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By

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Frost-Penetration Studies in Canada As an Aid to Construction

By C. B. Crawford

Division of Building Research, National Research Council, Ottawa, Ont.

The proper depth at which underground structures, including pipelines, water mains and sewers, should be installed has concerned construction and public-utility engineers and contractors for many years. Most specifications for these installations are still based on practical experience and, generally, experience is available. But in the many new construction developments in Canada, the determination of the depth of frost penetration is a difficult problem. A less arbitrary approach is required to determine the required soil cover for the extension of services in existing urban areas. Even within the boundaries of a town, frost penetration may vary from a few inches to several feet. The engineer should be able to estimate such differences readily and allow for them in design.

Where no experience is available on which to base these calculations, the scientific approach is becoming more prominent as a means of solving the problem. The Division of Building Research hopes that by its studies of frost-penetration data that certain criteria can be established to aid municipal engineers.

How to Collect Data

Data on frost penetration can be collected in various ways. The simplest method is by excavation or boring. Various special augers have been developed for this purpose. Certain gauges may be placed in the soil which indicate freezing by a rapid change in electrical resistance, or the actual temperature of the soil may be measured in a profile by a variety of instruments and the depth of frost determined by interpolating for the 32°F isotherm. The actual measurement of ground temperatures has the advantage of permitting the determination of the variation in frost depth with time and allows study of certain factors affecting the frost depth. It does, however, require the establishment and maintenance of elaborate instrumentation, and since soils do not freeze at exactly 32°F a small error may be introduced. It seems wise, therefore, to study the factors which affect frost penetration by laboratory experiments and field-temperature measurements and to gather frost depth data by excavation on a large-scale basis.

The need for a proper engineering approach to the determination of frost penetration has been adequately demonstrated. During the winter of

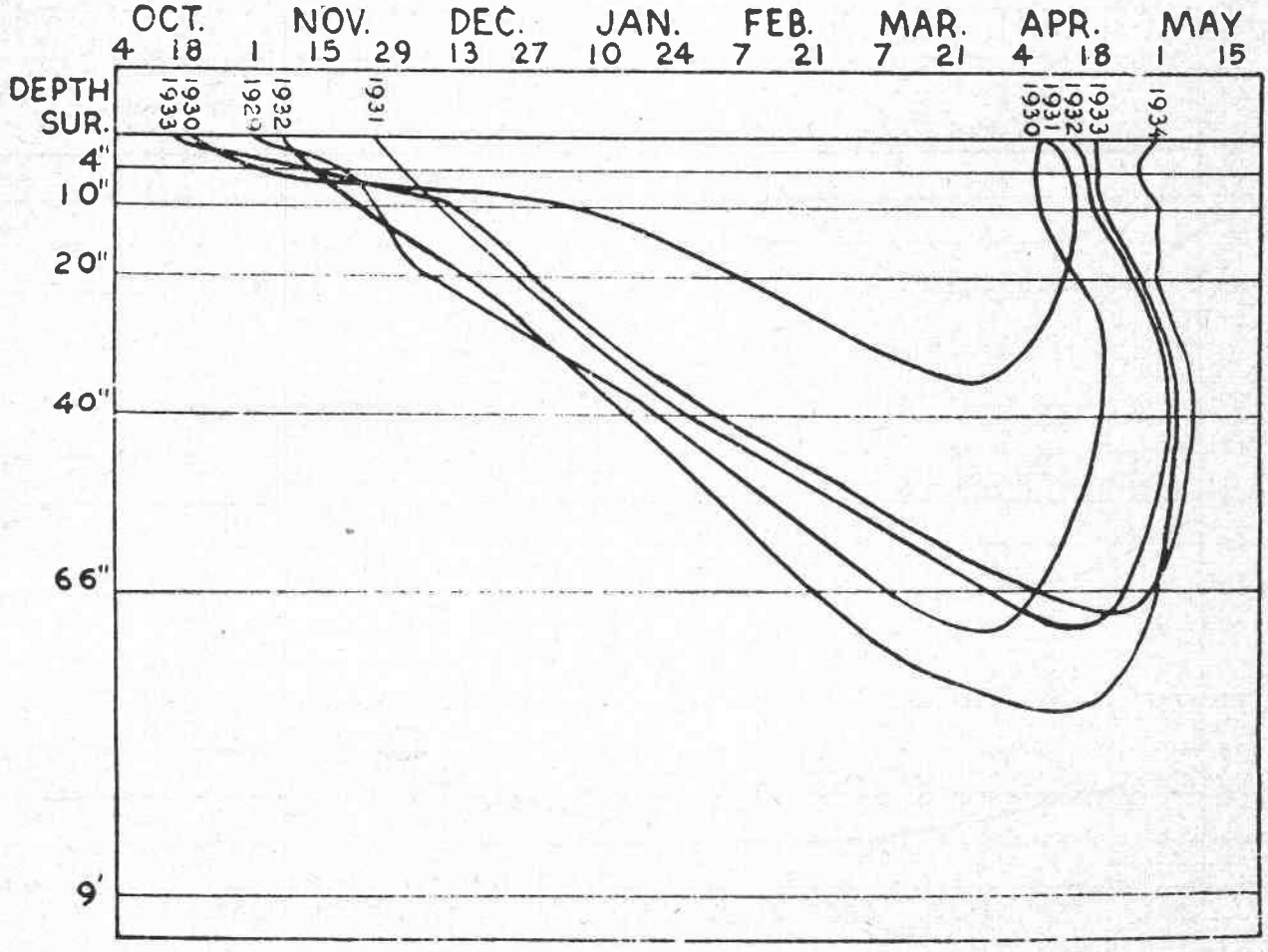

Fig. 1—Depth of frost penetration at Winnipeg, Man., during the winters 1929-1930 to 1933-34.

1935-36, for instance, Mabee (1937) reported the freezing of 2000 private service lines in Indianapolis. In Ottawa following the 1947-48 winter, nearly a quarter of a million dollars was spent to repair frost damage to the water-distribution system caused mainly by degree-days of freezing weather 15% above average and snowfall 35% below average. Many similar situations are on record. Without the necessary data the engineer is faced with an arbitrary determination of the required cover over services. This approach, to be safe, usually results in unnecessary excavation with accompanying increases in cost.

Early Investigations

A few years ago an engineer confronted with the problem of estimating ground temperatures at various depths during any particular season would have considerable difficulty in finding the necessary information. It was such a problem that prompted the beginning of ground-temperature measurements by the director of the Division of Building Research in 1944 (Legget and Peckover, 1949). Later,

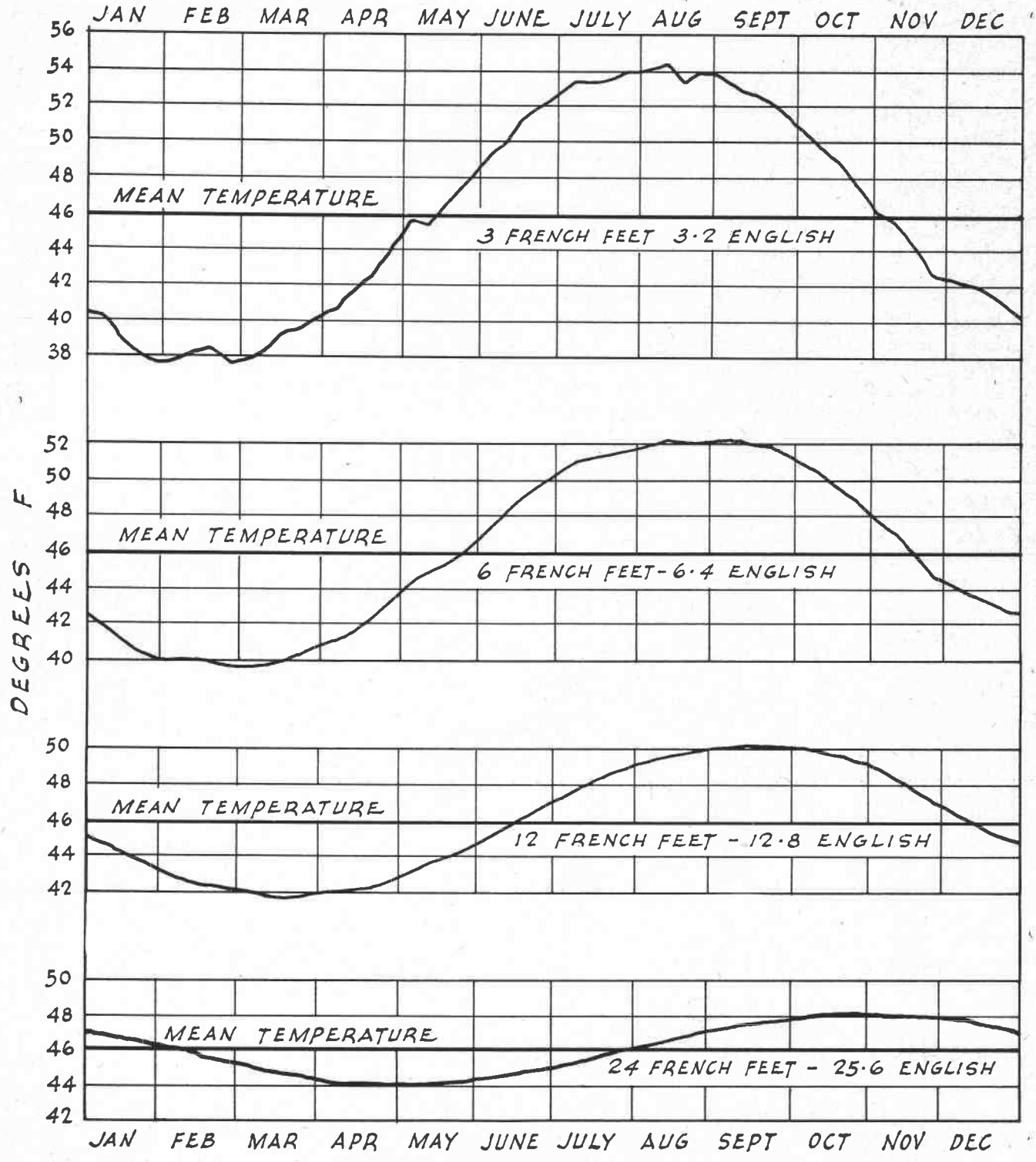

Fig. 2—How the mean temperature of soil at different depths varies according to the time of year (from Forbes, 1846).

a search of the literature (Crawford 1952) revealed an abundance of papers dealing with the problem—some dating back more than 100 years.

One of the most interesting early papers on the measurement of soil temperatures appeared in the Proceedings of the Royal Society of Edinburgh (Forbes, 1846). In the typical scientific language of the age, Forbes describes the construction of mercury-in-glass thermometers 26 ft. long, with capillary bore so fine that a one-degree temperature change moved the mercury 5 ft. It was necessary to add an enlarged stem to facilitate readings. Compensation was made for temperature variation along the tube and readings were made to one-hundredth of a degree Fahrenheit. Readings at depths of 3, 6, 12 and 24 ft. in three locations were begun in 1837. Typical results are shown in Fig. 2. These curves show temperature variations quite similar to those obtained recently in Ottawa which are later described. Reference is made of soil-temperature observations near Edinburgh as early as 1815. Some of these early writers computed thermal properties of the soil from their records of temperature variation.

In 1895, Professor Callendar of McGill University published results of ground-temperature measurements at Montreal (Callendar, 1895). A significant advancement in this work was the use of electrical resistance thermometers for remote measurements. This was followed in 1909 by Patten's laboratory study of the thermal properties of soil (Patten, 1909). In 1913, Professor Bouyoucos published his first study of the factors affecting soil temperatures (Bouyoucos, 1913). This was followed by a series of his reports which together laid the groundwork for many later investigations. This prominent work solved some of the questions concerning soil-temperature variations and posed many others.

In 1935, Beskow, in Sweden, published the results of many years of work on freezing problems (Beskow, 1935). A few years later W. O. Smith (1939) contributed generally to the understanding of the thermal properties of soils.

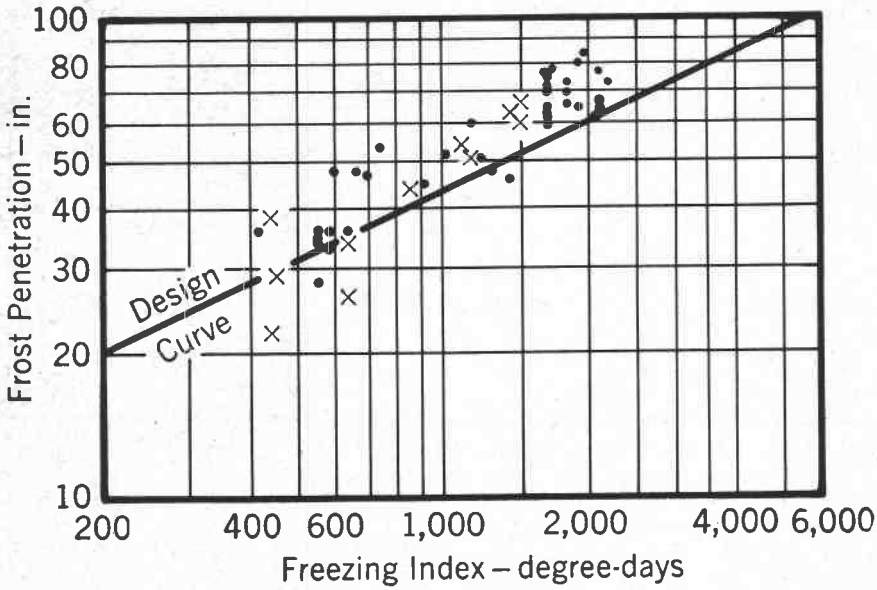

Fig. 3—"Design curve" including results at Ottawa, Ont., of observed frost penetration in excavations. Symbols: "X" represents sandy soil; "O" represents unclassified soils.

Berggren (1943) published a procedure for computing the depth of frost penertation and with some recent studies and modifications this may prove to be quite useful.

In 1949, Kersten published results of his extensive laboratory research on the thermal properties of soils. About this time workers in this field became concerned about the effects on temperature of migrating moisture in the natural soil. Bouyoucos (1915) had demonstrated in the laboratory (later shown more vividly by Smith, 1943) that moisture moved in soil in the direction of decreasing temperature. In addition to complicating any field analyses, this feature threw suspicion on the accuracy of previous laboratory measurements of the thermal properties of soils. This led to independent attempts by Hooper (1952) and Misener (1952) to measure thermal properties in situ by rapid methods in order to reduce the flow of water. The accuracy of these special types of apparatus is yet to be proven.

The earliest known record of soil temperature measurements in Western Canada was published by Harrington (1928). Observations were made at intervals of one foot to a depth of 8 ft. near the Engineering Building at the University of Saskatchewan. Thompson (1934) reported soil-temperature observations to a depth of 15 ft. at Winnipeg. Curves showing the penetration and retreat of frost under natural snow cover for the years 1929-34 at Winnipeg are shown in Fig. 1. These measurements permitted a valuable analysis of some of the factors affecting soil temperatures.

In recent years a new interest has been shown in the understanding of the variation of ground temperatures. The U.S. Corps of Engineers and the U.S. Meteorological Service have sponsored extensive field and laboratory studies. In Canada the Division of Building Research of the National Research Council is conducting an expanding program of research in this field.

Factors Involved

The variables which affect soil temperatures and frost penetration can be divided into two groups: major factors and minor factors. Minor factors which influence the temperature of the soil include sunshine, wind, relative humidity, precipitation and evaporation, radiation and absorption, topographic position, concentration of salts and organic content, density, specific heat and thermal conductivity of the soil. Some of these factors tend to heat the soil and others tend to cool it. It is impossible to include all of these minor variables in a practical analysis, and therefore, in general, only the major factors are considered. Major factors which are the most influential variables are: air temperature, surface cover, soil type, and water content.

A definite relationship between air temperature and depth of freezing was first shown by Casagrande (1931). Later Shannon (1945) and the U.S. Corps of Engineers (1947) presented data which substantiated this relation-

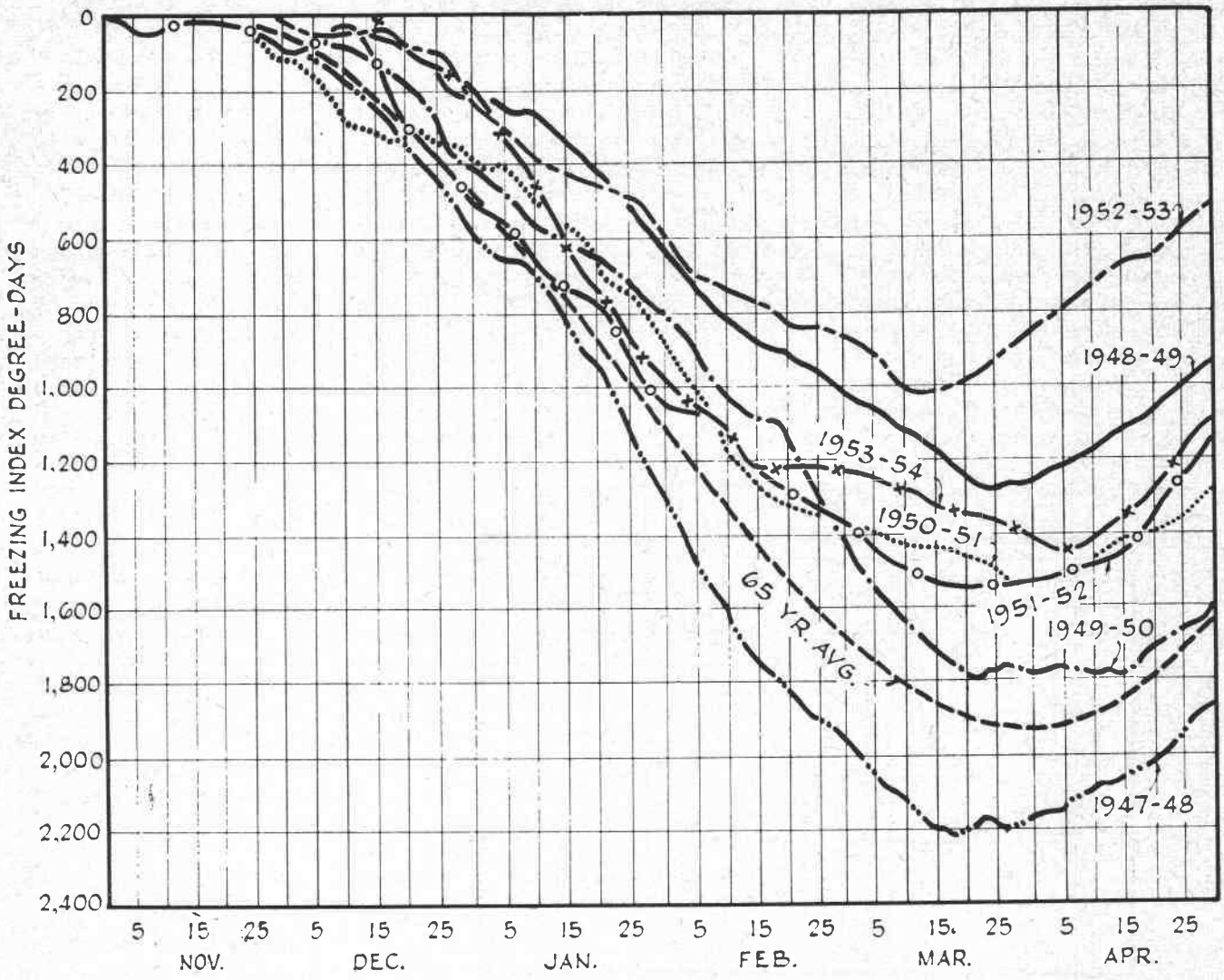

Fig. 4—Freezing index at Ottawa, Ont., 1947-54.

ship, now known as the "design curve". The curve (Fig. 3) takes into account only the air temperature. This curve represents an average relationship between "freezing index" and frost depth in granular base courses beneath cleared airport runways in the Northern United States.

The freezing index is the cumulative total of degree-days below freezing point during any winter (one degree-day represents a declination of 1° below 32°F in the mean air temperature for one day). The freezing indices for Ottawa since 1947-1948 are shown in Fig. 4. With the design curve in Fig. 3 are shown values for frost penetration at Ottawa in relation to the number of degree-days which had occurred at the time of excavation (Legget and Crawford, 1952). It can be seen that the Ottawa data show the design curve to be unsafe. Thus, more evidence is necessary for a proper interpretation of Canadian weather.

Next to air temperature the surface cover over the soil probably has the greatest effect on frost penetration. Undisturbed snow, as it lies on the ground, has a thermal conductivity of only about one-eighth that of soil. Also its thermal properties are such that under similar temperature conditions it will change temperature half as quickly as soil. Therefore it may be expected to act as a very good insulator against winter weather. Many investigators have noted this significant feature and have claimed various quantitative reductions in frost pentration due to snow cover. Comparisons of frost penetration under cleared streets and the adjacent snow-covered boulevard at a number of locations in

Table 1—Frost Penetration in Test Pits at Ottawa

Soil type	Year	Freezing index (degree-day)	Total snowfall (in.)	Snow depth (in.) Max.	Snow depth (in.) Winter average	Frost penetration (ft.) With snow cover	Frost penetration (ft.) Bare
Sand	1950-51	1530	94.9	18	10	1.5	3.9
"	1951-52	1538	115.3	20	14	1.6	3.1
"	1952-53	1030	40.3	7	3	3.1	3.1
"	1953-54	1450	86.2	18	8	—	3.3
Clay	1950-51	1530	94.9	18	10	0.7	2.4
"	1951-52	1538	115.3	20	14	0.6	2.3
"	1952-53	1030	40.3	7	3	2.2	2.3
"	1953-54	1450	86.2	18	8	1.0	2.5
65-year average		1930	87				

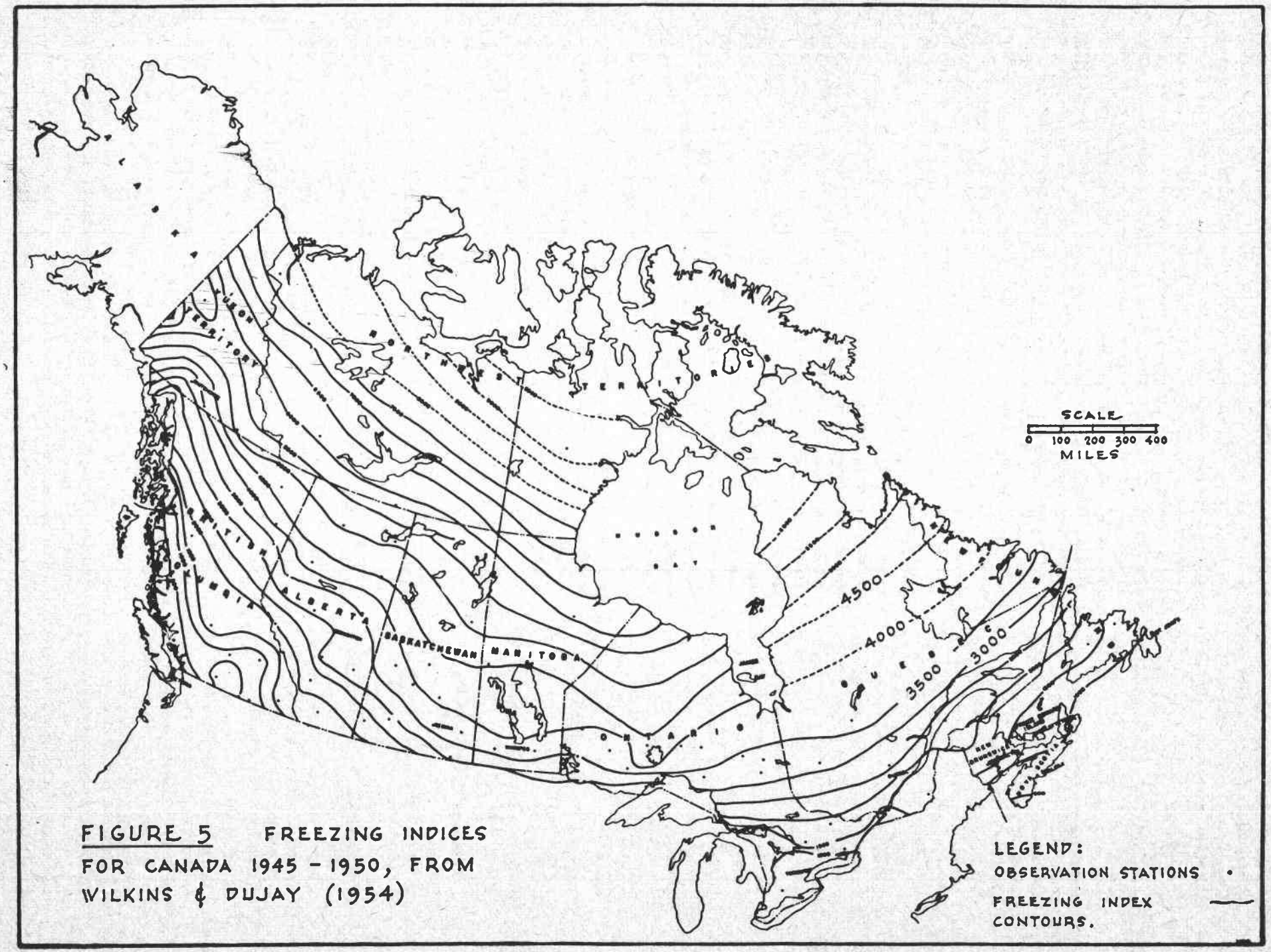

FIGURE 5 FREEZING INDICES FOR CANADA 1945 - 1950, FROM WILKINS & DUJAY (1954)

Ottawa show an average reduction in frost penetration of 2 ft. for each foot of snow cover. Packed snow and ice have a significant but lesser effect.

The effect of soil type and water content of the soil can probably be considered to have a combined effect. Gravels and crushed rock, with relatively low water contents, permit greater frost penetration than clays which usually have a much greater water content. Sands tend to permit a penetration less than gravels and more than clays. The reason for this variation can be attributed to the effect of water on the thermal properties of the soil. A slight amount of moisture will increase the thermal conductivity of a perfectly dry material, but greater amounts of moisture will increase the volumetric heat capacity to such an extent that a much larger heat extraction is necessary to lower the temperature. Also the latent heat of fusion of this additional water provides considerable heat to be extracted during freezing.

Table 1, giving a 4-year record of freezing index, snow cover, and frost penetration in test pits at Ottawa, clearly shows the significance of the effects of these major variables. It should be noted that the winter of 1952-53 was the mildest on record at Ottawa and the snowfall was the lowest on record. During most of the winter patches of bare ground were visible. As would be expected, the effect of snow cover was slight.

Research Council Studies

The studies of the Division of Building Research are following three distinct phases: field measurements, laboratory study, and a continuing review of the literature. Field measurements were begun in 1947, followed by a review of all available literature. To date, only routine soil analyses have been made, but this is now being extended to a laboratory investigation of freezing phenomena in soils.

In Ottawa soil temperatures are being recorded in sand and clay test pits and under a roadway both with and without snow cover. These installations are designed to study the effects of air temperatures, soil type, and snow cover. For two years, continuous records were taken under city streets at two locations. Also, records are kept by the City Waterworks Department of the depth of frost in all excavations made during the winter season. This simple information has contributed generously to the local information on frost penetration.

The Ottawa studies are regarded as control studies. The proximity of field measurements to the laboratory permits more careful and detailed observations. However, it is necessary to study the effect of other climates, and for this reason ground temperature installations have been established in other regions. For this work it is necessary to enlist the assistance of other agencies to do the field work. This has developed into several fruitful cooperative projects ranging from Resolute Bay in the Far North to Yellowknife, Uranium City and Knob Lake in Labrador, as well as several more temperate locations.

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The studies explained in this article are highly important to engineers and contractors concerned with wintertime construction or with structures liable to be affected by low ground temperature. As the author points out, the problem involves a great number of variables which are constantly changing, and therefore requires much more investigation before the margin of error can be substantially reduced. Nevertheless, the research on all phases of soil-temperature work is deserving of continued study in the interest of better construction.

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During the past winter, arrangements were made with a number of interested people to obtain frost-penetration data from excavations in order to extend the valuable work done by the Ottawa Waterworks Department. Locations of the observation points were chosen to give a wide coverage with a minimum of data. Accordingly, thirteen cities were selected with at least one in each province. Much useful data were collected during the past winter, but unfortunately for this study, in many locations few, if any, excavations are made during winter. Consequently it may take several years to collect sufficient records for general analysis.

After more than a century of soil-temperature studies of various types, what do we know that can be applied in a practical sense and what do we still need to know? We know that we are dealing with a most complex heat-flow problem in which the external heat-energy applications never recur exactly and that the great number of variables are constantly changing. It would appear then, that no analysis, theoretical or empirical, can give us an exact answer. Nevertheless it does seem quite practical to study the effects of the major variables and to predict frost penetration on this basis. We know, for instance, that snow cover will reduce frost penetration appreciably and that its effect is reasonably predictable even though its properties will vary greatly. We know that, in general, frost penetrates farther in gravel than in clays and that there is an approximate relationship between air temperatures and frost penetration. This knowledge, however, is by no means complete. In order to reduce the margin of error we need much more data under various climatic conditions. Since a complete annual weather cycle is required for each maximum frost depth figure, it will take several years to complete this study.

For immediate design information, the best known relationship is the "design curve" shown in Fig. 3. It should be remembered, however, that this curve is based on the limiting conditions previously stated. Fortunately, the Construction Division of the Department of Transport has published a "Freezing Indices" map of Canada (Wilkins & Dujay, 1954) shown in Fig. 5, which can be used with the design curve to approximate frost penetration anywhere in Canada. This map is based on 5-year temperature averages and is now being revised to include 10-year averages. If extensive service installations are to be made in regions where no experience is available it is almost necessary to observe soil temperatures in advance of the work. Often limited observations may then be analyzed, together with data from other similar regions, to give a reasonable engineering design.

An attempt has been made to discuss all phases of soil-temperature work in relation to its significance in engineering design. It is evident that, with our present knowledge, precision

design is not possible, but it is equally clear that with continuing observation the margin of error will be substantially reduced. This work will require a co-operative effort with municipal engineers all across Canada. The writer therefore requests the support of all municipal engineers in collecting frost-penetration data as a routine matter. This information, while primarily of local interest, would be welcomed by the Division of Building Research where it can be processed for general use in municipal engineering.

Acknowledgements

In addition to those members of the Division of Building Research who contribute to the study of soil temperatures as a matter of routine the writer wishes to express appreciation to the engineers who have co-operated so generously on regional studies across Canada. Special appreciation is due to R. F. Legget, the director of the Division of Building Research, whose early studies and continuing interest have added much to this work, and with whose permission this paper is presented.

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