Frost Design Practice in Canada

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This paper discusses the methods being used by Canadian highway engineers to combat frost action. It was compiled from information supplied by the two Federal agencies concerned with pavement design for roads and airfields and the highway departments of the Provincial Governments.

A description is given of the varied climatic, soil, and traffic conditions and of the type and extent of frost damage encountered. A survey of frost design and construction practices for flexible pavements, rigid pavements, and highway structures is given. The present standards of frost design practice are reviewed, and problem areas requiring research are indicated.

•CLIMATIC CONDITIONS in Canada are such that frost action is a problem of major importance for highway engineers throughout the country. The aim of this paper is to describe the considerations given to frost action by the various agencies concerned with the design of highways and airfields.

Twelve agencies have contributed to the preparation of this paper, including the Federal Departments of Transport and Public Works, and the Highway Departments of the ten Provinces.

With minor exceptions each Province is responsible for all highway construction within its boundaries. The Federal Department of Public Works is responsible for the design and construction of highways in the National Parks, the Northwest Territories, and the Yukon Territory. The Federal Department of Transport is responsible for the design and construction of the principal airfields throughout the country.

ENVIRONMENTAL CONDITIONS

Climatic Conditions

Canada is the world's third largest country and thus it is not surprising that it is a land of many climates. Stretching through nearly 90° of longitude, it also extends in a northerly direction from latitude 42° to within a few hundred miles of the North Pole. Practically all the country is subject to seasonal frost and approximately one-third lies within the regions of discontinuous or continuous permafrost (Fig. 1). The design principles discussed in this paper refer specifically to areas of seasonal frost.

Canada has six climatic regions, the characteristic features of which are briefly summarized.

The Southeastern Climatic Region takes in Southern Ontario and Quebec, along with the Maritime Provinces of New Brunswick, Nova Scotia, Prince Edward Island, and the island portion of Newfoundland. This region is the most densely populated and the climate is very similar to that of the Northeastern United States. The winter is shorter than it is in the adjoining northern regions, and the summer (in Ontario, at least) may be quite warm. The Great Lakes have a moderating effect on the climate in Southwestern Ontario, but this effect is scarcely noticeable in Southeastern Ontario and in Southern Quebec. Temperatures in the interior of New Brunswick are similar to those

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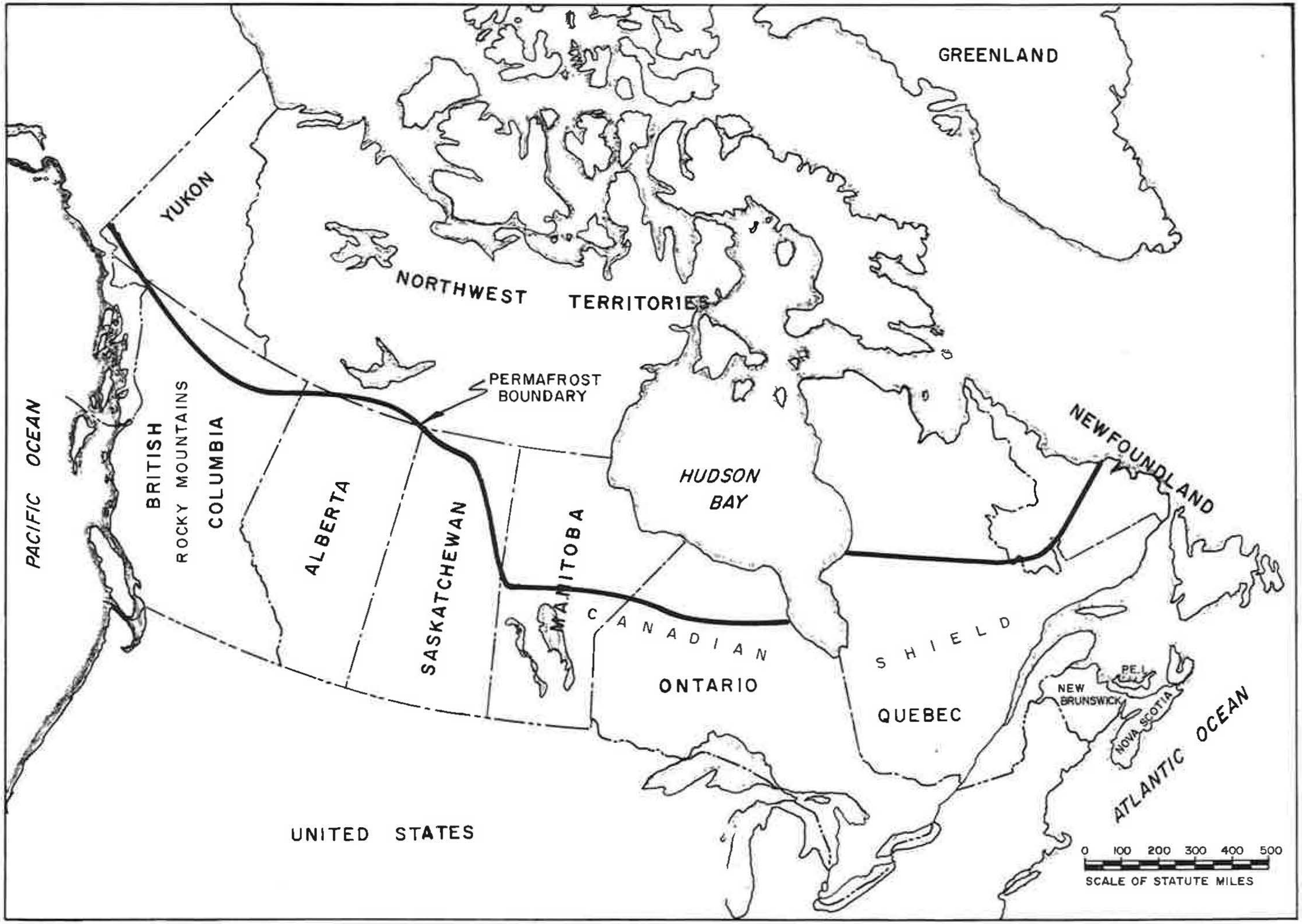


Figure 1. Permafrost boundary in Canada.

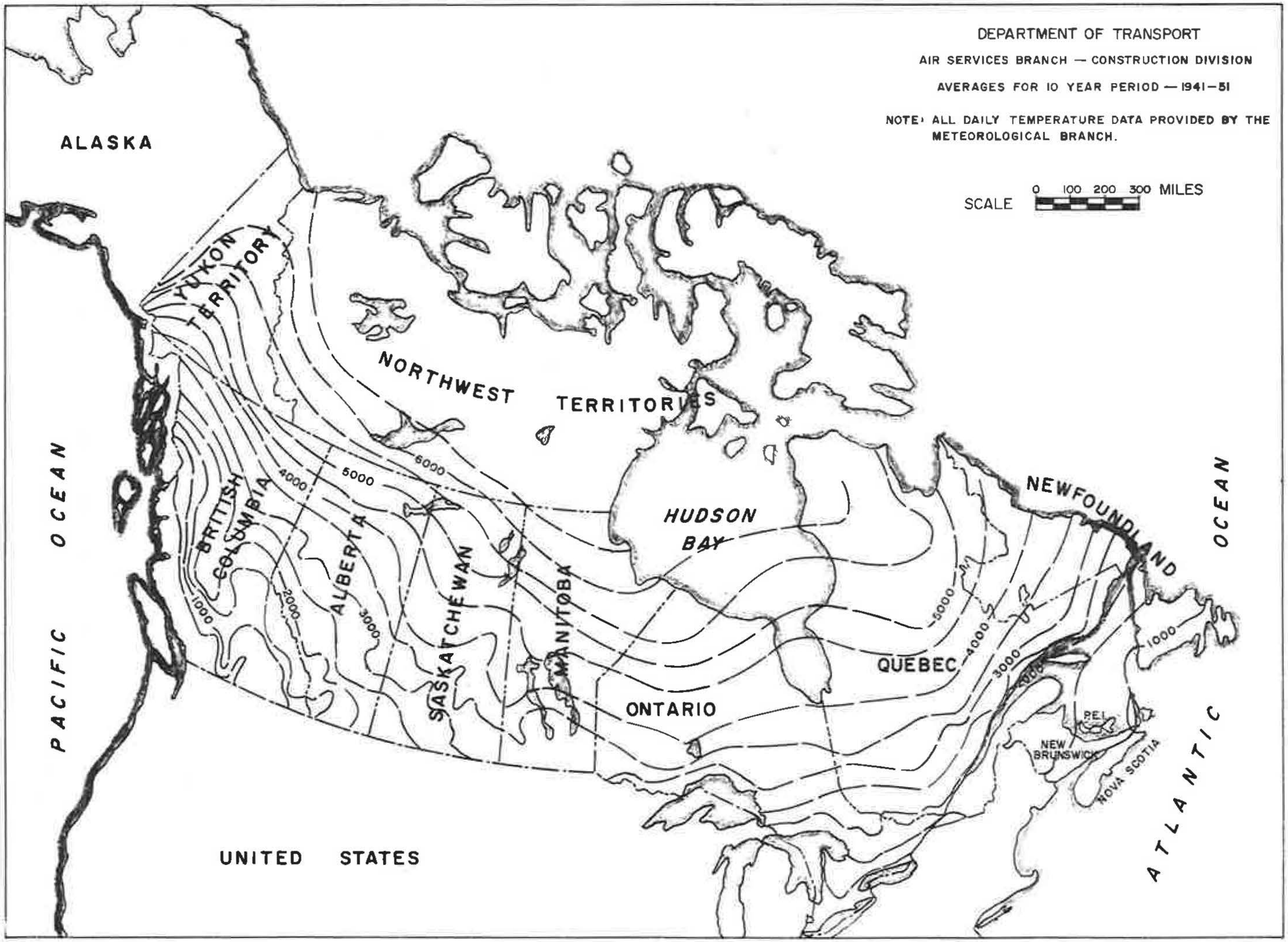


Figure 2. Freezing indexes in Canada.

TABLE 1

CLIMATIC DATA FOR THE PROVINCES OF CANADA[a]

Province	Temperature (°F)									No. of Frost-Free Days	Freezing Index (degree-days)	Frost Penetration (ft)	Precipitation (in.)					
	Mean Annual	Mean Daily				Extreme Lowest	Extreme Highest	2.5% Design Value[b]					Mean Annual Total[c]	Mean Annual Rain	Mean Seasonal Rainfall			
		Jan.	Apr.	July	Oct.			Wint.	Sum.						Wint.	Spr.	Sum.	Fall
British Columbia:																		
Coast	40-50	30-40	40-50	55-65	40-50	$\underline{30}$-0^s	90-100	0-10	70-75	200-275	0- 500	0- 3	50-100	40-100	5-40	5-30	5-20	5-40
Int.	35-45	0-30	35-50	55-70	35-45	$\underline{65}$-$\underline{30}$	95-105	$\underline{30}$- 0	75-90	50-150	500-4,000	2- 8	15- 50	10- 30	1-10	2- 6	3- 6	3-10
Alberta	30-40	0-10	35-45	60-65	35-45	$\underline{65}$-$\underline{40}$	100-105	$\underline{40}$-$\underline{30}$	80-90	150-250	2,000-4,000	4- 8	15- 20	10- 15	0- 1	1- 3	5-10	2- 3
Saskatchewen	30-40	$\underline{10}$-10	30-40	60-65	35-40	$\underline{60}$-$\underline{50}$	100-110	$\underline{40}$-$\underline{30}$	85-90	150-250	2,500-4,500	6- 8	15- 20	10- 15	0- 1	1- 3	5- 8	2- 3
Manitoba	25-35	$\underline{10}$- 0	25-35	60-65	30-40	$\underline{60}$-$\underline{50}$	95-110	$\underline{40}$-$\underline{30}$	80-85	125-175	3,000-6,000	4-10	15- 20	10- 15	0- 1	1- 3	6- 8	2- 3
Ontario:																		
North	30-40	$\underline{5}$-10	25-35	60-65	35-45	$\underline{60}$-$\underline{45}$	100-105	$\underline{40}$-$\underline{20}$	80-85	125-175	1,500-4,500	6- 8	25- 35	20- 25	0- 1	2- 5	8-10	5-10
South	40-50	$\underline{10}$-20	35-45	65-70	45-50	$\underline{45}$-$\underline{20}$	100-105	$\underline{20}$- 0	85-90	200-250	500-1,500	2- 4	30- 35	20- 30	1- 3	5- 8	8-10	6-10
Quebec	30-40	$\underline{10}$-10	25-40	55-65	35-45	$\underline{60}$-$\underline{40}$	95-100	$\underline{30}$-$\underline{10}$	75-85	150-200	2,000-4,000	4- 8	35- 40	20- 30	0- 2	2- 6	10-12	7-10
Newfoundland	30-40	10-20	25-35	55-65	40-45	$\underline{40}$-$\underline{20}$	85- 90	$\underline{20}$- 0	70-80	200-250	500-1,500	2- 4	35- 50	25- 40	2-10	4-10	10-12	8-12
New Brunswick	35-45	10-20	35-40	65-70	40-45	$\underline{40}$-$\underline{30}$	100-105	$\underline{20}$-$\underline{10}$	75-85	80-120	1,500-2,000	4- 6	35- 40	25- 35	2- 5	5- 8	10-12	8-10
Pr. Edward I.	40-45	15-20	35-40	65-70	45-50	$\underline{30}$-$\underline{20}$	95-100	$\underline{10}$- 0	75-80	200-250	1,000-1,500	2- 4	35- 40	25- 30	2- 5	5- 7	10-12	8-12
Nova Scotia	40-50	20-25	35-40	65-70	45-50	$\underline{30}$-$\underline{20}$	90-100	$\underline{10}$- 0	75-80	200-275	500-1,000	2- 4	40- 50	30- 40	5-10	7-10	10-12	8-12

[a]Underlined values are negative.
[b]The value at or below (above) which 2.5 percent of the January (July) hourly temperatures occur.
[c]Rainfall + 0.1 snowfall.

in Quebec, but in the other Maritime areas both the summers and the winters are modified to a great extent by the ocean. Precipitation is ample in this region.

The Prairie Climatic Region includes the settled southern half of Alberta, Saskatchewan, and Manitoba. The climate of this area is characterized by extreme differences between summer and winter temperatures and relatively low annual precipitation. Temperatures in any season fluctuate widely from day to day and from day to night. About one-half the total precipitation falls during the summer months.

Proceeding westward the third and most complex climatic region of Canada is encountered. This is the Cordillera which includes part of British Columbia and the Yukon Territory. In this region of mountains, plateaus, and valleys, altitude is usually more of a climatic determinant than latitude. The rugged terrain of the country makes it almost impossible to map the climate accurately but, in general, precipitation decreases eastward from the Pacific region, especially in the lee of the successive mountain ranges. On the other hand, temperature variability and severity increase as the mountain region is traversed to the east. In this region the daily temperature variations are greater than anywhere else in Canada. Summers in the southern interior mountain valleys are hotter than any location in the Prairies, but the northern portions are much colder.

The Pacific Climatic Region consists of the islands and the narrow coastal belt of British Columbia, which varies in width from a few miles up to 100 miles. Temperatures rarely drop below 0 F in the winter or rise above 90 F in the summer. With a winter season maximum, this region is rainier than any other in the country.

The Northern Climatic Region might well be called sub-Arctic. Bordered on the north by the Arctic Tundra, this region includes the sourthern part of the Northwest Territories, the northern half of Alberta, Saskatchewan and Manitoba, northern Ontario, most of Quebec, and the mainland part of Newfoundland. The region consists of sparse, lightly-treed barren land in the north and the more heavily forested native boreal forest in the south. Appreciable snow cover lasts for more than one-half the year, especially in the northeastern section. Extremely low temperatures occur every winter throughout most of the northwestern section, and very high temperatures may occur in summer. Precipitation is light in the northwest; in fact this section is subhumid, but ample in most of the southeastern portion. The Central Quebec portion has a very high snowfall each winter.

The sixth climatic region, the Arctic, lies in the upper parts of the permafrost area and is not included in the scope of this paper.

Figure 2 is a freezing index map for Canada. Other characteristic climatic data for the individual Provinces are briefly summarized in Table 1. The values are average figures for general information, and are representative of those parts of the Provinces where an appreciable amount of highway construction has been carried out.

Soil Conditions

Most of Canada's soils are of glacial origin. The most recent period of glacial action, the Wisconsin, was the most important, but there are some soils in the Yukon that belong to an earlier period.

The only place where nonglacial soils have significance is the western Yukon Territory, although they also occur in Alberta and Saskatchewan. Alluvial soils of the postglacial period are to be found only in the Fraser (British Columbia) and MacKenzie (Northwest Territories) River deltas.

The Wisconsin glaciers blanketed great tracts of land with an unsorted mixture of materials that are commonly known as till. This mantle is usually referred to as ground moraine. Glacial till is generally a very compact mixture of materials varying in particle size from clay to boulders, the actual composition depending on the type of terrain. Large areas are also covered with end moraine or hummocky moraine. These are broadly similar to ground moraine in composition, although generally more sandy or gravelly. Glaciofluvial deposits are also widespread in Canada. A further important feature is the vast extent of clays deposited in the great glacial lakes and in the encroachments of the sea. Both the lacustrine and marine clays are usually sensitive.

In the Western Provinces of British Columbia, Alberta, Saskatchewan, and Manitoba the thickness of the ground moraine ranges from a few feet to over 400 feet. The end moraines are normally subdued, and are often only traceable with difficulty. The predominant terrain feature is the wide-scale hummocky moraine. The till soils are normally resorted and contain variable quantities of silt, sand, and gravel. The tills in the Rocky Mountain region are particularly variable, ranging in texture from clayey to gravelly. Cretaceous shales occur in a strip several hundred miles wide to the east of the Rocky Mountains. A large portion of Saskatchewan is underlain by the Bearpaw shale. There are important lacustrine sand, silt, and clay deposits in southern Saskatchewan and Manitoba. Alluvial deposits and loess-type soils are confined to small areas.

In Ontario and Quebec, the predominant soil type is glacial till. The end moraines are usually less than 10 miles wide, but many tens of miles long. A characteristic feature of the terrain is the frequent occurrence of large eskers. The till is mostly sandy or gravelly, only occasionally clayey. Clay tills are found in southern Ontario and in the St. Lawrence River Valley. There are large areas of marine and lacustrine clay deposits in the Ottawa and St. Lawrence valleys and around the coast of Hudson Bay. In general the soil conditions are extremely variable, even over short distances, due to the fact that both Provinces have been fully glaciated.

Glacial deposits are also predominant in the Atlantic Provinces of Newfoundland, New Brunswick, Prince Edward Island, and Nova Scotia. In Newfoundland, the most common subgrade material is a silty till, but there are some areas of marine sediments on the west coast. There is an abundance of water throughout the island, and the ground water table is often very close to the surface. The subgrade soil types in New Brunswick range from rocky tills to clayey tills, and in general the ground water is fairly near the surface.

Highway location within the mountainous National Parks is controlled predominantly by the existence of valleys and alpine passes carved by glacial and river action. Soil conditions are extremely variable over short distances in these areas. The main subgrade soil types are bedrock, glacial and fluvial granular deposits, and a third group comprising glacial tills, very silty gravels, and pockets of pure silt. Although surface drainage is seldom a problem, subsurface drainage is often critical due to the erratic nature of drainage conditions in the mountainous areas.

One important aspect of the common occurrence of glacial soil features, (such as moraines, eskers, and kames) is that they provide an excellent supply of granular materials for highway construction throughout most parts of the country. Except in the areas of the heavy lacustrine and marine clays, granular material is usually available within economical haul distances.

The most dangerous soil types from the frost point of view are the lacustrine and alluvial silts and the resorted glacial tills in the Western Provinces, soils with high short-term capillarity (such as loams and silts), and soils that undergo large changes in bearing capacity with changes in moisture content (such as plastic clays in Ontario and Quebec, and the silty or loamy glacial tills of the Maritime Provinces).

Highway-Operating Conditions

It is naturally the aim of every highway agency in Canada to provide at least a primary system of roads that need not be restricted in the spring because of the weakening of the subgrade due to frost action. The various Provinces differ in their financial ability to achieve this and, in fact, all the Provinces place restrictions on some of their roads in the spring period. In general, all the newly constructed roads on the primary system are designed to remain unrestricted; e.g., the Trans-Canada Highway. However, except in British Columbia, Alberta, and Ontario, the extent of such recent construction is relatively small, and thus the whole of most of the provincial road systems are still subjected to spring restrictions. As time goes on, however, all Provinces will have more and more continuous highway routes that will remain unrestricted.

Restrictions are normally envisaged for all secondary roads and for at least some of the intermediate roads. In most Provinces, restrictions call for half-loading in the spring, but in some Provinces (for instance, British Columbia), loads are limited to a proportion of the full load, depending on the actual measured loss of pavement strength.

Legal limitations during the normal nonrestricted seasons are such that in most Provinces the maximum single axle load is 18,000 lb, the maximum tandem axle load is 32,000 lb, and the maximum load per inch of tire widths is 500 to 600 lb. For instance, in Saskatchewan the following load limit regulations apply: 500 lb per 1-in. width of tire on any wheel or wheel group 18,000 lb per single axle when the axles are more than 8 ft apart, 32,000 lb per axle group when the extreme axles of the group are less than 8 ft apart, 44,000 lb per axle group when the extreme axles of the group are more than 8 ft but less than 20 ft apart. In addition to these limits, there are regulations for maximum gross weights for the various vehicle types.

The volume of traffic on the main trunk routes varies from 1,000 to 40,000 AADT and in certain exceptional cases runs as high as 70,000 AADT.

Four traffic categories are distinguished in the Department of Public Works' practice, based on the daily number of cars, heavy trucks, and buses. Traffic conditions within the mountain parks presently fall into the "medium" category during the summer tourist season, which means that more than 2,000 cars and 50 heavy trucks and buses use the roads each day. Roads being built in the Territories are of relatively low category, and only a small percentage of them have been paved.

On airfields built by the Department of Transport the design aircraft loadings vary from an 11,000-lb single wheel load to a 230,000-lb multiple wheel gear load.

FROST DAMAGE AND CORRECTIVE MEASURES

Heaving Damage

Most Provinces acknowledge the fact that the depth of frost penetration is too great to permit them to construct highways that will be entirely free of frost heave in the winter. Their efforts are therefore directed towards minimizing the detrimental effects of frost heaves. Due to higher standards of modern construction, severe frost heaves occur almost exclusively on older roads that have underdesigned pavements. A uniform heave of 10 in. and a differential heave of 5 in. are regarded as severe.

The most common critical subsurface conditions with respect to frost heaving arise in silty subsoils where the water table is within capillary reach of the frost front. Pockets of silt in glacial tills, or pockets of very fine sand, are also frequently the source of trouble. Grade-points at transitions from cut to fill are liable to become locations of differential heaving, as are areas where there are abrupt changes in the type of embankment material, or cuts having stratified soil conditions. Depressions in underlying ledge rock or in other impervious layers, and excess hydrostatic pressures in the subgrade associated with side-hill cuts also generate heaving conditions.

Bad heaving conditions may develop in areas with heavy showfall if all the snow is pushed onto the shoulders. The snow banks, sometimes several feet in height, act as insulators so that no heaving occurs at the shoulder. The bare roadway, however, has no insulation and deep frost penetration takes place, often accompanied by a heave of several inches with a maximum near the centerline. This results in "backbreaking" stresses and a substantial crack adjacent and parallel to the centerline.

The intensity of heaving depends to a considerable extent on temperature and precipitation conditions. Frost action is normally at its worst in a winter following a very wet fall, and heaving will be accentuated if the descent of the the frost line is slow (according to Alberta experience). In addition, Ontario experience shows that repeated freeze-thaw cycles at the beginning of the cold season will produce large heaves. New Brunswick, on the other hand, reports that most of the heaving seems to occur in the latter half of the winter season, probably when the frost line has reached its maximum penetration. The adverse effect of freeze-thaw cycles is stressed by the experience of the Department of Public Works in the area of the Mountain Parks. Very warm dry winds (commonly referred to as "Chinook") can change the ambient temperature by as much as 60^{0} within a 6-hr period. Such changes usually occur about four times each winter.

Among the airfields for which the Department of Transport is responsible, serious frost damage is restricted to the older pavements which were probably not constructed to present standards. The heaves reported do not generally exceed 4 in., although in one case a heave of 10 in. was reported. The diameter of the area affected varies from 2 ft or less up to 50 ft or more in some cases. On some airfields only a single small area of heaving is reported, whereas on others heaving is reported to be general over the whole field. Of 140 airfields investigated only 24 showed significant frost heaving, and these were in areas having freezing indexes ranging from 400 to 6,600 degree-days. Some of the more serious cases of heaving occur in regions with freezing indexes around 1,000 degree-days. Frost heaves are most often associated with silty subsoils, and though a high water table appears to be conducive to heaving, it is not a prime factor. In several cases, pronounced heaving has been reported in pavements where the water table was more than 10 ft below the surface. Cases have been reported where painted areas of the airfield pavements heaved more than adjacent unpainted areas.

As soon as differential heaves develop, "bump" signs are installed by all Provinces, but actual maintenance work is kept to the minimum consistent with safety. In certain cases, severe differential heaves are eased by placing cold mix patching adjacent to the heaves. This patching is removed with a grader the following spring, as the heaves subside. Heaves are normally recorded on the highway profile in February or March each year for several years before, and for 2 to 3 years after, reconstruction. On roads not scheduled for reconstruction, corrective measures are taken during the summer, in the form of excavation and backfilling with non frost-susceptible granular material, provision of adequate drainage, removal of boulders, etc.

The usual construction practice for Department of Public Works' project is to lay a 3-in. thick asphaltic base course (150 to 200 pen. asphalt cement) within one year of completion of the subgrade, subbase, and base courses. The final pavement is not normally applied until two to three years later or as warranted by traffic volumes and weights. Between these stages of construction the road is kept under close observation to detect any areas of differential frost heaving or other structural deficiencies. Frost heaves are marked and recorded, the height of heaving is measured and the effect of differential heaving on driving comfort is noted so that proper measures can be taken during the summer or fall period.

Thawing Damage

The worst aspect of frost action on Canadian highways is the weakening of the subgrade during the thawing period. Older pavements with inadequate design thickness show considerable damage during the spring and require extensive maintenance; this is particularly true of flexible pavements. Concrete pavements are generally not seriously affected by thawing damage, except for the occasional occurrence of pumping.

According to general experience, thawing damage is dependent on the strength of the pavement system. An extensive study of the seasonal variations in pavement strength has been carried out under the auspices of the Canadian Good Roads Association. All Provinces have participated in this study for which the Benkelman beam deflection test was used to record the variations in strength of sections of pavement chosen to be representative of all soil and traffic conditions. Reductions in load-carrying capacity of the order of 40 percent were reported from Alberta, 50 percent from Ontario, and 30 to 60 percent from New Brunswick.

The soil and moisture conditions that are critical from the heaving point of view are also critical as far as thawing damage is concerned. The worst conditions are again encountered when the water table is high and the subgrade soil consists of silty glacial tills, loam tills, clay loam tills, varved clays, or organic silts. High seasonal loss of subgrade support is reported from the clay-plain areas of Southwestern Ontario. The general experience is that the greatest losses are encountered when a wet fall is followed by a winter with many cycles of freezing and thawing without much snow, and then by a rapid thaw during the spring. If the thaw takes place before the ditches are clear of snow and ice, then conditions become even worse because dispersal of surface and melt waters is very slow. Warm spring rains and high ambient temperatures that cause rapid thawing contribute to heavy thawing damage. In Saskatchewan it has been found that the reduction in load-carrying capacity during the spring period is dependent on the amount of rain during the two preceding years. Some pavement sections that required spring load restrictions at one time have been found to be in less need of restrictions following periods of low rainfall and vice versa.

Spring reduction in load-carrying capacity due to the thawing of frozen subgrades is also the worst aspect of frost action in the airfields maintained by the Department of Transport, and here again the effect is worse on flexible pavements than on rigid pavements.

Both the heaving and thawing phases of frost action often lead to the cracking of the pavement surface. It is an important yearly maintenance task to fill the cracks to keep water out of the base and subgrade. Inasmuch as some of these cracks extend into the subgrade, some sand or similar material is used to minimize the amount of asphalt required for crack filling. Areas of extensive cracking are individually investigated and the corrective measures adopted normally involve excavation and backfilling together with the improvement of the surface and subsurface drainage conditions.

Figure 3 shows an example of corrective treatment applied in British Columbia at frost heave locations. The length and width of the excavation will be dictated by the size of the frost heave and the soil conditions. The excavation, which normally varies from 3 to 4 ft in depth, must extend to one shoulder, each end is cut to a slope of 12 to 1, and the floor is sloped towards the shoulder to ensure proper drainage. The excavation is then backfilled with clean granular material.

The depth of the excavation is normally between 3 and 5 ft in Ontario (with both ends of the excavation tapered off at a slope of 20 to 1); at least one-half the depth of frost penetration according to New Brunswick specifications, and 4 to 6 ft (or down to the lower boundary of the frost susceptible soil) in the practice of the Department of Public Works. Adequate drainage is provided from the bottom of the excavation, which is then backfilled with select granular material.

Other Types of Frost Damage

This section discusses types of frost damage that are of secondary importance as compared to the usual heaving or thawing damage along the main routes of highway. The most common examples are deformation and dislocation of structures, erosion of slopes and shoulders, and surface icing.

Almost all Provinces report differential heaving, resulting in cracking of the pavement surface, at culverts and occasionally at other structures. There have been recorded instances of frost heave lifting bridge piers, but the deformation and dislocation of structures is normally caused by the movement of the fill adjacent to the abutment rather than by the movement of the structure itself. This movement is controlled in recent years by the use of non-frost-susceptible fill material adjacent to structures and by compacting to standard Proctor density to minimize settlement and movement due to freeze-thaw conditions. Complete icing of culverts also occurs occasionally.

The erosion of sideslopes and ditches due to the loosening effect of freeze-thaw cycles is a considerable problem in several Provinces, especially where the predominant soil type is a silt. Severe erosion problems are encountered in the glacial till areas as well. Simple measures are taken to combat sloughing; for example, in New Brunswick, slopes are either sodded or covered with a gravel blanket 6 to 12 in. thick. In Ontario, slopes are normally stabilized either by vegetation or by flattening the slope and are rounded at the top to reduce erosion. Newly seeded slopes are protected with a hay mulch and a light covering of bituminous material to protect the surface. Other means of soil stabilization are pegging, wire-meshing, placement of granular sheet or topsoil. Cut-off ditches are provided where needed and catch-basins may also be installed. Rock slopes are inspected in the spring and pieces loosened by freeze-thaw cycles are removed. On roads built by the Department of Public Works, rock falls due to frost action in excavated solid rock backslopes in mountainous areas are a constant problem. These falls seldom extend to the travel lanes but are a menace

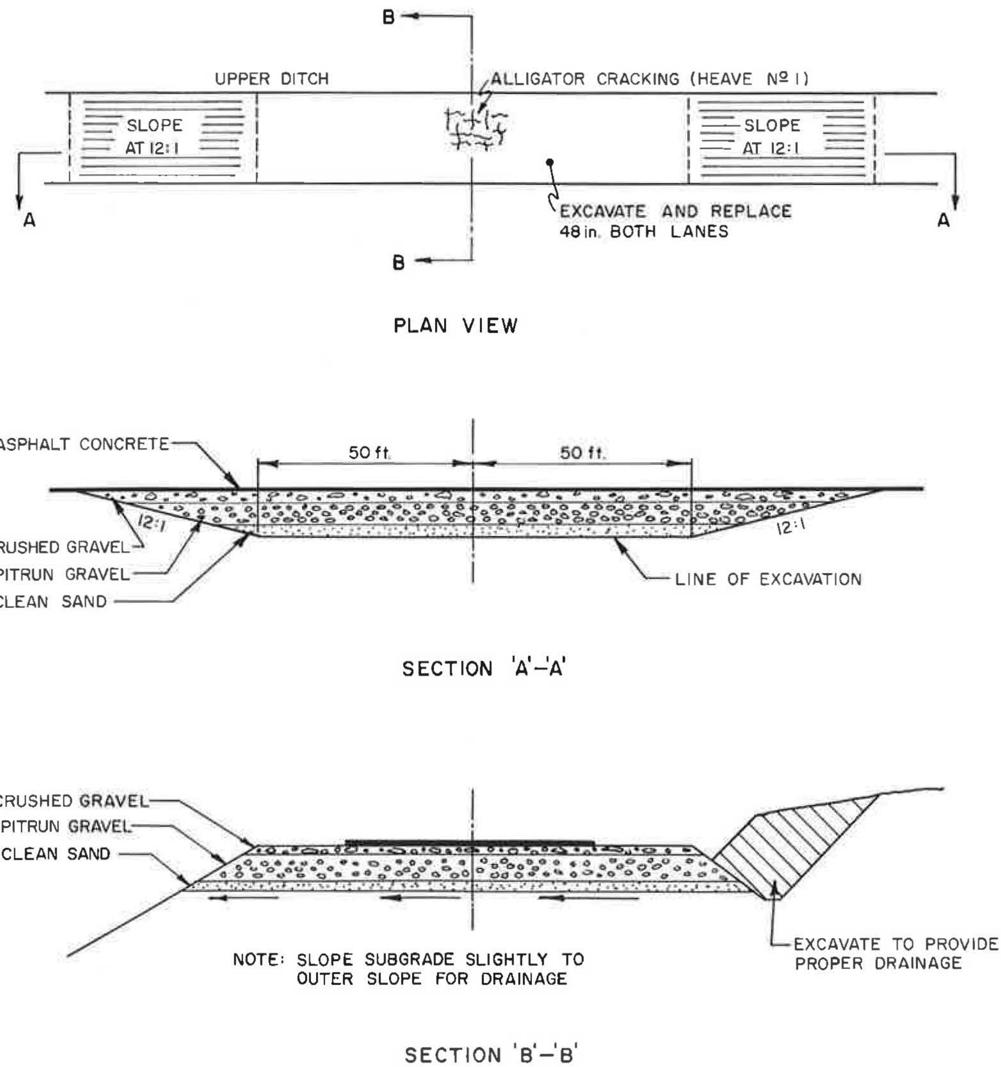


Figure 3. Treatment of a frost heave area in British Columbia.

to effective ditch drainage. No solution, besides the rather impractical step of cutting flatter backslopes, has been tendered for this problem. The erosion of common cuts due to frost slides has been handled effectively by grass seeding and extensive installation of horizontal drains.

Surface icing due to freeze-thaw temperatures in the presence of snow is reported to be a considerable problem in the Mountain National Parks, in New Brunswick, and to some extent in Manitoba. Icing conditions are normally reduced to a tolerable level by spreading salt or sand on the road surface.

On airfields built by the Department of Transport some spalling of portland cement concrete surfaces and deterioration of asphaltic concrete surfaces is evident. This difficulty has been overcome in recent years by more rigid quality control measures during construction. It has sometimes been observed that a relatively sudden, large drop in temperature (say, from 60 to 20 F in 24 hr) has caused cracking in asphaltic pavements. Frequently these are along joints, or coincide with cracks in the underlying pavement in the case of overlays. Such cracks have been observed to extend from the paved area into the adjacent graded area, indicating subgrade contraction. This cracking appears to be more prevalent in granular than in cohesive soils. Structures (such as manholes and catch-basins) extending below the pavement layer are especially prone to heaving. In this condition they constitute one source of damage to snow-removal equipment. In addition, they may fracture concrete slabs at the surface or break subsurface drains.

FROST DESIGN PRACTICES EMPLOYED BY THE VARIOUS AGENCIES

Throughout Canada the depth of frost penetration is such that it is impracticable to provide pavement thicknesses that would prohibit frost penetration into the subgrade. Such thicknesses would far exceed the requirements for bearing capacity, thus construction would definitely be uneconomical. Efforts are therefore confined to minimizing the undesirable effects of frost rather than eliminating frost action altogether.

In this section consideration is given to the three basic factors in the mechanism of frost action, and specific reference is then made to the design practices of the individual agencies.

Temperature Factor

The normal practice of the Provincial highway departments is to consider an average frost penetration depth, based on general experience, for design purposes. Throughout the country, this value ranges from 2 to 8 ft. Except for Northern Ontario, freezing indexes are not normally used to determine expected frost penetration. It was found that designs based on freezing indexes were not economical because the calculated depths of frost penetration were much greater than those normally used in practice.

The Federal Department of Public Works found from field studies that the depth of frost penetration did not depend exclusively on temperature conditions but varied markedly from point to point according to the soil type, the degree of exposure, and the elevation of the site under consideration. As a result of detailed studies made in Banff, this authority evolved a series of empirical relationships that can be used to determine the depth of frost penetration at a particular site.

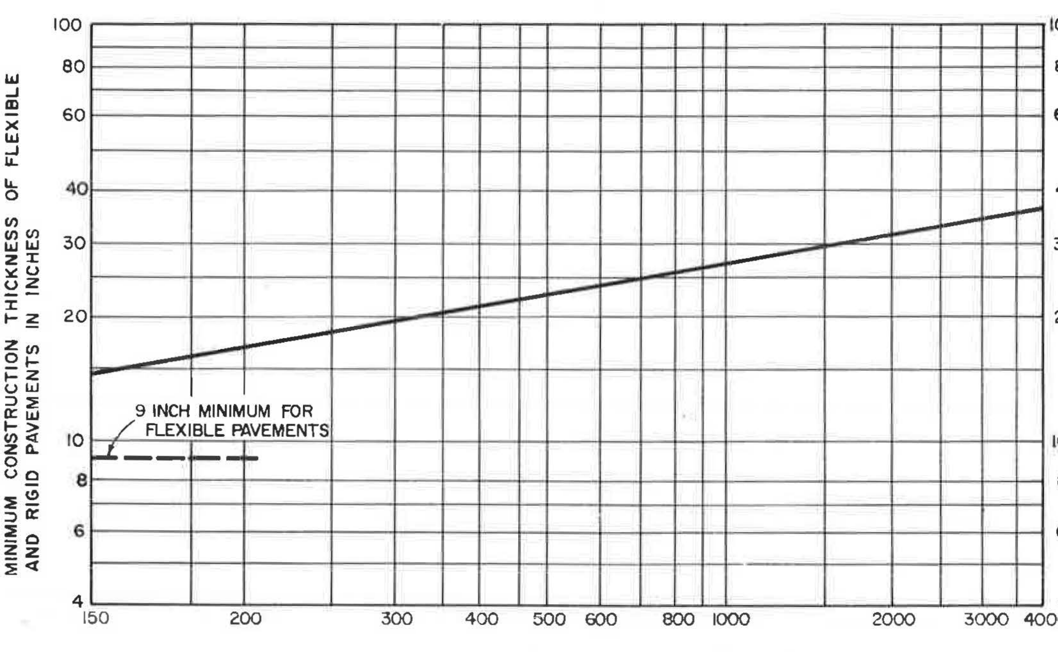


Figure 4. Department of Transport minimum depth of frost protection for flexible and rigid pavements.

Since the early 1950's the Department of Transport design procedures call for a minimum depth of pavement structure (pavement, base, and subbase) of approximately one-half the average depth of frost penetration, regardless of strength requirements. This minimum depth is determined normally from the 10-year average freezing index for the site, according to Figure 4. This method has been found to be effective in reducing frost damage to a minimum.

Soil Factor

All except one of the Canadian highway agencies base their frost design on the degree of frost susceptibility of the subgrade soil as established by various criteria based essentially on particle-size distribution and Atterberg limits. The exception is the Province of British Columbia which makes no direct use of the soil characteristics in estimating the frost susceptibility of the subgrade. In this Province, pavement design is based on the results of deflection tests made on the surface of existing pavements at different times of the year. The tests carried out in the spring period reveal the weakening effect of the thawing process, and this weakening is taken into account in the Province's design method. Identification tests are carried out on the subgrade soils, however, because the seasonal deflection studies are made only on a relatively small number of control sections, and the estimation of the loss in strength of a particular section of pavement in the spring involves the selection of a control section on the same type of soil.

All the other agencies make use of the results of the sieve analysis, liquid limit, and plastic limit tests to identify the frost-susceptible soil types. Two Provinces (Alberta and Saskatchewan) make use of the U.S. Corps of Engineers' system of classification. The Department of Public Works uses the criteria of Beskow and Casagrande; Manitoba, Ontario, and New Brunswick have related their frost experience to the proportion of silt and clay in the soil. Quebec, Nova Scotia, and Newfoundland also base their assessment on the amounts of fine material in the subgrade soil.

None of the agencies reported the use of laboratory freezing tests in their evaluation method.

In the National Parks, the Department of Public Works requires that A-4 or finer soils be kept at least 3 ft below the final pavement level, and that all organic material be removed from the subgrade. A-6 or finer soils are kept 5 ft below the pavement level, whereas all A-2 to A-4 and cleaner granular soils are selectively placed in the top 2 ft of the subgrade (they are also used as cushion over rock excavation).

In Manitoba, soils with clay fractions less than 20 percent and combined silt and sand fractions over 60 percent are considered frost susceptible. Some borderline soils with clay contents as high as 30 percent may be considered frost active.

Ontario, New Brunswick, and Newfoundland make use of empirical design charts in which the minimum thickness of nonsusceptible granular cover is obtained directly from the particle-size characteristics of the subgrade soil. The Ontario chart (Table 2) is based on the silt and clay fractions, and gives design information for flexible and rigid pavements. The Newfoundland chart (Table 3) relies on the percentage passing the No. 200 sieve. The practice in New Brunswick is to place a 1 to 2 ft layer of nonsusceptible material on soils with silt content between 35 and 50 percent. When the silt content exceeds 50 percent, a 3-ft thick layer of nonactive material is required together with a 6-in. thick filter layer to prevent fine-grained soil from working up into the overlying granular materials. Experience has shown that when the silt content of granular materials reaches 6 to 8 percent, and the moisture supply is ample, heaving is significant and thawing is accompanied by loss of density and bearing capacity. When certain clay loam and loam tills contain mica in small sizes (passing the No. 200 sieve), the frost susceptibility of these soils appears to be increased and their recovery is delayed.

The criteria used in Quebec are shown in Table 4. In general, any soil with more than 8 percent passing the No. 200 sieve is regarded as potentially frost susceptible. In Nova Scotia, the only property used to assess frost susceptibility is the amount of material passing the No. 200 sieve.

TABLE 2

ONTARIO DESIGN THICKNESSES

Soil Type	% Silt[a]	% Very Fine Sand and Silt[a]	Minimum Granular Cover[b] (in.)	
			Flexible Pavement	Rigid Pavement
Granular:				
Base course			0	0
Subbase course			4- 9[c]	4[c]
Intermediate	0- 40	0- 45	12-21	9
	40- 50	45- 60	18-24	9
	50-100	60-100	24-36	9-12
Clay[d]:				
Nonvarved			18-24	9
Varved			18-36	9-12

[a]Grain-size limits for silt are 0.005 to 0.05 mm, for sand 0.05 to 0.1 mm.
[b]Range in thicknesses covers various classes of roads.
[c]Required for stability and not for frost protection.
[d]If percentage finer than 0.005 mm is greater than 30, material is classified as clay.

TABLE 3

NEWFOUNDLAND GRANULAR BASE THICKNESSES[a]

Frost Susceptibility Classification	% Passing No. 200 Sieve	Thickness of Granular Base (in.)
Non susceptible	0- 6	3[b]
Moderately susceptible	6- 8	6
	8-10	9
	10-12	12
Susceptible	12-15	15
	15-19	18
	19-24	24

[a]It is assumed that 3 in. of Class A granular base-course material will always be used, the remaining thickness to consist of Class B granular base-course material.
[b]Leveling course.

TABLE 4

QUEBEC FROST-SUSCEPTIBILITY CRITERIA

% Passing No. 200 Sieve	% Silt and Fine Sand	Frost Susceptibility Classification
0 - 10	0 - 20	Non susceptible
10 - 30	20 - 40	Susceptible
>30	>40	Very susceptible

The Department of Transport uses a zoned particle-size distribution diagram (Fig. 5), in conjuncture with pavement condition reports and data concerning the ground water conditions, to estimate the probable spring loss in bearing capacity when actual spring load-test information is not available. This diagram gives a load reduction factor which is used in the Department's pavement design method (1).

Most agencies recognize the risk involved if boulders are introduced in fill materials or are left in the upper layers of cuts. Ontario, for instance, does not permit boulders over 6 in. in diameter within 36 in. of profile grade. New Brunswick excludes boulders over 8 in. in diameter from the top 24 in. of the subgrade; Manitoba allows none over 4 in. in diameter in the top 12 in.; and Newfoundland requires that all borrow material be smaller than a 6-in. maximum size. The Department of Transport requires that all boulders be removed from the top 24 in. of the subgrade.

Moisture Factor

All agencies recognize the important effect of ground water on frost action, and all except two require that the subgrade surface shall be at a specified minimum height above the ground water table. The two exceptions are British Columbia, where the minimum height requirement is replaced by the specification that ditches shall go down to the bottom of the base gravel, and Newfoundland, where frost design is based exclusively on the control of the soil factor.

As an alternative to the minimum height requirement, certain Provinces call for the use of a granular or clay capillary cutoff layer in circumstances where this treatment is more economical.

The ground water table is normally kept at allowable level by means of side ditches. Subdrains are not generally used by any of the highway agencies except to cut off seepage flows. The Department of Transport employs subdrains along all paved surfaces to drain the base and subbase layers. In some Provinces, the general practice now is to construct full-width granular subbases and bases to facilitate drainage.

British Columbia

The design of flexible pavements in British Columbia is based entirely on studies of the bearing capacity changes that occur on existing pavements at different times of the year. No direct account is taken of the varying frost susceptibility of the subgrade soils because this is reflected in the seasonal fluctuation of bearing capacity.

The method of design involves the seasonal study of load-bearing capacity of a number of control sections, using the Benkelman beam field test to measure the deflection of the pavement under a standard axle load. These deflections are converted, using a Department of Transport relationship between the Benkelman beam deflection and the plate-bearing capacity for a 30-in. diameter plate, to equivalent load-carrying capacities. The records of the seasonal fluctuations in load-carrying capacity are used to estimate the loss in bearing capacity that will take place on the section of pavement under consideration between the time at which the tests are made and the worst period in the spring. Once the minimum bearing capacity of the pavement has been estimated, the MacLeod equation $T = K. \log P/S$ is used to calculate the thickness required to reduce the estimated worst deflection to the maximum permissible deflection for the particular type of road. A detailed description of this procedure is given in the Appendix.

Experience has shown that the design thicknesses derived by the preceding method are very similar for frost-susceptible and non-frost-susceptible subgrades.

In British Columbia the validity of specifying a minimum depth to the water table is questioned, as heaves have been observed in fills 10 ft and even 15 ft high. In this Province, ditches are required to go down to the level of the bottom of the base gravel.

The selection of subgrade materials is not normally practiced because the pavements are designed for the actual soil conditions existing at the site. If the subgrade is very poor, its weakness will be revealed by load tests and the thickness of structure will be increased accordingly.

Compaction control requires proof-rolling of the upper 2 ft of the subgrade using a

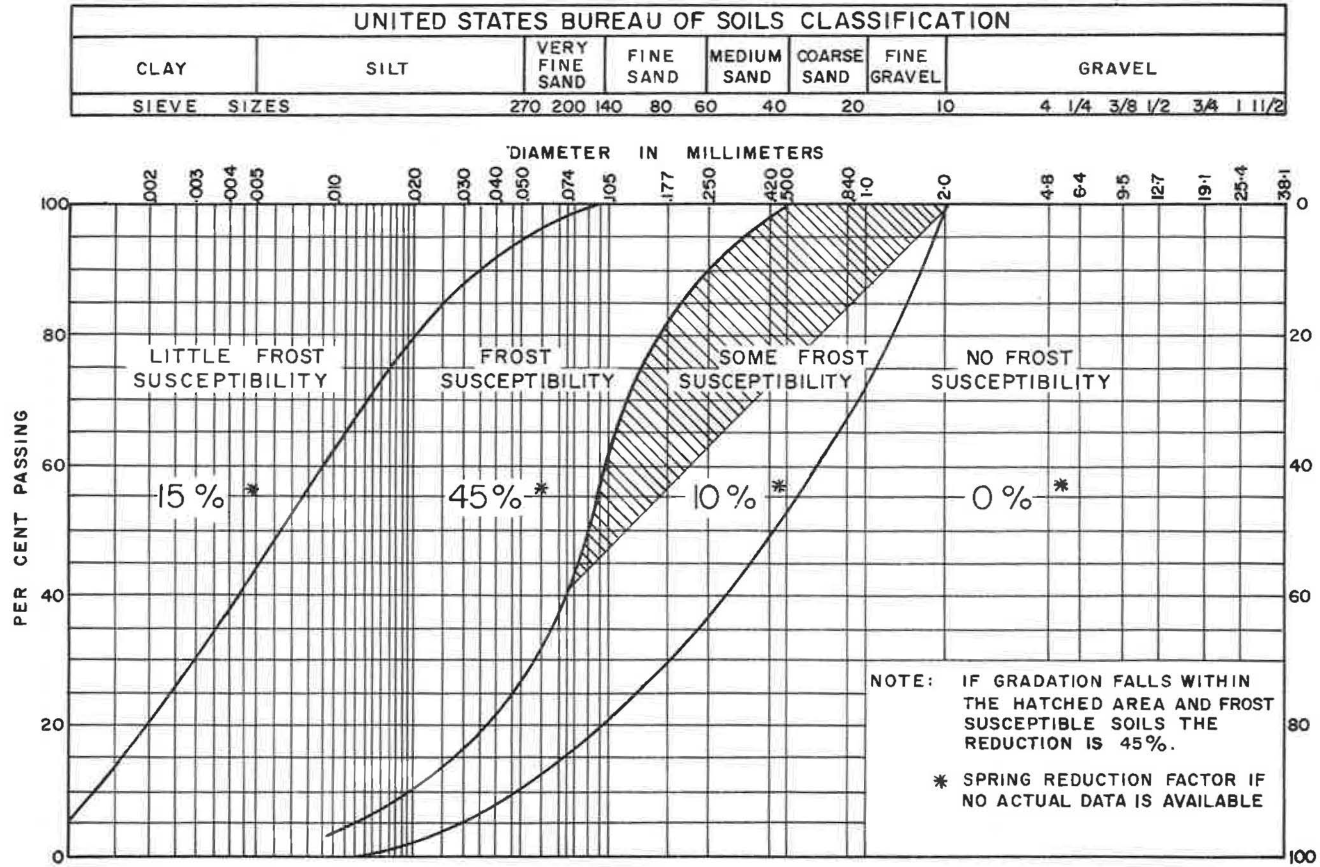


Figure 5. Department of Transport spring reduction factors.

50-ton roller. In the course of this testing weak spots that may be revealed are either recompacted or, if this does not achieve the desired strength, the trouble spots are replaced with better material. Construction is discontinued in freezing temperatures and, as a protective measure, crossfalls of 0.02 ft per foot are maintained on all earthworks to facilitate runoff.

Alberta

In Alberta wet and frost susceptible materials are usually replaced with select clay or granular material, and the ends of the excavations are sloped to prevent abrupt changes in the frost susceptibility characteristics of the completed subgrade. This replacement of susceptible or wet material is not always practicable, because in large areas of the Province no alternative materials are available. Under these circumstances some success has been achieved in minimizing frost action by special ground water control measures.

Perforated pipe subdrains or filter layers are used in cut sections and in subsurface excavations at traffic interchanges. Subdrains are also used to cut off seepage. Wherever possible these drains are installed below the frost line. It is now general practice to employ full-width granular bases to facilitate drainage of the pavement layers. Ditch bottoms are 5 ft below subgrade level.

Compaction requirements are as follows: fill materials, 95 percent of standard Proctor density; subgrade (top 12 in.) and base materials, each 100 percent of standard Proctor density.

Saskatchewan

In Saskatchewan a minimum of 4 ft of non-frost-active soil is specified for fills placed on frost-active foundations, or in cases where the water table is less than 10 ft below the ground level. In urban areas or in other circumstances where elevations are controlled (e.g., at level crossings), the top 4 ft is excavated and replaced with non-frost-active backfill. It is recognized that even the non-frost-active soils (including most base and subbase materials) support frost heaving to some extent and thus some heaving is more or less inevitable. It is attempted, however, to avoid or minimize differential heaving by making soil conditions as uniform as possible; e.g., by the use of gradual transitions at all discontinuities in the subgrade.

To facilitate drainage, grade lines are set 2.5 ft above the natural ground level. Grades are normally set 5 ft above the ground water level, but on silty soils this height is increased to about 8 ft. In some cases a granular cutoff layer placed above the water table might be required as an alternative; the thickness of such a layer would depend on the capillarity of the cutoff material. As another alternative the silty material may be excavated and replaced with suitable backfill soil. Subdrains are employed sometimes to improve drainage. In certain cases they are installed above the frost line and are expected to function during the warmer seasons only.

In bases and the top 12 in. of the subgrade, 100 percent of standard Proctor density is required, and 95 percent is required in the remaining fill material. The placing of material in thin layers is rigorously controlled and no work is permitted on the base course when the temperature falls below 35 F.

Manitoba

Frost-susceptible soils are generally replaced to a depth of 3 ft with selected granular material, clay, or other nonsusceptible soil. The backfill is placed in 6- to 8-in. thick layers, compacted to 95 percent of AASHO standard density. Grades are set at least 4 ft above the water table, and in silty soils this is increased to 5 ft.

Side ditches are used with backslopes and sideslopes at 4 to 1, and the ditch bottom is sloped away from the subgrade. The width of the ditches is between 25 and 30 ft, depending on the right-of-way and earth quantity requirements. Earthwork is discontinued when the soil begins to freeze, and no paving is permitted when the temperature falls below 40 F.

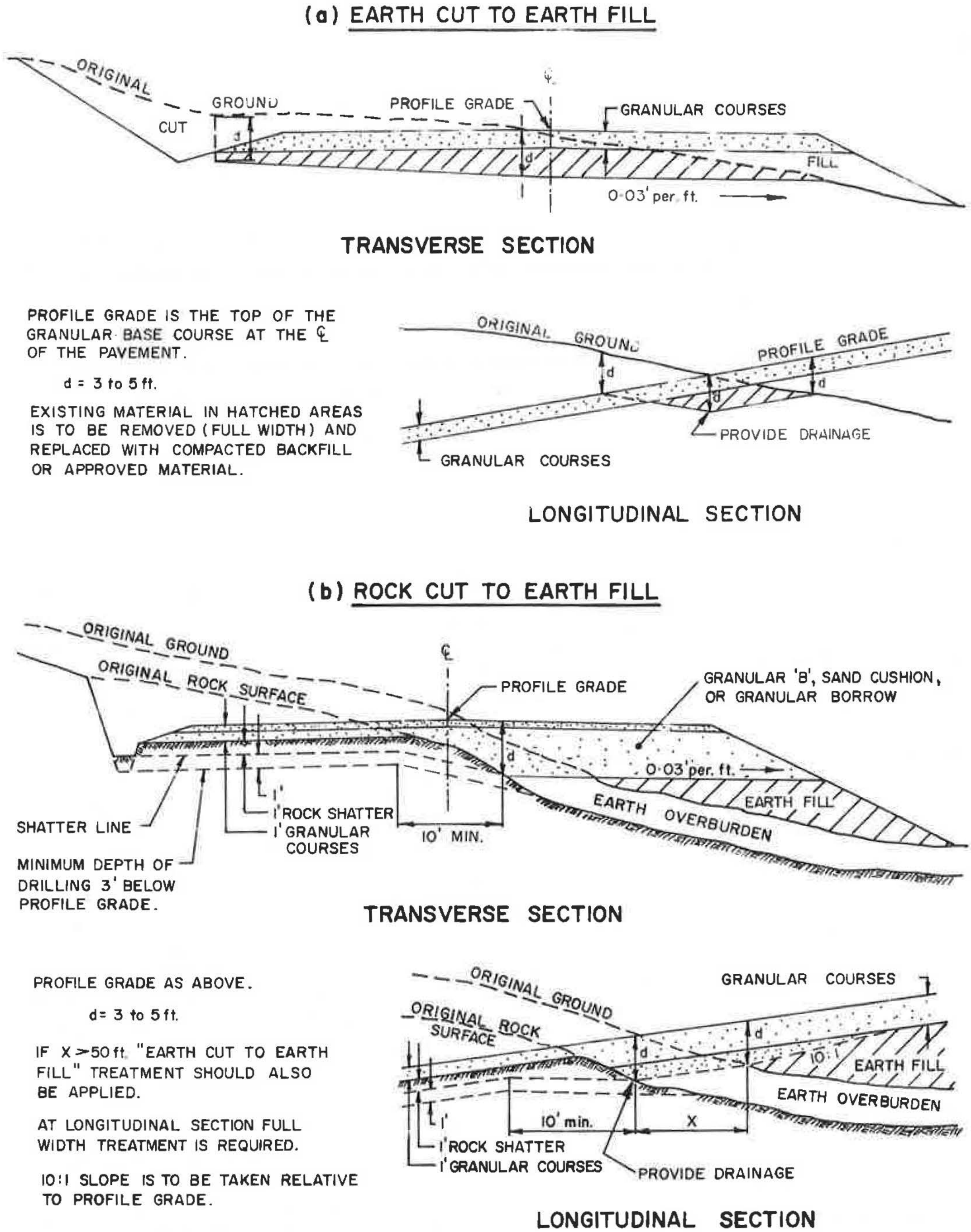


Figure 6. Ontario treatment of transition sections.

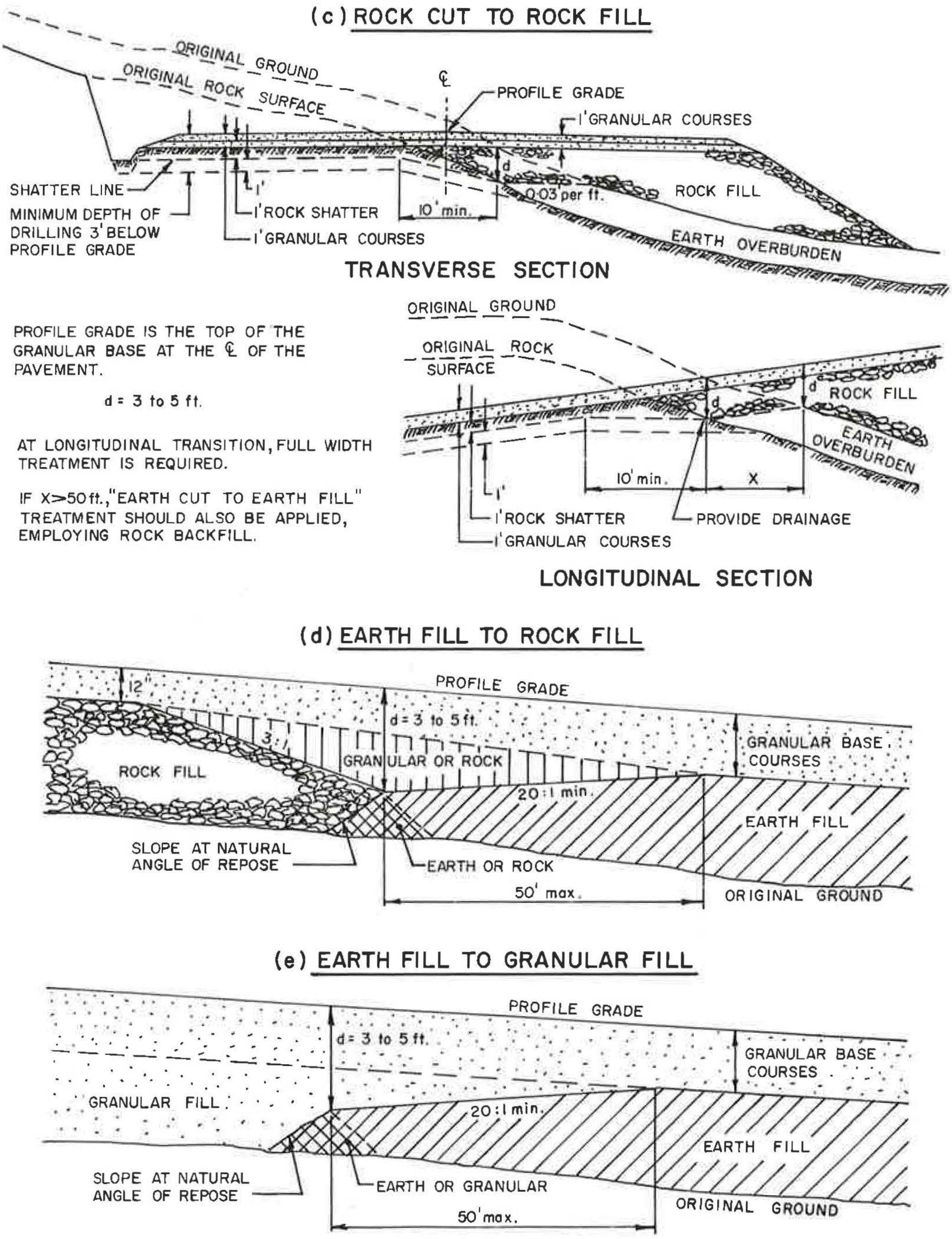


Figure 6. Continued.

Attempts have been made to use calcium chloride and sodium chloride to reduce the frost susceptibility of soils. The evaluation of these tests has not yet been completed and the method has not been accepted for general practice.

Ontario

Grades are kept at least 4 ft above the ground water table and 1 to 4 ft (or more) above ground level, depending on the drainage characteristics of the subsoil. There is a tendency to set the grade 3 ft above the ground line regardless of internal drainage characteristics, for snow control purposes. Subbases are generally placed full width and side ditches are constructed at least 18 in. below subgrade elevation. When this is not possible (e.g., due to property restrictions), perforated pipe subdrains are placed.

Pavements are usually designed for a thickness of about 0.5 to 0.75 times the depth of frost penetration. The minimum thicknesses of granular material to be used on subgrades of the various types are shown in Table 2. Though the thicknesses given by this table are used as a general guide, special account is taken of the following factors in each particular case: depth of frost penetration in the area, frost-susceptibility of the subsoils as revealed by by special investigations, susceptibility of subsoils to large changes in bearing strength, adverse moisture conditions and poor drainage, topography, and type of road.

Transition points between cut and fill require special treatment if differential heaving is to be avoided, and a series of standard treatments have been evolved for use under the various combinations of circumstances which are met in practice. These standard treatments are shown in Figure 6.

Compaction requirements for earthworks call for a minimum of 95 percent of the maximum AASHO density. For granular base and subbases, 100 percent of the maximum AASHO density is required. Construction is normally suspended in early December and no paving is permitted when the temperature falls below 35 F.

Quebec

The general rule in Quebec is to ensure that no frost-susceptible material lies within 4.5 ft of the final grade. The frost-susceptible material is either excavated and replaced with nonsusceptible material or the gradeline is raised to provide the minimum clearance.

In areas of high water table a cutoff blanket of nonsusceptible sand or gravel is used, and a sand cushion is placed at the base of embankments between the natural soil and the embankment material in cases where the subgrade is a fine-grained soil. It is now general practice to employ full-width granular construction. Side ditches are carried down to a level 18 in. below subgrade.

Newfoundland

In Newfoundland highly frost-susceptible materials are removed from the subgrade but, contrary to the general practice in the other Provinces where the replacement material is usually a selected granular material, the material removed is replaced with soil similar to that of the rest of the subgrade. The use of granular backfill material is not favored, as this is thought to produce differential conditions in the subgrade which will result in differential frost heaving. The edges of excavations are sloped back gradually to provide transitions between the different sections of the subgrade.

Rigorous compaction control is not exercised partly due to shortages of trained personnel, but also because an interval of at least 12 mo usually elapses between subgrade preparation and paving operations, during which time weak points will normally be discovered and treated. Full-width granular base-course construction is used and specifications require that all granular material should contain between 3 and 6 percent of material passing the No. 200 sieve. The thickness of granular base courses is based on the silt content of the subgrade (Table 3), and so far, the performance of the roads constructed to these requirements has been quite satisfactory.

Economic circumstances curtail freedom to choose borrow material, but when borrow materials are used they are chosen with the lowest susceptibility characteristics consistent with economy. The placing of frozen materials is not permitted.

Prince Edward Island

The general principle of frost design in Prince Edward Island is to remove highly frost-susceptible soils or to replace them with materials of better quality. In cuts, the subgrade is undercut by a minimum of 18 in. to ensure a homogeneous subgrade. The natural water table is normally lowered by deep ditching. Sand layers are sometimes used between the subgrade and the granular base in areas of high water table. Where rock strata intersect the subgrade and would lead ground water to it, the rock is shattered by drilling and blasting. Soil cement is being used on an expanding scale to improve bearing capacity and to minimize differential frost heaving.

Nova Scotia

Frost design practice in Nova Scotia is very similar to that in the other Maritime Provinces. Grades are set 4 ft above the water table and full-width granular construction is generally used. The criteria for base course materials are that not more than 10 percent should pass the No. 100 sieve and not more than 5 percent should pass the No. 200 sieve. The steepest slope used in earthworks is 2 to 1 and the minimum ditch width at the bottom is 4 ft.

New Brunswick

In New Brunswick the depth of frost penetration is considered a check on the upper limit of pavement thicknesses. Grades are set 4 ft above the water table and frost susceptible materials are usually removed and replaced with selected granular material. At grade points, the subgrade is excavated to a depth of 2 ft. The cut is carried forward toward the fill at a minimum gradient of 0.5 percent, and toward the cut at a gradient parallel to the slope of the natural ground or to maintain a depth of cut of 2 ft beneath the gradeline.

Subgrade soils are compacted to a minimum of 95 percent of standard Proctor density and granular materials are compacted to 100 percent of standard Proctor density. Paving is discontinued when the ambient temperature falls below 40 F.

Department of Public Works

Grades are set 3.5 ft above the water table in cuts and 4.5 ft in fills. Ditches are kept at least 1 ft below the subgrade level in areas of frost-susceptible soil and high water table. Compaction standards call for soils to be compacted to 95 percent of standard Proctor density, with the top 6 in. of the subgrade compacted to 100 percent. Sand filters are used on top of subgrades containing saturated silt soils.

In cuts, frost-susceptible soils are excavated and replaced with suitable nonsusceptible material. Where subexcavation is not required and a granular subbase is provided, the subgrade soil is scarified to a depth of 6 in., and recompacted to 100 percent Proctor density. If no granular subbase is placed, the top 12 in. of the subgrade is treated in a similar manner.

Full-width granular construction is the normal practice. Granular materials are restricted to a maximum of 8 percent passing the No. 200 sieve and are compacted to 100 percent of standard Proctor density. The paved surface includes the shoulders.

During construction, a 6-in. crown is maintained on earthworks to facilitate drainage. Embankment material is not placed in a frozen state nor on a frozen surface.

Department of Transport

The Department of Transport flexible design procedure for airfields assumes that the bearing capacity of a pavement surface is proportional to that of the subgrade, so that the spring reduction in subgrade bearing capacity is a very important design consideration. The effect on flexible pavements is much more severe than on rigid pavements. In the rigid pavement design procedure employed (Westergaard, central loading condition), the effect of the subgrade strength on the strength of the pavement is more complex but, in general, a 50 percent reduction in the subgrade strength will only reduce the load-carrying capacity of the slab by approximately 20 percent. However, there is evidence that the subgrade or base has a greater influence on the load-carrying capacity of a concrete slab than is apparent from the Westergaard theory.

In the case of rigid pavements the thickness of the pavement structure is almost invariably governed bv the frost protection requirements, whereas in the cases of flexible pavements, the pavement depth is governed by frost in the case of light aircraft loads or strong subgrades, and by strength conditions in the case of weak subgrades or heavy aircraft loads. Where the existing subgrade consists of a nonsusceptible granular soil, the minimum depth requirements may be waived.

Grading requirements call for the removal of all frost-susceptible material to a depth of 3 ft below the pavement surface. If such materials occur in isolated pockets, removal to greater depths may be required by the engineer. Where changes in subsoil conditions occur, transitions are made as gradual as possible.

All fills are compacted to a minimum of 90 percent of modified Proctor maximum density, and the top 5 in. of cohesive soils or the top 12 in. of granular soils are compacted to a minimum of 95 percent of modified Proctor density. In cut sections, the soils are scarified and recompacted in a similar manner. Subbases are compacted to 98 percent and bases to a minimum of 100 percent of the modified Proctor maximum density.

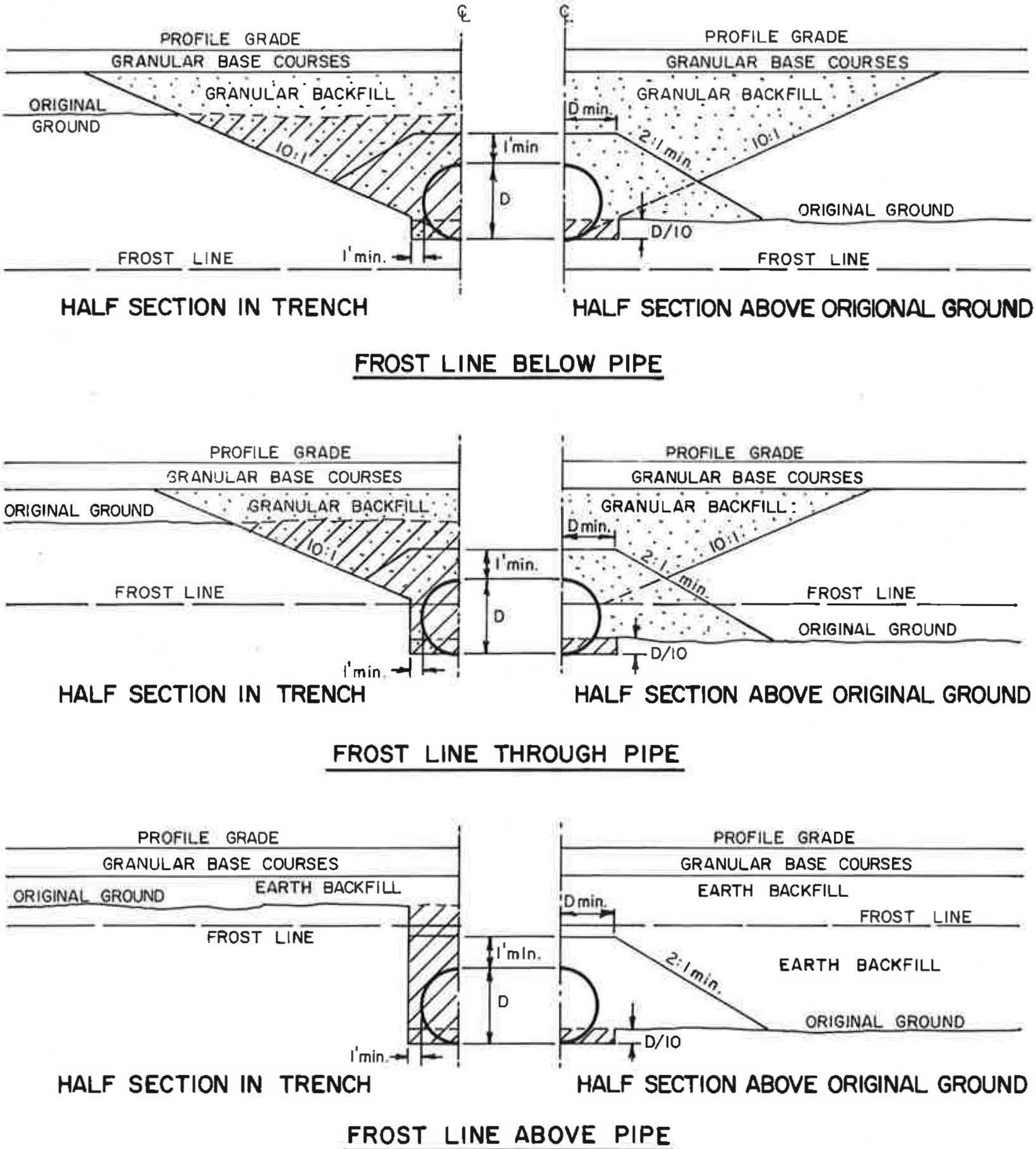
Except in clean granular soils, perforated metal drains are laid along all pavement edges to drain the base and subbase. If possible these pipes are placed below the frost line and the trenches are filled with graded filter material. In rock cuts, it is common practice to remove some of the rock, replace it with granular material, and in addition, to shatter the surface of the rock to a depth of approximately 12 in. to facilitate drainage further.

The Department of Transport normally attempts to keep the finished pavement surface at least 3 to 4 ft above the ground water level. The selection of the minimum height depends on such conditions as climate, soil type, drainage characteristics, and economic considerations. When the depth of ground water table is less than 3 ft, the spring load reduction factor (Fig. 5) is increased by 10 percent on all soil types.

Special Treatment at Structures

In the cases of bridges, foundations are normally located below the frost line so that the bridge structure itself will not normally be affected by frost action. The main treatment at structures involves the use of nonsusceptible granular material as backfill. All agencies specify the use of such granular material and all stress the need to ensure that the adjacent fill is cut back at a slope to make the transition from the fill to the structure as gradual as possible, in order to minimize differential movements and heaving between the pavement and the structure itself. British Columbia, for instance, requires the use of non-frost-susceptible material in backfills within 50 ft of bridge abutments. New Brunswick requires the slope of the surface of the fill to be beveled back at the rate of 1 in 4. Ontario calls for slopes of 10:1 from the point where the frost line intersects the backface of the abutment.

Similarly to bridges, granular backfill is used to avoid differential heaving at culverts. The Department of Public Works specifies 8 in. of granular material below the invert of the culverts and the use of granular backfill to a point 1 ft above the top of the culvert. Where the culvert is placed below the frost line, the trench is cut back at a slope of 10:1 or to a maximum of 50 ft. The standard design practices adopted in Ontario are shown in Figure 7.



NOTES.

D = INSIDE DIAMETER OF PIPE. WHERE PIPE-ARCH IS USED SUBSTITUTE SPAN FOR D.

HATCHED VOLUMES TO BE EXCAVATED AND BACKFILLED.

GRANULAR BACKFILL, WHERE APPLICABLE, TO EXTEND ACROSS ENTIRE ROAD SECTION.

Figure 7. Use of granular backfill at culverts (Ontario).

SPRING LOAD RESTRICTIONS

Although new sections of the primary highway routes are being designed and constructed to the standards required to carry the maximum authorized loads throughout the year, some Provinces are still constructing secondary highways with the intention of applying load restrictions in the spring period. In addition to these new sections of road, there are large mileages of older roads that must be protected in the spring by limiting loads, and the various Provinces have evolved their own techniques for deciding when and where to apply these limits, and what the limits shall be.

In British Columbia the period of restriction and the extent of the load reduction is fixed on the basis of the results of deflection tests made on a number of specially selected control sections at frequent intervals throughout the year, and particularly in the spring period.

The deflection tests are made with the Benkelman beam, using the standard axle load and the standard test procedure of the CGRA (2). As the most important tests are made when the pavements are in their weakest condition and the results may be influenced by the size of the deflection bowl, the CGRA procedure for correcting this possible error is rigorously followed. Also, as the strength of asphalt pavements is affected by their temperature, the test results are converted to an equivalent deflection at 32 F, using a correction factor determined experimentally by the Department of Transport (0.001-in. deflection for every 5 F difference in temperature). On each of the control sections, which are chosen to be as representative as possible of the complete range of climatic, soil, traffic and drainage conditions in the Province, 10 deflection tests are made at randomly selected positions.

After correction for possible inaccuracy due to large deflection bowls and for temperature, the mean value for the control section is found, and to this is added 1.5 times the standard deviation of the 10 results. The resulting figure is a prediction of the deflection value which would be exceeded only in six tests in every hundred if an unlimited number of tests could be carried out; it is called the "restriction deflection."

Experience has shown that if pavements are to remain undamaged in the spring under normal vehicle loadings the maximum deflection obtained by the standard procedure should not exceed the "critical deflection" of 0.040 in. If the restriction deflection exceeds the critical deflection, vehicle loads are restricted to a percentage of the normally allowed maximum load which would produce a restriction deflection of 0.040 in. if applied to the pavement at the worst time in the spring period.

It is possible to calculate the permissible percentage of normal full load for a given pavement from a knowledge of the restriction deflection and the critical deflection using a Department of Transport relationship between Benkelman beam deflection and plate load capacity (3), but in practice it is read directly from Figure 8. The two values of deflection plotted on the chart and the zone into which the point falls indicates the permissible percentage of full load. As a general rule the permissible load is not reduced below 70 percent of full load on primary highways and below 50 percent on secondary highways.

In a somewhat similar manner, the results of Benkelman beam tests serve as basis to determine the time, duration, and location of the spring restrictions necessary in the Province of Alberta.

In Saskatchewan, as soon as the frost begins to leave the pavement, a number of Benkelman beam trucks are placed on continuous circuits to test the paved highways. These tests are continued well beyond the critical spring period. These results and the observations of the Maintenance Branch District engineers are the information on which load restrictions are based. The load restrictions are usually in effect by April 1 and removed by May 15. The deflection tests are taken on the weaker controlling sections between destinations for commercial traffic. The restriction limit is either 350 lb per inch of tire width (gross limit 72,000 lb) or 250 lb per inch of tire width (gross limit again 72,000 lb). Restrictions are not specifically related to climatic conditions. They are related to pavement type and soil type, in that the control sections are the weakest pavement sections between destinations.

Observations and past experience are used to predict the time of load restrictions

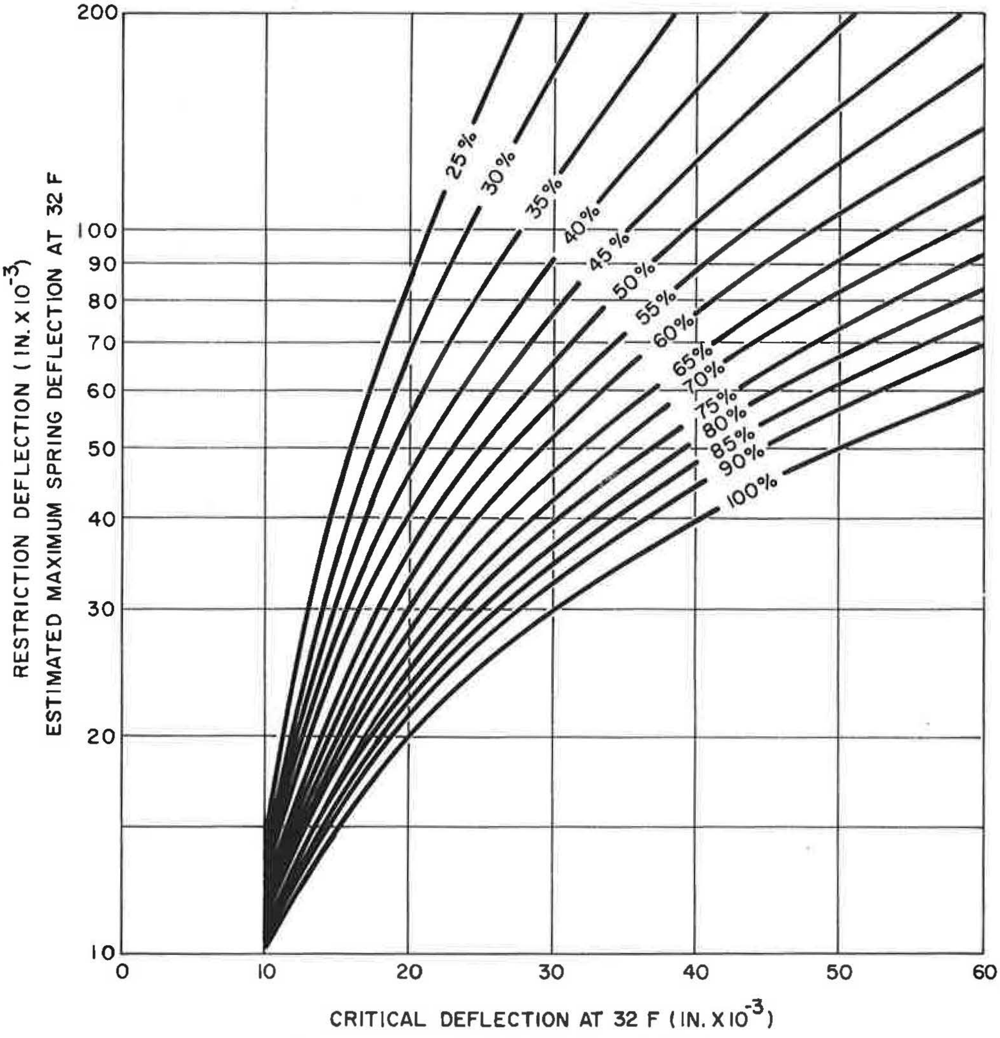


Figure 8. British Columbia load restriction chart.

in Manitoba. This is done in conjunction with Benkelman beam deflection data which has become an increasingly more important factor in placing of load restrictions. Restrictions are generally placed on highways in the northern part of the Province at a later date than those in the southern part, with the average period being April 1 to June 1. Roads other than Provincial trunk highways are generally restricted to 350 lb per inch of width of tire or 250 lb per inch of width of tire, and the maximum load is sometimes limited to 6,000 lb. No restrictions are imposed on concrete pavements.

Half-load restrictions are applied to certain highways in Southern Ontario and to most highways in the northern part of the Province. Most secondary highways and country roads throughout the Province are subject to spring restrictions. The actual sections of road to be restricted, the start of the restriction and the duration are decided by the Maintenance Branch on the basis of past experience.

The method of determining the needed load restrictions in Newfoundland is somewhat arbitrary at the present time, and is generally carried out on the basis of the experience of the District maintenance personnel. When restrictions are imposed, commercial vehicles are limited to one-half their registered gross loads. Half-load limit signs are posted on all roads affected and the public is informed of restrictions by the news media.

In New Brunswick, the duration of load restrictions and the time of lifting these restrictions are determined by the Benkelman beam deflection method. For purposes of weight restriction application the Province is divided into the southern and northern halves, between which there is a time difference of about 2 to 3 weeks both in imposing and lifting of weight restrictions. There are two main reasons for this: the difference in latitude, and the fact that the northern half is at a generally higher elevation than the southern half. Soil types also cause some difference in timing the lifting of the weight restrictions, because of the slow rate of strength recovery shown by certain soils.

Alberta, Nova Scotia, and Quebec also employ the Benkelman beam to measure the spring reduction of load-carrying capacity.

TRENDS AND RESEARCH NEEDS

Recent developments resulting in a better understanding of the complex phenomena of frost action contributed considerably to improved design and construction methods throughout the country. Research findings of such organizations as the CGRA, NRC, HRB, and certain universities are often quoted and gradually more and more used in the everyday practice. Each Province reports a major upgrading of design standards in recent years, and that the problem of frost action is generally being given more consideration during the investigation, design, and construction stages. As a result, gradually more and more applied research work connected with frost action problems is being carried out by the various highway agencies, which in turn will inevitably contribute to a better understanding of the underlying theoretical principles. Samples of present research activities and further needs follow.

In British Columbia major emphasis is being placed on improving the technique and interpretation of the Benkelman beam method in evaluating frost heave problems. Some consideration is being given to establishing a research project on injecting chemicals into the roadbed in frost heave areas.

Steps have been taken in Saskatchewan to correlate freezing index with the required thickness of non-frost-active material under the road surfacing. There appears to be considerable merit in this approach. On the basis of observations, tests on winter core-samples, and data reported by investigators outside the Province, the criteria for frost susceptibility have been improved. This improvement should continue with the evaluation of existing special design sections in frost-active areas. Further field and laboratory research is considered necessary to establish better design methods in areas of high freezing indexes.

Manitoba reports that frost heave measurements are being taken on several highways involving several different soil types, and are related to such factors as precipitation and temperature variations, as well as depth of frost penetration. Stabilization and treatment of susceptible soils may be tried although economical considerations do not usually allow this approach. The use of an insulation layer on the pavement may be attempted soon to ensure or assist frost escape from the bottom up. This would prevent the trapping of moisture above the frost line and the subsequent supersaturation of the roadbed. Calcium chloride has been injected in troublesome frost boils to reduce heaves. A study of soil type, drainage, pavement structure, and maintenance costs may be made to determine economics of wasting or treating frost-susceptible soils as opposed to simply maintaining the road by repairing it after partial failure. Clay mineralogy studies are being carried out using both differential-thermal analysis and X-ray defraction analysis, and it will be attempted to relate this information to frost susceptibility.

During the course of an Ontario research project, started in 1961, reference nails were installed at 20 representative highway locations throughout the Province. The elevation of these reference nails is checked on a weekly basis during the freezing and thawing seasons. These data are being analyzed with reference to the magnitude, timing, and pattern of pavement movements. It is also attempted to correlate pavement movements with the variation of climatic factors. Several smaller investigations are being carried out concerning the effect of soil type on the nature of frost action, involving the use of laboratory freezing cabinets. Field experiments have been conducted to evaluate the method of injecting lignosol into areas of bad differential heaving. Efforts are continued to establish reliable correlation between the degree of frost susceptibility and pore-size characteristics.

In Newfoundland non-frost-susceptible materials are in short supply, consequently the provision of granular base course materials is very costly, especially because these materials must have not more than 6 percent minus No. 200 material. It would be of great assistance if research could show a relationship between the critical minus No. 200 percentage and the physical properties of the minus No. 200 material. Perhaps the maximum of 6 percent could be increased without detrimentally affecting the road structure during the spring break-up conditions. So far, all minus No. 200 material has been considered as a uniform material, mainly because it seems to be reasonably uniform from a grain-size point of view. However, there is probably some significance in the shape of these particles, especially with regard to potential capillary action, and research in this direction might produce some very useful results.

The most notable change in recent design practice in New Brunswick is the use of the Benkelman beam deflection method for determining overlay thicknesses to rehabilitate old pavements. When the loss in spring bearing capacity of the road is known, this may be combined with the detailed deflection data to make a design that will provide a higher and more uniform spring bearing capacity. Research is needed in the evaluation of soil-cement as a base course layer, the maximum and minimum layer thickness, and effective methods of placing a seal coat on soil-cement. Research is also needed to devise a method of getting in-place densities in granular materials so as to give more reproducible results.

A substantial degree of success has been attained by using the present methods in the practice of the Department of Public Works, but is felt that further improvement and economy can be gained by paying more attention to better drainage of the highways. Soil types that are presently being excluded from the highway embankment could be used within the core of large fills if the postconstruction drainage conditions could be predicted and effectively handled. Stage construction should be planned wherever practical as a means of locating and correcting frost heave and structural deficiencies before the application of the final pavement. Present field research activities include the measurement of frost penetration, frost heaving magnitude and the rate, extent, and pattern of ice lensing. Such aspects as the effect of sanitary services on the thermal regime of the soil, the effect of snow cover on frost penetration, the variation of surface deflections due to variation of soil and temperature conditions, the effect of ambient temperatures on frost penetration, and the effectiveness of sulfide liquor treatment are also investigated. These investigations are still in the initial stages and the results will be published later. Further research should be carried out in connection with such aspects as the thermal conductivity of the different soil types, the effect of pore size on frost susceptibility, and the effectiveness of chemical treatments.

Studies of frost penetration by the Department of Public Works in the Banff area of Alberta resulted in the general equation:

$$D = a + b.\sqrt{F}$$

in which

D = frost penetration depth (in feet); and
F = cumulative degree-days below 29 F (air temperature).

The values of a and b depend on the type of the soil, drainage conditions, and the nature of the snow cover. It was found that a varied between 0.5 and 3.5, and b between 0.05 and 0.40, with average values of 1.3 and 0.12, respectively.

The most urgently needed improvement in the practice of the Department of Transport is a better method of determining the reduction in pavement load-carrying capacity during the thawing period. The most promising approach to the problem appears to be the present program of determining the actual strength reduction by field strength tests and the correlation of these reductions with relevant factors, such as subgrade soil type and condition, pavement thickness, and freezing index.

In the interest of economy, it will never be practical to eliminate entirely all heaving of the highway due to frost action. What is desirable and probably within economic and technological reach is the elimination of perceptible degree of differential heaving. A prerequisite to tolerable uniform heaving is a high degree of uniformity of the variables contributing to the phenomena. These conditions are rarely found in nature but should be attainable by selective disposition of subgrade soils, effective drainage, and over-all quality control of construction. The majority of data, criteria, and technology necessary to accomplish this is presently available, although further research and consequently a greater understanding of the mechanism of frost action will undoubtedly bring about a wider and more economical application of the necessary control measures.

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Appendix

PAVEMENT DESIGN IN BRITISH COLUMBIA

The structural design of flexible pavements in British Columbia is based on the seasonal fluctuations in strength characteristics estimated from Benkelman beam deflection values. Obviously, it is quite impracticable to make seasonal deflection studies on every section of highway that comes up for design; therefore, use is made of a system of "control sections" distributed throughout the Province.

The control sections are chosen to be as representative as possible of the full range of soil, climatic, traffic, and drainage conditions existing in the Province, and the different types of road structure and maintenance practices. They are 1,000 ft long; 10 Benkelman beam tests are made on them at randomly selected points at weekly intervals throughout the year to provide a record of the seasonal fluctuation of pavement strength. The deflection tests are carried out using the CGRA standard axle load and test procedure (2); the individual results are corrected for possible measurement errors due to very large deflection bowls which upset the reference plane of the beam. The results are also converted to equivalent deflections at 32 F using a conversion allowance of 0.001 in. per 5 F evolved by the Department of Transport.

When the design of a project is under consideration, the proposed route is divided into 1,000-ft lengths and, using a table of random numbers, 10 deflection tests are made on each section. At the same time, tests are carried out on corresponding control sections and the results are used to estimate the loss in load-carrying capacity that each section of the project would undergo between the time of testing and the weakest

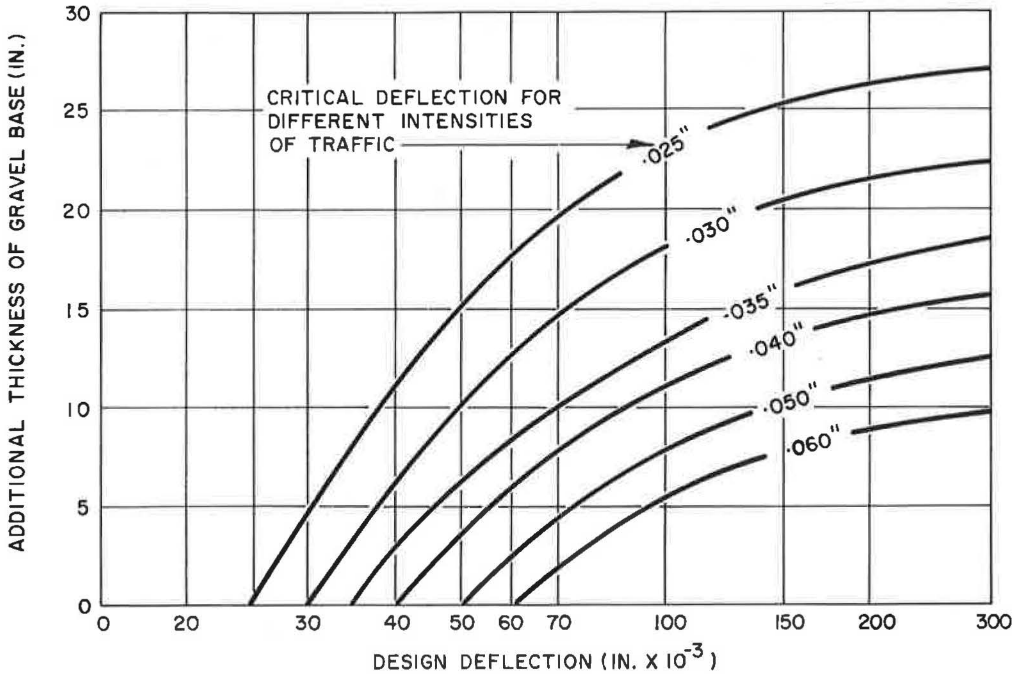

Figure 9. British Columbia pavement design chart.

time in the spring. The conversion from Benkelman beam deflection values to load-carrying capacity is made using an experimental relationship derived by the Department of Transport from extensive testing of airfield pavements (3).

Each of the test results on the individual sections of the project is converted to an estimated worst spring value and the mean for each section is calculated. To each mean is added an amount equal to 3 times the standard deviation of the 10 converted spring values to obtain an estimate of the deflection that would probably only be exceeded in one test out of a thousand if an unlimited number of tests could be carried out in each section. This estimated worst deflection is used as the design deflection.

Experience in British Columbia has shown that the maximum permissible deflection (or critical deflection) must not exceed 0.037 in. for heavily trafficked roads, 0.045 in. for medium or average traffic, and 0.056 for light traffic.

A design chart devised by Wilkins (4) is available (Fig. 9) which enables the extra thickness of granular material required on each section of the project to be determined quite readily. As an example of the use of this chart, if the design deflection of one section is assumed to be 0.090 in. and the estimated traffic is such that the maximum permissible deflection (or critical deflection) is 0.045 in., then the chart is entered on the horizontal axle at a value of 0.090 in. and a vertical line is followed until the curve for 0.045-in. deflection is encountered. From this point, a horizontal line is drawn to intersect the vertical axis and the additional thickness of granular base is read off. If an asphaltic concrete surfacing is to be placed, it is taken as equivalent to twice its thickness of gravel. So that in this example, where the extra depth of gravel required is 10 in., if an asphaltic concrete surfacing 3 in. thick is contemplated, the net thickness of gravel required would be 10 - 6 = 4 in.

The design chart is based on the Department of Transport relationship between Benkelman beam deflection and the load capacity of a 30-in. diameter plate, and the McLeod design formula T = K. log P/S, in which T is the required thickness of gravel; K is equal to 35 (a constant for highways); P is the required bearing capacity of the pavement (equivalent to the Benkelman deflection permitted for the given traffic conditions); and S is the actual bearing capacity of the existing pavement (equivalent to the estimated worst spring deflection).

Discussion

K. N. BURN, Soil Mechanics Section, Division of Building Research, National Research Council, Ottawa, Canada—The authors are to be complimented on the excellent manner in which they have produced their very comprehensive report. Because of its wide scope, it was probably not possible to include detailed information on field studies of frost heave and subsequent damage. Some measurements made a few years ago at the site of the Building Research Centre in Ottawa might prove interesting and useful in this connection.

Early in the spring of 1955 as snow began to melt, longitudinal cracks in the surface of a pavement were discovered in a cut section of a road leading down to a basement level service area. The pavement had obviously heaved badly, so points from which to measure surface elevations across the road were quickly established and surveys conducted periodically until thawing of the roadway had ended.

The subgrade material is a post-glacial clay known as Leda clay which often contains up to 45 percent silt-size particles. It is weathered to a depth of 10 to 12 ft and is frequently fissured to about 20 ft. The roadbed was prepared by first compacting this material. An 8-in. base of graded coarse material was placed and compacted, followed by a 4-in. subsurface layer of bituminous concrete and a $1\frac{1}{2}$-in. wearing surface.

Traffic is light and slow moving over this service road but it is occasionally used by quite heavy vehicles. It is kept clear of snow during the winter, but because it is low-lying, the area has a tendency to trap drifting snow and this is piled high on either side of the roadway. During the winter preceding these measurements, the roadway was plowed off-center with the result that the western side was always covered with snow but the eastern side was bare beyond the pavement.

The summer of 1954 was only slightly drier than normal, but autumn rains as usual returned the soil to a saturated condition. Snowfall was nearly normal (86 in.) and the freezing index of 1, 700 degree-days was quite close to the 65-year mean.

Figure 11 shows the positions of the cross-sections that were observed in relation to the longitudinal cracks that appeared. The roadway is actually a ramp running from field level beyond the top of the figure to basement level in the large service area next to the building. The small inset cross-section is for that at B where the surface of the road is about 7 ft below field level.

Figure 12 shows pavement elevations for four surveys made during April for all three sections. The maximum heave measured in this manner was 8 in. in the center section. (It probably was somewhat greater than that because other plots of frost heave against time indicated that a maximum occurs early in March. Measurements made the following winter again indicated a maximum of approximately 8 in., but this followed an exceptionally dry summer and fall.) Measurements of the width of the crack in the pavement at each section are shown to illustrate how it closed as the subgrade thawed out.

Eight inches appears to be quite large, but conditions for ice lensing were obviously just right. Free water must have been supplied to the freezing soil beneath the roadway through the fissures in the clay which was kept from freezing by the deep insulating cover of snow on either side.

During the same winter measurements of heave were also made on the surface of an adjacent roadway including the point where it crossed a heated service tunnel. The upper surface of the tunnel is just at subgrade level and the road itself was constructed in the same manner as the one previously described. A number of points were established on the centerline of the road, but heave with time is plotted for only four of them in Figure 13: the point that heaved the most at 6 ft from the centerline of the tunnel (Curve C), a point over the center of the tunnel where the measured heave was the least (Curve B), a point 50 ft from the tunnel (Curve A), and a point over a culvert that exhibited an unusual time-heave plot.

Near the tunnel there was little snow insulation but water was readily available to the zone of ice lensing because heat losses from the tunnel kept the subsoil unfrozen and supplied with melting snow. Movement of moisture to the freezing zone would be

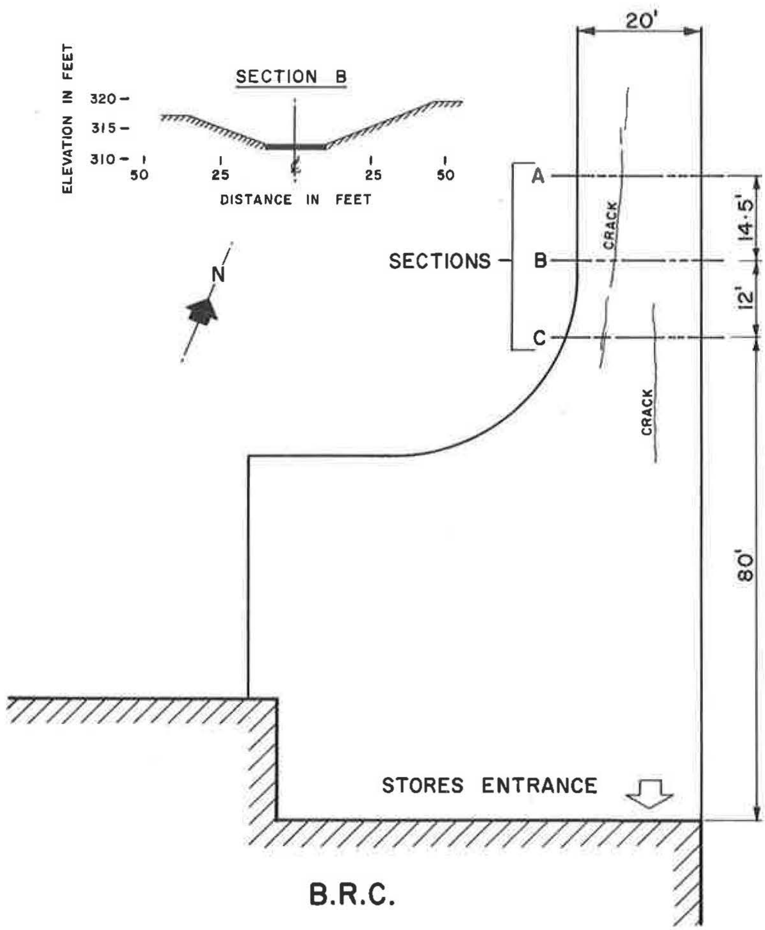

Figure 11. Plan of rear of Building Research Centre showing position of cracks in roadway and sections studied.

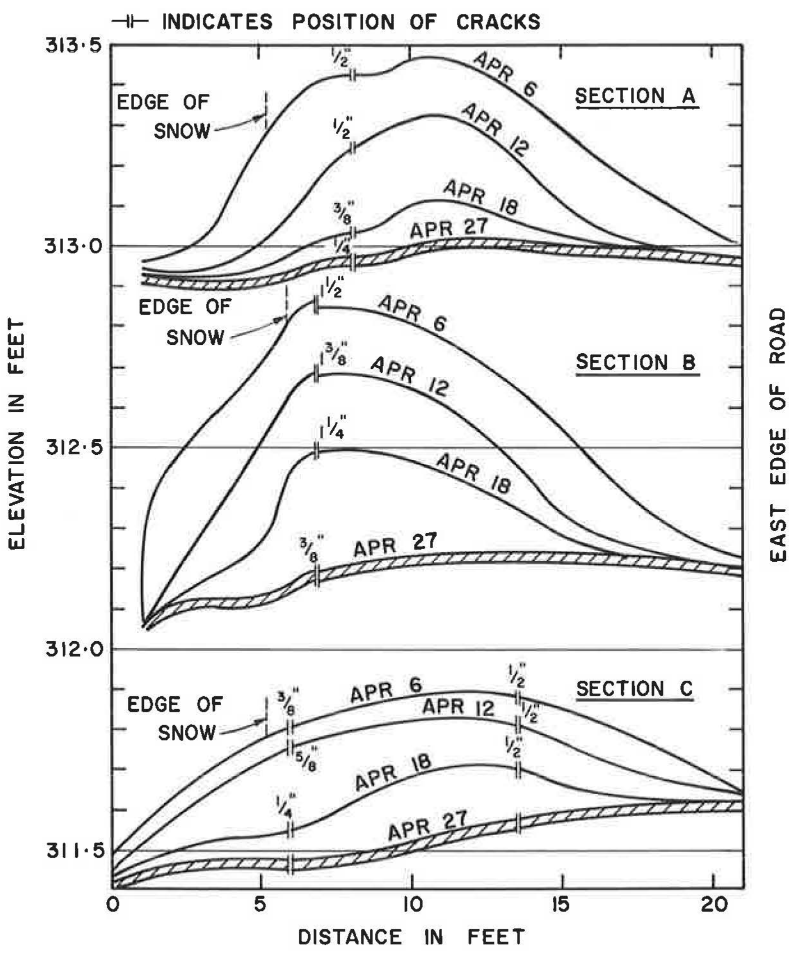

Figure 12. Settlement of road surface during thaw, April 1955, at the Building Research Centre.

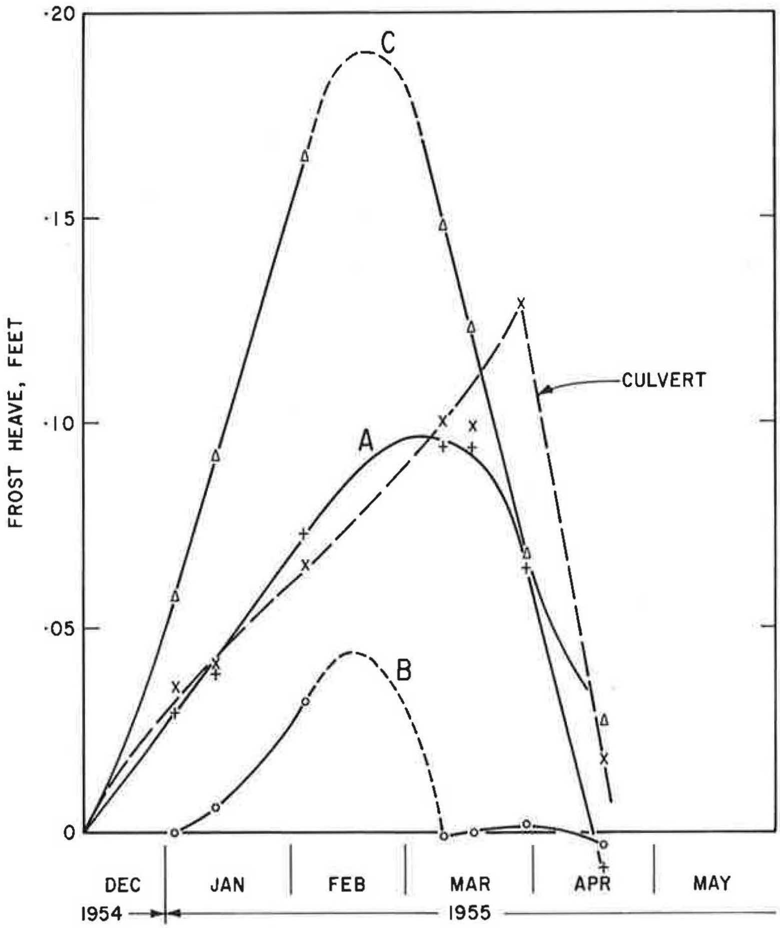

Figure 13. Measured frost heave of a road over a heated tunnel.

aided by the high thermal gradient existing between the tunnel and the zone of ice lensing. This differential heave along the centerline of the road, occurring as it does over a very short distance, very quickly resulted in cracking of the pavement on each side of the tunnel and parallel with its axis.

Frost heaving at two widely separated culverts on same roadway was also measured. Here the road stands about 3 ft above field level and the two culverts of corrugated steel beneath it are $1\frac{1}{2}$ ft in diameter. Road fill was all compacted crushed stone above natural ground surface with the inverts of the culverts at the same level. Because drainage of this flat area is almost non-existent during the winter, no free water can be fed to the soil around the culverts and the measured heaves over the centerline of these culverts and points 5 ft away from them in the center of the road are practically identical with the heave measured at a point well removed from such influences. When the first thaw occurs, usually in March, water does become available at the culverts in gradually increasing quantities and although the unaffected road surface is starting to come down, ice lensing and heave continue to increase in the vicinity of the culvert, until it is overcome by the general thaw. The time-heave curve for one of the two culverts shown in Figure 13 illustrates the unusual condition in early spring. This was the case at both culverts and the preceding explanation may account for the common belief that frost heaving is especially severe just before breakup.