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Article abstract

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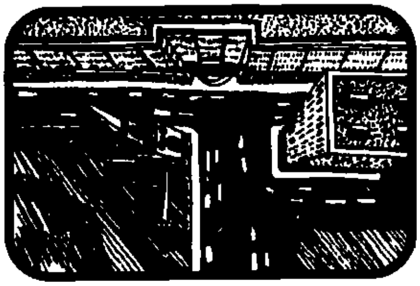

# Living on Ice: Problems of Urban Development in Canada's North

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## SUMMARY

Canada is a cold country. It is only along the maritime lowland fringes of the Pacific coast that snow and sub-freezing temperatures are rare. By contrast, those areas along the southern borders, where most of the Canadian population resides, are seasonally cold. In these regions, seasonal agriculture is possible, plant and animal productivity is high, and the constraints of cold can be temporarily forgotten during the summer months. Elsewhere, over the vast majority of the Canadian landmass, and certainly north of 60°N, the problems created by coldness persist throughout the year. Although there are few urban settlements in excess of 5000 people, these constraints dominate urban and socio-economic activities. The purpose of this paper is to illustrate the nature of such constraints, paying particular attention to the character of perennially frozen substrates (permafrost), terrain disturbances caused by various types of construction activity, and problems associated with ground and surface waters.

## RÉSUMÉ

Le Canada est un pays froid. C'est seulement dans ses régions côtières des basses-terres du Pacifique que la neige et les températures sous le point de congélation sont rares. Par contre, les régions longeant sa frontière sud, là où presque toute la population est concentrée, connaissent la froidure cyclique de l'hiver. Dans ces régions, l'agriculture saisonnière est possible, la productivité végétale et animal est élevée, et on peut oublier temporairement les désagréments du froid durant les mois d'été. Presque partout ailleurs au pays, et très certainement au nord du 60° parallèle, les problèmes liés au froid sont permanents. Dans les rares agglomérations de plus de 5000 habitants, les contraintes dues au froid dominent les préoccupations et les activités socio-économiques urbaines. Le présent article a pour but d'illustrer la nature de ces contraintes, en s'intéressant en particulier aux caractéristiques des substratums gelés en permanence (pergélisol), aux modifications des terrains induites par diverses constructions, et aux problèmes reliés aux eaux de surface et souterraines.

## INTRODUCTION

The severity of Canada's northern climate is best illustrated by the comparison of freezing degree-days (FDD) and growing degree-days (GDD) for some of Canada's largest cities with similar data for some of the more important northern settlements (Table 1). The northern localities all experience more than 3000 FDDs and fewer than 1000 GDDs. The one exception is Whitehorse, Yukon, because of its mountain location.

An important consequence of the long period of winter cold and the relatively short period of summer thaw in northern Canada is the formation of a layer of frozen ground that does not completely thaw during the summer. This perennially frozen ground is termed permafrost, a word first coined by Muller (1943) of the United States Army Corps of Engineers following his experiences in building the Alaska Highway during the Second World War. Referring specifically to Alaska, Muller (1943) wrote:

> "The destructive action of permafrost phenomenon has materially impeded the colonization and development of extensive and potentially rich areas in the north. Roads, railroads, bridges, houses and factories have suffered deformation, at times beyond repair, because the condition of permafrost ground was not examined beforehand, and because the behaviour of frozen ground was little if at all understood." (p. 12)

Such a comment applies equally to Canada, where approximately one-half of the country (5.7 million km$^2$) is underlain by permafrost of one sort or another (Fig. 1). The big difference between the 1940s and today, however, is that there is a better understanding of the problems associated with permafrost terrain. In this context, the aim here is to summarize the geotechnical and engineering challenges presented by permafrost, and to outline the impact which permafrost has upon settlement and economic development in northern Canada.

### Permafrost

Traditionally, permafrost is defined on the basis of temperature; that is, ground (*i.e.*, soil and/or rock) that remains at or below 0°C. Therefore, to differentiate between the temperature and state conditions (*i.e.*, frozen or unfrozen) of permafrost, the terms cryotic and non-cryotic have been proposed. These terms refer solely to the temperature of the material independent of its water/ice content (Associate Committee on Geotechnical Research, 1988). Perennially cryotic ground is, therefore, synonymous with permafrost, and permafrost may be unfrozen, partially frozen, and frozen, depending upon the state of the ice/water content.

Several other terms are used to describe the stratigraphy of permafrost. The permafrost table is the upper surface of the permafrost, and the ground above the permafrost table is called the supra-permafrost layer (Fig. 2). The active layer is that part of the supra-permafrost layer that freezes in the winter and thaws during the summer, *i.e.*, it is seasonally frozen ground. Although seasonal frost usually penetrates to the permafrost table in most areas, in some areas an unfrozen zone exists between the bottom of seasonal frost and the permafrost table. This unfrozen zone is called a talik. Unfrozen zones within and below the permafrost are also termed taliks.

***Extent and Thickness of Permafrost in Canada.*** In Canada, the broad outlines of permafrost distribution are relatively well known and a number of detailed permafrost maps are now available (Heginbottom and Radforth, 1992; Natural Resources Canada, 1995). Some of the more important urban centres located in permafrost terrain in-

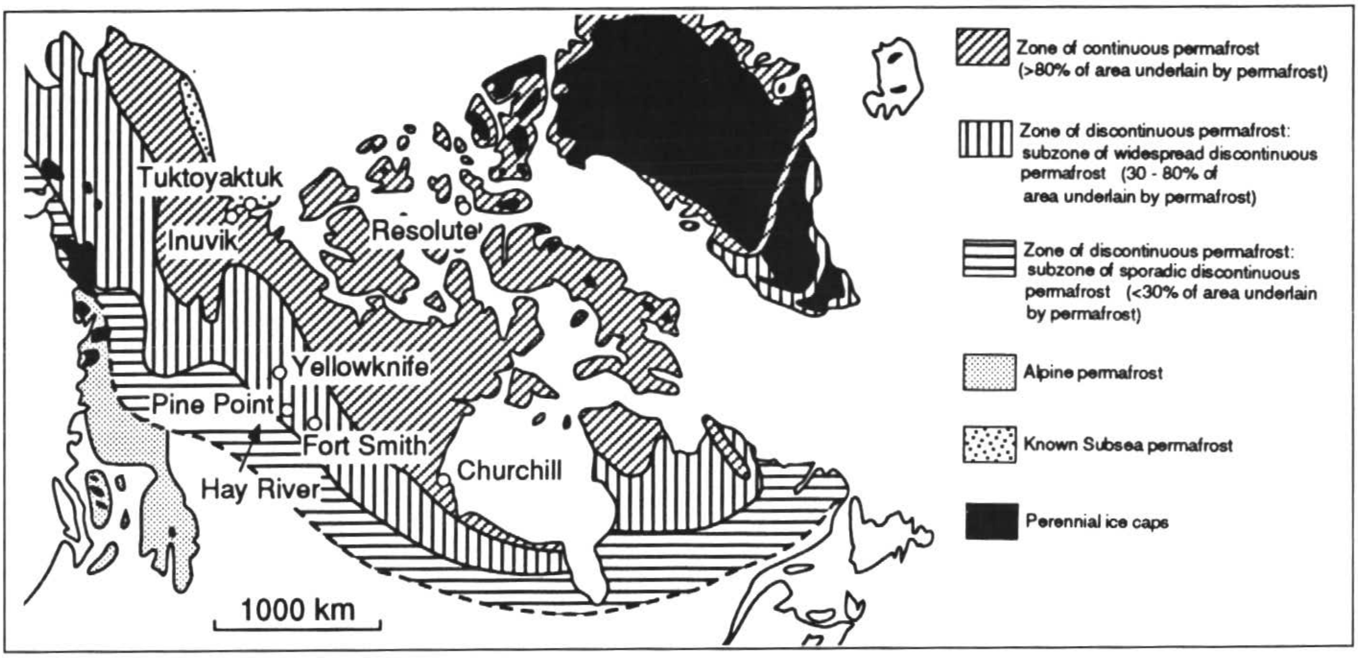



**Figure 1** *Distribution of permafrost in North America (from Associate Committee on Geotechnical Research, 1988) and location of the larger communities in northern Canada.*

**Table 1** Climatic statistics for selected Canadian stations in northern and non-northern locations (data from Hare and Thomas; 1974 and Wahl *et al.*, 1987).

| Station | Latitude (N) | Longitude (E) | Mean Annual Temperature (°C) | GDD | Frost-free Period (days) | Snow Cover (days) | FDD | Annual Total Precipitation (mm) |
|---|---|---|---|---|---|---|---|---|
| ***A "Non-northern"*** | | | | | | | | |
| Vancouver | 49°11′ | 123°10′ | 9.8 | 2019 | 212 | 7 | 45 | 1068 |
| Edmonton | 53°34′ | 113°31′ | 2.8 | 1516 | 127 | 117 | 1501 | 477 |
| Saskatoon | 52°10′ | 106°41′ | 1.6 | 1618 | 110 | 128 | 1977 | 353 |
| Winnipeg | 40°54′ | 97°14′ | 2.3 | 1791 | 118 | 122 | 1903 | 535 |
| Toronto | 43°40′ | 79°24′ | 8.9 | 2434 | 192 | 59 | 438 | 790 |
| Ottawa | 45°19′ | 75°40′ | 5.8 | 2069 | 137 | 117 | 1040 | 851 |
| Montreal | 45°30′ | 73°35′ | 7.2 | 2301 | 183 | 117 | 813 | 999 |
| Quebec City | 46°48′ | 71°23′ | 4.4 | 1729 | 132 | 140 | 1153 | 1089 |
| Halifax | 44°38′ | 63°30′ | 6.8 | 1708 | 183 | 63 | 422 | 1381 |
| ***B "Northern"*** | | | | | | | | |
| Churchill, MN | 58°45′ | 94°04′ | −7.3 | 688 | 81 | 213 | 3791 | 397 |
| Baker Lake, NWT | 64°18′ | 96°00′ | −12.3 | 326 | 61 | 240 | 5206 | 213 |
| Resolute, NWT | 74°43′ | 94°59′ | −16.4 | 36 | 9 | 283 | 6238 | 136 |
| Whitehorse, YT | 60°43′ | 135°04′ | −0.8 | 897 | 87 | 167 | 1970 | 260 |
| Yellowknife, NWT | 62°28′ | 114°27′ | −5.6 | 955 | 108 | 190 | 3614 | 250 |
| Dawson, YT | 64°04′ | 139°24′ | −4.7 | 1014 | 91 | n/a | 8135 | 325 |
| Iqualuit, NWT | 63°45′ | 68°34′ | −5.2 | 159 | 59 | 237 | 3903 | 415 |
| Aklavik, NWT | 68°14′ | 135°00′ | −8.9 | 859 | 77 | 234 | 4474 | 236 |

clude Yellowknife, Inuvik, Churchill, and Resolute (Fig. 1).

Permafrost is usually classified as being either continuous or discontinous in nature. In areas of continuous permafrost, frozen ground is present at all localities except for localized thawed zones (taliks) existing beneath lakes and river channels. In discontinuous permafrost, bodies of frozen ground are separated by areas of unfrozen ground. At the southern latitudinal limit of this zone, permafrost becomes restricted to isolated islands, typically occurring beneath peaty organic sediments. At the local level, variations in permafrost conditions are determined by a variety of terrain and other factors. Of widespread importance are the effects of relief, and the nature of the physical properties of soil and rock. More complex are controls exerted by vegetation, snowcover, waterbodies, drainage and fire.

The thickness to which permafrost develops is determined by a balance between the internal heat gain with depth and the heat loss from the surface. Heat flow from the Earth's interior normally results in a temperature increase of approximately 1°C per 30-60 m increase in depth. This is known as the geothermal gradient. Thus, the lower limit of permafrost occurs at that depth at which the temperature increase due to the geothermal gradient just offsets the amount by which the freezing point exceeds the mean surface temperature. If there is a change in the climatic conditions at the ground surface, the thickness of the permafrost will change appropriately. For example, an increase in mean surface temperature will result in a decrease in permafrost thickness, while a decrease in surface temperature will give the reverse.

**Table 2** Ground ice volumes in the upper 5 m of permafrost in three localities in the western Canadian Arctic (from French, 1993).

| Area | Pore/segregated ice (%) | | Wedge ice (%) | | Total ice (%) |
|---|---|---|---|---|---|
| King Point, Yukon (100) | 43.5 | (79.2) | 11.4 | (20.8) | 54.9 |
| Richards Island, NWT (100) | 28.3 | (79.3) | 7.5 | (21.0) | 35.7 |
| Southwest Banks Island, NWT (100) | 38.7 | (66.2) | 19.8 | (33.8) | 58.5 |

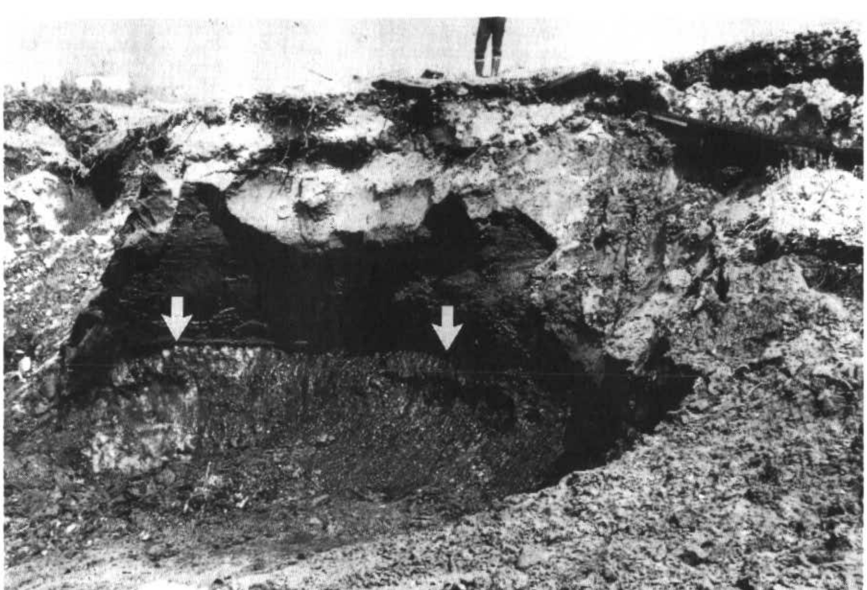


**Figure 2** *Exposure showing permafrost table (arrowed), underlying frozen silts (permafrost) and overlying supra-permafrost layer that freezes in winter and thaws in summer. Figure for scale.*

### Ice Within Permafrost

The amount of ground ice present within permafrost can vary from negligible, as in certain igneous and metamorphic rocks, to considerable, as in the case of unconsolidated, fine-grained Quaternary-age sediments. In general, it is highest near the permafrost table and decreases with depth (Pollard and French, 1980). Table 2 lists typical ground ice volumes that exist in the upper 5 m of permafrost at three localities in the western Canadian Arctic. The total volumetric ice content usually varies between 35% and 60%, of which by far the majority (66-80%) forms either distinct ice masses (segregated ice) or fills pores (pore ice). Segregated ice may grow to form large, massive icy bodies (termed ground ice), commonly found as downward tapering ice wedges. The presence of pore ice gives rise to icy sediments. In regions underlain by fine-grained, unconsolidated surficial materials (*e.g.*, till, lacustrine clay), ground ice can be an extremely important component of permafrost. These fine-grained and ice-rich permafrost sediments are regarded as thaw-sensitive because of the large-scale disturbance to sediments that results from the thawing of such ice. Exensive subsidence of the ground surface results. An extreme case of high-ice-content permafrost occurs in the Mackenzie Delta area, in the vicinity of the settlement of Tuktoyaktuk. There, massive icy bodies and icy sediments, several tens of metres thick, occur under the townsite. If these ice masses and sediments were to thaw, the entire townsite would disappear beneath sea level.

## PERMAFROST AND URBAN DEVELOPMENT

As stressed by Muller (1943), many important geotechnical and engineering problems result from the occurrence of permafrost. For the most part they relate to the water and/or ice content of the permafrost. They are summarized below.

### Frost Heave

Pure water freezes at 0°C and, in doing so, expands by approximately 9% of its volume. The most obvious result of soil freezing is the volume increase that results and the associated deformation of host sediment and rock. The resulting frost heave has considerable practical significance since it causes the displacement of buildings, foundations and road surfaces. For the soil to heave, the ice must first overcome the resistance to its expansion caused by the strength of the overlying frozen soil. This usually occurs only when segregated ice lenses form. Frost heave results in significant damage to structures and foundations (Ferrians *et al.*, 1969). The annual cost of rectifying seasonal frost damage to roads, utility foundations, and buildings in areas of permafrost and deep seasonal frost is considerable.

### Subsidence

As outlined above, ground ice is a major component of permafrost, particularly in unconsolidated sediments. Numerous case studies have been documented in Canada where, following the thaw of permafrost, ground subsidence has resulted (Mackay, 1970). Thaw consolidation may also occur as thawed sediments compact and settle under their own weight; the high pore-water pressures that are generated may also favour soil instability and slumping. The various processes associated with permafrost degradation are termed thermokarst. A related problem is that the physical properties of icy sediments, in which soil particles are cemented together by pore ice, may be considerably different to those of the same material in an unfrozen state. For example, in unconsolidated and/or soft sediments there is often a significant loss of bearing strength upon thawing. Beneath heated buildings, therefore, it is often essential to maintain the frozen state of the underlying material in order to support the structure.

### Ground Water

The hydrological and ground-water characteristics of permafrost terrain are different from those of non-permafrost terrain (Sloan and van Everdingen, 1988). For example, the presence of both perennially and seasonally frozen ground prevents the infiltration of water into the ground or, at best, confines it to the active layer. At the same time, subsurface flow is restricted to unfrozen zones or taliks. A high degree of mineralization in subsurface permafrost is often typical, caused by the restricted circulation imposed by permafrost and the concentration of dissolved solids in the taliks. Thus, frozen ground eliminates many shallow-depth aquifers, reduces the volume of unconsolidated deposits or bedrock in which water is stored, influences the quality of ground-water supply, and necessitates that wells be drilled deeper than in non-permafrost regions.

**Figure 3** *Examples of man-induced terrain disturbances in northern Canada.* (**A**) *(top) Themokarst mounds and standing waterbodies developed in disturbed terrrain adjacent to the SOBC Blackstone D-77 exploratory well site, interior Yukon (65°40'N; 137°15'W). The well was drilled in the summer of 1962. Thaw depths in the disturbed terrain now commonly exceed 90 cm; those in undisturbed terrain are less than 50 cm (photograph taken July 1979).* (**B**) *(bottom) Gully erosion along a vehicle track made in the summer of 1970 near the site of the Drake Point blow-out (76°26'N; 108°55'W), Sabine Peninsula, Melville Island, N.W.T. The terrain is underlain by ice-rich shale (photograph taken August 1976).*

***Thermokarst and Site Disturbance***

The thawing of permafrost, and the heaving and subsidence caused by frost action, result in severe damage to roads, bridges and other structures. In Alaska, following the realization of these effects in the 1940s, a determined effort was made by federal and state agencies to improve construction practices and to document permafrost problems (Ferrians *et al.*, 1969; Péwé, 1966; Péwé and Paige, 1963). In Canada, where large- scale development projects in permafrost regions occurred slightly later, it was possible to benefit from Alaskan experience.

A general problem related to urban development and economic activity in and around Canada's northern communities relates to artificial disturbances to the forest tundra and tundra vegetation (Fig. 3). Where the underlying permafrost is ice-rich, the thawing of the near-surface soils results in a thickening of the active layer. Distinctive hummocky terrain and thermokarst mounds can develop (French, 1975, 1987). Buildings and other structures can be undermined or eroded, requiring costly renovation and maintenance. In some instances, structures have to be abandoned due to excessive terrain disturbance and thermokarst activity. In an attempt to minimize such disturbances, especially in terrain underlain by thaw-sensitive permafrost, the Federal Government, through the Territorial Arctic Land Use Act and Regulations, has imposed strict regulations associated with the movement of heavy machinery, the mining of aggregate sources, the timing of exploratory drilling and seismic activity, and the unnecessary disturbance of vegetation. All aspects of oil exploration activity are closely regulated (French, 1980, 1984) and the right-of-way associated with the recently completed Normal Wells pipeline is monitored regularly to ensure that terrain stability is being maintained (Burgess and Harry, 1990). Recent diamond exploration activities in the Northwest Territories are also subject to these land use regulations.

It must be emphasized that even very small disturbances to the surface may be sufficient to induce thermokarst activity. Mackay (1970), for example, describes how a sled dog in the Mackenzie Delta was tied to a stake with a 1.5 m long chain. In the ten days of tether, the animal trampled and destroyed the tundra vegetation of that area. Within two years, the site had subsided like a pie dish by a depth of 18-23 cm, and the active-layer thickness had increased by more than 10 cm within the depression.

Several case studies of man-induced disturbance provide insight into the nature and speed at which such terrain becomes and remains unstable. In many cases, stabilization only begins 10 years to 15 years after the initial disturbance and is not complete until 30 or more years have passed. Thus, man-induced disturbances to permafrost terrain have the potential to permanently scar the landscape for decades, and the minimization of terrain disturbance is an important consideration in the municipal planning of all northern communities.

With respect to minimizing the effects of construction on permafrost, a number of approaches are available, depending on site conditions and fiscal limitations. If the site is underlain by hard consolidated bedrock, as is the case for some regions of the Canadian Shield, ground ice is usually non-existent and permafrost problems can be largely ignored. In most areas, however, this simple approach is not feasible, since an overburden of unconsolidated silty or organic sediments is usually present. In the majority of cases, therefore, construction techniques are employed which aim to maintain the thermal equilibrium of the permafrost and avoid the onset of thermokarst.

The most common technique is the use of a pad or some sort of fill which is placed on the surface (Fig. 4). This compensates for the increase in thaw which results from the warmth of the structure. By using a pad of appropriate thickness the thermal regime of the underlying permafrost is unaltered. It is

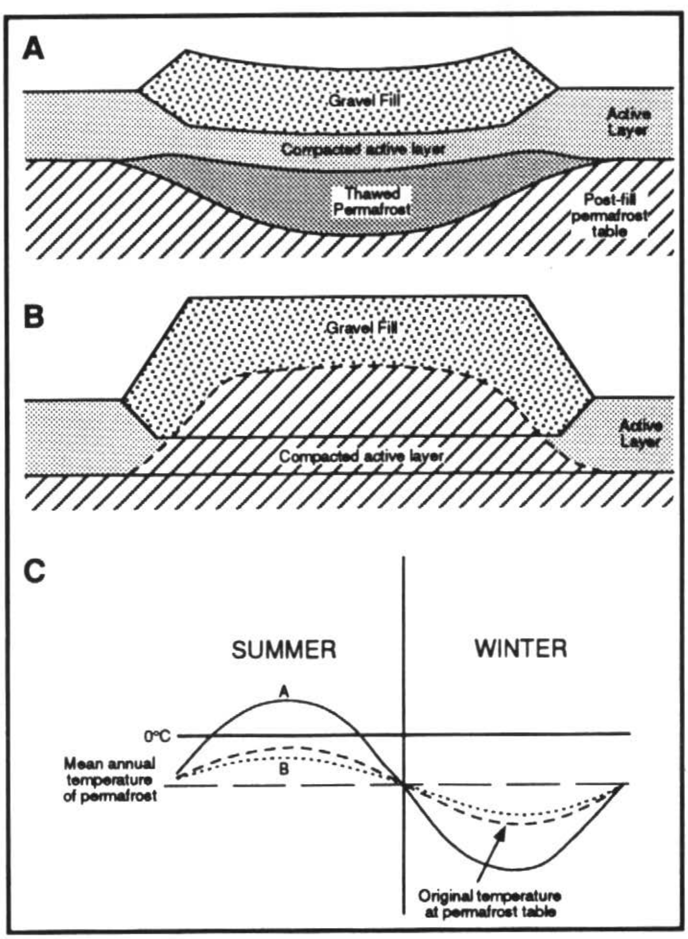



**Figure 4** *Diagram illustrating the effects of a gravel fill upon the thermal regime and thickness of the active layer.* (**A**) *Too little fill;* (**B**) *Too much fill;* (**C**) *Effects of cases* (**A**) *and* (**B**) *upon the thermal regime; too little fill increases the amplitude of seasonal temperature fluctuation at the permafrost table and promotes the development of subsidence (thermokarst; from Ferrians* et al., *1969).*

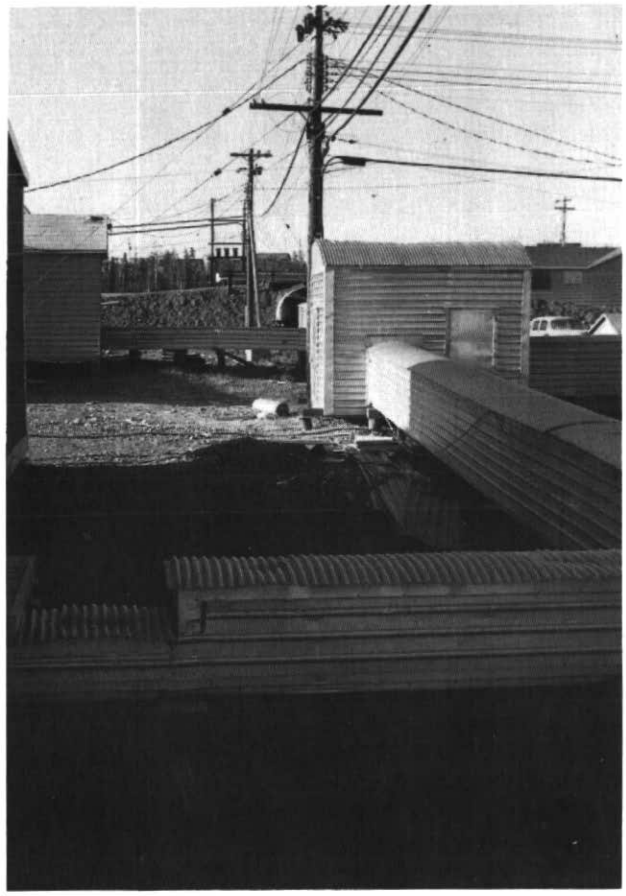
possible, given the thermal conductivity of the materials involved and the mean air and ground temperatures at the site, to calculate the thickness of fill required. Too little fill, plus the increased conductivity of the compacted active layer beneath the fill, will result in thawing of the permafrost and in subsidence (Morgenstern and Nixon, 1971; Fig. 4A). On the other hand, too much fill will provide too much insulation, and the permafrost source will aggrade on account of the reduced amplitude of the seasonal temperature fluctuation (Figs. 4B, C). In northern Canada and Alaska, gravel is the most common aggregate used, since it is reasonably widely available and is not as susceptible to frost heave as more fine-grained sediments.

In instances where the structure concerned is capable of supplying significant quantities of heat to the underlying permafrost, as is the case of a heated building or a warm oil pipeline, additional measures are frequently adopted. Usually the structure is mounted on piles which are inserted into the permafrost. An air space left between the ground surface and the structure enables the free circulation of cold air which dissipates the heat emanating from the structure. Other techniques used include the insertion of open-ended culverts into the pad, the placing of insulating matting immediately beneath the pad and, if the nature of the structure justifies it, the insertion of refrigeration units or Cryo-Anchors (Hayley, 1982) around the pad or through the pilings.

The following sections provide illustrations of the various problems and solutions in dealing with permafrost terrain, using examples from a number of Canadian urban communities.

***Inuvik.*** The construction of the town of Inuvik in the Mackenzie Delta in the early 1960s was an example of the careful manner in which large-scale construction projects need to be undertaken in permafrost regions. A major factor governing the location of the town was the presence of a large body of fluvio-glacial gravel a few kilometres to the south that could be used to construct a gravel pad below the entire townsite. Today, the gravel deposit has been exhausted and the future growth of the community is dependent upon the exploitation of more distant aggregate sources with their associated higher costs of haulage.

The provision of municipal services such as water supply and sewage disposal are particularly difficult in permafrost regions. Pipes to carry these services cannot be laid below ground beneath the depth of seasonal frost, as is the case in non-permafrost regions,



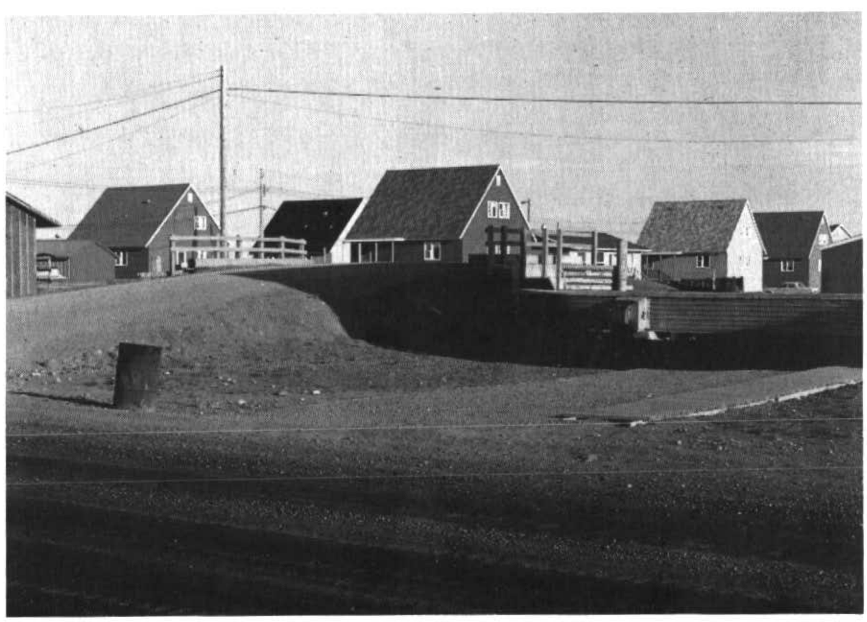
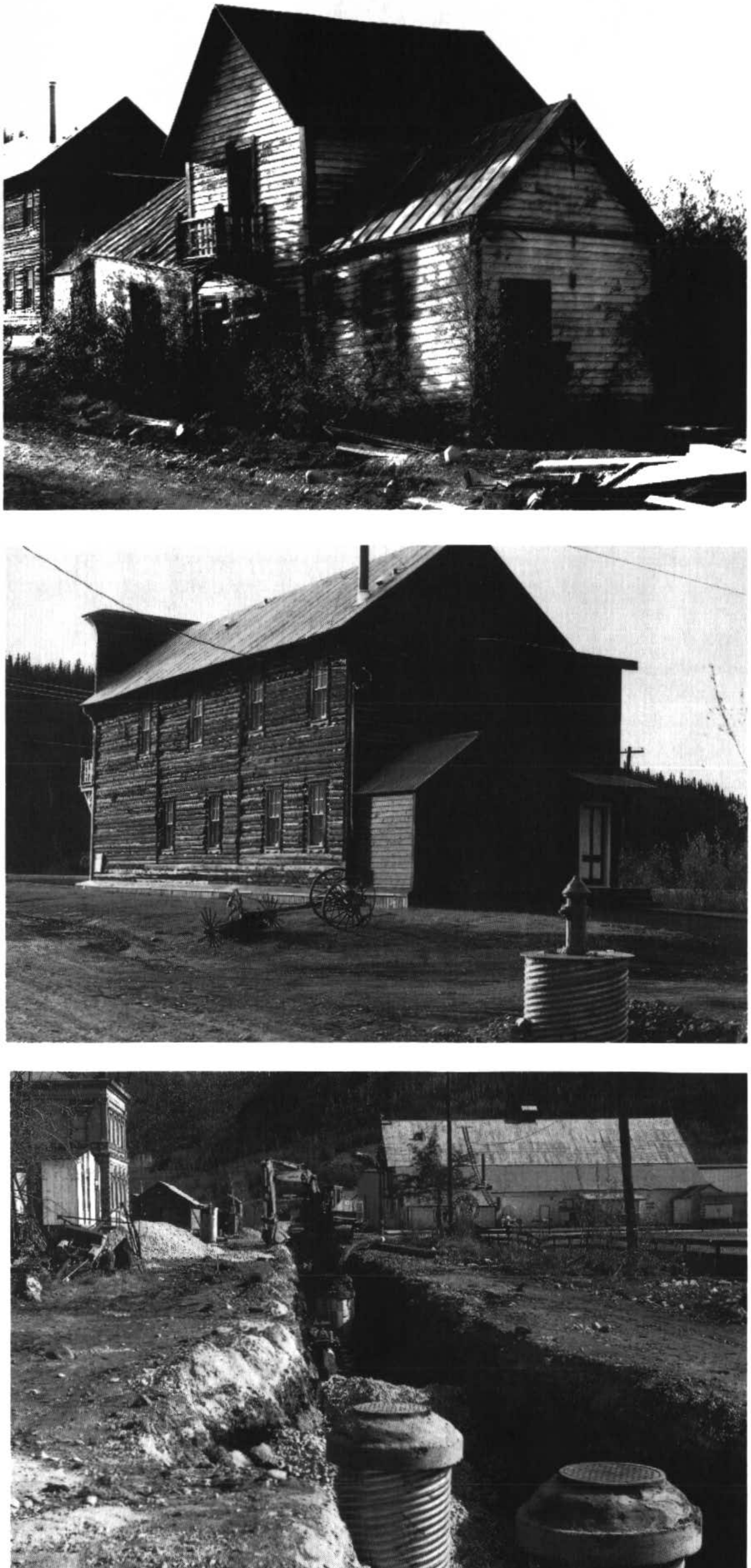


**Figure 5** *Inuvik, NWT, buildings are placed upon wooden piles. Services such as water and sewage are effected by a utilidor system which links each building to a central plant.* **(A)** *(top) Typical utilidor topography.* **(B)** *(bottom) Roads pass over utilidors on bridges.*



since the heat from the pipes will promote thawing of the surrounding permafrost and subsequent subsidence and fracture of the pipe. At Inuvik, the provision of these utilities has been achieved through the use of utilidors: continuously insulated aluminium boxes that run above ground on supports and link each building to a central system (Fig. 5A, B). The cost of such utilidor systems is high, involving a high degree of town planning and constant maintenance, and can only be justified in the larger settlements.

***Dawson City.*** In Dawson City, Yukon, a slightly different approach has been taken by Parks Canada and the Yukon government in restoration and maintenance of historic buildings, and in the provision of utilities to the townsite. The city of Dawson is located on a restricted area of the flood plain of the Yukon River, underlain by 2-4 m of silt over alluvial gravel. Permafrost at temperatures between -3°C and -1°C, is present to a depth of about 20 m below the city. The occurrence of segregated ice lenses and ice wedges means that the soils are thaw sensitive and subject to settlement if disturbed. The earliest buildings in Dawson were log structures or frame buildings placed on large squared timbers laid at or near the surface. Virtually all old buildings still remaining have settled differentially, necessitating periodic jacking and levelling with additional cribbing, and/or eventual abandonment (Fig. 6A). Similar deformations in old structures placed directly upon ice-rich permafrost have been described from Alaska and Siberia (Péwé, 1983, 11-62). Since the early 1960s all new buildings in Dawson have been constructed on wooden piles or gravel pads. In restoring some of the

**Figure 6** *Dawson City, Yukon* (**A**) *(top) Abandoned building illustrating severe settlement due to permafrost degradation.* (**B**) *(middle) Heritage building restored by Parks Canada and placed upon non-frost susceptible granular infill following removal of silty permafrost sediments. Note the adjacent modern fire hydrant requiring deep burial of municipal services.* (**C**) *(bottom) The installation of modern municipal services in 1980 was by means of trenches excavated to a minimum depth of 2.0 m and backfilled with coarse non-frost susceptible aggregate.*

historic buildings, Parks Canada has tried to maintain the original levels of the buildings with respect to the streets, ruling out the emplacement of thick gravel pads or the use of piles. Instead, the silty ice-rich material has been excavated and replaced by thaw-stable granular material to a depth of 5-7 m, and the historic buildings have been replaced in their original positions, supported by adjustable jacks (Fig. 6B).

The provision of municipal services in Dawson has also been upgraded at considerable cost. The town uses water from infiltration wells situated near the bank of the Klondike River. Prior to 1980, the city water distribution and sewage systems were those that had been constructed in 1904. They consisted of woodstave pipes laid in gravel in the active layer: all were shallower than 1.2 m. In winter, the water was heated by electricity to +5.5°C and enough flow was maintained to prevent freezing by bleeding into each house. At the end of the circulation system, the water temperature was about 1.1°C. Needless to say, these water and sewage systems required frequent repairs due to seasonal frost heave, settlement of the pipes through thaw, and frost deterioration of the pipes. During the winter and spring of 1979-1980, a new system of underground services was installed in trenches that were excavated to a minimum depth of 2.0 m and backfilled with coarse (frost-stable) gravel fill (Fig. 6C). Similar costly procedures are now regarded as inevitable in many of the smaller northern communities in Canada if reliable and up-to-date utilities are to be provided.

***Ross River and Old Crow.*** The biggest disadvantage of pile foundations is their cost. This is especially the case for very small buildings, such as individual houses. Equally, in certain communities where good-quality non-frost-susceptible aggregate is scarce, the cost of gravel pad construction is also high. As a result, additional new technologies are being tested. For example, in 1987, the Institute for Research in Construction, National Research Council of Canada, joined with the Yukon government in constructing two 350-m² multipurpose municipal buildings in the communities of Ross River and Old Crow, on heat-pump-chilled foundations (Goodrich and Plunkett, 1990). The aim here is to prevent the thaw of permafrost beneath the buildings. Ross River has a mean annual ground temperature greater than -0.5°C and is typical of relatively warm permafrost in the discontinuous zone. Old Crow has a mean annual ground temperature of -5° to

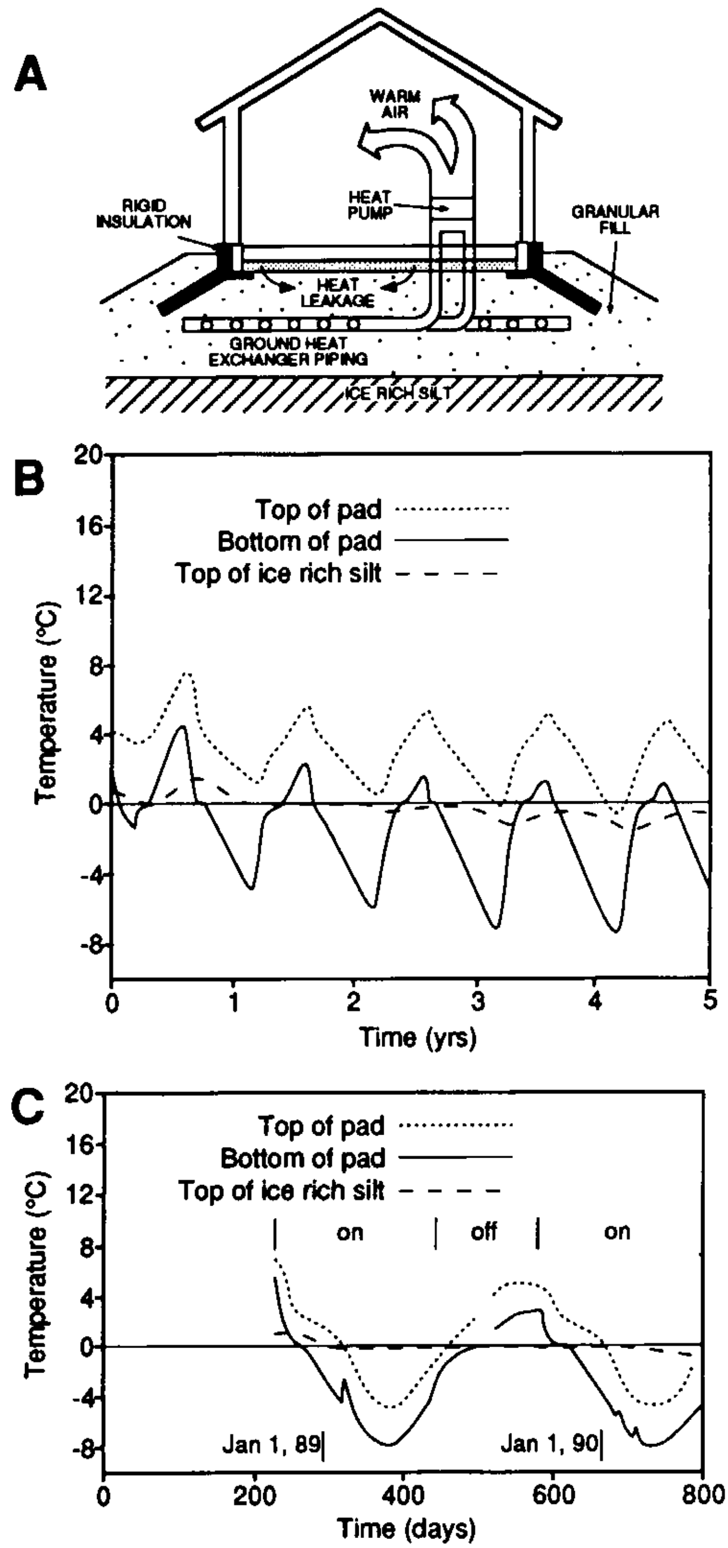



**Figure 7** *Ross River, Yukon.* (**A**) *Design of insulated building using heat pump chilled foundations.* (**B**) *Calculated temperatures.* (**C**) *Measured temperatures (from Baker and Goodrich, 1990).*

-7°C and is more typical of cold permafrost in the continuous zone. The design of the heat-pump-chilled foundation is illustrated in Figure 7A. The heat exchangers were placed in a sand layer within the granular fill used to level the site. Heat flowing down through the floor is captured by the heat exchangers and pumped back into the building. Thus, while the house is being heated, the ground is being chilled. Comparisons of predicted and measured temperatures at the top and bottom of the gravel pad and at the top of the ice-rich silt layer (Figs. 7 B,C), for the first two years of operation at Ross River, suggest that the system is working well and that permafrost is being maintained beneath the structure.

**Figure 8** *The Eagle River bridge, Dempster Highway, Yukon. This is a single span structure with minimal pile support in the river.*

## Bridge Construction in the North

Frost heaving of the seasonally frozen, supra-permafrost zone is a major engineering problem encountered in permafrost regions, and is particularly damaging to urban infrastructure. Not only can differential heave cause structural damage to buildings, but equally important, frost heaving affects the use of piles for the support of structures. While in warmer climates the chief problem of piles is to obtain sufficient bearing strength, in permafrost regions the problem is to keep the pilings in the ground since frost action tends to heave them upward. Since heaving becomes progressively greater as the active layer freezes, it follows that the thicker the active layer, the greater is the upward heaving force. In the discontinuous permafrost zone, where the active layer may exceed 2 m in thickness, frost heaving of piles assumes critical importance. In parts of Alaska, for example, old bridge structures illustrate the

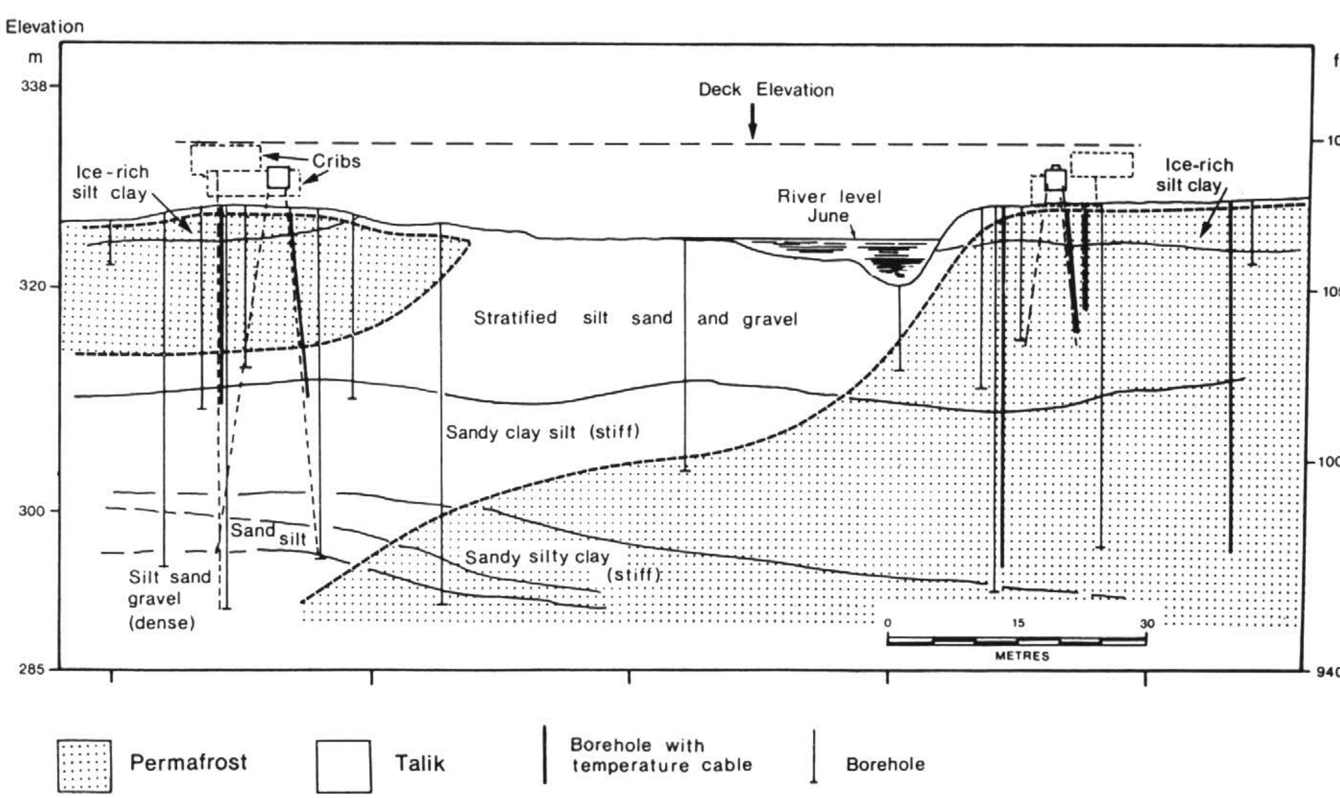



**Figure 9** *Design plan and subsurface profile at the Eagle River bridge site, with stratigraphic and permafrost information determined by drilling (from Johnston, 1980).*

effects of differential frost heave (see Péwé, 1983). In these regions, it is not uncommon for a thawed zone to exist beneath the river channel. Thus, piles inserted in the stream bed itself experience little or no frost heave, and piles inserted within permafrost on either side of the river are also unaffected. However, the piles adjacent to the river bank experience repeated heave since they are located in the zone of seasonal freezing. As a result, arching of both ends of the bridge may occur.

In order to prevent these problems in Canada, alternative structures involving minimal pile support have been considered. A case in point is the recent construction of the Eagle River bridge on the Dempster Highway, northern Yukon (Fig. 8). The bridge consists of a single 100-m-long steel span with the footings on the north side placed in ice-rich permafrost. Drilling prior to construction indicated that permafrost was present on the north bank to a depth of ≈90 m. However, a deep near-isothermal talik existed beneath the main river channel, while near the proposed south bridge abutment, relatively warm (~0.4°C) permafrost was present to depths of 8-9 m.

In order to maintain the delicate permafrost conditions and to provide structural integrity, 15 steel piles were inserted at each abutment (Fig. 9). Conventional engineering and freeze analysis indicated the optimum depth of emplacement of each pile was ≈5 m. However, because of the very warm permafrost at the south abutment, the piles were driven to a depth of about 30 m. On the north abutment, where the permafrost was colder, the piles were installed in holes augered to a depth of 12 m. These were then backfilled with a sand slurry to promote freezing. A further complexity was that construction had to be carried out during the winter (1976-1977), in order to minimize surface terrain damage. Subsequent monitoring has indicated that the piles have experienced minimal heave, the thermal regime of the permafrost has been maintained, and the bridge structure is performing satisfactorily (Johnston, 1980).

A major consideration in recent road building in northern Canada has been the design of river-crossing facilities that avoid the expense associated with bridges. Large diameter culverts have been employed along the Dempster Highway, with their diameter based upon a flood discharge with a recurrence interval of 50 years. Since the higher and sustained water velocities that occur within culverts may block fish migration in the upstream direction, culverts are installed such that the mean water velocity does not usually exceed 0.9 m/s except during the mean annual flood and during the 50-year design flood. To further minimize culvert utilization, roads such as the Dempster Highway follow upland interfluve locations wherever possible. They are also installed with their bases at or below the natural stream bed elevation to discourage the formation of upstream ponds or downstream plunge pools.

In the case of larger river crossings, such as the Peel and Mackenzie on the Dempster Highway, it has been found that summer ferries and winter ice crossings are the best alternative to expensive and difficult bridge designs.

**Oil and Gas Pipelines**

The construction of warm oil pipelines through permafrost terrain further illustrates the complexity of frost heave and related permafrost problems. For example, the construction of the Trans-Alaska Pipeline System (TAPS) from Prudhoe Bay on the North Slope to Valdez on the Pacific Coast between 1974 and 1977 used many procedures designed to minimize permafrost problems (Metz *et al.*, 1982; Heuer *et al.*, 1982). Approximately half of the route was elevated on vertical support members (VSMs), many with cooling devices (heat tubes) to prevent heat transfer to ice-rich (*i.e.*, thaw-sensitive) permafrost (Fig. 10).

In Canada, the recently completed small-diameter Norman Wells pipeline did not have to address the problems of thaw subsidence to the same extent as the Alaska line, since it operates at or close to the prevailing ground temperature. Many of the terrain problems associated with this pipeline lie in the stability of wood-chip-covered embankments

**Figure 10** *Trans-Alaska oil pipeline using vertical support members (VSMs) with cooling devices (fins) designed to prevent heat transfer to ice-rich, thaw-sensitive permafrost.*

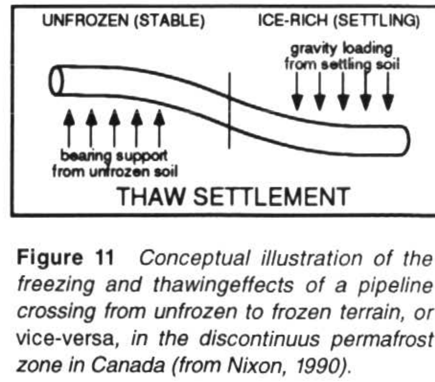



**Figure 11** *Conceptual illustration of the freezing and thawingeffects of a pipeline crossing from unfrozen to frozen terrain, or vice-versa, in the discontinuus permafrost zone in Canada (from Nixon, 1990).*

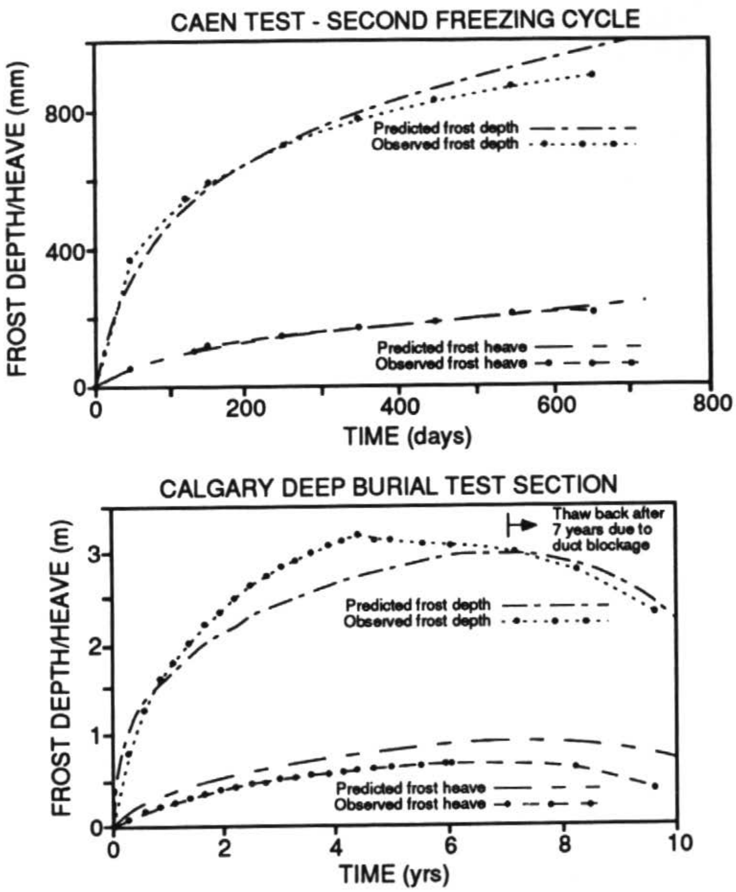



**Figure 12** *Results of the Calgary and Caen frost heave test facilities. Observed frost heave and frost depth are compared to predicted values (from Nixon, 1990).*

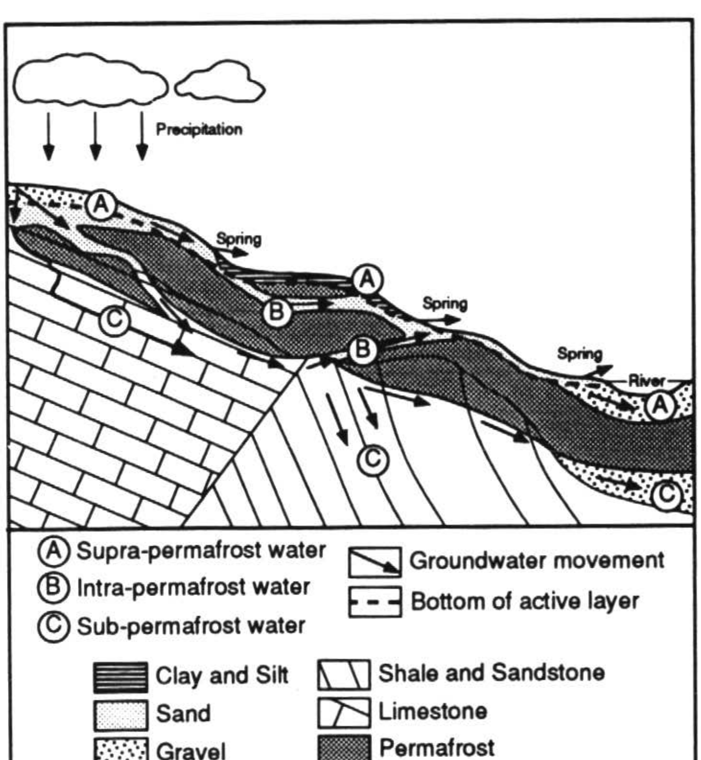



**Figure 13** *Generalized model for the occurrence of ground water in permafrost regions.*

along the right of way, and in the crossing of streams (Burgess and Harry, 1990).

The proposed construction of buried chilled-gas pipelines presents more complex problems that are, as yet, not completely resolved. Here, the problem is one of prolonged frost heave adjacent to the pipe with the possibility of eventual rupture (Fig. 11). This might occur in the discontinuous permafrost zone wherever the pipe crosses unfrozen ground and where there would be relatively unlimited moisture migration towards the cold pipe. Equally, when the pipe passes from unfrozen (stable) to ice-rich (unstable) terrain, or *vice versa*, thaw settlement and/or frost heave may result depending upon the situation.

In order to understand these problems, several natural-scale experiments are currently in progress at Calgary, Caen (France) and Fairbanks (Alaska), which aim to study the behaviour of soil around a refrigerated pipeline (Fig. 12). The Calgary frost heave test facility has been in operation since 1974 and circulates air at -10°C in a 1.2 m diameter pipe buried to represent a number of possible gas pipeline modes (Carlson *et al.*, 1982). Within a couple of years of operation, a frost bulb had formed around the pipe, and in the deep burial mode, the pipe had heaved more than 60 cm, while frost depths had penetrated to 3 m below the pipe. At Caen, a non-insulated pipe, 2.7 m in diameter, was buried in initially unfrozen soil with a lateral transition from a frost-susceptible silt to a non-frost-susceptible sand, thereby simulating a major soil type boundary common to permafrost ter rain. During a first freezing experiment run in 1982-1983, with a pipe temperature of -2°C and a chamber temperature of -7°C, the pipe heaved 11 cm on the 16-m-long section, and frost penetrated 45 cm beneath the pipe in the sand and 30 cm beneath the pipe in the silt (Burgess, 1985). Results from the Fairbanks test facility are not yet published; preliminary data indicate that in the first 166 days of operation, the pipe heaved at least 10 cm at the critical permafrost/non-permafrost boundary. One can afford to be reasonably optimistic that solutions to these problems will be found. The observed magnitudes of frost heave and the frost penetration depths at the experimental sites relate well with values obtained *via* numerical simulation. They suggest that the amounts of heave and settlement that will be experienced by northern pipelines are predictable to engineering levels of accuracy using existing methods (Nixon, 1990).

## GROUND AND SURFACE WATER PROBLEMS

The ground-water system of permafrost regions is unlike that of non-permafrost regions since permafrost acts as an impermeable layer. Under these conditions, the movement of ground water is restricted to taliks (Fig. 13). These may be of three types. First, a supra-permafrost talik may exist immediately above the permafrost table, but below the depth of seasonal frost. In the continuous permafrost zone, supra-permafrost taliks are rare. In the discontinuous permafrost zone, however, the depth of seasonal frost frequently fails to reach the top of the permafrost since the latter is often relict and unrelated to present climatic conditions. In these areas, supra-permafrost taliks are widespread and may be several metres or more thick. Second, intra-permafrost taliks are thawed zones confined within the permafrost and, third, sub-permafrost taliks refer to thawed zones beneath the permafrost.

Given these hydrological characteristics, a difficult problem in many permafrost regions is the provision of drinking water to settlements. Since supra-permafrost water is subject to contamination and usually of small volume, and intra-permafrost water is often highly mineralized and difficult to locate, the mapping of sub-permafrost water is vital.

In the discontinous permafrost zone, opportunities exist for ground-water recharge, and in parts of central Alaska and the Mackenzie Valley, North West Territories, extensive alluvial deposits provide an abundant source of ground water. In Fairbanks, houses rely on numerous small-diameter private wells (see Péwé, 1983). In parts of Siberia, the occurrence of perennial springs fed by sub-permafrost water assumes special importance since these may be the sole source of water available over large areas. However, in many areas of northern Canada (the Canadian Shield) the permafrost is several hundred metres deep and perennial springs are absent. In these situations, drilling is either not possible, since the well would freeze, or too costly. As a result, surface water-bodies, particularly those that do not freeze to their bottoms in winter, must be used, and great care taken to prevent contamination.

The supply of water is a severe limitation to any large-scale permanent settlement in much of the continuous permafrost zone. For example, the water supply problem of Sachs Harbour, a small Inuit community of approximately 250 people on southwest Banks Island, is typical of many situations. There, the water supply is derived from a lake approximately 3 km from the townsite. It is trucked, every 3-4 days, by water tanker, to individual homes that have indoor storage containers. Contamination is a problem, and the size of the lake, one of the few deep enough not to freeze to its bottom during winter, limits growth of the community.

A different group of hydrological problems relates to the formation of icings. These are sheet-like masses of ice that form at the surface in winter where water issues from the ground, usually from a supra-permafrost talik. Icings are of great practical concern as regards highway and railway construction and, in fact, are a distinct hazard to construction activity. These problems are most common in the discontinuous permafrost zone. Although sub- and intra-permafrost waters may be involved, the most frequently occurring icings are those associated with supra-permafrost water. A common occurrence is where a roadcut or other man-made excavation intersects with the supra-permafrost ground-water table. Seepage occurs and a sheet of ice forms, often over many tens of square metres in extent. In North America, icings were first encountered on a large scale during the building of the Alaskan Highway in the 1940s, and they occur widely in Alaska (see Péwé, 1983). Unless precautions are taken, icings can occur on most northern highways that traverse sloping terrain. Counter measures to reduce icing problems include the avoidance of roadcuts wherever possible, the installation of high-arch culverts to divert water from the source of the icing, and the provision of large drainage ditches adjacent to the road. Icings may also block culverts placed beneath road embankments and, by diverting melt water, initiate washouts in the spring thaw period. The costs of icing control and/or remedial measures can be considerable: van Everdingen (1982) provides a conservative estimate of $20,000 for ice control at a single locality on the Alaska Highway, Yukon, for the 1979-1980 winter.

## DISCUSSION

Permafrost, with its particular terrain, ground ice and hydrological conditions, exerts a dominant influence over urban activities in northern Canada, and poses unique environmental geological problems. Although the settlements in Canada's permafrost terrain are not numerous or large, the urban geology of such settlements, and the economic activity upon which they often rely, cannot be adequately understood without detailed appreciation of the peculiarities of frozen ground.

## ACKNOWLEDGEMENTS

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## REFERENCES

Associate Committee on Geotechnical Research, 1988, Glossary of permafrost and related ground-ice terms: National Research Council, Permafrost subcommittee, Technical Memorandum 142, 156 p.

Baker, T.H.W. and Goodrich, L.E., 1990, Heat pump chilled foundations for buildings on permafrost: Geotechnical News, v. 8, p. 26-28.

Burgess, M., 1985, Permafrost: Large-scale research at Calgary and Caen: Geoscience, v. 2, p. 19-22.

Burgess, M.M. and Harry, D.G., 1990, Norman Wells pipeline permafrost and terrain monitoring; geothermal and geomorphic observations: Canadian Geotechnical Journal, v. 27, p. 233-244.

Carlson, L.E., Ellwood, J.R., Nixon, J.F. and Slusarchuk, W.A., 1982, Field test results of operating a chilled buried pipeline in unfrozen ground, in Fourth Canadian Permafrost Conference: National Research Council of Canada, Ottawa, p. 475-480.

Ferrians, O., Kachadoorian, R. and Green, G.W., 1969, Permafrost and related engineering problems in Alaska: United States Geological Survey, Professional Paper 678, 37 p.

French, H.M., 1975, Man-induced thermokarst, Sachs Harbour airstrip, Banks Island, NWT: Canadian Journal of Earth Sciences, v. 12, p. 132-144.

French, H.M., 1980, Terrain, land use and waste drilling fluid disposal problems, Arctic Canada: Arctic, v. 33, p. 794-806.

French, H.M., 1984, Some terrain and land use problems associated with exploratory wellsites, northern interior Yukon, *in* Olsen, J., ed., Northern Ecology and Resources: University of Alberta Press, Edmonton, p. 365-385.
French, H.M., 1987, Permafrost and ground ice, *in* Gregory, K.J. and Walling, D., eds., Man and Environment Activity: J. Wiley and Sons Ltd., Chichester, U.K., p. 237-269.
French, H.M., 1993, Cold-climate processes and landforms, *in* French, H.M. and Slaymaker, O., eds., Canada's Cold Environments: McGill-Queens Press, Montreal, p. 143-167.
Goodrich, L.E. and Plunkett, J.C., 1990, Performance of heat pump chilled foundations, *in* 4th Canadian Permafrost Conference, Université Laval: Nordicana, 54, p. 409-418.
Hare, F.K. and Thomas, M.K., 1974, Climate Canada: Wiley Publishers of Canada Limited, Toronto, 256 p.
Hayley, D.W., 1982, Application of heat pipes to design of shallow foundations on permafrost, *in* Fourth Canadian Permafrost Conference: National Research Council of Canada, Ottawa, p. 535-544.
Heginbottom, J.A. and Radburn, L.K., 1992, Permafrost and ground ice conditions of Northwestern Canada: Geological Survey of Canada, Map 1691A, scale 1:1 000 000.
Heuer, C.E., Krzewinski, T.G. and Metz, M.C., 1982, Special thermal design to prevent thaw settlement and liquefaction, *in* Fourth Canadian Permafrost Conference: National Research Council of Canada, Ottawa, p. 507-522.
Johnston, G.H., 1980, Permafrost and the Eagle River bridge, Yukon Territory, Canada, *in* Permafrost Engineering Workshop, National Research Council of Canada: Technical Memorandum 130, p. 12-28.
Mackay, J.R., 1970, Disturbances to the tundra and forest tundra environment of the Western Arctic: Canadian Geotechnical Journal, v. 7, p. 430-432.
Metz, M.C., Krzewinski, T.G. and Clarke, E.S., 1982, The Trans-Alaska Pipeline workpad: an evaluation of present conditions, *in* Fourth Canadian Permafrost Conference: National Research Council of Canada, Ottawa, p. 523-534.
Morgenstern, N.R. and Nixon, J.F., 1971, One-dimensional consolidation of thawing soils: Canadian Geotechnical Journal, v. 8, p. 558-565.
Muller, S.W., 1943, Permafrost or permanently frozen ground and related engineering problems: U.S. Army, Office Chief of Engineers, Strategic Engineering Study Special Report 562, p. 231; 1945, second printing with corrections; reprinted in 1947, Ann Arbor, Mich., J.W. Edwards, Inc.
Natural Resources Canada, 1995, Canada Permafrost, The National Atlas of Canada, 5th Edition. Map. MCR 4177, scale 1:1 500 000, Canada Map Office, Ottawa.
Nixon, J.F., 1990, Northern pipelines in permafrost terrain: Geotechnical News, v. 8, p. 25-26.
Péwé, T.L., 1966, Permafrost and its effect on life in the north, *in* Hansen, H.P., ed., Arctic Biology, 2nd edition: Oregon State University Press, Corvallis, p. 27-66.
Péwé, T.L., 1983, Geologic hazards of the Fairbanks area, Alaska: Division of Geology and Geophysical Surveys, Alaska, Special Report 15, 109 p.
Péwé, T.L. and Paige, R.A., 1963, Frost heaving of piles with an example from the Fairbanks area, Alaska: United States Geological Survey, Report 1111-I, p. 333-407.
Pollard, W.H. and French, H.M., 1980, A first approximation of the volume of ground ice, Richards Island, Pleistocene Mackenzie Delta: Canadian Geotechnical Journal, v. 17, p. 509-516.
Sloan, C.E. and van Everdingen, R.O., 1988, Region 28, Permafrost region, *in* Back, W., Rosenshein, J.S. and Seaber, P.R., eds., Hydrogeology, The Geology of North America: Geological Society of America, v. 2, p. 263-270.
van Everdingen, R.O., 1982, Management of groundwater discharge for the solution of icing problems in the Yukon, *in* Fourth Canadian Permafrost Conference: National Research Council of Canada, Ottawa, p. 212-228.
Wahl, H.E., Fraser, D.B., Harry, R.C. and Maxwell, J.B., 1987, Climate of Yukon: Atmospheric Environment Service, Environmental Canada, Climatological Studies 40, 323 p.

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