Construction on permafrost
Crawford, C. B.; Johnston, G. H.

Publisher's version / Version de l'éditeur:

Canadian Geotechnical Journal, 8, 2, pp. 236-251, 1971-05

NATIONAL RESEARCH COUNCIL OF CANADA
CONSEIL NATIONAL DE RECHERCHES DU CANADA

CONSTRUCTION ON PERMAFROST

BY

C. B. CRAWFORD AND G. H. JOHNSTON

Reprinted from
CANADIAN GEOTECHNICAL JOURNAL
VOL. 8, NO. 2, MAY 1971
p. 236

TECHNICAL PAPER NO. 337
OF THE
DIVISION OF BUILDING RESEARCH

OTTAWA
May 1971

Price 25 cents

NRCC 11843

Construction on Permafrost[1]

C. B. CRAWFORD AND G. H. JOHNSTON

Division of Building Research, National Research Council of Canada, Ottawa, Canada

Received December 30, 1970

Permafrost, or perennially frozen ground, occurs widely throughout the northern half of Canada. Experience has shown that special design and construction techniques are required for building on permafrost in order to avoid disturbing the delicate thermal balance that preserves the frozen ground. The state of knowledge is reviewed with respect to site investigations, foundation designs, water supply and sewage disposal, the construction of transportation facilities, and the influence of surface flooding, drainage and other disturbances on the ground thermal regime. Attention is drawn to an extensive literature and research needs are outlined.

Le pergélisol, c'est-à-dire les sols gelés en permanence, se présentent largement partout dans la partie septentrionale du Canada. L'expérience a démontré que des calculs spéciaux et des techniques spéciales de construction sont nécessaires pour la construction sur le pergélisol pour éviter de modifier l'équilibre thermique délicat qui maintient les sols gelés. Les connaissances sont revues concernant les reconnaissances de sol, le calcul des fondations, l'approvisionnement d'eau, le traitement des eaux d'égoûts, la construction des facilités de transport et l'influence d'une inondation des surfaces, le drainage et les autres perturbations du régime thermique du sol. L'attention est dirigée vers une documentation importante et les besoins de la recherche sont indiqués.

Most Canadians have a keen interest in the Far North, but few choose to live there. Less than ¼% of the country's population lives in the Yukon and Northwest Territories, which together comprise almost 40% of the land area. Ninety percent of Canadians are strung along the southern border, with more than half concentrated in 1% of the land area in the lowlands of Southern Ontario and the St. Lawrence river valley.

The northern climate is harsh. Winters are long with limited daylight, although they are not so much colder than those of the Canadian Prairies. The average daily mean temperature throughout the five coldest months in Whitehorse, for example, is the same as that in Saskatoon and Winnipeg. It is the persistence of the cold weather rather than its severity that causes the low annual mean temperatures. The combined effects of wind, long periods of low temperatures, and darkness create difficulties for living and working in the North and pose special problems with respect to carrying out construction. Most construction problems result from a lack of appreciation of the nature of the land and climate and from inexperience with northern operations.

Men are attracted to the North by the prospect of wealth and adventure. This was clearly demonstrated by the rush to the Klondike at the turn of the century and more recently by the economic boom on the Alaska North Slope. Millions of dollars are now being invested in the Canadian North in the hope that large reservoirs of oil will be found. It is estimated, for example, that expenditures in the search for oil in 1969 exceeded 70 million dollars (compared with 5 million in 1958) (anonymous 1969). Much of this money is being spent in the Mackenzie delta and the Canadian Arctic Islands, where geological prospects are promising, but exploration is also being carried out in the Yukon, upper and mid-Mackenzie river areas, and in Hudson Bay.

Mr. J. A. MacDonald (until late 1969 Deputy Minister, Department of Indian Affairs and Northern Development) has pointed out that attention must be focused on the resource potential of the North and that "economic expansion . . . is dependent on the profitable exploitation of northern natural resources and this single fact must guide those who are concerned with planning and investment for the future of the North" (MacDonald 1966). At the recent symposium on "Arctic and Middle North Transportation" Wilson (1969) suggested that "massive public investments far in

[1]Prepared for presentation to the Western Congress of Canadian Engineers, 22 May 1970.

advance of major settlements or discoveries would constitute serious economic waste . . ." and that northern development should be confined to those regious of proved resources that can be economically marketed. Others drew attention to the abnormal costs of operating in the North and transporting the resulting products to market.

The conference summary by Bader *et al.* (1969) was optimistic that northern mineral resources will be explored, developed, and exploited at an accelerated rate in the immediate future, and that provision of the necessary administrative structure and public services must be accelerated to meet the need. It was concluded that most communities associated with mineral production will be small (a few thousands at the most) and that large towns will be rare. This will require a mixed transportation network that will vary from region to region, depending on the nature of the terrain and on local needs.

The relative isolation of most areas has retarded northern development, although access to the North has advanced dramatically in recent years, mainly through increased and more reliable air transport. Existing airports and communication facilities have been improved, new airstrips are being provided, the road network is expanding, water transport has greatly increased, and new modes of transportation are being investigated. Nevertheless, the logistic difficulties associated with the movement of personnel, equipment, and materials into and within our northern regions and, in general, the extremely high costs of operating and moving products to markets are serious problems still to be overcome.

In summary, it may be concluded that northern development is accelerating and that the rate of construction of buildings, transportation facilities, and other structures needed for the exploitation of resources will increase dramatically in the years ahead. The structural design of these facilities can be essentially the same as for similar structures in the south, but their foundations require special attention and treatment because they will rest on permafrost.

It is for this reason that the Division of Building Research, National Research Council of Canada, has maintained an active research interest in northern terrain for the last 20 years, an interest that has resulted in many publications on the nature and distribution of permafrost and the problems of designing and constructing buildings and other facilities on frozen ground. This paper is intended to acquaint the reader with highlights of this research and to draw attention to the problems.

Permafrost

About half of Canada is underlain by "permafrost" (perennially frozen ground), which by definition refers to ground that remains frozen for more than one complete year. At the southern boundary of the permafrost region it may be only a few inches thick but in the Far North permafrost may extend to depths greater than a thousand feet. The occurrence and distribution of permafrost is influenced by climate and the heat exchange characteristics of the ground surface. After many years of detailed field investigations across Canada, R. J. E. Brown, Division of Building Research, was able to map the southern limit of permafrost, which coincides approximately with the mean annual air temperature isotherm of 30 °F (−1.1 °C) (Fig. 1).

The permafrost region is divided into two zones, the discontinuous in the south and the continuous in the north. Within the discontinuous zone permafrost occurs together with unfrozen ground, being quite patchy in the southern fringe area where it is confined to certain types of terrain, mainly peatlands. The annual thaw may reach a depth of 10 ft (3 m) and lenses of permafrost may form and disappear, depending on local short-term influences. In the northern part of this zone permafrost is more widespread and occurs to depths of about 200 ft (60 m). The discontinuous and continuous zones merge where the mean annual air temperature is approximately 17 °F (−8.3 °C). Within the continuous zone, permafrost occurs everywhere under the land surface to depths of from 200 ft (60 m) to more than 1000 ft (300 m) and the depth of annual thaw varies from a few inches (≈ 10 cm) to perhaps 3 to 4 ft (1 m) (Brown 1970).

In the discontinuous zone variations in terrain are responsible for patchy occurrence of permafrost, size of permafrost islands, depth to the upper surface of permafrost (the permafrost table), and thickness of permafrost. In the continuous zone, the thermal properties of

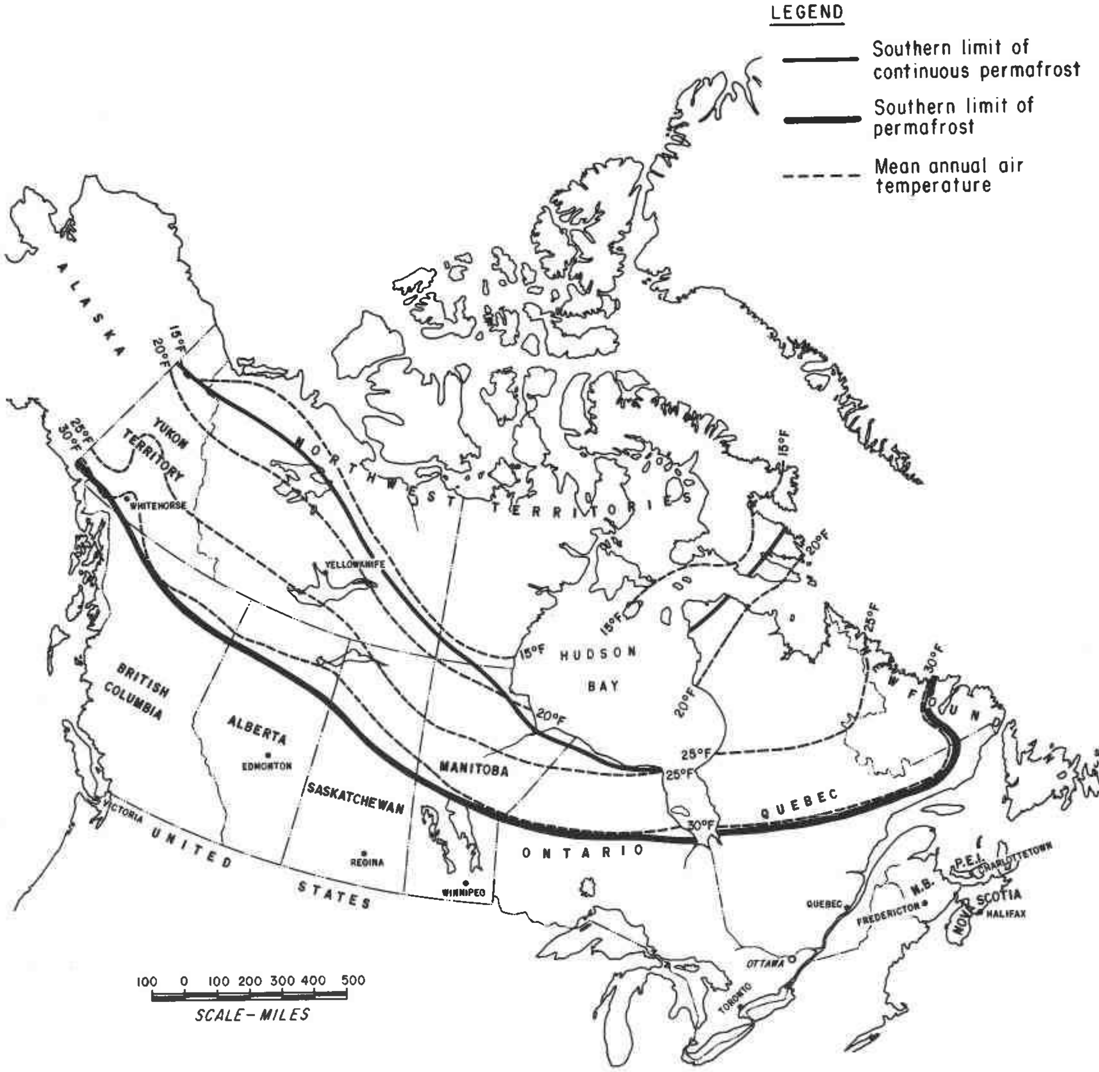

FIG. 1. Permafrost in Canada.

peat and other terrain factors assume a relatively minor role and the thermal properties of the ground as a whole, together with the climate, become dominant. The role that terrain factors including relief, drainage, vegetation (tree growth, and moss and peat cover), snow cover, and soil type play in affecting permafrost conditions has been assessed in studies carried out in northern Manitoba (Johnston *et al.* 1963).

Permafrost, which is the result of a thermal condition reflected in ground temperatures below 32 °F (0 °C), is particularly sensitive to thermal changes. The delicate natural thermal equilibrium is greatly affected by any natural or man-made changes in the environmental conditions under which permafrost exists. The clearing of an area, disruption of drainage, or erection of a structure may result in thawing of the frozen ground or raising of the permafrost table. For example, Watmore (1969) reports that a gulley 23 ft (7.0 m) wide and 8 ft (2.4 m) deep was eroded in 4 years along a bulldozed seismic line west of the Mackenzie river delta. Care must be taken, therefore, in all construction operations to ensure that detrimental conditions are not produced by changes in or disturbance of the original environment.

Most engineering problems are caused by thawing of perennially frozen ground containing large quantities of ice. Ice can occur in several ways ranging from coatings or films on individual soil particles and minute hairline lenses scarcely visible to the naked eye to large inclusions and massive deposits many feet thick. All forms of ice segregation can occur in the same material, including granular soils (Pihlainen and Johnston 1963).

Site Investigations

The need for adequate engineering site investigations to determine the distribution of permafrost, the conditions under which it exists, and its properties and characteristics cannot be overemphasized (Johnston 1963*a*). Air photo interpretation (black and white, and color) is a most useful tool for a preliminary evaluation of an area with respect to terrain and subsurface conditions. Soil types and permafrost conditions are indicated by or can be inferred from relief, vegetation, and drainage characteristics. Ice wedge polygons and patterned ground forms resulting from frost action, pingos, thermokarst lakes, "drunken forests", or ground subsidence caused by thawing of large buried ice masses, solifluction lobes or terraces, "palsas", peat plateaus, frost mounds, hummocks, mud boils, and "beaded" or "button" streams all indicate potentially unsuitable foundation conditions. These can be readily identified on air photos and thus areas of undesirable or detrimental permafrost can be delineated (Brown 1968).

Other remote sensing techniques such as infrared scanners and photography, side-looking radar, etc., are only now being investigated with respect to their suitability for mapping the occurrence and distribution of permafrost. Although not conclusive, preliminary field trials by the National Research Council in 1969, using an infrared scanner in permafrost areas, met with limited success.

Even though permafrost and general terrain conditions can be predicted fairly reliably from air photos, it is still necessary to carry out detailed on-site investigations to provide the information necessary for design and construction. Selected areas or sites are examined visually and by borings, test pits, and probings to check predictions and to determine actual subsurface conditions. The distribution of permafrost, its vertical and areal extent, and the factors that control its existence must be known. Types of ice segregation and the various materials and conditions with which they are associated must be determined. Geophysical prospecting methods, mainly seismic and electrical, can provide useful information on the distribution, thickness, and physical character of the permafrost, but their effectiveness varies from site to site.

Samples (disturbed and undisturbed) of frozen ground are required for the determination of ice content and other physical, mechanical, and thermal properties. Samples can be obtained from exposure or test pits or by drilling techniques, which have been developed successfully for coring frozen materials (Johnston 1963*b*). The measurement of ground temperatures is an important phase of site investigation, allowing assessment of the ground thermal regime and the effect that construction may have on it.

Strength of Frozen Ground

The strength of frozen ground is understood only in a very general sense. It is obviously dependent on temperature and soil composition. If it contains a lot of ice, it will have the creep properties of ice and its long-term load carrying or anchoring capacity will merit careful investigation. Just below the freezing point a fine-grained soil may contain a large proportion of unfrozen water (Williams 1968) and its strength will be correspondingly low.

Unfortunately the strength of frozen ground is deceptive because it is hard to excavate and can support very large transient loads. Tests have shown, however, that the long-term strength may be less than a tenth of the short-term value because of its plastic behavior due to its ice content (Vyalov 1963). The response of frozen soil samples to loads of different magnitude is shown in Fig. 2. Under a small load the material will undergo only a small initial strain. Under a moderate load initial deformation will be followed by a slow, constant rate of strain and finally by a rapidly increasing rate ending in failure. Under a large load the secondary creep phase is very brief. Vyalov has proposed,

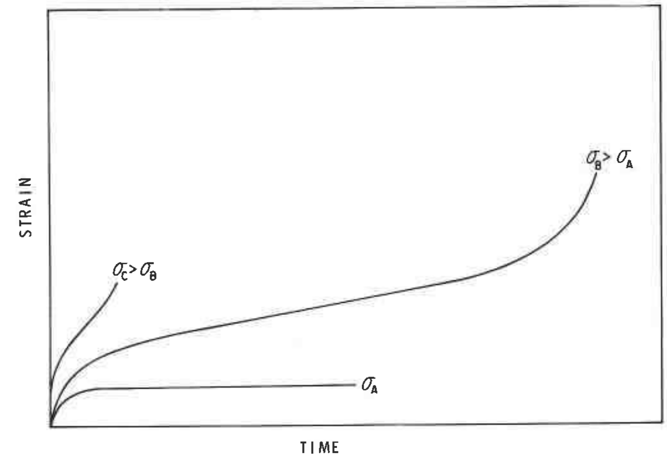

FIG. 2. Creep curves for constant loads on frozen soil (after Vyalov 1963).

for design purposes, a relation between the stress and the resulting time-dependent deformation. Sanger (1963*b*) reports some success with the method, but cautions that thermal and deformation computations cannot be separated in frozen ground engineering.

Recent laboratory tests at the Division of Building Research by P. J. Williams illustrate the need for refined testing of soils near the freezing point. These tests were carried out on frozen silt in a triaxial cell under very close temperature control ($\pm\frac{1}{50}$ °C) at various rates of strain and at ambient temperatures ranging from −0.64 to −0.10 °C. The results at −0.64 °C showed failure stress under rapid loading (0.1 h) to be about twice the value under slow loading (100 h). As the temperature was raised to −0.20 °C the strength decreased slightly, but further warming to −0.10 °C resulted in about a 50% reduction.

An estimate of the adfreezing strength of frozen ground may be required to assess the lifting force due to frost heaving on posts, piles, piers, or other structural units, or to assess the holding capacity of various types of anchorages in the ground. In such cases the creep properties of the ground reduce the detrimental lifting forces but correspondingly reduce the anchoring capacity. Recent field measurements by Penner and Irwin (1969) show that adfreezing strength is much less than would be predicted from short-term laboratory tests. The maximum adfreezing strength between clay and steel posts was less than 1 ton/ft^2 (96 kN/m^2) a value that agrees reasonably well with the computed value based on earlier Russian work.

Frost heave is an important consideration in the design of transmission tower foundations and anchors. Reinart (1969) has described the factors influencing designs for the Nelson river transmission line in Manitoba where, in addition to severe frost heave, degradation of permafrost during the life of the line was a major consideration.

Ground Thermal Regime

The earth is a great heat reservoir. During the day it absorbs heat from the sun in the form of short-wave radiation and at night it gives up heat to the atmosphere as long-wave radiation. The amount of heat energy absorbed will depend on the intensity and duration of solar radiation and the reflectivity of the surface. Under normal conditions the heat gained in summer is equal to the heat lost in winter. There is a constant flow of heat from the center of the earth to the surface, but the heat loss due to this geothermal gradient is almost four orders of magnitude less than that received from the sun and it has, therefore, no detectable influence on the earth's surface temperature (Lachenbruch and Marshall 1969). The geothermal gradient in Canada ranges, approximately, between 1 and 2 Fahrenheit degrees (0.5 and 1.1 centigrade degrees) for every 100 ft (30 m) of depth (Jessop 1964).

Near the surface the ground experiences a diurnal temperature variation superimposed on an annual variation that decreases with depth. At a depth of about 20 ft (6 m) the annual variation is very small and the temperature is about 6 months out of phase with the surface (*i.e.* warm in winter, cool in summer). In general, the mean annual ground temperature near the surface is almost constant with depth, although it may vary slightly from year to year (Gold 1963).

A world-wide study of soil temperatures (Jen-Hu Chang 1959) shows that the mean annual temperature near the surface differs only slightly from the mean annual air temperature, except where snow cover is abundant. In northern regions snow cover provides an important seasonal influence on the surface heat exchange and causes a substantial difference between the mean annual ground and air temperatures. In Canada this seems to have been measured first by Thomson (1934) at Winnipeg where the mean annual ground temperature during a 3-year period was nearly 5 F deg (2.8 C deg) warmer than the mean annual air temperature. Similar measurements at Ottawa (Crawford and Legget 1957) gave a difference of more than 6 F deg (3.3 C deg) under natural snow cover, but where the snow was cleared, as on roads, the mean annual temperature difference was substantially reduced. Further studies by Gold (1967) at Ottawa also show the influence that surface conditions, including snow cover, have on ground temperatures. A summary of observations made in permafrost regions of Canada indicates that the mean annual ground temperature ranges from 1 to 12 F deg (0.5 to 6.7 C deg) warmer than the mean annual air temperature (R. J. E. Brown 1963). The average difference is about 6 F deg (3.3 C deg).

The heat exchange mechanisms at the ground surface are so complex and variable that it has not been possible to establish a simple, practical relation between ground and air temperatures. Snow cover has an obvious influence, but other factors such as surface color, vegetation, moisture conditions, slope, and various meteorological conditions have an important effect. This is best demonstrated by the field observation that permafrost may exist in patches where the mean annual air temperature is only 1 F deg (0.5 C deg) below freezing, and that it may be absent where the mean annual air temperature is 12 F deg (6.7 C deg) below freezing. Detailed studies of the influence of microclimate and terrain factors on the distribution of permafrost in the discontinuous zone have been initiated by the Division of Building Research at Thompson, Manitoba.

The mean annual temperature and annual variations near the surface in permafrost regions are illustrated in Fig. 3 (Johnston 1965). The thickness of the active layer (*i.e.* the layer that thaws and freezes annually) will vary with latitude and subsurface and surface conditions. The geothermal gradient is a function of the thermal conductivity of the local earth materials and, since this varies significantly, the thickness of permafrost cannot be accurately estimated from surface or shallow temperature measurements.

Ground Temperature Determinations

The determination of long-term (steady-state) temperature changes in the ground as a result of changes applied at the surface has been greatly simplified by the application of graphical methods (W. G. Brown 1963). It is necessary to know only the size and shape of

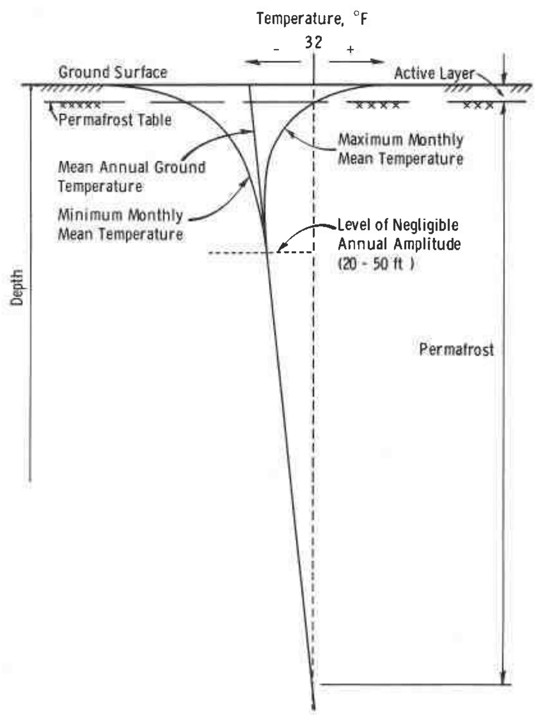

Fig. 3. Typical ground temperature regime in permafrost.

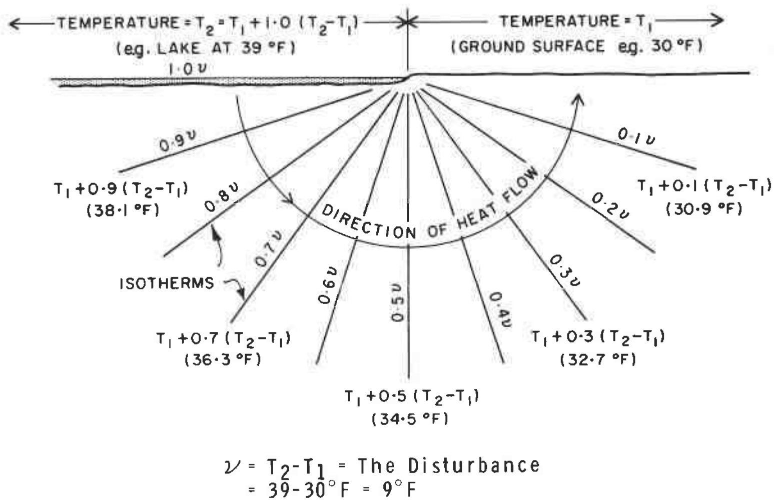

FIG. 4. The steady temperature under the straight side of a large area on the ground surface. (Example: A lake at 39 °F (4 °C) in a region where the mean annual temperature at the ground surface is 30 °F (−1 °C).

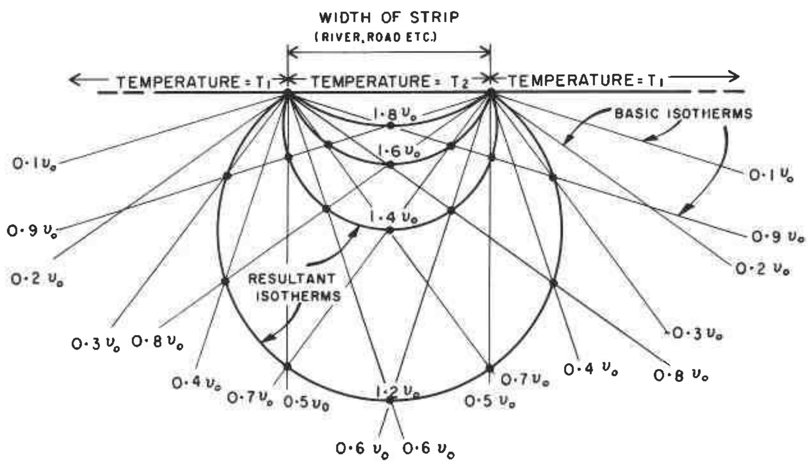

FIG. 5. The steady temperature under a long strip area on the ground surface; obtained by direct addition of the temperatures under two large areas whose edges are parallel to one another.

the surface area affected, the new and original surface temperatures, and the geothermal gradient of the region. A simple example is shown in Fig. 4, where the mean annual surface temperature has been raised by flooding. In this case, thermal conductivity is assumed to be everywhere constant and the geothermal gradient is disregarded. It may be noted that the heat flow path is perpendicular to the isotherms (lines of constant temperature) which radiate from the boundary between surfaces at different temperatures. Similarly, a long strip at a new temperature, such as a road or a river, when applied to the ground surface, will result in a set of circular isotherms passing through the boundaries of temperature difference (Fig. 5). The influence of the geothermal gradient can easily be added by simple superposition.

When surface changes occur on a geologic time scale, as in the formation of lakes or major drainage channels, the ground will have assumed steady-state temperature conditions below the depth of significant annual variation. When the surface changes occur on an engineering scale, the temperatures determined by the graphical method are those that will exist when equilibrium is reached. It is important to note that the final temperature is almost independent of soil properties, provided the soils are reasonably uniform. The magnitude of the geothermal gradient becomes important only when large areas are affected and significant temperature changes reach depths of several hundred feet.

These graphical methods (W. G. Brown 1963) can be used for estimating steady-state temperatures under complex areas and can be extended to temperature regimes varying with time. Estimates of temperature changes with time are less accurate because the thermal characteristics of the ground must be known.

The thermal properties of the ground depend primarily on soil type, density, water content, and temperature. Extensive laboratory tests by Kersten (1949) on a variety of natural soils have established the range in thermal conductivity that can be expected under all normal conditions. These tests show that conductivity increases rapidly with slight increases in water content from the dry state, and more slowly with further additions of water. The conductivity of frozen ground is greater than that of unfrozen ground because the thermal conductivity of ice is more than four times that of water. At temperatures just below freezing much of the water in fine-grained soils is not frozen and estimates of thermal conductivity are less accurate (Penner 1970).

Thermal conductivity K indicates the rate of heat flow, and volumetric heat capacity C determines the amount of heat per unit volume required to alter ground temperature by a given amount. The ratio K/C, called the thermal diffusivity, is a measure of the ease with which the ground can change temperature. Although both K and C increase with water content, the thermal diffusivity is usually a maximum at relatively low water contents (Fig. 6). Soils in this moisture condition freeze and thaw at maximum rates and experience large annual temperature variations in response to changes in air temperature. At higher moisture contents the latent heat capacity becomes a temperature moderator if freezing or thawing occurs.

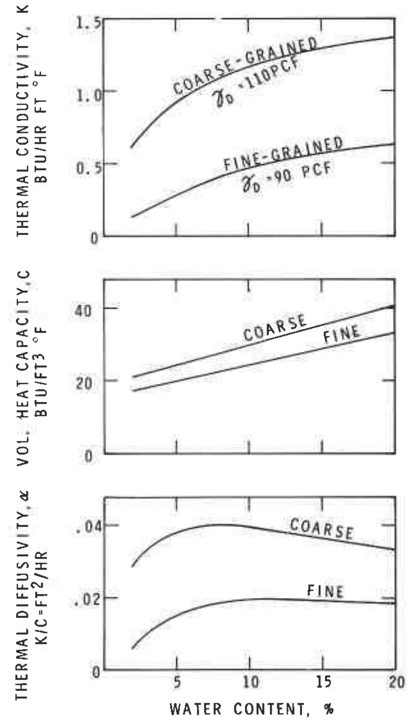

FIG. 6. Typical soil thermal properties.

Fortunately, increase in thermal conductivity due to increasing water content is compensated by an increasing heat capacity; consequently, a simple approximate relation exists between air temperature and the freezing or thawing of the ground. The relation between freezing index (degree-days below freezing) and frost penetration, first described by Casagrande (1931), was developed into a "design curve" by the U.S. Corps of Engineers (1949) on the basis of extensive field observations on bare ground. From calculations on a wide range of soils, Brown (1964) has modified the design curve slightly and shown that variations in frost penetration of less than two-to-one are obtained with the same freezing index. Owing to natural and seasonal variations in the ground the modified design curve is usually satisfactory for predicting depth of freezing under snow-cleared areas. Similarly, depth of thaw in permafrost can be estimated from the equivalent thawing index (degree-days above freezing), but the accuracy is limited owing to other influences, notably wind effect (Sanger 1963*a*).

More refined predictions of frost penetration can be made using the modified Berggren equation

$$X = \lambda \sqrt{\frac{48KI}{L}}$$

where X is penetration in feet, K is thermal conductivity in B.t.u./h/ft/°F, I is surface freezing index in °F-days, L is latent heat in B.t.u./ft^3, λ is a dimensionless coefficient (usually between 0.5 and 1.0). As a first approximation the surface freezing index can be assumed to be equal to 0.9 of the air freezing index. Sanger (1963*a*) has provided, in a convenient form, the values for the various parameters required in the Berggren equation.

Influence of Surface Water on Permafrost

Bodies of surface water that do not freeze to the bottom have a major influence on permafrost. In the Mackenzie river delta, for example, where the mean annual ground temperature is 23.8 °F (−4.6 °C), the mean annual temperature at the bottom of a shallow lake is estimated to be 33 to 35 °F (0.5 to 1.7 °C) (Brown *et al.* 1964). As a consequence, the ground beneath the lake is unfrozen, although the permafrost in the surrounding area extends to a depth of more than 300 ft (100 m). Even when bodies of water freeze completely during the winter they can have a significant effect on the thermal regime of the ground beneath, tending to reduce or eliminate the permafrost. Among factors that may be responsible for the generally higher temperatures found under bodies of water are the heat transport capability of flowing or collecting water which can bring heat from other locations, the temperature inversion with depth which occurs at the point of maximum density of water at 39.2 °F (4 °C), and the very substantial heat capacity of water in the form of sensible heat in liquid and solid forms and the latent heat involved in the change from one to the other. Other possible influences are the changes in the snow cover over ice compared with that over the ground and changes in radiation absorption and emission.

The influence of flooding has an important engineering significance in the design of hydroelectric facilities in permafrost regions. It was, for example, a major problem to be solved in the design and construction of the dikes enclosing the reservoir for the Kelsey Generating Station in northern Manitoba (MacDonald 1963). The dikes had to be founded on lacustrine varved clays having extensive patches or islands of permafrost to depths of 35 ft (10.7 m), with lenses of ice up to 8 in. (0.2 m) thick. Preliminary analyses indicated that the permafrost would thaw completely under the reservoir and to some extent under the dikes, causing an estimated settlement of about 6 ft (1.8 m).

When the dikes were built in 1958 and 1959, instruments were installed to measure temperatures at several locations before and after flooding and to record settlement of the thawing ground (Johnston 1969). Before flooding, these showed the mean annual surface temperature to be about 31 °F (−0.5 °C), with an annual range from about 20 to 60 °F (−6.7 to 15.6 °C) and an annual thaw extending to a depth of 5 ft (1.5 m). After flooding in 1960, the mean annual surface temperature under the water rose immediately to about 42 °F (5.6 °C), with an annual range from 32 to 65 °F (0 to 18.3 °C), and the depth of thaw increased steadily until it reached 17 ft (5.2 m) by the end of 1967. During the same period the sand dikes settled as much as 7 ft (2.1 m), and stability has been maintained by periodic filling.

The observations at Kelsey have now been analyzed to assess the reliability of analytical methods in predicting thaw and settlement (Brown and Johnston 1970). The analysis was simplified to some extent because controlled seepage through the dikes created more or less uniform temperatures at the natural ground surface under both the reservoir and the dikes.

The quantity of heat per unit area conducted from the original ground surface to the thaw plane was computed, using simple conduction theory. The quantity of heat required to satisfy the volumetric heat capacity of the thawing ground plus the quantity removed by percolating water were subtracted from the calculated heat input at the surface and equated to the quantity of heat required to melt the ice in the soil. The thermal conductivity of the ground was estimated from rational assumptions of unit weight and saturated water content and the ice content of the frozen soil was determined by visual inspection of borehole samples. These values, when entered into the general heat flow equation, gave a total thaw depth $x = 6.8\sqrt{t}$ feet where t is the time in years after flooding. On this basis the predicted magnitude and rate of thaw were very close to the measured values.

It is encouraging that quite reliable predictions of temperature changes can be made using approximate values for the soil thermal properties, but much research is needed in this area. One of the greatest needs is for a widespread collection of annual temperature variations in the ground and under water in association with engineering works. A special small temperature recorder that will operate unattended for a full year has been developed by Johnston (1966) to assist with such measurements.

Transportation Facilities

Roads, railroads, and airfields are vital to northern development. Although the present Canadian network is by no means extensive, it is expanding and experience with design and construction has been gained (Charles 1959; Savage 1965; Thomson 1963). The construction and maintenance of these facilities, which traverse many types of terrain in permafrost areas, are characterized by a wide range of unique problems in addition to the difficulties usually experienced. Differential frost heaving and thaw settlement of subgrade materials, solifluction, and icings occur as a result of permafrost, poor drainage, and ice-rich, frost-susceptible soils.

The design approach normally taken is to prevent thawing and preserve the frozen ground condition. Fills are placed on the ground surface, with minimum disturbance to the moss cover, and cuts below grade are avoided. Drainage is a most important consideration, for the presence of water may intensify frost action or accelerate thawing. Obtaining sufficient quantities of suitable fill material is a particular problem because granular deposits are scarce and difficult to excavate when frozen. Special emphasis must be placed on site investigations to aid in the selection of the best possible route across the widely varying terrain.

The effects of roads and airfields on the ground thermal regime constitute one of the more important problems in permafrost engineering. The major effect is usually that of increasing the sensitivity of ground temperature to changes in air temperature and surface radiation from summer to winter and from year to year. Fills are usually warmer than the adjacent ground in summer owing to the greater absorption of radiation by the relatively dark, exposed surface and the absence of the cooling effect of evaporating moisture. In the winter, fills are generally cooler than the surrounding ground because the insulating snow cover is removed by plow and wind or its effect is greatly reduced or destroyed by compaction.

Estimates of changes in the ground thermal regime and the depth of frost and thaw penetration can be made using the previously mentioned graphical methods of W. G. Brown (1963) and the techniques described by Sanger (1963*a*). Lachenbruch (1959) presents a solution for the determination of temperature fluctuations in a stratified medium caused by periodically varying surface temperature. Particular attention is given to the important problem of determining the minimum thickness of gravel fill required to maintain the subgrade in a perennially frozen state. At Inuvik, for example, the airstrip was built on a fill 3 to 12 ft (2.4 to 3.7 m) thick. Temperature measurements by the Division of Building Research have shown that the permafrost has actually risen into the fill at least 2 ft (0.6 m).

The problem of transporting large quantities of oil from the Arctic has not yet been solved. A recent analysis by Lachenbruch (1970) indicates that a 48-in. (1.2-m) pipeline buried 6 ft (1.8 m) in permafrost and carrying oil at the estimated operating temperature of about 175 °F (80 °C) would thaw the ground to a depth of more than 30 ft (9 m) within 5 years. The actual temperature of the oil in the pipeline would depend on its initial temperature, frictional heating, and the rate of heat loss per foot of pipe. Frictional heating is a function of the pumping energy input and may be sufficient to maintain the oil at a constant temperature over its entire length. If this is the case, the total heat loss from the pipe must equal the pumping energy input, although the rate of heat loss at any particular location may depend primarily on ground conditions. Lachenbruch points out that if ice-rich soil around the pipe forms a slurry that can flow away, the thawing process can be accelerated as much as a thousand times. Insulating the pipe will simply tend to increase the temperature of the oil rather than decrease thawing if the energy input from pumping is maintained constant. It is impossible to predict accurately all the consequences of rapid, large-scale thawing of ice-rich soil without a detailed knowledge of the many pertinent factors and conditions.

Similar problems are encountered with the transportation of gas in pipelines, although gas temperatures are much lower than oil, and heat loss and thawing would be at greatly reduced rates. Artificial cooling of the gas can be considered to maintain temperatures in the line at the same temperature as the ground. The most difficult problems associated with pipelines in permafrost areas can be anticipated in the discontinuous permafrost zone where the occurrence of frozen ground is sporadic, ground temperatures are near thawing, and the ground thermal regime is very sensitive to any disturbance.

Water Supply and Sewage Disposal

As northern communities grow in size, it becomes more and more difficult and less economical for residents to provide their own water supply on an individual basis. There is, furthermore, a need to provide modern conveniences, including electrical services, water supply, and sewage disposal in order to attract workers from the south. Consequently, many community service systems have been installed, usually with substantial government assistance (Yates and Stanley 1963).

In spite of abundant surface water in the North adequate supplies of domestic water are often not available (Dickens 1959). Much of the surface water occurs in shallow ponds and lakes that freeze to the bottom in winter and in a few large turbid rivers. Groundwater is often unsatisfactory in quality and difficult to obtain, although several such supplies are in use and kept flowing by electric heating or continuous flow (Grainge 1959).

At the new town of Inuvik in the Mackenzie river delta an unconventional system was built to avoid the difficulties of constructing a permanent water intake and conventional water treatment plant on unstable soil. This resulted in substantial savings in capital and operating costs (Grainge 1959). The water supply for Inuvik is stored in a small upland lake by pumping it from the Mackenzie river during periods of low turbidity. At such times the water from the river can be fed directly into the system after chlorination. The water is distributed through a utilidor (insulated box) system founded on piles. This also carries the sewer mains and high-temperature hot water for heating from a central power plant.

Utilidors are expensive and can only be justified for major communities where permafrost conditions are severe. In the discontinuous zone the water mains are usually buried, and freezing is prevented by heating the water, as required, or by providing for continuous flow. The depth of burial is usually from 8 to 12 ft (2.4 to 3.7 m) and the water is heated during winter to 40 °F (4.4 °C) or more. Continuous circulation is maintained by bleeding to the sewer at each house and at dead ends in the mains or by dual-main distribution, as at Yellowknife, or single-main recirculation, as at Fairbanks, Alaska. At Yellowknife the installation of municipal services appears to have thawed the relatively ice-free, frozen sandy soils without causing any difficulty (Copp *et al.* 1956). At Thompson, Manitoba, when permafrost was encountered, trenches were excavated and backfilled with granular materials several feet below the pipe grade (Klassen 1965). Breaks occur occasionally due to subsidence, especially at boundaries between permafrost and nonpermafrost areas. Most of the permafrost is expected to dissipate within 10 years after construction.

In a community whose future is uncertain it may still be necessary to provide a proper water distribution system, but with a low capital investment. At Asbestos Hill in northern Quebec, for example, a proposed system was designed to serve a population of 500, using a shallow, insulated, recirculating line in which the water is heated to 50 °F (10 °C) (Hahn and Sauer 1968). The high water temperature is required because the mean annual ground temperature is only about 20 °F (−6.7 °C). Another inexpensive method is to lay the pipe on the ground surface and cover it with moss (Grainge 1959).

The population density in northern regions is still so sparse that quite primitive methods of sewage collection are often used. Cold temperatures retard the natural biological processes to such an extent that sewage digestion in the ground is not practical. In most cases, therefore, raw sewage is simply hauled to remote areas or discharged directly into local water courses (Dickens 1959).

The few sewage collection systems that have been built in the North are quite conventional. Mains are either buried or carried in utilidors. If sewage is not fed directly into a water course, it is usually stored in lagoons for a degree of natural digestion. The treatment is generally satisfactory but the capacity of the lagoon must be larger than would be required in the south. Several actual water and sewer systems are described by Stanley (1965), Grainge (1959), and Brown (1970).

Building Foundations

The only certainty in founding structures on permafrost is that the foundation conditions will be variable and generally unpredictable. Extensive observations across northern Canada have revealed failures and successes with all types of foundations. Modern methods call for careful site selection, followed by a thorough site investigation and the flexibility to adjust designs after construction begins (Pihlainen 1951; Pritchard 1963).

Permafrost will provide adequate bearing capacity for most structures that have to be founded on it, provided it remains frozen. If thawing is permitted, however, frozen ground may be transformed into a slurry of soil particles and water unable to support any significant load. The degree of change will depend on the original ice content, the rate of thaw, and the kind of soil. Even bedrock cannot be assumed to be ice-free. Sanger (1969) presents a summary of Russian practice for the design-bearing pressure for large structures on frozen ground at various temperatures.

The interaction of a structure with the ground is always the primary consideration in foundation selection and design, but in permafrost areas this must include thermal interaction. In a few ideal locations where bedrock is sound or ice-free, coarse-grained soils are present and the thermal factor can be neglected, but such sites are rare. In most cases the proper design approach is to preserve the permafrost in its original condition by insulating the structure and leaving a ventilated space between the structure and the ground. This will usually require a piled foundation, although posts, piers, and ordinary spread footings can also be used (Dickens and Gray 1960).

Some major structures cannot be raised above the natural ground level, but special precautions can be taken. For example, a proposed, huge maintenance building for railroad cars and locomotives on Baffin Island has been designed with 3.5-ft (1.1-m) diameter ducts on 8.5-ft (2.6-m) centers through which cold air can be circulated mechanically as required (Hahn and Sauer 1968).

For minor structures, where some differential settlement can be tolerated or where heating is not required, simple mud sills or pads of timber or concrete are used. These foundations can be improved by placing a layer of gravel directly on the natural ground before construction. In some cases the method has been extended by excavating or thawing the permafrost and backfilling with gravel (Sanger 1969), but this is usually expensive and difficult. It is attractive only where the permafrost is limited in depth.

In southern permafrost regions, where the frozen ground is in a delicate thermal balance, it may be necessary to provide a means of adjusting for long-term thaw settlements by jacking and shimming. The disadvantages of the method are that movements are quite unpredictable and adjustments have to be made on a regular basis. Several buildings at Thompson, Manitoba, have been founded on large concrete spread footings on permafrost. Steel columns have been connected to the footings with adjustable splice plates so that the columns can be jacked and shim plates inserted as settlement of the footings takes place. Differential movements are severe and settlements of as much as 14 in. (35 cm) had to be corrected within the first 2 years. Observations of movements and corrective maintenance must be continually carried out as thawing of the permafrost occurs.

A summary of design and construction considerations and performance of piles in permafrost has been given by Sanger (1969), who concludes that a pile foundation design should be based on previous experience and pile tests at the site. The most extensive use of piles for foundations on permafrost in Canada has been at the new town of Inuvik (Johnston 1963*c*). More than 20 000 piles were placed during the original construction period from 1957 to 1960 and many more have been installed since that time. Almost all were of local spruce 20 to 22 ft (6.1 to 6.7 m) long. About 800 creosoted Douglas fir piles were imported for the oil storage tanks and powerhouse foundations, and a few precast concrete and steel piles were used for special purposes. The fir piles were installed in drilled holes, but all the others were placed in steam-thawed holes and driven to refusal with a 2000-lb (907-kg) drop hammer. The steaming interval was always kept to a minimum, and the piles were normally placed at least 6 months before use to ensure that they were adequately anchored and free of movement from freezing and heaving of the active layer. For most buildings the piles were driven to a depth of 15 ft (4.6 m), giving an embedment equal to twice the expected maximum depth of thaw during the life of the building.

The performance of pile foundations at Inuvik has been extremely good. This can be attributed in large measure to proper planning and site preparation, with all construction operations under strict control in order to disturb the natural terrain as little as possible. At each building site a gravel pad 18 to 24 in. (46 to 61 cm) thick was placed over the natural moss cover before piles were installed. In addition to providing a proper working base, these fills have prevented the local accumulation of surface water, which is always followed by deterioration of the permafrost.

The Canadian *Building Code for the North* established by the National Research Council of Canada (1968) describes the most acceptable practice for good foundation design in permafrost areas. Where the permafrost condition of the supporting soil or rock is such that the material is "stable upon thawing" no special precautions are required, but where the permafrost is "unstable upon thawing", foundations for all buildings more than one story in height and 500 ft^2 (46 m^2) in area should be designed to maintain the permafrost in a frozen condition at and below the load-carrying level. Basements or cellars are discouraged, and the importance of controlling surface drainage and liquid waste discharge from the building is stressed. The Code calls for careful site preparation similar to the methods used at Inuvik.

Needed Research

Recent interest in the practicality of transporting oil from the North has suddenly focused attention on many unsolved engineering problems related to permafrost. Fortunately, much general information is available on the occurrence and character of permafrost, but sustained research is still required on the following subjects:

1. development of remote sensing techniques for detecting permafrost in the discontinous region, including correlations with surface features and subsurface conditions, and the properties of frozen ground, principally the ice or moisture content;
2. detailed field studies of the influence of general terrain conditions on ground temperatures and on the active layer;
3. studies of the influence of construction activities, earth fills, cuts, pipelines, and other disturbances on permafrost;
4. development of reliable probes or other convenient methods for measuring thermal properties of frozen or unfrozen soils in the field and laboratory;
5. studies of consolidation settlements due to thawing, including measurements of pore water pressures and water movements and correlations between predictions and observations;
6. creep studies of frozen soils, laboratory and field test methods, analytical techniques, and correlations between predictions and observations;
7. collection of performance data on the operation of municipal services in permafrost areas, especially for low-cost systems.

The Division of Building Research is continuing to study some of these problems but staff and budgets are severely limited. A good library is maintained for general use and the staff is available to provide information and assistance to industry and universities. Private companies, especially those involved in the oil and pipeline industries, are sponsoring a substantial amount of research at the present time. Universities are becoming involved to some extent. The rapidly developing technology concerned with construction on permafrost requires good communication among researchers and designers. A number of industry-sponsored organizations have been formed for this purpose and the National Research Council's Associate Committee on Geotechnical Research has expanded its activities to improve communication in this field.

Conclusions

The Canadian North contains a wealth of nonrenewable resources that are and will be exploited at an accelerating rate. This activity can be sustained only with a rapidly expanding mixed transportation system and it will be accompanied by a great deal of new construction. If this new construction is to be successfully completed special attention must be paid to the problems of foundations on the permafrost that underlies the northern half of the country. The state of knowledge appears to be the following.

1. Location of permafrost is generally known, as is something of its character. Some considerable advance has been made in distinguishing permafrost from nonpermafrost areas by visual inspection on the ground or by air photos. There have not yet been any remarkable breakthroughs in other remote sensing techniques.

2. Preliminary analyses must be followed by thorough site investigations before construction. This requirement is even more important than for investigations in nonpermafrost areas.

3. Frozen soils creep under sustained loading and the creep characteristics are temperature dependent. This must be taken into account in designing foundations and anchorages, and in computing lifting forces due to adfreezing of heaving ground.

4. The heat exchange mechanism at the ground surface is so complex that the occurrence of permafrost cannot be accurately predicted from air temperatures. If the mean ground temperature is known, however, the long-term effect of applied temperature changes can be predicted with reasonable accuracy. The rate of change is subject to uncertainty because its computation requires knowledge of thermal properties of the ground.

5. Surface water has a great influence on surface temperature and, therefore, on permafrost. If flooding is caused by engineering works such as dams and dikes, subsequent thawing of permafrost may have a substantial influence on their performance. Experience in northern Manitoba is encouraging as to the predictability of rate and amount of thawing when material properties are known even approximately.

6. The essential requirements for successful foundations on permafrost are a thorough site investigation and continuous control of ground temperatures. Temperature control is usually achieved with the use of piles. The successful experiences with foundations at Inuvik and several other northern communities have been used to develop design guidelines in the *Building Code for the North.*

The state of knowledge of permafrost in Canada is fairly satisfactory, considering the modest level of research on the problem. Nevertheless, it will be necessary to increase greatly the research on permafrost and the performance of structures on frozen ground if satisfactory and economic design information is to be available to meet future needs. The terrain is tender, and even one major blunder could leave its devastating effects forever.

This paper is a contribution from the Division of Building Research, National Research Council of Canada, and is published with the approval of the Director of the Division.

ANONYMOUS. 1969. A critical period for northern exploration. Oilweek, 3 Nov. 1969. pp. 34–35.

BADER, H., VAN STEENBURGH, W. E., and TYREE, D. M. 1969. Arctic and middle north transportation: A summary. *In* Arctic and middle north transportation. *Edited by* Slater, B. F. Arct. Inst. North Am. Symposium held in Montreal, 5–7 Mar. 1969. pp. 1–13.

BROWN, R. J. E. 1963. Relation between mean annual air and ground temperatures in the permafrost region of Canada. Proc. Permafrost Int. Conf., Nov. 1963. pp. 241–246. (NRC 9272)

——— 1968. Occurrence of permafrost in Canadian peatlands. Proc. 3rd Peat Congr., Quebec City, 18–23 Aug. 1968. pp. 174–181.

——— 1970. Permafrost in Canada: its influence on northern development. University of Toronto Press, Toronto. p. 234.

BROWN, W. G. 1963. Graphical determination of temperature under heated or cooled areas on the ground surface. Natl. Res. Counc. Can., Div. Build. Res. NRC 7660, p. 58.

——— 1964. Difficulties associated with predicting depth of freeze or thaw. Can. Geotech. J. **1**, pp. 215–226. (NRC 8276)

BROWN, W. G., and JOHNSTON, G. H. 1970. Dikes on permafrost: Predicting thaw and settlement. Can. Geotech. J. **7**, pp. 365–371. (NRC 11540)

BROWN, W. G., JOHNSTON, G. H., and BROWN, R. J. E. 1964. Comparison of observed and calculated ground temperatures with permafrost distribution under a northern lake. Can. Geotech. J. **1**, pp. 147–154. (NRC 8129)

CASAGRANDE, A. 1931. Discussion on frost heaving. Proc., Highw. Res. Board. Vol. XI, Part I. pp. 168–172.

CHARLES, J. L. 1959. Permafrost aspects of the Hudson Bay Railroad. Proc. Amer. Soc. Civil Eng. J. Soil Mech. Found. Div. Vol. 85, No. SM6, pp. 125–135. (NRC 5574)

COPP, S. C., CRAWFORD, C. B., and GRAINGE, J. W. 1956. Protection of utilities against permafrost in northern Canada. Amer. Water Works Assoc. J. **48**, pp. 1155–1168. (NRC 4056)

CRAWFORD, C. B., and LEGGET, R. F. 1957. Ground temperature investigations in Canada. Eng. J. **40**, pp. 263–269, 290. (NRC 4302)

DICKENS, H. B. 1959. Water supply and sewage disposal in permafrost areas of northern Canada. Polar Rec. **9**, pp. 421–432. (NRC 5169)

DICKENS, H. B., and GRAY, D. M. 1960. Experience with a pier-supported building over permafrost. Proc. Amer. Soc. Civil Eng., J. Soil Mech. Found. Div. **86**, No. SM 5, pp. 1–14. (NRC 5942)

GOLD, L. W. 1963. Influence of the snow cover on the average annual ground temperature at Ottawa, Canada. Int. Assoc. Sci. Hydrol. Pub. No. 61, pp. 82–91. (NRC 7505)

——— 1967. Influence of surface conditions on ground temperature. Can. J. Earth Sci. **4**, pp. 199–208. (NRC 9227)

GRAINGE, J. W. 1959. Water supplies in the central and western Canadian North. Amer. Water Works Assoc. J. **51**, pp. 55–66.

HAHN, J., and SAUER, B. 1968. Engineering for the arctic. Eng. J. **51** (4), pp. 23–28.

JEN-HU CHANG. 1959. World patterns of monthly soil temperature distributions. Assoc. Amer. Geogr. Ann. **47**, pp. 241–249.

JESSOP, A. M. 1964. Geothermal research in Canada. Can. Min. Metall. Bull. Feb. 1964. pp. 152–155.

JOHNSTON, G. H. 1963*a*. Engineering site investigations in permafrost areas. Proc. Permafrost Int. Conf. Nov. 1963. pp. 371–374. (NRC 9270)

——— 1963*b*. Soil sampling in permafrost areas. Ann. Meet. Eng. Inst. Can., Quebec City, May 1963. (NRC 7417)

——— 1963*c*. Pile construction in permafrost. Proc. Permafrost Int. Conf., Nov. 1963, pp. 477–480. (NRC 9269)

——— 1965. Permafrost and foundations. Natl. Res. Counc. Can., Div. Build. Res. CBD 64, p. 4.

——— 1966. A compact self-contained ground temperature recorder. Can. Geotech. J. **3**, pp. 246–250. (NRC 9316)

——— 1969. Dykes on permafrost: Kelsey Generating Station, Manitoba. Can. Geotech. J. **6**, p. 131. (NRC 10611)

JOHNSTON, G. H., BROWN, R. J. E., and PICKERSGILL, D. N. 1963. Permafrost investigations at Thompson, Manitoba — Terrain studies. Natl. Res. Counc. Can., Div. Build. Res. NRC 7568, p. 105.

KERSTEN, M. S. 1949. The thermal properties of soils. Eng. Exp. Stn. Univ. Minn. Bull. No. 28.

KLASSEN, H. P. 1965. Public utilities problems in the discontinuous permafrost areas. Proc. Can. Reg. Permafrost Conf. 1–2 Dec. 1964. pp. 106–118.

LACHENBRUCH, A. H. 1959. Periodic heat flow in a stratified medium with applications to permafrost problems. U.S. Dep. Inter. Geol. Surv. Bull. 1083-A.

——— 1970. Some estimates of the thermal effects of a heated pipeline in permafrost. Wash. U.S. Geol. Surv. Circ. 632, p. 23.

LACHENBRUCH, A. H., and MARSHALL, B. V. 1969. Heat flow in the Arctic. Arctic, **22**, pp. 300–311.

MACDONALD, D. H. 1963. Design of Kelsey dikes. Proc. Permafrost Int. Conf., Nov. 1963. pp. 492–496.

MACDONALD, J. A. 1966. Research and development in the natural resources of Northern Canada. Eng. J. **49** (8), pp. 15–20.

NATIONAL RESEARCH COUNCIL OF CANADA. 1968. Building code for the North. Assoc. Comm. Natl. Build. Code Can. NRC 9945. (See also *Supplement to the building code for the North*, NRC 10368.)

PENNER, E. 1970. Thermal conductivity of frozen soils. Can. J. Earth Sci. **7** (3), pp. 982–987. (NRC 11277)

PENNER, E., and IRWIN, W. W. 1969. Adfreezing of Leda clay to anchored footing columns. Can. Geotech. J., **6**, p. 327. (NRC 10834)

PIHLAINEN, J. A. 1951. Building foundations on permafrost, Mackenzie valley, N.W.T. Natl. Res. Counc. Can., Div. Build. Res. DBR 22, p. 63.

PIHLAINEN, J. A., and JOHNSTON, G. H. 1963. Guide to a field description of permafrost for engineering purposes. Natl. Res. Counc. Can., Assoc. Comm. Geotech. Res. T.M. 79, p. 23. (NRC 7576)

PRITCHARD, G. B. 1963. Foundations in permafrost areas. Proc. Permafrost Int. Conf., Nov. 1963, pp. 515–518.

REINART, I. 1969. Design of foundations for the Nelson river transmission line. Paper presented at the Engineering Institute of Canada Annual Meeting. 9–13 Sept. 1969, Vancouver, B.C.

SANGER, F. J. 1963*a*. Degree-days and heat conduction in soils. Proc. Permafrost Int. Conf., Nov. 1963, pp. 253–262.

——— 1963*b*. Discussion—session 6. Proc. Permafrost Int. Conf., Nov. 1963, pp. 340–342.

——— 1969. Foundations of structures in cold regions. Cold Reg. Res. Eng. Lab. Cold Reg. Sci. Eng. Monogr. III-C4. June 1969.

SAVAGE, J. E. 1965. Location and construction of roads in the discontinuous permafrost zone, Mackenzie District, Northwest Territories. Proc. Can. Reg. Permafrost Conf., 1–2 Dec. 1964, pp. 119–131.

STANLEY, D. R. 1965. Water and sewage problems in discontinuous permafrost regions. Proc. Can. Reg. Permafrost Conf. Assoc. Comm. Soil Snow Mech. T.M. No. 86, pp. 93–105.

THOMSON, S. 1963. Icings on the Alaska highway. Proc. Permafrost Int. Conf., Nov. 1963, pp. 526–529.

THOMSON, W. A. 1934. Soil temperatures at Winnipeg, Manitoba. Sci. Agric., Can. **15**, pp. 209–217.

U.S. CORPS OF ENGINEERS. 1949. Addendum No. 1, 1945–47, *to* Report on frost penetration, 1944–45. Corps Eng., U.S. Army, New Engl. Div., Boston.

VYALOV, S. S. 1963. Rheology of frozen soils. Proc. Permafrost Int. Conf., Nov. 1963, pp. 332–337.

WATMORE, T. G. 1969. Thermal erosion problems in Pipelining. Proc. 3rd Can. Conf. Permafrost, Assoc. Comm. Geotech. Res. T.M. 96, pp. 142–162.

WILLIAMS, P. J. 1968. Properties and behaviour of freezing soils, Norw. Geotech. Inst., Pub. No. 72, p. 119. (NRC 9854)

WILSON, G. W. 1969. World market potential for northern resources. *In* Arctic and middle north transportation, *Edited by* Sater, B. F. Arct. Inst. North Am. Symp., Montreal, 5–7 March, 1969, pp. 31–41.

YATES, A. B., and STANLEY, D. R. 1963. Domestic water supply and sewage disposal in the Canadian North. Proc. Permafrost Int. Conf., Nov. 1963. pp. 413–419.