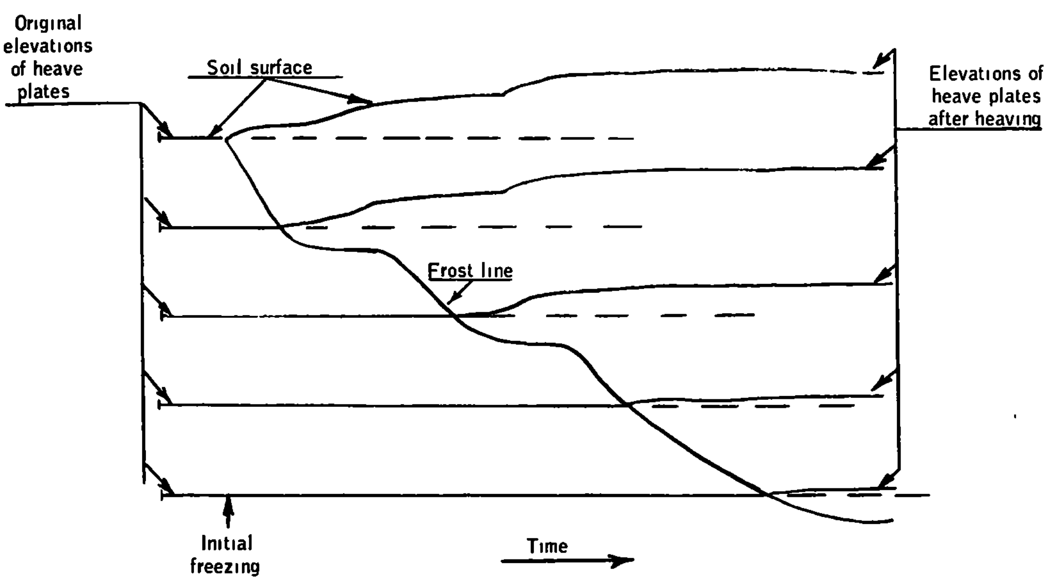

Figure 2. General relationship of frost penetration and frost heaving at various levels with time.

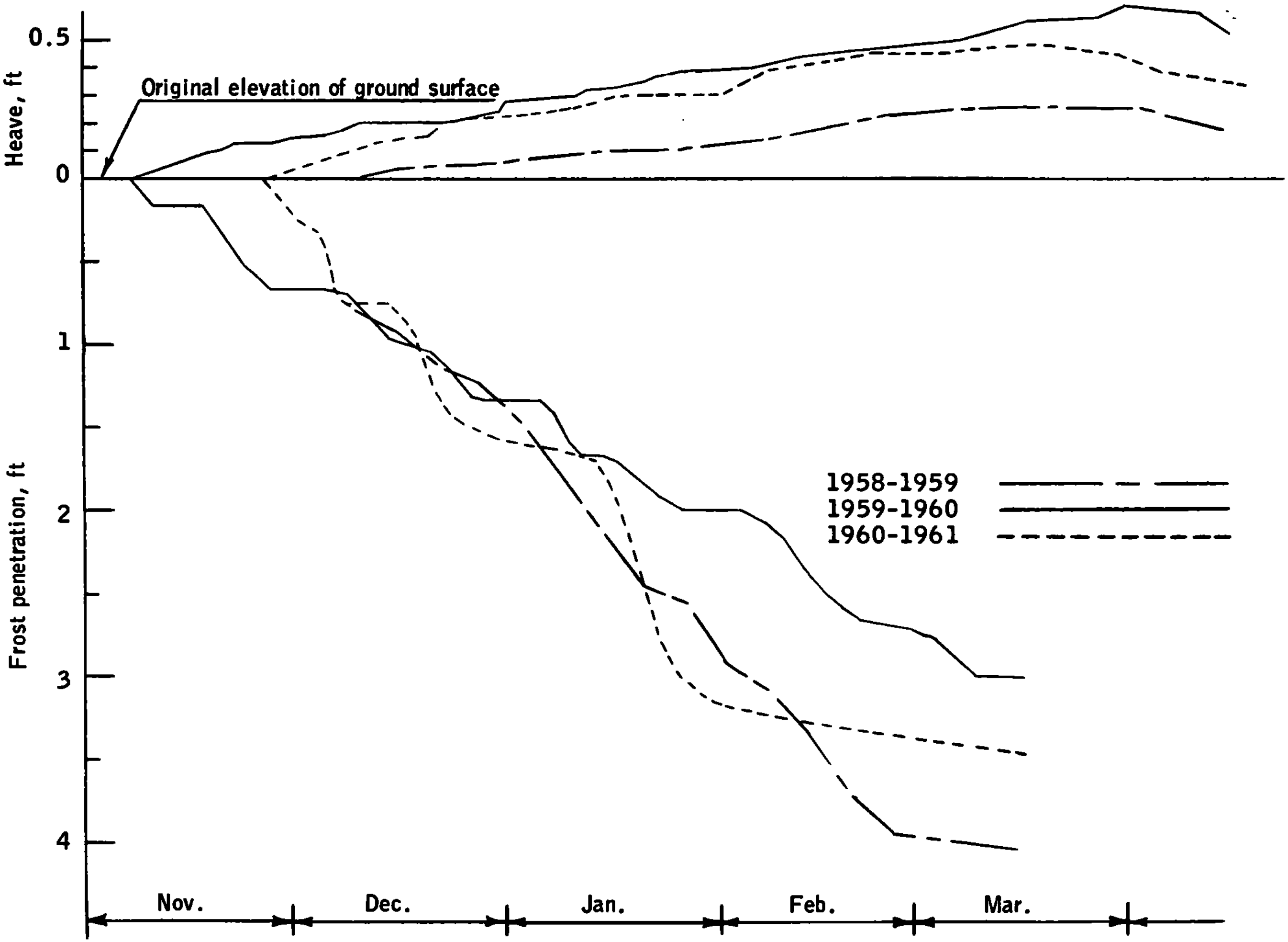

Figure 3. Surface heave and frost penetration for three seasons. Laminga silt (ML).

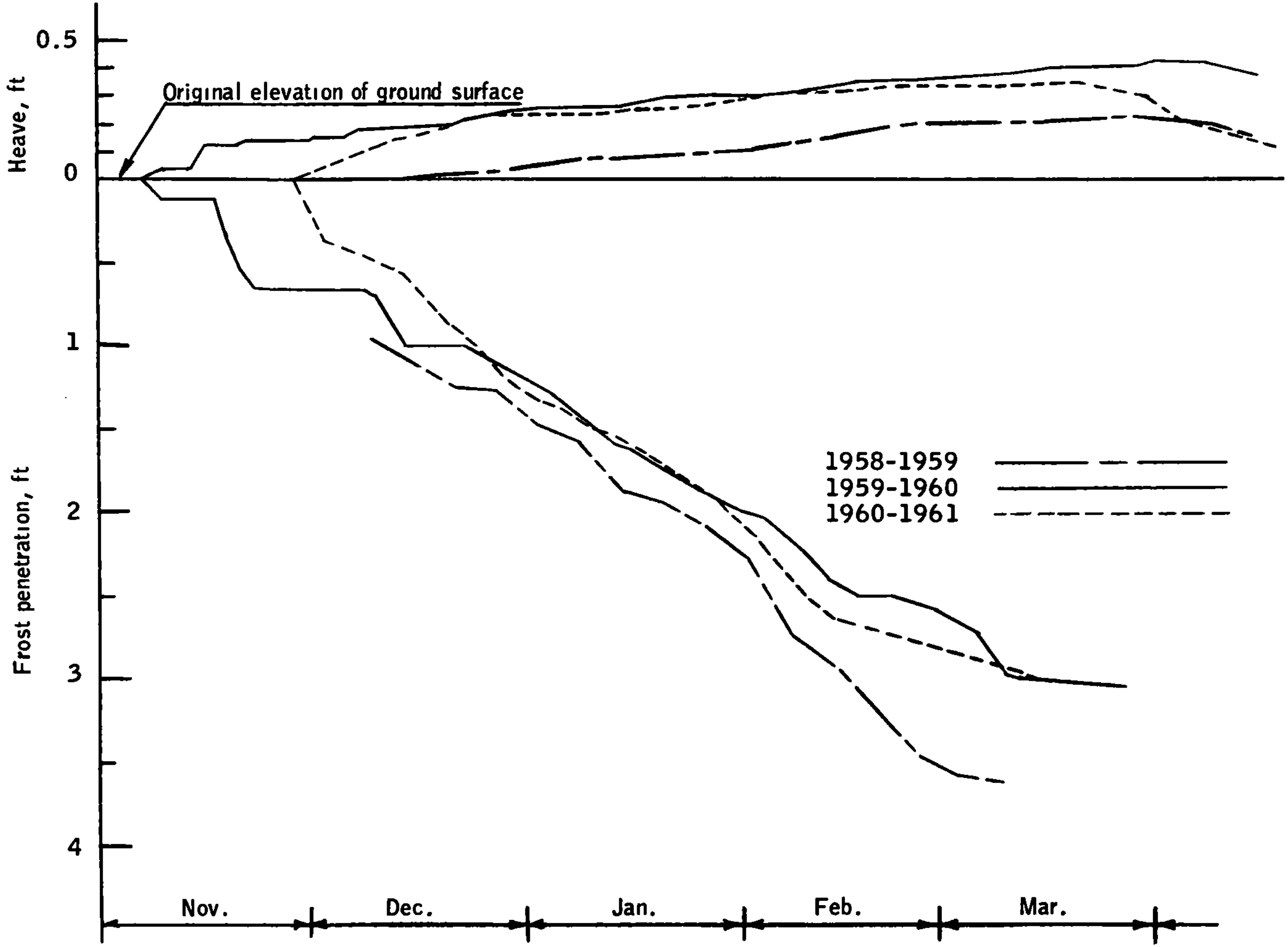

Figure 4. Surface heave and frost penetration for three seasons. Oneco sand (SP).

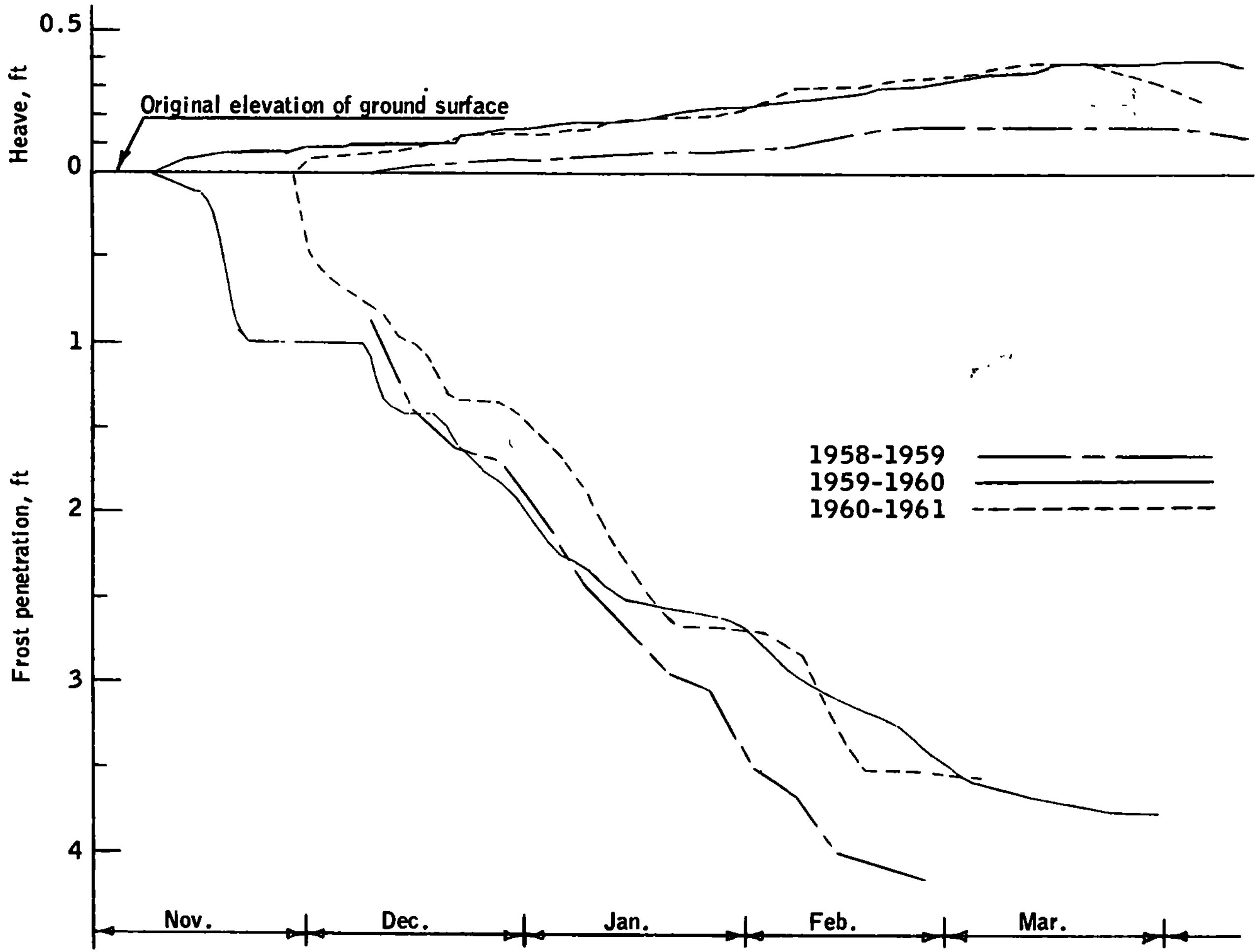

Figure 5. Surface heave and frost penetration for three seasons. Pike Bay (SC).

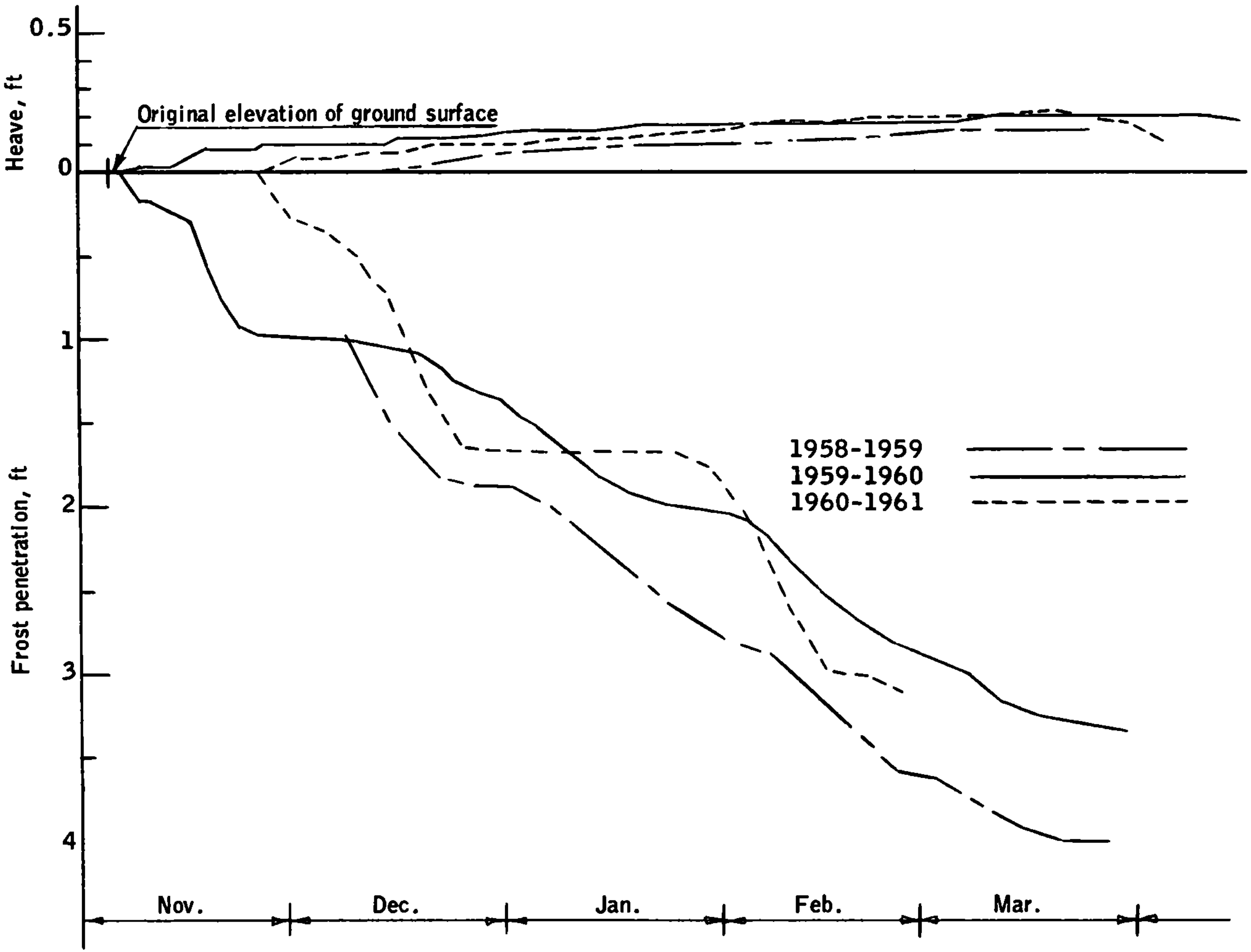

Figure 6. Surface heave and frost penetration for three seasons. Canal clay (CH).

ANALYSIS

In considering the energy balance that applies to frost action in soils, a number of terms or quantities must be considered. The most important of them may be summed up as follows: the heat flow by conduction through the frozen zone must be supplied by (a) the heat flow by conduction through the unfrozen zone, (b) the latent heat of fusion of migrating moisture when it reaches the freezing front, (c) the over-all cooling of the unfrozen soil and its included water when the frost front advances or proceeds deeper into the soil, and (d) the latent heat of fusion of the included water as it is frozen out by an advancing frost front (see Fig. 7). Other terms that might be considered include the mechanical work of raising the water of migration from the free water table to the frost line, and the mechanical work of lifting the frozen overburden. These terms do not appear to be very important when compared with the several heat terms itemized, however, and are not considered further.

The listing is for the most general case, in which both heaving and frost penetration are taking place. If the frost line penetration rate is zero or the freezing is taking place at a fixed level, the heat flow through the frozen zone is balanced by only the heat flow by conduction through the unfrozen zone and the latent heat of fusion of the migrating moisture as it is brought up to the frost front and converted into ice. This is an important case and is of interest because it permits some simplification of the problem.

To establish the background for the analysis of the field observations, the theory advanced by Higashi is reviewed here, followed by some comments of the present author. Because of their pertinence to the problem, some of Penner's data will also be presented.

Higashi's Concepts and Studies

Higashi suggested that frost action falls into two cases when considered on the basis of the heat balance. Which of these cases applies at a given time depends on the thermal regime at that time. The first case is that in which there is no penetration of the frost line. For this case, the heave rate is proportional to the excess of the heat flow through the frozen zone over that by conduction through the unfrozen zone. This quantity will be

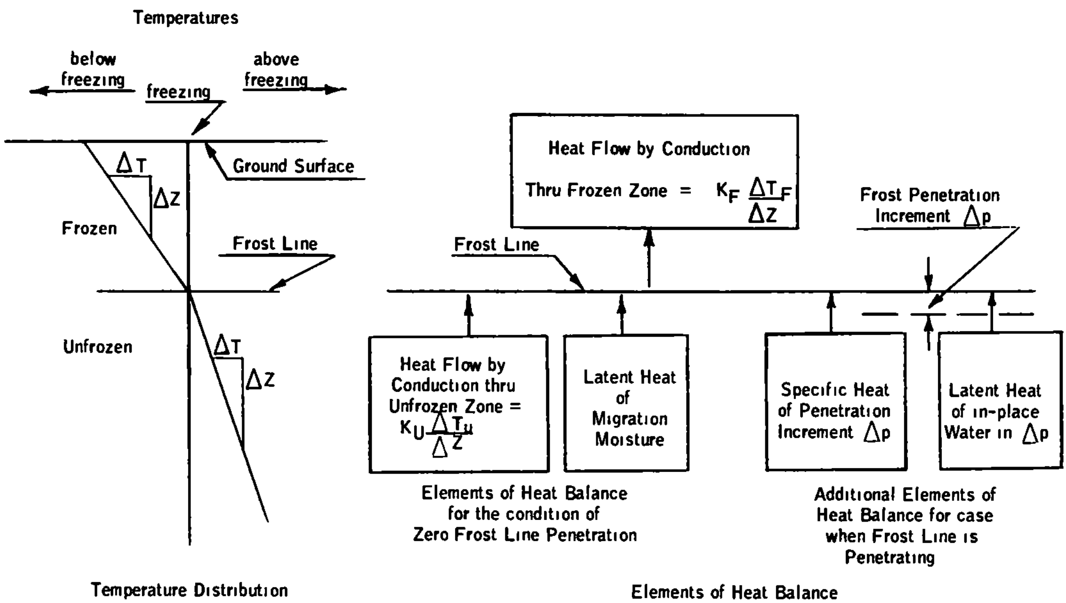

Figure 7. Schematic heat balance in soil freezing.

called the heat conduction difference in this paper. The heat conduction difference must be made up by the latent heat of fusion of the migrating water as it freezes out at the frost line. As the migrating water causes an increase of the over-all volume of the soil system the heave is proportional to the heat supplied by the latent heat of fusion. As this heat quantity relates only to the migration moisture, the proportionality can be determined from the latent heat and the specific volume of ice, and is therefore independent of soil characteristics or properties. This, of course, assumes that all of the migration moisture is changed to ice.

Although the theoretical proportionality factor is independent of soil properties, the limits of this case are not. For the condition when the heave rate is zero and the penetration rate is zero, the latent heat quantity is zero and the heat flow by conduction through the frozen zone is exactly balanced by the heat flow by conduction through the unfrozen zone. This condition then depends on the existence of a suitable thermal regime and on the thermal conductivities of the frozen and unfrozen soils.

The other limit of this case would represent the maximum heave rate. The proportionality between heave rate and the heat conduction difference is valid only up to the point that the necessary flow rate of moisture through the soil can actually occur. As the flow is the product of the unsaturated permeability and the moisture tension gradient, this flow will be limited by the unsaturated permeability of the soil, the moisture tension regime that occurs at a given time, and the overburden effect of the frozen layer. If the heat flow through the frozen zone cannot be supplied by the conduction through the unfrozen soil plus the migration moisture, then an additional heat source is required. This would probably be supplied by the heat given up the over-all cooling of the unfrozen zone which would accompany further penetration of the frost line. When this situation occurs, the first case no longer applies, and a second case must be considered.

On the basis of certain assumptions made in his analysis of this second case, Higashi suggests that penetration of the frost line will be accompanied by a reduction in the heaving rate. Thus as the cooling rate increases beyond the limit for the first case (that of zero penetration rate), the heaving rate would decrease from the maximum as the penetration rate increases. In theory, at least, such a large penetration rate might be reached that there would be no heaving at all.

Higashi presented data from laboratory freezing tests on a glacial clay (CL in the unified classification system) compacted to two density ranges. His data showed good agreement with theory for the first case (zero frost penetration rate) and indicated an empirical agreement with his theory for the second case Examples of his results for the two cases are shown in Figures 8 and 9. Higashi's samples were frozen in an open system with wicks simulating a depth to ground water of several feet.

A Generalized Concept

The basic considerations involved in the energy balance, when considered in conjunction with Higashi's results, suggest a unified concept of the relationship between the heaving rate, the penetration rate, and the thermal regime of the freezing soil system. This is shown schematically by Figure 10. At some low cooling rate, the heat flow by conduction through the frozen zone is just balanced by the conduction heat flow through the unfrozen zone. No migration moisture is required to maintain the heat balance, thus neither heaving nor penetration occurs. With an increase in the cooling rate, the heat flow through the frozen zone increases, with the increase being balanced by the latent heat of the migration water and therefore requiring no additional conduction of heat in the unfrozen zone nor any penetration. This type of balance would continue to exist with increasing cooling rate until the further increase in the flow of migration water would be limited by the unsaturated permeability, the moisture tension regime, and the overburden effect. That this limit would be a function of the distance to the water table is somewhat implicit in the consideration of the moisture tension regime.

As the cooling rate increases beyond the critical value associated with the critical heave rate, penetration of the frost line occurs, probably increasing with an increase in the cooling rate. The effect of this behavior on the heaving could depend on various factors. Certainly the relationship is made more complex by the fact that the temperature regime is less stable when penetration is occurring than when it is not. It would

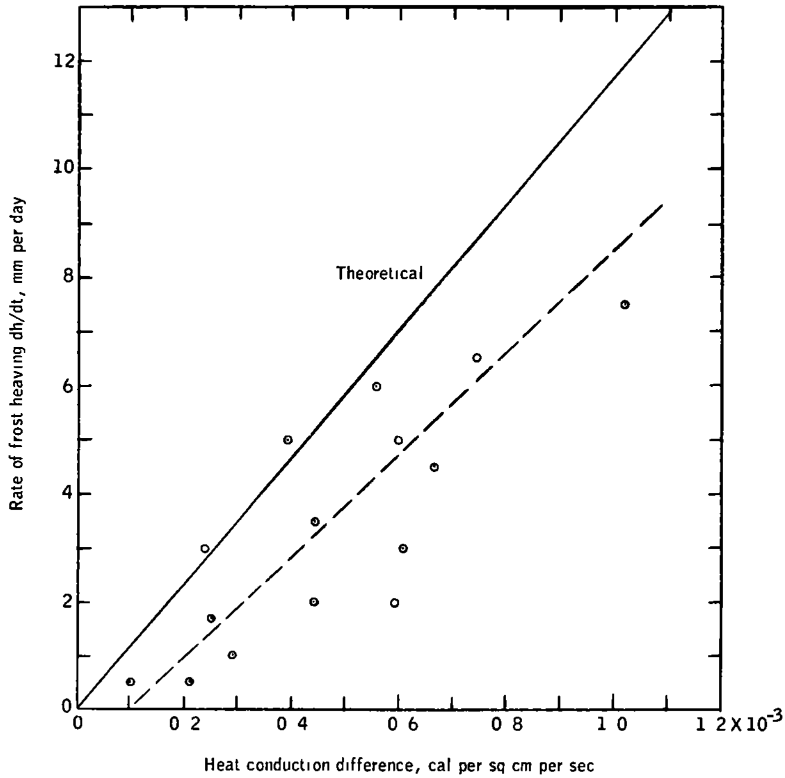

Figure 8. Relation between rate of heaving and heat conduction difference when frost penetration rate is zero.

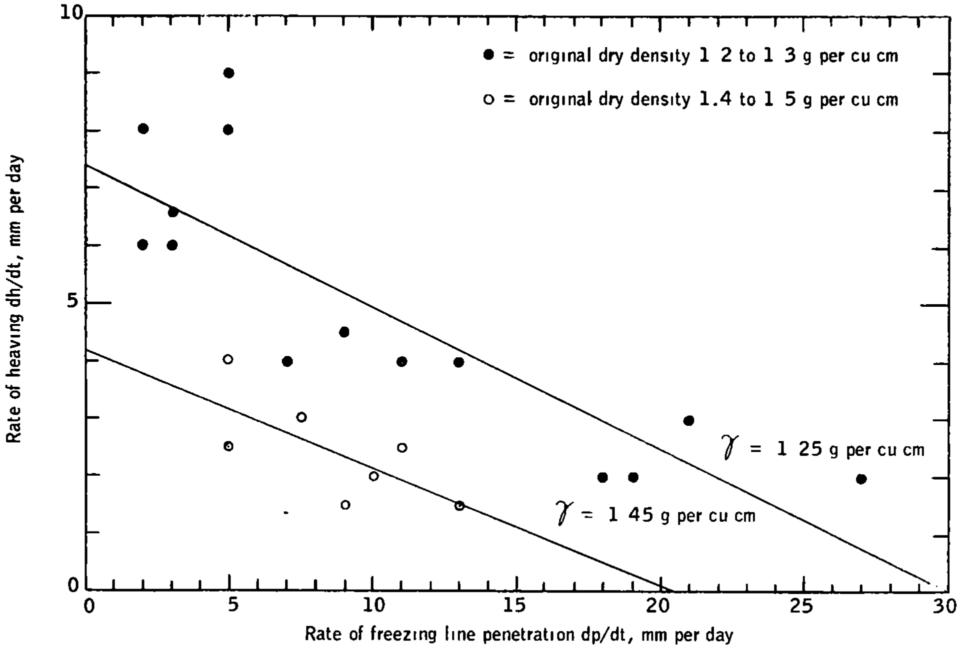

Figure 9. Rate of heaving vs rate of freezing line penetration.

seem that there are two possibilities. The first is that indicated by Higashi, in which the heaving rate decreases as the penetration rate increases. Keeping in mind that his experiments simulated the condition of a distance of several feet to the free water table, this possibility seems reasonable for the case of a relatively deep water table.

The second possibility is that the heave rate could continue at or near the critical or maximum value in spite of penetration of the frost line. This might be the case if the cooling rate were to increase rather slowly beyond the critical value, or the distance from the frost line to the free water table were moderate.

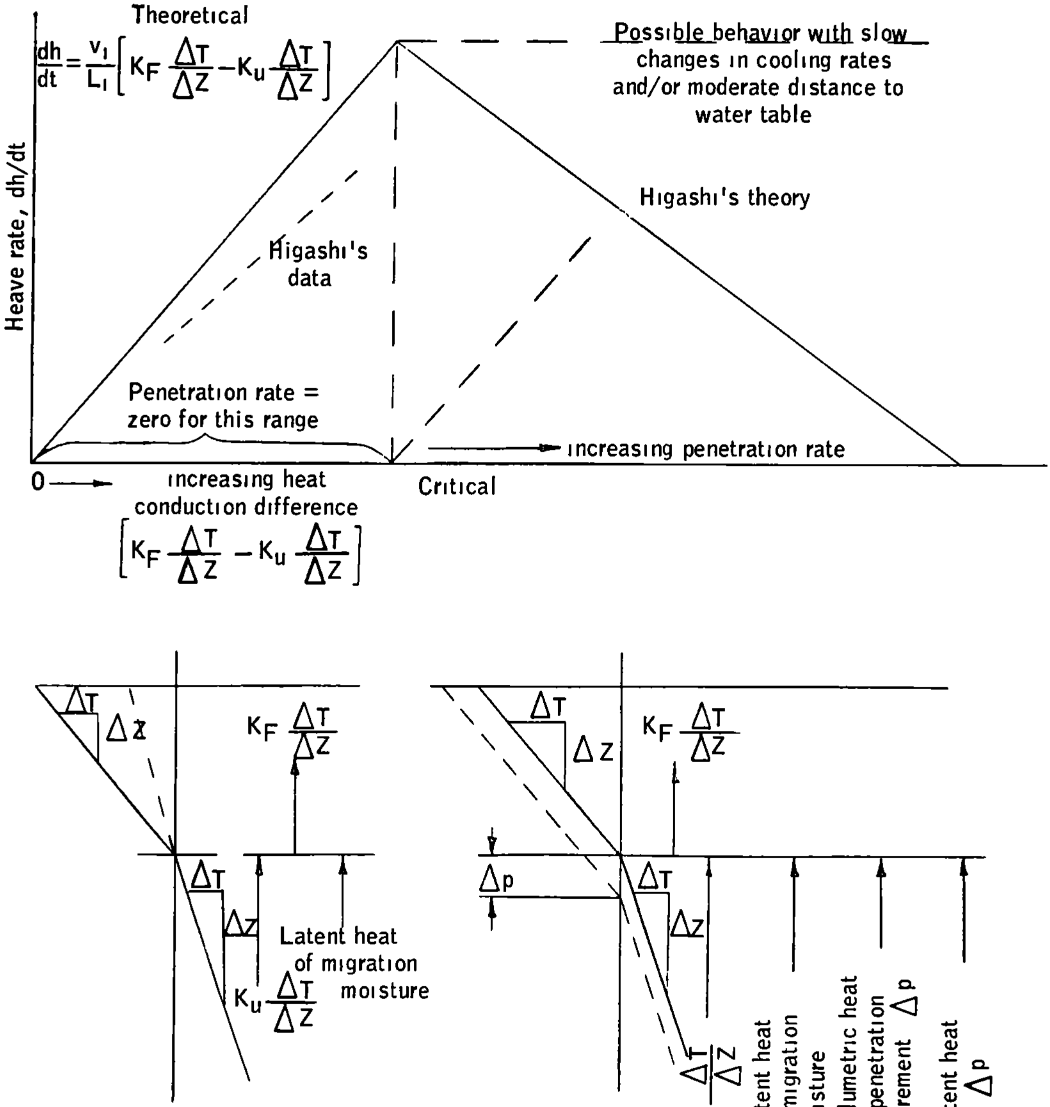

Figure 10. Generalized concept of frost heave and penetration with heat balance considered.

It is recognized that other factors may enter into these relationships, such as the amount of water remaining unfrozen in what has been termed the frozen zone. Although factors such as this may prove to be important, is it believed that this generalized concept provides a good starting point for further discussion and research.

Penner's Investigations

Penner's experiments involving the direct measurement of heat flows are of interest, as he found that the heave rate increased with the penetration rate. He measured the heat flow into the warm end (bottom) of a sample 3 in. high and also measured the heat flow out of the cold end. In this way he was able to determine the difference between the conduction in the two zones. His technique did not distinguish between zero frost penetration rates and fairly large penetration rates. Apparently his samples had some definite penetration during most of the duration of the test. One series of tests was run with the free water table at the base of the 3-in. high samples, and another series was run with the free water table 12 in. below the base of the samples. There was little difference between the results of these two series. Some of Penner's results are shown in Figure 11. The author has taken the liberty to place the theoretical line relating heave and heat conduction difference on these plots. In general, his points lie to the right of this theoretical line, as was also the case with Higashi's experiments.

Analysis of Data from Field Observation Plots

Analysis of the heave and penetration plots indicated that there were distinct intervals or periods of time when both the heave rate and the penetration rate were constant. Thus, a given interval ended and the next one started with a change in the heave rate, the penetration rate, or both. For the intervals of zero or very small penetration rate, the temperature gradients were determined for both the frozen and unfrozen zones. The gradients used in the subsequent calculations were the average gradients for all the days of the given interval.

Thermal conductivities were selected from Kersten's curves (3) for similar materials and also from limited thermal conductivity determinations made in conjunction with these field studies. Thus the heat flow values for conduction in the frozen and unfrozen zones could be calculated, and the excess of the conduction in the frozen zone over that of the unfrozen zone was determined. These values of heat conduction difference were then plotted against the corresponding heave rates. The results for the four soils are shown in Figure 12.

Although there is some scatter in the points, probably due to errors in determining the temperature gradients or to variations of the actual thermal conductivities from

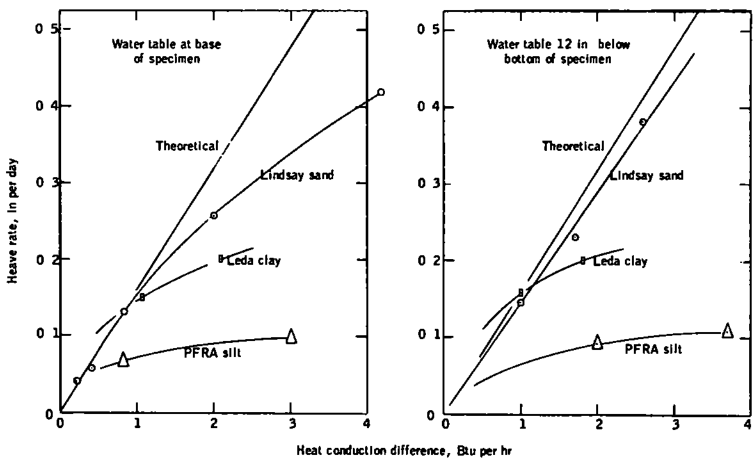

Figure 11. Heave rate vs heat conduction difference.

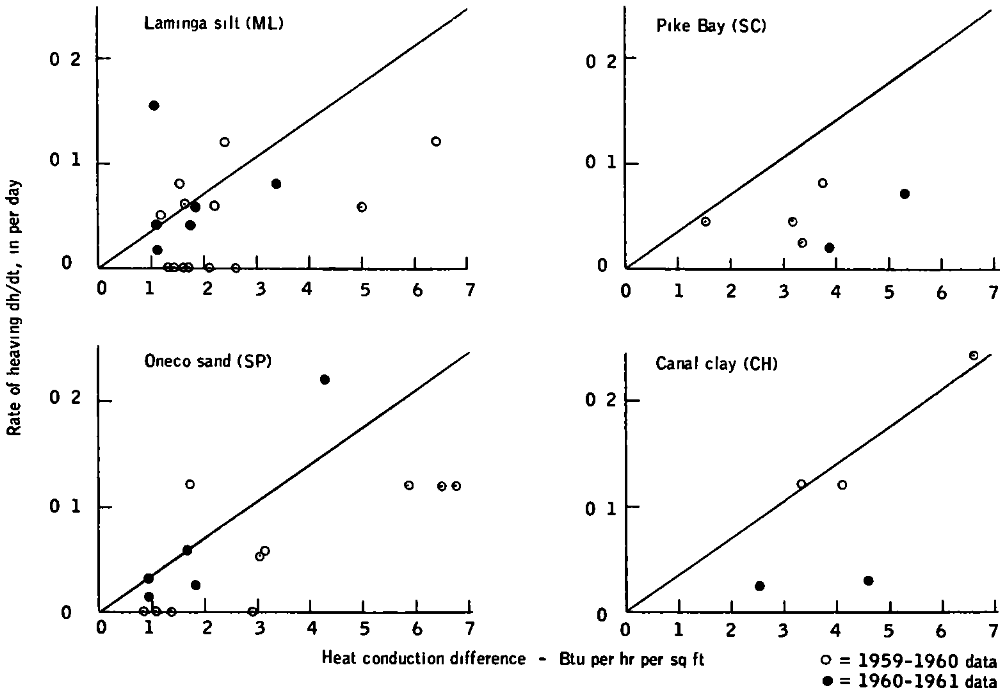

Figure 12. Heave rate vs heat conduction difference (based on field observations): symbols in parentheses indicate unified soil classification.

the selected values, the general trend of the data corresponds to the theoretical curve reasonably well. Most of the points lie to the right of (or below) the theoretical curve, just as in Higashi's and Penner's data. Also, in general the data are closer to the theoretical curve for the season of moderate temperature fluctuations (1959-1960) than are the data for the season of rather sharp temperature fluctuations (1960-1961). This suggests that the relationship is affected by a stronger cooling rate or that some other factor not presently understood is acting.

Data are also shown for the condition of significant penetration of the frost line. In this case, the penetration rate is plotted against the heaving rate. The scatter of the data is such that it is difficult to establish any over-all trend with certainty. However, some fairly definite trends can be noted for specific soils (see Fig. 13).

In the case of the silt, several of the points very nearly fit a straight line through the origin of these plots. This is true for both seasons, and furthermore, the slopes of these lines are nearly identical. Heave rate equals 0.14 times the penetration rate for 1959-1960, and heave rate equals 0.13 times the penetration rate for 1960-1961. If this is in fact the most valid interpretation of these data, it would agree in general with Penner's observations.

On the other hand, if the data for the sand are considered for the season 1959-1960 a a line with a negative slope would envelop nearly all the data points. This would agree more nearly with Higashi's concepts. Although several of the points for the 1960-1961 season do fit this envelope quite well, the scatter is noticeably greater for this season.

The data for the Pike Bay soil (sand with plastic fines) also suggest that the penetration rate will increase at the expense of the heave rate. This trend seems to be better established for this soil than for the sand, especially if the two seasons are considered separately. Two lines are drawn on the plot of heave rate vs penetration rate for this soil to correspond to the data for the two seasons considered. The trend is somewhat better defined for the 1959-1960 season, when the temperature changes were comparatively moderate.

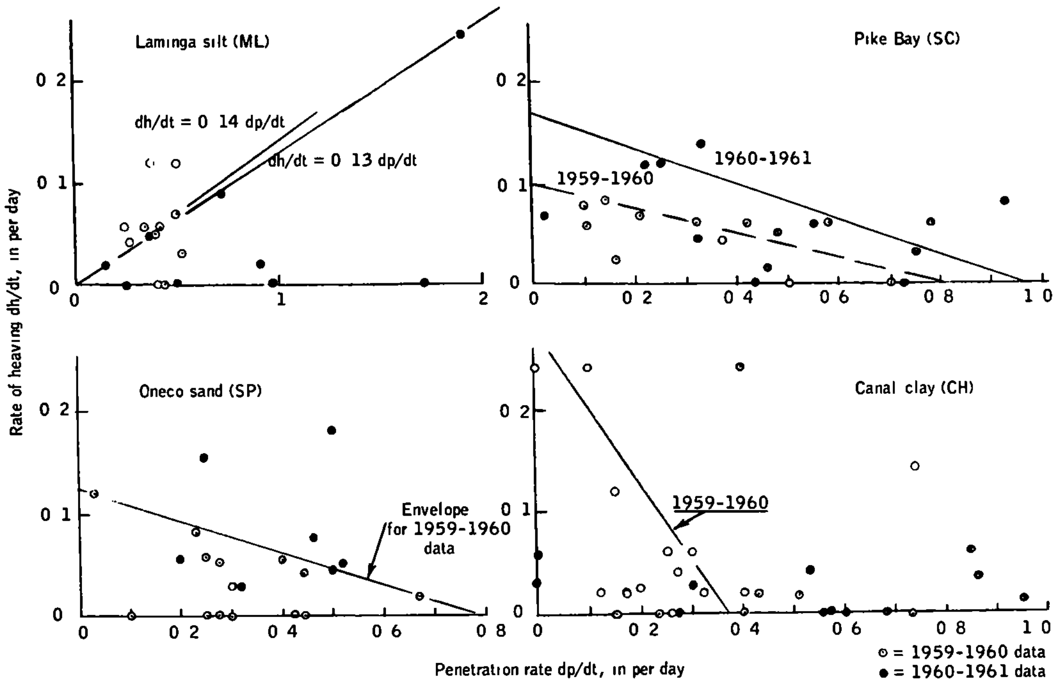

Figure 13. Heave rate vs penetration rate for rapid penetration case: symbols in parentheses indicate unified soil classification.

The data for the clay are not as conclusive. Considering the 1960-1961 data, there appears to be no relationship between heave rate and frost penetration rate. However, the heaving rate for this season is generally low for all penetration rates as well as for the case of zero penetration rate.

The data on the clay for the 1959-1960 season include some higher heave rates than for 1960-1961. This is true for the zero frost penetration case as well as for the rapid penetrating case. One possible interpretation of these data is sketched on the figure, showing an increase in the frost penetration rate with a decrease in the heave rate. Although it probably should not be considered as conclusive because of the scatter of data, it can be seen that this interpretation is compatible with Higashi's concepts.

SUMMARY AND CONCLUSIONS

A theoretical analysis of the mechanism of frost action in soils has been presented, with particular emphasis on the heat balance and its relationship to the heaving rate and rate of penetration of the frost line. The results of two previous laboratory investigations have been presented and discussed. A generalized concept of frost action mechansim has been suggested, based on theoretical considerations and on the results of previous investigations. The results of observations of soil freezing under natural conditions have been presented and analyzed for the purpose of attempting to verify the validity of the general concept and to test its applicability to freezing under natural conditions.

The following conclusions are drawn from this investigation: (a) when the frost line is not penetrating, the heaving rate is essentially proportional to the heat conduction difference between the frozen zone and the unfrozen zone, the conduction through the frozen zone being the larger quantity; (b) the observed relationship of the previous conclusion agrees quite closely with theoretical predictions in the case of laboratory studies were relatively accurate measurements are possible; (c) observed field behavior agrees reasonably well with the theoretical, considering the somewhat less favorable conditions for obtaining good measurements; (d) the relationship between the rate of frost line penetration and the heaving rate needs further study, but limited data indicate some specific trends for specific cases; (e) the reported apparent conflict of opinion of previous investigations, based on somewhat contradictory laboratory results, may in fact be due to significantly different moisture conditions in the respective test procedures; and (f) the agreement of observed behavior with theoretically predicted behavior seems to depend on the magnitude and rate of natural air temperature fluctuations, although the data are somewhat limited.

ACKNOWLEDGMENTS

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The author would like to express his appreciation to W.K. Boyd, James Bender, and Kenneth Linell of the Cold Regions Research and Engineering Laboratory for their encouragement and helpful suggestions. William Parrott, Director of the Keweenaw Field Station, and his staff supported the investigation in a very substantial manner. Alan Isola and Larry Watson, formerly of the Keweenaw Field Station, planned and supervised the construction of the observation plots and their instrumentation and obtained the data for the first frost season. Martin Britz of the Keweenaw Field Station obtained field data and helped in various other ways. The author is also indebted to the several student research assistants who have participated in this investigation, especially to Marvin Oosterbaan, Maurice Bowers, and Allan Green, who contributed in particular to this portion of the over-all project.

The author wishes to thank the American Society for Testing and Materials and the National Research Council of Canada for permission to reproduce the figures showing the results of Penner's investigation.

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Discussion

E. PENNER, Soil Mechanics Section, Division of Building Research, National Research Council of Canada—The writer was interested in the theories presented in this paper but wishes to comment on the interpretation of the information given in Figure 13. The usually accepted procedure to evaluate the usefulness of the information contained in such scatter diagrams is by analyzing the results statistically. In addition, the best fitting line is normally determined by the method of least squares. In the opinion of the writer the majority of the experimental results in Figure 13 cannot be used as a sound basis to judge the validity of the various proposed relationships between the frost penetration rate and rate of frost heaving.

To support this statement, the writer has carried out these statistical computations on the author's results and the information is presented in this discussion.

Assuming the frost penetration rate to be the independent variable, the frost heaving rate the dependent variable and that the relation between the variables is linear, regression equations have been determined for most of the results in Figure 13 by the method of least squares. These regression lines are shown in Figure 1 on the author's scatter diagrams and differ markedly from his interpretation.

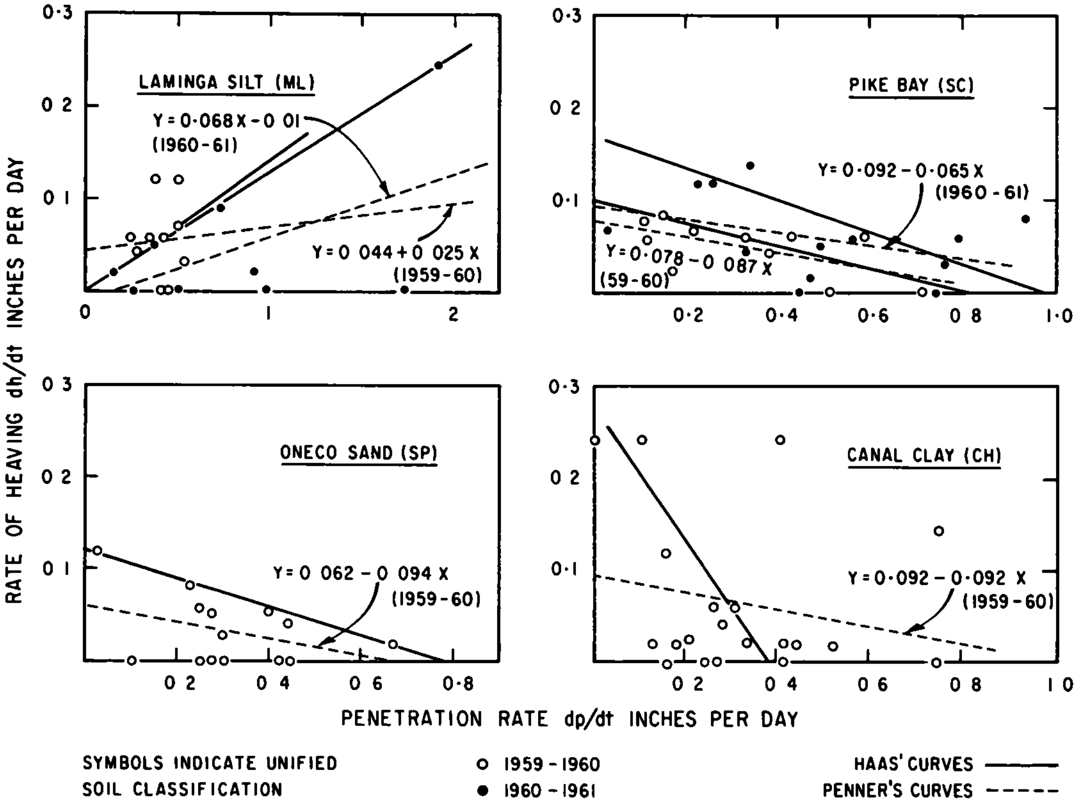

Figure 1. Regression lines calculated by least squares method from results in Figure 13 of author's paper.

TABLE 1

RESULTS OF THE STATISTICAL ANALYSES OF FIGURE 13

Soil	Year	Number of Paired Comparisons, n	Correlation Coefficient, r	Dependence of Frost Heaving on Frost Penetration, r^2 x 100 (%)	Error Variance, 100-(r^2x100) (%)	Slope of Regression Line	Statistical Significance 5 Percent	1 Percent
(1a)	(1b)	(2)	(3)	(4)	(5)	(6)	(7)	
Laminga silt	1959-60	11	0 059	0 31	99 7	0 025	Not sig	Not sig
	1960-61	9	0 543	29 5	70 5	0 068	Not sig	Not sig
Oneco sand	1959-60	14	0 389	15 1	84 9	-0 094	Not sig	Not sig
Pike Bay	1959-60	11	0 624	39 0	61 0	-0 087	Sig	Not sig
	1960-61	13	0 381	14 5	85 5	-0 065	Not sig	Not sig.
Canal clay	1959-60	20	0 210	4 4	95 6	-0 092	Not sig	Not sig

To test the significance of the correlation between the rate of frost heaving and rate of frost penetration, the correlation coefficient was determined and its statistical significance was tested by the widely accepted t-test. The results of the t-test show that no statistically significant correlation exists between these variables, except in one case, and thus the validity of the other regression lines must be rejected on statistical grounds.

Table 1 gives the results of the statistical analyses. The first column identifies the soil and the year of the experiment. Column 2 gives n, the number of paired determinations shown on the author's Figure 13. Column 3 gives the calculated correlation coefficient r and column 4 gives $r^2 \times 100$ which is the percentage variation in y (frost heaving rate) directly attributable to x (frost penetration rate). By subtracting this percentage from 100, the percentage variance of the errors of estimation (error variance) is obtained and is given in column 5. Column 6 gives the slopes of the regression lines, which are in fact statistically inadmissible, except in one case, because the t-test results show that at the levels of significance (5 or 1 percent) usually acceptable, the correlation coefficient r is statistically not significant.