FROST HEAVING VERSUS DEPTH TO WATER TABLE

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A laboratory investigation of the influence of water table depth on the freezing characteristics of four soil types is described. The soils ranged from gravelly sand to sandy clay. Specimens were 42 in. long, with external water tables maintained at depths of 6, 18, 30, and 42 in. Specimens were frozen to a depth of 6 in. at rates of penetration between 0.10 and 0.50 in./day. The following relationships were obtained and are shown in the paper: rate of heave versus rate of penetration, rate of heave versus water table depth, and heave ratio versus water table depth. Portions of the data are extended graphically to give estimates of the influence of water table depths in excess of 3.5 ft. Rate of heave and heave ratio (ratio of heave rate to penetration rate) were observed to be functions both of water table depth and rate of penetration. With water table depth held constant, rate of heave increased with faster penetration rates. With freezing rate constant, rate of heave decreased with deeper water tables. With a single exception, heave ratio was reduced by increases in either penetration rate or water table depth. A reduction in heave ratio is shown to indicate a reduction in the water content of the frozen soil. A simple method is described by which heave ratio data may be used to obtain an estimate of the initial stability of a soil upon thawing.

•ONE of the major factors that controls the amount of heave exhibited by a freezing soil is the availability of free water, which in turn is a function of the proximity of a water table. This report describes a laboratory investigation of the frost heaving characteristics of four typical soil types under various conditions of water table depth.

A laboratory water table is typically developed by placing a specimen on a porous stone to which is applied a pressure head determined by the height of an external constant-level reservoir. The elevation at which the pressure of the soil water is equal to atmospheric pressure is taken to be the elevation of the water table. Under static conditions, the presence of the porous stone is of no consequence, and the water table in the specimen coincides with the water surface in the external reservoir. Under conditions of upward flow, as during freezing from above, the porous stone represents a constant-pressure aquifer of unlimited capacity and hence of essentially infinite permeability. In a dynamic situation, the proximity to the freezing front of the region of constant fluid pressure may be an important factor in producing heave.

Figure 1 shows typical moisture tension profiles at three distinct times during freezing for specimens of similar soil that differ only in length. In each case, the static water table is 6 in. below the top of the specimen. Moisture tensions at the freezing front are taken to be similar, and freezing is at the same rate. Nevertheless, heaving will be greater for the shorter specimen because hydraulic gradients will be generally greater. The effect of the porous stone is to eliminate pressure changes below its own elevation, thereby contributing to the development of high gradients in short specimens concurrent with high levels of hydraulic conductivity (unsaturated permeability). In long specimens (Fig. 1b), the dynamic level of the water table gradually decreases in elevation and hydraulic gradients increase more slowly. In a long specimen, as in most field situations, water will be drawn from lower depths at reduced rates of flow.

Investigations of the effect of water table depth on heaving have been reported elsewhere (1, 2). The results in these reports were tabulated under height of sample (1) and proximity of water table (2). The range of depths investigated was from 4 to 12 in. in the first series and from 12 to 42 in. in the second series; the specimen length in all cases was the same as the depth to the water table. Freezing rate was approximately 0.25 in./day throughout. An additional unpublished series of tests with two silts from Alaska and Idaho further investigated the effect of the water table at the base of specimens that were 6 to 42 in. in length.

These earlier tests measured the influence of a nonartesian aquifer placed at various distances from a freezing front; the water table was at the upper surface of the aquifer as shown in Figure 1a. Results indicated that heaving could be increased 2 to 3 times by decreasing the distance to the porous stone from 42 to 12 in. A further decrease to 4 in. increased heaving by another 3 to 7 times. It was evident that the proximity of an aquifer to the freezing front had a pronounced effect on heaving.

On the other hand, there are many field situations in which either no aquifer is present or the depth of the aquifer is great. The purpose of the investigation described here was to measure the influence of the water table when an aquifer was sufficiently remote such that moisture tension gradients below the zone of freezing could develop freely. In these tests, the minimum distance between the freezing front and the porous stone at the base of a specimen was 3 ft. Although the arrangement represented a compromise between full simulation and various practical considerations, it was judged to be adequate for the comparatively slow rates of freezing utilized.

There was no evidence to indicate that moisture tension profiles during freezing were restrained by the presence of the porous stones. Because specimen behavior was apparently similar to that of soil layers many feet in thickness, the graphs of heaving results have been extrapolated to indicate the possible effect of water tables at depths in excess of 3.5 ft. Certain tentative conclusions have been drawn from the results of these extrapolations.

MATERIALS AND METHODS

The four soils selected for investigation were a gravelly sand from Pittsfield, Massachusetts; a glacial till from East Boston, Massachusetts; a uniform silt from Manchester, New Hampshire; and a sandy clay from an AASHO Road Test in Illinois. Gradations are shown in Figure 2, and general properties are given in Table 1. Specimen condition before freezing is given in Table 2 for the upper 6-in. portion; water content and degree of saturation were measured after 2 days' drainage under the imposed water table. Complete moisture and density data were obtained for the full specimens, both before and after freezing, but are not shown here.

Sixteen specimens in all were compacted, saturated, and frozen in 42-in. long lucite cylinders (Fig. 3). Half-inch diameter holes along the cylinder length, which were tightly stoppered during the tests, enabled water content samples to be obtained. To minimize wall friction during heaving, we tapered the upper 6-in. portion of each cylinder and lined it with overlapping acetate strips that were lubricated with silicone grease.

Specimens of the first three soils were molded in layers at optimum water content to near-maximum density by using the engineers modified compaction procedure (3) (25 blows of a 10-lb hammer with an 18-in. drop over a 4-in. diameter specimen). Specimens were then saturated from the base with distilled de-aired water under pressure. The clay soil was compacted on the wet side of optimum at 20 percent water content to 90 percent of the engineers standard maximum (25 blows, 5.5-lb hammer, 12.0-in. drop) so that it would correspond to the natural subgrade material. The four specimens of a given soil were then mounted in the freezing cabinet for simultaneous freezing. Thermocouples were inserted at intervals along each cylinder, and water levels were adjusted to the test elevations. After 2 days of drainage, water content samples were taken through the holes in the lucite cylinders. The resulting voids were tightly packed with additional soil of similar water content.

Cabinet temperature was decreased to 33 F and held for 5 days to allow temperature gradients to develop. Freezing was initiated by reducing cabinet temperature to 20 F and by seeding the soil surface with frost crystals. When it was evident that freezing had begun, a precooled steel surcharge weight of 0.5-psi intensity was placed on the

Figure 1. Moisture tension during freezing.

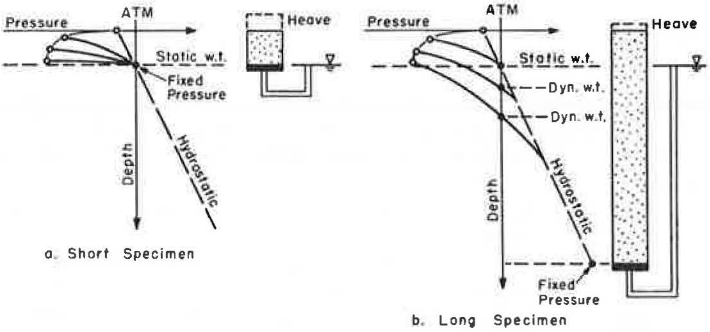


Figure 2. Soil gradations.

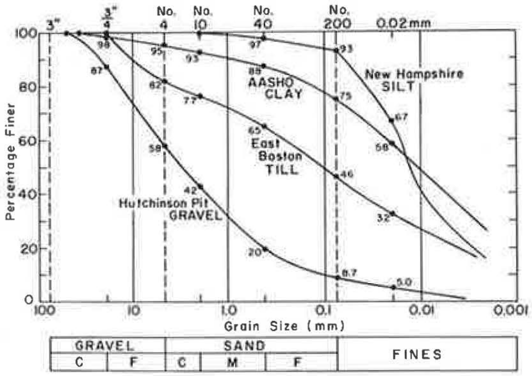


Figure 3. Test arrangement.

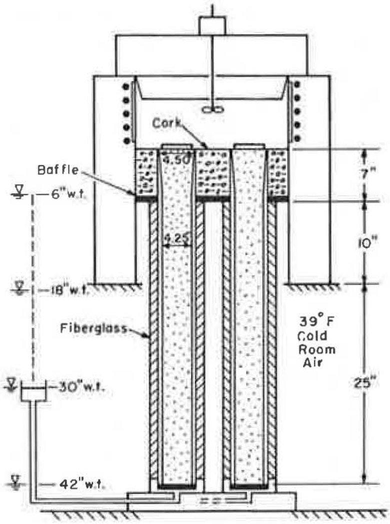


Table 1. General soil properties.

Soil Name	Soil Description	Unified Symbol	Specific Gravity	Atterberg Limits: Liquid Limit (percent)	Atterberg Limits: Plastic Limit (percent)	Plasticity Index
Hutchinson pit gravel	Gravelly sand	SW-SM	2.75	–	–	0.0
East Boston till	Clayey sand	SC	2.75	22.5	14.5	8.0
New Hampshire silt	Silt	ML	2.71	26.5	20.5	6.0
AASHO clay	Sandy clay	CL	2.74	27.5	15.5	12.0

Table 2. Specimen condition before freezing (upper 6-in. portion).

Soil Name	Specimen Number	Water Table Depth (in.)	Dry Unit Weight (pcf)	Water Content, w_o (percent)	Initial Degree of Saturation, S_o (percent)	Initial Porosity, n_o	Permeability cm/sec × 10^{-5}	Permeability mm/day
Hutchinson pit gravel	4	6	141	7.7	96	0.18	–	–
	3	18	143	7.5	98	0.17	–	–
	2	30	141	7.9	99	0.18	–	–
	5	42	144	6.5	96	0.16	–	–
East Boston till	51	6	137	7.6	84	0.20	0.2	1.7
	52	18	134	9.2	90	0.22	0.2	1.7
	53	30	136	8.7	89	0.21	0.2	1.7
	54	42	136	9.0	94	0.21	0.2	1.7
New Hampshire silt	96	6	110	19.2	94	0.35	1.0	8.6
	97	18	110	18.1	92	0.35	1.0	8.6
	95	30	108	20.7	99	0.36	1.0	8.6
	94	42	107	21.4	99	0.37	1.0	8.6
AASHO clay	24	6	109	18.5	91	0.36	0.2	1.7
	22	18	109	19.6	96	0.36	0.2	1.7
	23	30	109	19.5	96	0.36	0.2	1.7
	21	42	108	20.4	96	0.37	0.2	1.7

surface of each cylinder of soil, and cabinet temperature was raised to 28 F. Thereafter, temperature was reduced on a daily basis such that the 32 F isotherm moved downward at a rate of approximately 0.25 in./day. Heave and 32 F depth penetration were recorded daily.

Specimens of the non-clay soils were removed from the cabinet when penetration had reached approximately 6 in. The frozen portion was separated from the column and chilled to 10 F for ease of handling, after which the water content profile was determined by using successive inches of height. Undisturbed samples of the unfrozen portion were cut out at locations that were free of disturbance from previous sampling or the insertion of thermocouples. Complete density and water content profiles were determined.

Water content samples of the unfrozen portions of the clay specimens were taken after penetration had reached 7 in.; the voids were repacked as before. Then the specimens were left in the cabinet for an additional month to investigate heaving under the influence of a stationary freezing front. It was observed that heaving continued virtually undiminished. The final moisture profile showed that further moisture depletion, accompanied by considerable shrinkage and horizontal cracking, had occurred throughout the length of all four specimens.

The results obtained for the frozen portions of the specimens are presented in three sections: rate of heave versus penetration rate, rate of heave versus water table depth, and heave ratio versus water table depth.

RESULTS

Rate of Heave Versus Penetration Rate

The downward progress of the 32 F isotherm was designed to average approximately 0.25 in./day during the test period. It was anticipated, however, that daily and perhaps weekly variations from this average would routinely occur. These variations were utilized in the analysis to provide an estimate of the influence of water table depth for rates of penetration in the range of 0.10 to 0.50 in./day. The indications are that the heave resulting from a given depth of water table depends on the rate of penetration as well as on the type of soil.

The first step in the analysis was to plot penetration of the freezing front p, heave h, and final water content w_f versus days of freezing t for each frozen specimen. Because the temperature of initial freezing is somewhat less than 32 F, total penetration (as measured by the observed height of the frozen column at the end of a test) was always less than the penetration of the 32 F isotherm. Intermediate penetrations of the freezing front were assumed to be in the same proportion. Heave was measured directly, whereas final water content was obtained from the divided frozen column.

Rate of penetration r_p, rate of heaving r_h, and final water content were scaled from these plots. Rates were averaged over periods of 3 to 5 days, except in the New Hampshire silt series where single-day values supplemented the 5-day averages that served as control values. Figures 4 through 7 show the influence of rate of penetration on water content and on rate of heave for each specimen.

In accordance with usual practice, rate of penetration has been expressed as in./day and rate of heave as mm/day; conversion of the latter units to in./day using the approximate value of 25 mm/in. results in an error of less than 2 percent. Intercepts which cross the curves at penetration rates of 0.10, 0.25, and 0.50 in./day mark off the rates of heave that are used in the next section to develop the relationship between rate of heave and water table depth. Numbers placed near the intersections give the corresponding ratio of heave rate to penetration rate in units of mm/in. This ratio is related to the heaving and thawing characteristics of a soil and has been designated the heave ratio (analogous to void ratio) with symbol R. Thus,

$$R = r_h/r_p = (dh/dt)/(dp/dt) = dh/dp \tag{1}$$

where h = h(t) and p = p(t) are the heave and penetration intervals occurring in time t (measured in opposite directions from a common reference level).

Figure 4. Water content and rate of heave as functions of rate of penetration (Hutchinson pit gravel).

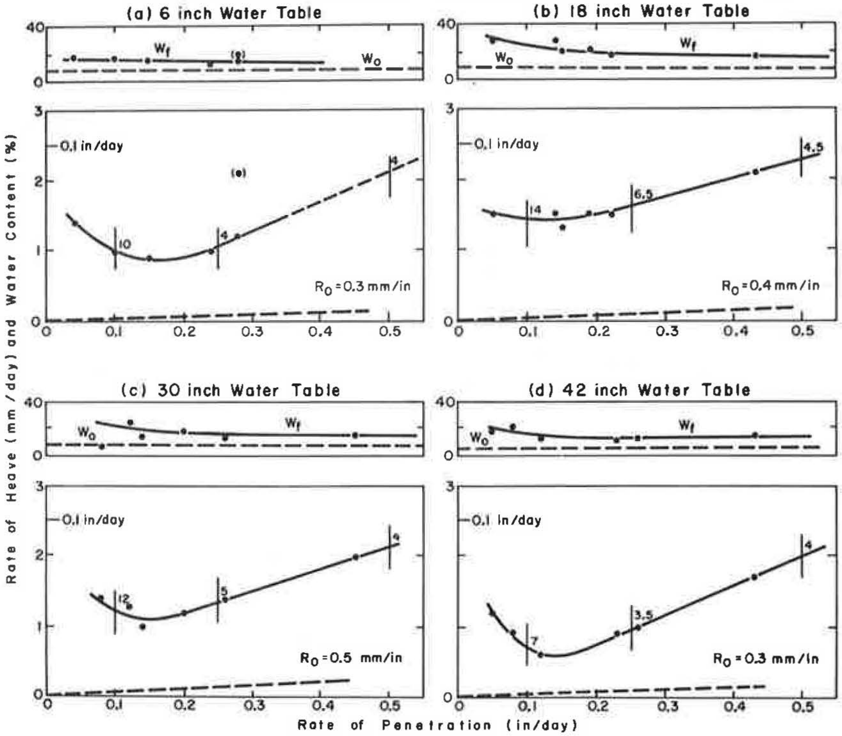


Figure 5. Water content and rate of heave as functions of rate of penetration (East Boston till).

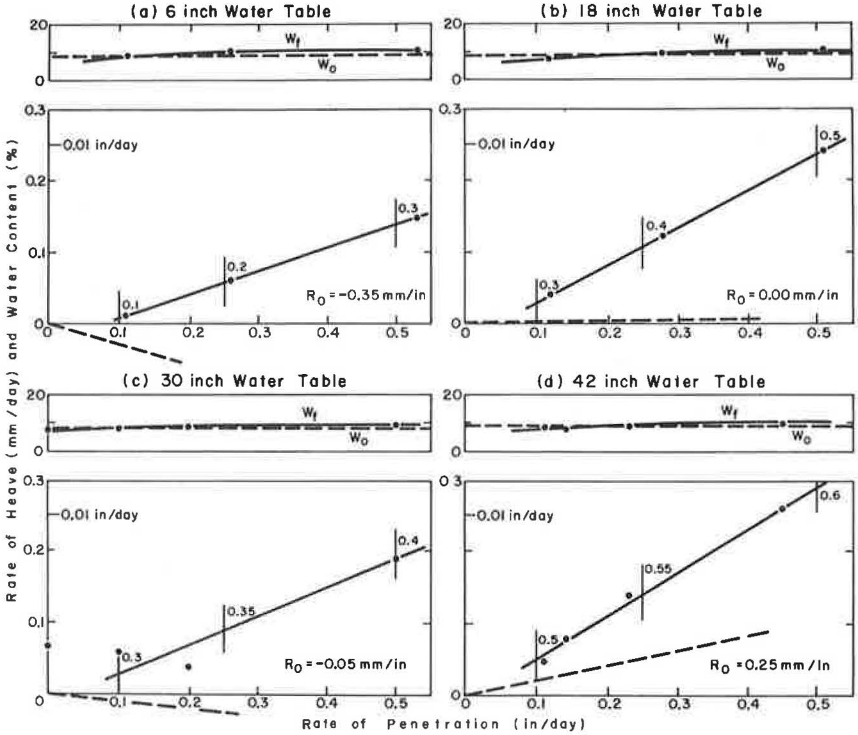


Figure 6. Water content and rate of heave as functions of rate of penetration (New Hampshire silt).

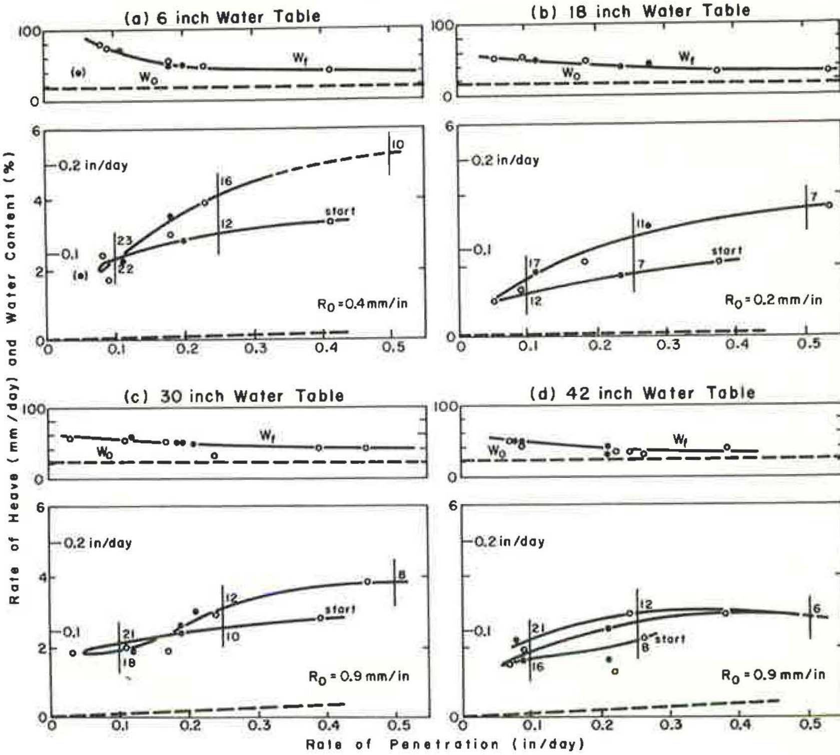
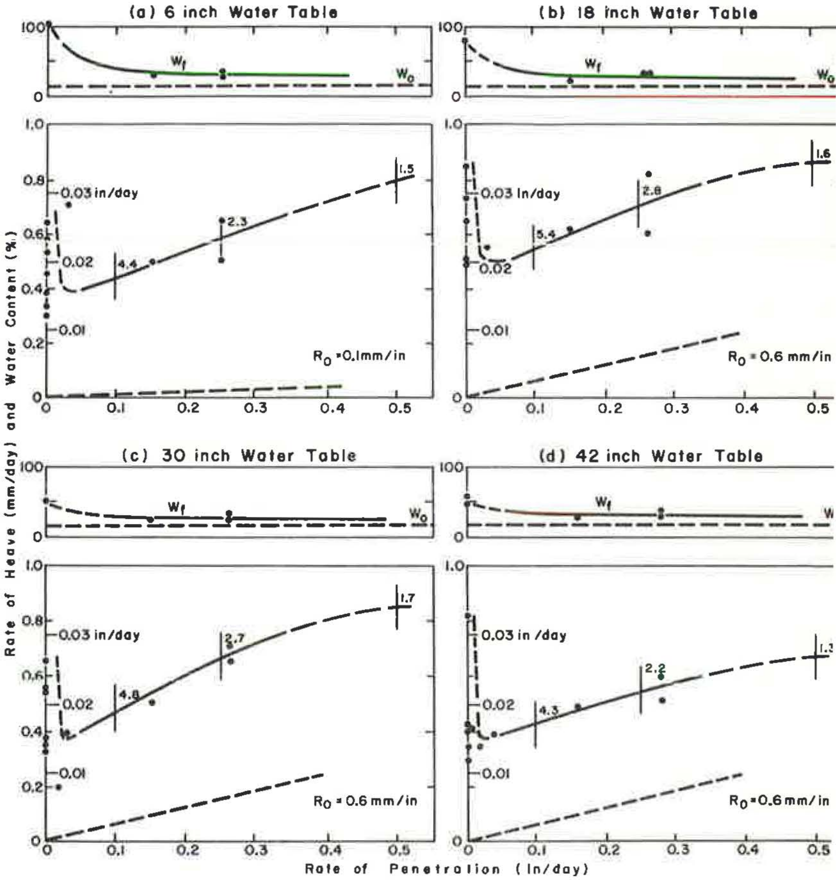


Figure 7. Water content and rate of heave as functions of rate of penetration (AASHO clay).



The relationship between heave ratio and water table depth is developed in a subsequent section. However, a remark concerning R_o is pertinent here. R_o is the heave ratio resulting from the expansion of the initial in situ water upon freezing; one expression for its calculation can be shown as

$$R_o = n_o[(S_o/S_f) - 1] \qquad (2)$$

where n_o is the initial porosity and S_o and S_f are the initial and final degrees of water saturation respectively. Total expansion ($R_o \cdot r_p$) is indicated by a dashed line at the bottom of the graphs shown in Figures 4 through 7.

Values of n_o and S_o are given in Table 2. The maximum value of S_f for an ice-saturated specimen would be 91.7 percent. However, S_f has been taken to be 90 percent in the calculations to allow for a small volume of air entrapped in the frozen soil.

The test data indicate that the rate of heave generally increases with the rate of penetration but to a smaller degree with deeper water tables. There is also a region at very low rates of penetration where heaving appears to be governed by factors other than penetration rate. Presumably, the silt would have shown a similar region had rate of penetration been sufficiently slow. On the other hand, it is not so likely with East Boston till, inasmuch as the heave rate had dropped to zero while the penetration rate was still finite.

Rate of Heave Versus Water Table Depth

Figures 8 through 11 show the results for the rate of heave versus the depth to water table. Relationships are shown for three rates of penetrations: 0.10, 0.25, and 0.50 in./day. As expected, rate of heave generally decreases with water table depth for a single rate of penetration. The figures also show, as in the previous section, that the rate of heaving at a given water table depth changes with the rate of freezing.

Two plots of the East Boston till data are given. The data in Figure 9a are taken directly from Figure 5 and give the impression that the rate of heave is increasing with the water table depth. This impression is caused by a discrepancy in the initial degrees of saturation among the four specimens. From Figures 5a and 5c, it can be observed that R_o was calculated to be negative because S_o was less than 90 percent. The interpretation in such a case is that the expansion of the in-situ moisture can be more than accommodated by the initial voids; heaving will not begin until an appreciable water content change has occurred. Specifically, raw heaving rates for this soil are not directly comparable because they are of the same order of magnitude as the heaving due to the initial in situ moisture and because the in situ moisture varies among specimens. For this reason, the data plotted in Figure 9b have been adjusted for an assumed initial degree of saturation of 90 percent. It is then clear that an increase in the water table depth decreases the heaving rate for this soil.

In Figure 11, the data for the specimen with the 6-in. water table have been adjusted to an S_o value of 96 percent on identical grounds.

The results shown in Figure 8 for Hutchinson pit gravel are interesting in that the maximum rate of heave apparently occurs with the 18-in. water table. The variation in initial conditions is negligible for this soil, and the effect is apparently a real one. It is possible that such a relation is common to certain soil types, inasmuch as velocity of flow to a freezing front is the product of hydraulic conductivity and moisture tension gradient, factors that vary inversely one to the other but at different rates.

As previously mentioned, the data have been extrapolated graphically to show the approximate water table depths required to control or eliminate heaving for each soil, all other factors being equal. Within the experimental error, these depths vary with penetration rate. For the gravel, the greatest depths are required with fast freezing. The silt and the clay require the greatest depths with slow freezing.

The result for the fine-grained soils is apparently consistent with the anomaly observed by Higashi (4) in 1958, when he restricted upward flow in fine-grained soil specimens by using textile filaments. Higashi found that, with a simulated deep water table, the slower he allowed freezing to progress, the more heaving he observed. Figures 10 and 11 show a similar effect with the deeper water tables.

Figure 8. Influence of water table depth on rate of heave (Hutchinson pit gravel).

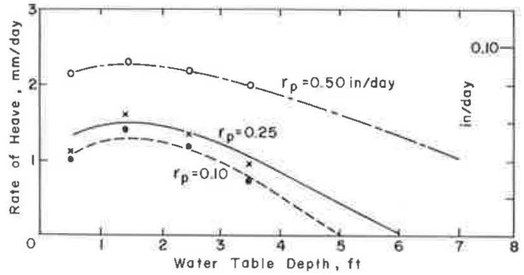


Table 3. Comparison of heave rates (6-in. water table, penetration 0.25 in./day).

Soil Name	Standard Tests (mm/day)	Present Tests (mm/day)	Ratio
Hutchinson pit gravel	6.0	1.0	6
East Boston till	4.5	0.15	30
New Hampshire silt	13 to 26	3 to 4	5
AASHO clay	7.0	0.6	11

Figure 9. Influence of water table depth on rate of heave (East Boston till).

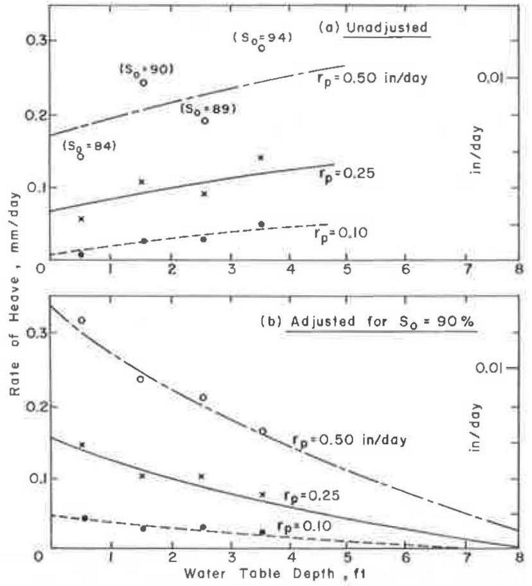


Figure 10. Influence of water table depth on rate of heave (New Hampshire silt).

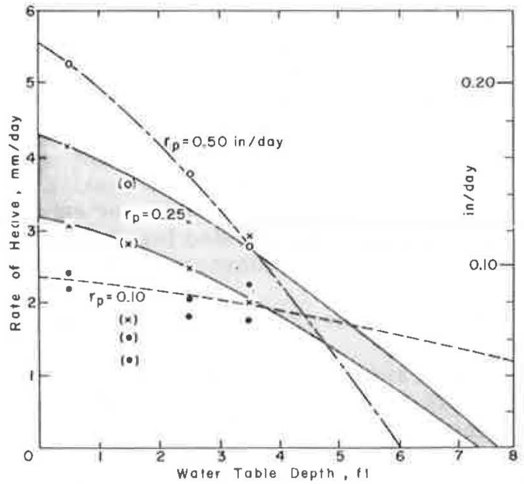
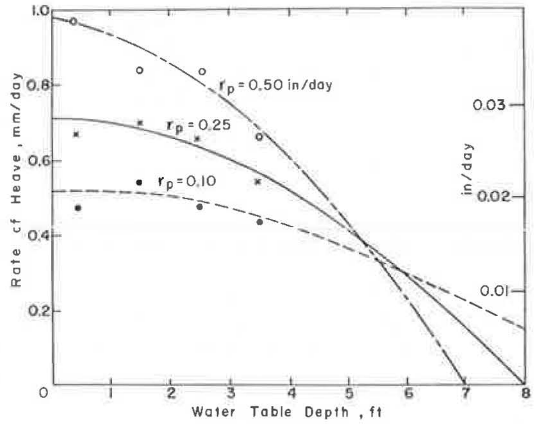


Figure 11. Influence of water table depth on rate of heave (AASHO clay).



The rates of heave obtained in the present tests for the 6-in. water table and a penetration rate of 0.25 in./day are compared in Table 3 with average values previously obtained with the Corps of Engineers standard test (5), which was intentionally designed to represent a severe freezing condition. Because the only difference in the test procedures is that the standard test utilizes a specimen length of 6 in., the comparison is exactly as shown in Figure 1. In effect, the standard test magnifies rate of heave by a factor between 5 and 30, the magnification factor being greater for the smaller rates of heave. The values obtained here may be considered more nearly representative of heave rates to be expected under average field conditions where the soil column is non-layered.

Heave Ratio Versus Water Table Depth

Figures 12 through 15 show the results for heave ratio versus water table depth. The data shown in Figure 13 are again adjusted for an initial degree of saturation of 90 percent. Relationships are shown for the three rates of penetration. Although the general picture appears similar to that for the rate of heave, there is an important difference. Except for East Boston till, the curves for a given soil are in the reverse order; whereas a slow rate of penetration of 0.10 in./day produced the lowest rates of heave, the same rate of penetration produces the highest heave ratios.

The heave ratio parameter has appeared from time to time in the literature on frost behavior; however, its meaning and importance will likely be unfamiliar to some. A word of explanation may therefore be useful. The quantity R may be expressed in any convenient units of length/length, for example, mm/in. or in./in. It may also be expressed nondimensionally, either as a percentage or as a decimal.

Physically, heave ratio is a useful indicator of the frozen condition because heave ratio, frozen water content, and final porosity are related in a unique way independently of penetration rate. Thus, with a given initial condition, a higher heave ratio always means a higher frozen water content w_f, as a study of the graphs of water content in the first section (Figs. 4 to 7) will verify; a higher final porosity n_f will also result.

A careful study of Figure 5 will reveal that although both the water content and the heave ratio for East Boston till increase in the same direction, the direction is opposite to that for the other three soils. A graphical clue to this anomalous behavior is the intercept on the x-axis when the curves are extended toward the low rates of penetration. Physically, the anomaly is undoubtedly due to a specific combination of moisture tension, degree of saturation, and hydraulic conductivity.

The relations among heave ratio, frozen water content, and final porosity may be derived as follows. From the volume change associated with heaving, it may be shown that the void ratio in the frozen condition is given by

$$e_f = e_o + R(1 + e_o) \tag{3}$$

from whence,

$$w_f = (S_f/G)\left[e_o + R(1 + e_o)\right] \tag{4}$$

or equivalently,

$$w_f = (S_f/G)\left[(n_o + R)/(1 - n_o)\right] \tag{5}$$

and,

$$n_f = (n_o + R)/(1 + R) \tag{6}$$

In these expressions, S_f is the water-equivalent degree of saturation (here taken to be 90 percent), and G is the specific gravity of the solids (Table 1). R must be entered in decimal form.

Water content w_f and porosity n_f are shown in Figures 12 to 15 as auxiliary scales to aid in the understanding of parameter R. It may be noted that these two factors also describe the condition of a newly thawed soil, prior to drainage or compression. Thus, final porosity is a direct indicator of the average denseness of the granular skeleton, whereas frozen water content is a measure of the drainage required to reach a more stable condition. An estimate of the remolded strength of the initially thawed soil may be

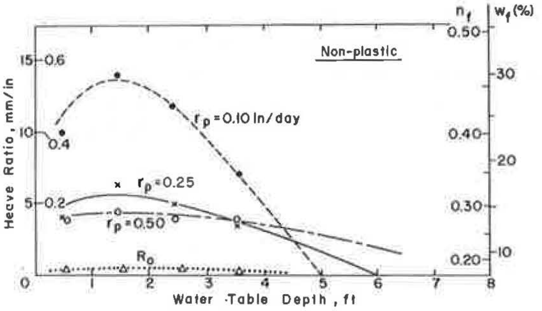


Figure 12. Variation of heave ratio with water table depth (Hutchinson pit gravel).

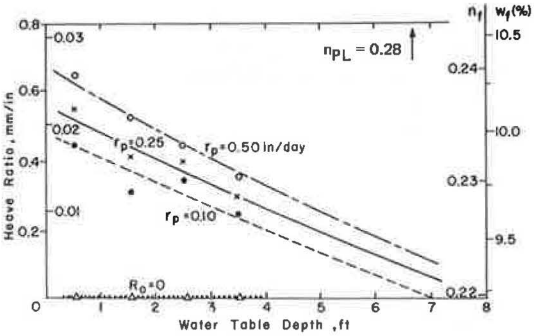


Figure 13. Variation of heave ratio with water table depth (East Boston till, adjusted for an S_0 value of 90 percent).

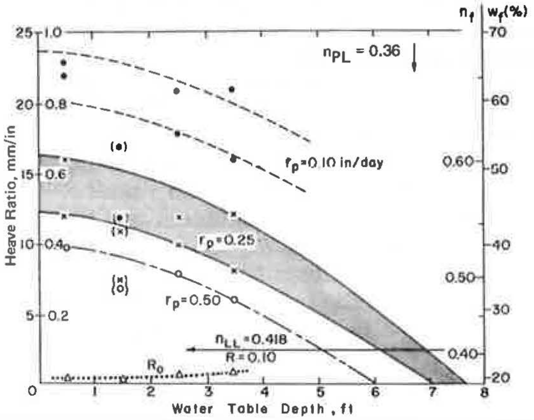


Figure 14. Variation of heave ratio with water table depth (New Hampshire silt).

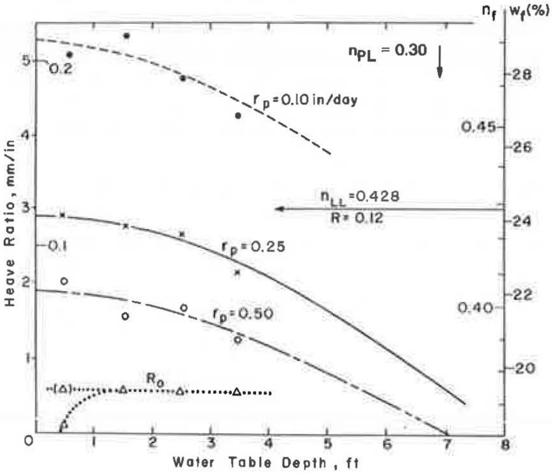


Figure 15. Variation of heave ratio with water table depth (AASHO clay).

obtained by a comparison of n_f with the porosity corresponding to the liquid or plastic limit for the soil. These porosities are indicated in the figures.

The extreme loss of strength that often occurs in silt and clay soils upon thawing may be predicted from data shown in Figures 14 and 15 by comparison with the porosity at the liquid limit. For both soils, the liquid limit porosity corresponds to a heave ratio of approximately 0.10. When the overburden pressure is low, as in the tests reported here, only very fast freezing or a deep water table will prevent this heave ratio from developing. It is immediately obvious that the silt soil will be especially sensitive to detrimental freezing.

SUMMARY

The influence of water table depth on the freezing characteristics of four soils has been investigated in the laboratory. The four soils tested were a gravelly sand, a clayey sand, a silt, and a sandy clay. Water table depths were in the range of 0.5 to 3.5 ft, with a specimen length of 3.5 ft. Rate of frost penetration varied between 0.1 and 0.5 in./day. Relationships were found among rate of heave, rate of penetration, heave ratio, and water table depth. Extrapolations were made graphically to water table depths greater than 3.5 ft.

Rate of heave and heave ratio were found to vary with water table depth and with frost penetration rate. At a single rate of penetration, deeper water tables limited both rate of heave and heave ratio. As rate of penetration increased, rate of heave increased while heave ratio decreased.

Heave ratio and water content after freezing varied inversely with rate of penetration and with water table depth. A decrease in frozen water content always accompanied a decrease in heave ratio.

An apparent anomaly was found for fine-grained soils with deep water tables. As observed by Higashi, when water flow was restricted, rate of heave decreased with an increase in freezing rate. As he also observed, heave ratio continued to decrease.

Heave ratio was shown to be related to the porosity, water content, and stability of a newly thawed soil. The consistency of the undrained thawed soil can be estimated by comparing the porosity after freezing with porosities corresponding to the liquid and plastic limits for the soil.

ACKNOWLEDGMENT

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REFERENCES

1. Arctic Construction and Frost Effects Laboratory. Second Interim Report of Cold Room Studies. U. S. Army Engineer Division (New England), Waltham, Massachusetts, 1951.
2. Arctic Construction and Frost Effects Laboratory. Third Interim Report of Cold Room Studies. U. S. Army Engineer Division (New England), Waltham, Massachusetts, 1958.
3. EM 1110-2-1906 Laboratory Soils Testing. Office of the Chief of Engineers, Washington, D. C., 1965.
4. Higashi, A. Experimental Study of Frost Heaving. U. S. Army Snow, Ice, and Permafrost Research Establishment, Res. Rept. 45, Wilmette, Illinois, 1958.
5. Kaplar, C. W. Personal communication. U. S. Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire, 1970.