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SOIL TEMPERATURES IN WATER WORKS PRACTICE

BY

R. F. LEGGET AND C. B. CRAWFORD

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Soil Temperatures in Water Works Practice

By R. F. Legget and C. B. Crawford

A paper presented on May 26, 1952, at the Canadian Section Meeting, Montreal, Que., by R. F. Legget, Director, and C. B. Crawford, Asst. Research Officer, both of the Div. of Building Research, National Research Council, Ottawa, Ont.

THE variation of the temperature of the soil, throughout the year and at different depths below ground surface, might seem to be a scientific curiosity of little practical interest to the water works engineer until the relation of soil temperature to the freezing of water pipes is appreciated. The freezing of water in buried mains is due, largely, to the cooling of the surrounding soil below the freezing point of water. This cooling is but one particular feature of a general pattern of the changing soil temperature profile as the effect of winter air temperatures is felt beneath the surface of the ground.

Soil temperature variations are unusually complex, and have a wide practical significance. They affect the performance of buried pipes used for the passage of fluids which freeze at normal temperatures, and are clearly a determining influence in the performance of heat pumps. Soil temperature variations are related to the flow of heat in the ground, and thus influence heat losses from the basements and foundations of buildings, the performance of cold storage buildings, and the innumerable problems associated with foundation designs. Frost-boil and associated difficulties in road and airfield construction are further evidences of changing soil temperatures.

Canada's Div. of Building Research, National Research Council, is keenly interested in this important natural phenomenon. The initial studies of the senior author were begun in 1943, and were transferred to Ottawa at the start of the work of the Div. of Building Research in 1947. There were serious snow and ice problems in Ottawa the following winter, which resulted in difficulties in water main maintenance. The division was consulted by the Works and Water Works Commissioners of Ottawa about these difficulties. As the Ottawa problems were closely linked to the more general soil temperature studies already being conducted by the division, a cooperative program was developed. This paper represents the first public progress report upon the work.

Many variables are encountered in soil temperature studies, one of which is the weather. Ironically, the winters in Ottawa since this cooperative work started have not been exceptionally cold and there has been no opportunity to study extreme conditions. As the time unit in all soil temperature work is one year, and as weather is not yet susceptible to control, this limitation upon experimental work must be accepted, but the reporting of results cannot be delayed too long if they are to be of general interest. This paper

represents a sharing of experience to date rather than a finished statement of specific results. The authors feel that the information which has been developed will be of assistance to water works engineers in solving maintenance problems.

at Ottawa is 42 F, and the mean soil temperature at 20 ft is approximately 48 F. Ground temperatures near the surface, however, must naturally vary greatly throughout the year.

Figure 1 shows the general pattern of soil temperature in the upper 20 ft

Fig. 1. Temperatures in Undisturbed Clay With Natural Snow Cover

The temperatures were recorded in Ottawa for the year 1950 by means of sensitive measuring devices inserted into minute holes formed in the sides of a pit.

Soil Temperature Variations

If accurate measurements of the temperature in the ground are made and recorded throughout a year, it will be found that there is no appreciable variation in temperature below a depth of approximately 20 ft. The steady temperature at this depth is usually slightly above the mean annual air temperature for the locality, as is the usual temperature of ground water—for example, the mean annual air temperature

of the earth's crust, which is the region of interest to water utilities. The main features are a rapid decrease in the range of temperature, and a steadily increasing time lag, both varying with depth. The time lag, which is due to the slow transfer of heat through the ground, eventually reaches approximately six months at a depth of 20 ft in Ottawa. Thus, the coolest spot in Ottawa in mid-August is 20 ft below the surface of the ground, where the

Fig. 2. Installation of Temperature-Recording Instruments in Ottawa

The instruments are automatic, mercury bulb, and were installed under two city streets, 2 and 5 ft under the center of the street, the gutter, and the boulevard.

full effect of the previous winter is just being experienced.

This pattern of soil temperature variation is an understandable one and for homogeneous soil conditions can be determined by calculation, using certain simplifying assumptions. The pattern shown in Fig. 1 is based on records taken in undisturbed ground. This means, in practice, that the records of temperature have been taken by means of sensitive measuring devices inserted into minute holes formed in the sides of a pit, and long enough horizontally to eliminate the effects of the disturbance of the soil in the pit. For such conditions, and with undisturbed snow cover, it has been found that frost penetration is less than is generally supposed.

Some of the factors which influence soil temperature include: the state of the soil, whether disturbed or undisturbed; the type of soil; the state of the snow cover, whether disturbed or undisturbed; the nature of the ground surface; and the moisture content and thermal properties of the soil. All these factors may influence the soil temperature profile throughout the year, particularly in the upper few feet, the critical few feet from the point

of view of the water works engineer. Agricultural soil scientists have studied extensively the effect of these factors in the top few inches of the soil profile, and some engineering studies have been made. The junior author has made a detailed analysis of the engineering literature in this field (1).

As would be expected, the engineering literature emphasizes the overriding influence of the annual variations in air temperature. The character of the surface cover is also an important factor, particularly the insulating value of undisturbed snow, but this is an uncertain quantity as snow can and does vary so much with time. The type of soil is naturally important, but the degree of disturbance as represented by its density relative to its undisturbed density is perhaps the fac-

Fig. 3. Installation of Temperature-Recording Instruments at Montreal Road Laboratories

This installation was planned for a theoretical study of air temperature, snow cover, density of soil, type of soil, and disturbance of clay soils. ○ represents a thermocouple and □ a moisture-measuring unit.

tor of greatest significance. The presence or absence of ground water within the top few feet is another important factor. Thus it can be seen that any statements about the depth of frost for any general area can only be approximate and may even be misleading. The excavation of trenches for water main installation automatically introduces a special complication into the local soil temperature condition.

Fig. 4. Frost Penetration in Clay

Measurements were made in Ottawa for the years 1948-51.

Experimental Installations

The field installations for the study of soil temperatures have been described by Legget and Peckover (2) and, therefore, only a general description will be given. In Ottawa, automatic, mercury-bulb, temperature-recording instruments were installed under two city streets in November 1948. The bulbs were placed 2 and 5 ft under the center of the street, the gutter, and the adjoining strips of turf,

or boulevard, as shown in Fig. 2. One set of instruments was installed in sandy soil and the other set in a clay type soil. Continuous readings during most of the year were obtained in the sand from November 1948 until June 1950, and in the clay from November 1948 until September 1951.

For a more theoretical study of some of the basic factors affecting soil temperatures under field conditions, two test sites were chosen at the Montreal Road Laboratories of the National Research Council, one site in sand and

Fig. 5. Frost Penetration in Sand

Measurements were made in Ottawa for the years 1948-50.

the other in clay. This project was planned particularly for the study of five variables—air temperature, snow cover, density of soil, type of soil, and disturbance of clay soils. Four test pits, 8 ft square and 6 ft deep, were dug at each site, and each pit was equipped with thermocouples at 1-ft intervals of depth and was backfilled under controlled conditions (Fig. 3).

Two pits at each location were back-filled loosely and two were made compact with pneumatic tampers. During the winter, one loose and one dense pit

at each site were kept cleared of snow. Measurements are also being made in undisturbed clay to 15 ft below the surface. Temperature readings were begun in December 1949 and are continuing. Moisture meters were installed with the thermocouples, but these have proved to be unsatisfactory. Soil moisture variation is being measured using samples obtained from test borings.

Fig. 6. Frost Depths and Freezing Index in Winter Excavations

The design curve included in the figure was developed by the U.S. Corps of Engineers (3-5) from an analysis of frost penetration records of the northern U.S. • represents 1947-48 frost depth in unclassified soil. × represents 1950-51 frost depth in sand.

Results in Ottawa

Many difficulties were encountered in the field work. Corrosion of the recorder bulbs at the clay installation in Ottawa made replacement necessary in September 1949, and interrupted record continuity. It was necessary to remove the recorders in the sand when the instruments were damaged by vandals during the summer of 1950. After reviewing the results, it became apparent that three measuring points under the road and three under the boulevard would have given more satisfactory data. Such an installation would have

eliminated gutter measurements which were of limited value as it was impossible to control snow cover at the edge of the roadway. Probably the most serious error was the discovery, after installation, that a 12-in. sewer line was located near the measuring bulbs in the sand. This sewer line has complicated the analysis of soil temperatures, but at the same time, has shown how significantly a sewer will

Fig. 7. Maximum Frost Penetration and Maximum Freezing Index

Measurements were made in Ottawa for the years 1947-51. The right-hand end of the horizontal line indicates maximum frost depth at maximum freezing index. The left-hand end indicates freezing index at the time of maximum frost depth. • refers to measurements made in sand (interpolated); ⊙ clay (interpolated); × sand (by excavation); and + clay (by excavation).

raise the temperature of the surrounding soil.

Nevertheless, some pertinent observations can be made from the records which are shown in Fig. 4 and 5. The frost penetration was generally deepest from mid-February until mid-March, and was considerably greater under the center of the road than under the gutter or boulevard. An exception, probably a result of the sewer, occurred in the sand, where the frost penetration

under the gutter was nearly as great, and at one time greater, than that under the road. The effect of the sewer at the sand installation is evident in Fig. 5. The temperature at the 5-ft depth under the center of the road was consistently warmer than the temperature of the surrounding soil at 5 ft. The reverse occurred at the clay site. As the frost depth was interpolated assuming a linear temperature gradient between 2 and 5 ft, the computed penetration in sand is less than it would be under normal conditions. The winter temperatures under the boulevard are usually warmer than the others. In one winter, 1948-49, at the clay site, the gutter temperatures were warmer than the boulevard temperatures, probably a result of the greater snow cover over the gutter. In February 1950 the trend of the frost line under the gutter and boulevard in the clay suddenly reversed. A transfer of snow from the gutter to the boulevard appears to be a reasonable explanation for this change.

Snow conditions at the clay site were observed during 1950-51. For February these records show an average of 3 in. of packed snow on the road, 3½ ft of snow over the gutter, and 4 in. of snow on the boulevard. During this period, temperatures at the 2-ft depth under the gutter were abnormally high.

Cooler temperatures under the boulevard in clay, during the summer of 1950, illustrate the insulating effect of sod. This insulation is also present during the winter, although probably to a lesser extent. Sod does, however, complicate an evaluation of snow cover alone.

In addition to recording temperatures at these two sites in Ottawa, the Water Works Dept. has recorded frost depths in most winter excavations

which have been made since 1947. This record has proved to be valuable, perhaps more valuable to the water works engineer than the measurement of actual soil temperatures, as it gives average values of frost penetration throughout the city rather than values at certain sites that are assumed to be typical. These data are given in Fig. 6, 7, and 8. Figure 6 shows the relation between freezing index, which will be described later, and measured frost

Fig. 8. Approximate Frost Penetration in Ottawa Area

These observations were made when there was no snow cover.

penetration. The "design curve" developed by the U.S. Corps of Engineers (3-5) from an analysis of many records of frost penetration in northern U.S., measured mainly under snow-cleared airport runways on stabilized base course, is also shown in Fig. 6. The values for Ottawa show a trend parallel to the design curve but considerably above it.

The design curve, however, is based on maximum freezing index and maxi-

mum frost penetration for each winter. This relation is shown in Fig. 7, together with the horizontal displacement obtained by showing the freezing index at the time of maximum frost depth. The data are in agreement with the design curve for conservative estimates of frost penetration, except for the frost depths observed in sand excavations.

often show maximum frost penetration occurring several weeks before maximum freezing index for the winter. In western Canada the reverse is usually true as maximum frost penetration occurs long after the maximum freezing index. Water mains have frozen as late as June in Winnipeg. The reason for the later occurrence of maxi-

Fig. 9. Cumulative Freezing Index at Ottawa

The upper point at 84 in. penetration occurred during the winter of 1947-48, which appears to have been more severe than the freezing index indicates. Figure 8 shows variations in frost penetration between ground-temperature measuring installations and frost penetration as determined by excavation. These curves, compared with Fig. 9,

mum frost depth in western Canada is due to greater time lag with the deeper frost line. Even when the mean daily temperature is well above freezing, heat continues to flow from the frost line to the lowest temperature region in the soil which may be several feet above the frost line. This extraction of heat will send the frost line deeper.

TABLE 1
Maximum Frost Penetration at Montreal Road Laboratories

Soil Type	Winter Studied	Maximum Frost Penetration—ft				
		Snow-Covered Soil			Uncovered Soil	
		Undisturbed Soil	Dense Soil	Loose Soil	Dense Soil	Loose Soil
Sand	1949-50	—	4.1	4.2	4.6	4.6
	1950-51	—	1.5	1.4	4.1	3.7
Clay	1949-50	1.8	3.0	3.0	3.4	3.15
	1950-51	0.45	0.6	0.9	2.5	2.45

Results at Road Laboratories

The first soil temperatures were recorded at the Montreal Road Laboratories of the Div. of Building Research in the winter of 1949-50. During the first winter trouble was experienced with instrumentation and there may be some inaccuracies in the records, but subsequent records are considered accurate. The average penetration of the 32 F isotherm for two winters is shown in Fig. 8 and Table 1.

As more records become available, a better interpretation of the results may be made. At present only a few general statements can be made:

1. Density of the soil appears to have little effect on frost penetration. This conclusion may not be valid when the actual density of the soil in the pits is checked.

2. Frost penetration averages about $1\frac{1}{2}$ times as deep in sand as in clay, with, or without, snow cover. The effect of snow cover in this respect is not clear.

3. Disturbance of clay soils increases frost penetration to $1\frac{1}{2}$ times the depth in undisturbed clay.

4. Frost penetration is considerably reduced by a blanket of undisturbed

snow. The actual effect is uncertain because the snow blanket of 1949-50 was unusual, as shown in Fig. 10. During the winter of 1949-50, snow cover had little effect. In the following winter, 1950-51, removal of the snow tripled the frost penetration.

Factors Affecting Soil Temperature

A brief examination of the theory of heat flow (6) indicates some of the practical difficulties of a purely theoretical analysis of soil temperature variations. A simple equation expresses the rate of heat flow along a thermal gradient from warm to cold areas:

$$Q = KiAt$$

where Q = quantity of heat flowing, K = thermal conductivity, i = thermal gradient, A = area, and t = time. Thus the rate of heat flow over any given area is proportional to the thermal conductivity and to the thermal gradient.

The rate of change of temperature is expressed by a more complicated differential equation involving the thermal diffusivity of the soil. "Thermal diffusivity" is a term which expresses the ease with which temperature

changes can occur in the soil. If the soil freezes, latent heat is released, which adds to the complications.

These theoretical relations show that the rate of heat flow is proportional to the thermal conductivity, but the rate of temperature change, or the rate of frost penetration, is proportional to a more complex set of variables.

A detailed discussion of all the factors affecting soil temperature is not necessary, but some consideration of the variables is essential for an understanding of the problem. The variables may be divided into external factors

surprising degree. They illustrate, however, the difficulties in a theoretical calculation of frost penetration.

As present knowledge of the thermal properties of soils is limited, it is necessary to neglect many of the variables in both the theoretical and practical analyses. Of the external factors, only air temperature can be conveniently considered, but, fortunately, changes in the other external factors are generally reflected in the air temperature. Some of the intrinsic factors must be known for the theoretical analysis. A glance at some others will suffice to indicate their relative effect on soil temperatures.

Air temperature is, of course, the most important factor. The second most important variable is probably surface cover—for example, snow and vegetation reduce frost penetration and frost retreat. Pavement, on the other hand, increases penetration and accelerates retreat. Dark surface colors increase the absorption of solar energy—high temperature radiation—but do not have the same effect on the emission of heat from the soil—low temperature radiation. Radiation from the soil is governed largely by the soil's water content. All soils, when wet, tend to lose heat by radiation equally, as if they were black bodies. Many of the intrinsic factors are closely related to the texture and structure of the soil. About all that can be safely said of these variables is that frost penetration is generally greater in granular soils than in fine-grained cohesive soils.

Frost Penetration

High thermal conductivity aids frost penetration. Organic matter generally increases moisture content which, in turn, affects thermal conductivity and

Fig. 10. Undisturbed Snow Depths at Montreal Road Laboratories

and intrinsic factors (7). The external factors are meteorological, such as air temperature, precipitation, sunshine, relative humidity, wind velocity, dew point, and barometric pressure. Intrinsic factors include topographic position, nature of surface and type of cover, moisture content of soil and its thermal conductivity, specific heat, organic content, specific gravity, radiation, absorption, texture and structure, evaporation, and concentration of salts in solution. This is a formidable list of variables, yet they are so interrelated that they compensate one another to a

volumetric heat capacity. In general, moisture appears to be a temperature modifier, reducing fluctuations and rapid penetration. Topographic position has an appreciable effect on frost penetration, northern exposures having greater frost penetration than southern exposures.

The freezing point of the soil has been a controversial subject for some time. It is thought that fine-grained soils freeze at a temperature slightly lower than 32 F. Dissolved salts in the soil moisture would contribute to the lowering of the freezing point. Many comparisons by the U.S. Corps of Engineers (4) of soil temperatures with actual frost penetration, measured by excavation, show that the average freezing temperature is close to 32 F.

Theoretical reasoning indicates that density and water content may have considerable effect on frost penetration in soil owing to the effect of these variables on the volumetric heat capacity and the thermal conductivity of the soil. As noted previously, the ease with which temperature changes can occur in soil is governed by the thermal diffusivity. Thermal diffusivity is equal to the thermal conductivity divided by the volumetric heat capacity. Thermal conductivity indicates the amount of heat flowing per degree Fahrenheit, and the volumetric heat capacity indicates the amount of heat required to raise or lower the temperature 1 F. As increases in density or moisture content cause increases in both thermal conductivity and volumetric heat capacity, these changes may have little effect on the thermal diffusivity of the soil.

Heat Flow

At the present time, the calculation of heat flow in the ground is based on

general heat flow theory, using values of the coefficient of conductivity modified to compensate for the effect of moisture. These special values of the coefficient of conductivity are usually determined by placing a soil sample between a heated and a cooled plate, and measuring the heat input and temperature after steady-state conditions are achieved. It is generally recognized that under such a temperature gradient, the moisture begins to move from the hot side to the cold side. There is considerable discussion in the literature (8-10) of whether the water moves as liquid or by a process of evaporation, vapor migration, and condensation, or both. These opposing points of view have not yet been resolved, but are important in determining heat transmission in the ground. If any appreciable moisture movement as vapor takes place, resulting in the transmission of additional heat as latent heat in the migrating vapor, the usual heat flow theory may not be adequate.

The effect of vapor migration is to increase the heat flow, not only in the laboratory tests made to determine the coefficient of conductivity values, but also in the ground. The relative rates of vapor migration, however, may vary widely between the laboratory tests and the actual ground conditions, so that considerable errors may result. It is possible that future work will indicate such vapor migrations to be negligible in the soil. Until this is demonstrated, however, the possibility of error from this source must be admitted.

Transient methods capable of measuring the thermal properties of soils in place are now being developed (11, 12). These methods employ heated wires or spheres, and testing is carried out over a period of a few minutes. The migration of moisture occurring

during such a short time might be small but the rate of migration might be relatively high, and if the moisture movement occurs as water vapor, it might lead to fictitious results. It has been suggested that more heat arrives at a cooled coil in the ground—such as is used for a heat pump system of heating—than can be explained on

Effect of Air Temperature

As stated previously, air temperature is the most important factor affecting soil temperature and frost penetration. The common method of expressing the effect of winter air temperatures is the freezing index (13). The freezing index is the cumulative

Fig. 11. Freezing Index Computations for the Years 1885-1950

Computations were made from records of the Experimental Farm at Ottawa.

the basis of the usual theory. The cause of this apparent discrepancy may well be the transmission of heat as latent heat in the migrating vapor.

Until the combined mechanisms of heat and moisture flow are more adequately understood, the application of heat flow theory alone in assessing the effects of density and moisture content must be made with reservations.

total of degree-days* below freezing point in any winter. To compute the index, the mean air temperature for each day is subtracted from 32 F to obtain the degree-days of frost, and the values obtained are added together for the whole winter. Values for mid-

* A unit representing 1° of declination from a given point (here 32 F) in the mean outdoor temperature for one day.

winter days with mean temperatures above freezing—that is, negative values of freezing index—are subtracted from the total. In the spring when the temperature trend is upward and temperatures are above freezing, the cumulation is discontinued.

Computation of the freezing index using mean daily temperatures is laborious if many years of records are to be analyzed. It is equally accurate to use the monthly means for Decem-

days of frost for the fall and spring months, and usually includes frost in late November and early April. The cumulation does not necessarily begin at first frost as its effect may be cancelled by subsequent higher temperatures. The freezing index for Ottawa air temperature records has been plotted for four years in Fig. 9.

The freezing index has also been computed from the records of the Experimental Farm at Ottawa for the

Fig. 12. Freezing Index Frequency Curve for the Years 1885-1950

The frequency curve was obtained from a statistical analysis of records of the experimental farm at Ottawa.

ber, January, February, and March if a correction is applied for the transitional months in the fall and spring. The following formula can then be used:

Freezing index = $30.3x$ + correction
in which 30.3 is the average number of days in December, January, February, and March, and x is the average of the monthly means for these four months subtracted from 32 F. The correction is the cumulative total of the degree-

Fig. 13. Freezing Index for Two Winters

The two winters had the same total freezing index but were of different duration.

years 1885 to 1950, and the results of these computations are shown in Fig. 11. The freezing index frequency, which was obtained from a statistical analysis of these records, is shown in Fig. 12. This figure shows that the 50 per cent frequency was 1,930 degree-days—that is, that half of the years studied had winters with a freezing index greater than 1,930 degree-days—and the 10 per cent frequency was 2,460 degree-days. The winter of 1947-48 had 2,234 degree-days of frost. The records indicate that a winter with this freezing index will occur every four or five years.

The classification of the severity of winters using the freezing index is probably oversimplified but no alternative has yet been suggested. For example, the winter of 1947-48 had some peculiarities which indicate that it was more severe than would be gathered from the freezing index. Figure 9 shows that it was a normal fall and an early spring, the maximum number of degree-days occurring in mid-March. Furthermore, it was a year of light snowfall—59 in. The 50-yr average for Ottawa is 88 in. The winter of

which would include a time factor to account for a variety of weather conditions throughout the country. The purpose of this family of curves is to show greater frost penetration for a steeper freezing index curve, and was a suggestion of N. B. Hutcheon of the University of Saskatchewan, a consultant to the Div. of Building Research.

The Ottawa winter of 1947-48, which had a steep freezing index curve and deep frost penetration, lends strength to this conviction. In addition, the rapid accumulation of degree-days during 1947-48 at Ottawa is similar to the normal winter weather in western Canada, and it seems unlikely that only one curve of frost penetration against freezing index would accurately include the wide variety of weather experienced in Canada. Many field records of frost penetration will be required to complete this analysis, and it is hoped that a collection of these will begin during the next winter season.

Fig. 14. Relation of Freezing Index to Frost Penetration

The time factor accounts for a variety of weather conditions throughout the country.

1942-43 had 2,770 degree-days of frost but the snowfall was 116 in. It is reasonable to believe that snowfall and the rate of accumulation of degree-days have some effect on winter severity. Figure 13 shows a qualitative plot of freezing index for two winters having the same total freezing index but of different duration. It is possible that the winter of 100 days duration would be more severe than the longer winter owing to the greater thermal gradient acting at the surface. If this reasoning is correct, it may be possible to draw a series of curves (Fig. 14)

Effect of Snow Cover

Snow cover has considerable effect on soil temperatures and frost penetration. Some investigators of winter soil temperatures have noted its effect in the undisturbed state, and a few have compared the effect of undisturbed and compacted snow. All have agreed that snow cover will appreciably reduce frost penetration. The thermal conductivity of snow is a function of its density. Independent investigators have agreed, within fairly narrow limits, in their measurements of conductivity, as shown in Fig. 15, which is based upon a study of the properties of snow and ice (14).

Snow depths and density have been measured by the Div. of Building Re-

TABLE 2
*Undisturbed Snow Depths and Densities**

Date of Observation	Elevation of Samples in.	Specific Gravity of Snow	Snow Depth in.	Average $\frac{k^\dagger}{\text{Btu/ft/}^\circ\text{F/hr}}$
12/1/49	4	0.21	7	0.09
12/15/49	2	0.31	3	0.16
2/16/50	4½ 7½	0.22 0.24	10	0.10
3/8/50	2 5 9	0.28 0.25 0.24	12	0.12
3/16/50	2 6 12	0.36 0.33 0.14	15	0.14
1/15/51	2 7	0.22 0.16	10 10	0.08
1/30/51	2 4 9 11	0.25 0.20 0.12 0.19	11	0.08
2/15/51	3 7 12 15	0.28 0.22 0.24 0.30	17	0.12

* The observations were made at the Montreal Road Laboratories.

† Coefficient of conductivity.

search since 1948. These data are shown in Fig. 9 and Table 2, and from them the values of thermal conductivity for undisturbed snow can be estimated.

The warming effect of snow cover is clearly shown in Fig. 16, which shows that maximum frost penetration during 1950-51 in sand with no snow cover was 46 in., and with snow cover was 18 in.; in clay with no snow cover it was 29 in., and with snow cover was 11 in. In undisturbed clay with snow cover, the penetration was only 6 in. Part of the difference between the mean

annual air temperature and the almost constant soil temperature at 15 or 20 ft below the surface can be attributed to the insulating effect of snow.

Heat flows along the thermal gradient from warm to cold regions. Snow acts as an insulating blanket which reduces the penetration of frost. As frost penetration is dependent on more than simple relations of thermal conductivity, the degree of protection offered by snow cover is not a simple function of its depth and density. It is interesting to note, however, the relative values of thermal conductivity for the various materials affecting soil temperatures—for example, in terms of British thermal units per degree Fahrenheit per foot per hour, the thermal conductivity for undisturbed snow is 0.1; for ice, 1.3; for concrete, 0.5; and for soil, 0.8. Obviously these values are rough approximations, as the thermal conductivity is usually a function of such variables as density, moisture content, and mineral type and also depends on whether or not the soil is frozen. Nevertheless, the numerical values give an impression of the protection offered by snow, ice, concrete, and soil. Of the four thermal conductivity values given, the most significant value is that for ice, which shows that the protection against heat loss offered by pure ice is less than that of soil.

It may be more illustrative to compare, in a general way, the values for thermal diffusivity of soil, snow, and ice. On the average, the thermal diffusivity of ice is about 3 times as great as that of undisturbed, but not fresh, snow, and the thermal diffusivity of soil ranges from 2 to 3 times that of snow. These values indicate that, for a certain thermal gradient, ice and soil will change temperature at about the

same rate, and that undisturbed snow will resist temperature change as much as $1\frac{1}{2}$ or 2 times its depth of soil.

The protection against frost provided by partially disturbed snow was revealed by a study of field records of excavations in Ottawa of actual frost penetration under snow-free streets and the adjacent snow-covered boulevard. These records show that frost penetration is reduced by 1.7 to 2.7 ft for

the unknowns in the problem will gradually be reduced.

Theoretical equations for the computation of frost depth have been developed by several workers, but comparisons of actual and theoretically computed frost depths indicate that the theoretical approach is not yet free from error. An empirical design curve, developed by the U.S. Corps of Engineers (3-5), appears to be, at present, the best aid in frost prediction, and its application under Ottawa conditions is illustrated in this paper.

In spite of the uncertainties still awaiting solution, a careful study of the results obtained from the experimental work conducted at Ottawa suggests certain general conclusions:

1. The significant difference between the depth of frost penetration in disturbed and undisturbed soil suggests that if soil can be backfilled to something approaching its original undisturbed condition, some reduction in the depth of pipe trenches might be possible. This possibility is being studied.

2. It is clear that water pipes may safely be placed at less depth in clay soils than in sandy soils.

3. The design curve shown in Fig. 6 shows a reasonable relation between frost penetration and freezing index for most of the soils studied, but its use must be tempered with caution until more corroborative evidence is available for Canadian conditions.

4. If 500 or more degree-days occur before the end of December in Ottawa, some consideration should be given to restricted snow plowing in areas where water pipes are vulnerable.

5. The authors suggest a modification of the freezing index concept to take account of the rate at which freezing weather occurs. An outline of this modification has been given; the au-

Fig. 15. Thermal Conductivity of Snow

each foot of snow cover. The probability average of the records is approximately 2 ft.

Conclusions

An understanding of soil temperature variations in soils of different types, both disturbed and undisturbed, is a basic requirement for a full appreciation of the problem of freezing water mains. Although knowledge of all aspects of soil variations is still far from complete, a steadily increasing interest is being shown. As more field observations are published, and details of laboratory investigations are reported,

Fig. 16. Effect of Snow Cover on Frost Penetration

Measurements were made in the Ottawa test pits in 1950-51.

thors hope to publish design curves when sufficient evidence has been accumulated.

6. The extent of the effect of snow cover in its various states is still in doubt. It is now known, however, that an undisturbed continuous snow cover will reduce frost penetration in

the Ottawa climate by an amount equal to or greater than its own thickness.

7. Traffic-packed snow will reduce frost penetration somewhat more than pure ice, depending on the density of the snow. This points to the desirability of conserving snow cover whenever possible in water works practice.

Only by the steady and patient accumulation of factual evidence will it be possible to advance in this study with confidence. A number of research organizations are conducting investigations under controlled conditions and in laboratories. Additional information is required, however, from actual field experience.

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