Measurement and Prediction of Frost Penetration in Highways

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Knowledge of the depths of frost penetration in highway roadbeds is essential to determining the safe location of structural foundations, sewers, pipelines, and water mains. Most of the current knowledge of frost penetration is limited to sparsely documented information gained from studying boreholes and excavations, even though a method exists for predicting the relationship of frost penetration to air freezing index. Through a 5-year program of measuring frost depth by use of frost depth indicators at 62 locations in Ontario, a body of data has been acquired and used to make the relationship between frost penetration and air freezing index more appropriate to Ontario. To further assist the user of this relationship, a freezing index map of the province has been created from published temperature data observed at 224 locations during the period from 1941 to 1970. The map was prepared by using a method recently developed by the National Research Council of Canada that calculates the air freezing index from mean monthly temperatures. Although the method is simple to use, local factors such as soil type and moisture content influence the actual depth of frost penetration. To enable such effects to be evaluated and to provide the capability of examining the effects of insulation and frost retaining layers, a computer program to solve the heat flow relationships was developed for the Ministry by Carleton University. The program can predict the maximum frost penetration and ground temperatures from information that is, in most cases, readily available. Computer predictions at several sites have been favorably compared with measurements of actual frost penetration and time profiles.

Winter temperatures in Ontario often fall to -50°C and remain at temperatures below -30°C for long periods in many parts of the province. Moreover, many areas of Ontario experience more than 150 days of below-freezing weather each year. Under these conditions, freezing temperatures penetrate 1.5 to 3 m below the road surface. The resulting changes in volume cause portions of pavement surface to heave upward as much as 0.3 m. Frost heave threatens the integrity of roadway structures, sewers, pipelines, and water mains. To prevent disruption of these services and to avoid structural foundation problems due to frost action, these structures and foundations must be located below the frost line. Because cost and difficulty increase rapidly with the depth of excavation needed to locate the structure below the frost line, a knowledge of the greatest depth of frost penetration is essential.

One method of estimating frost penetration, established by the U.S. Army Corps of Engineers in 1947 (1), uses a relationship between frost penetration and air freezing index. This relationship takes the form "P (meters of frost penetration) equals a constant times the square root of F (the air freezing index in degree-days)." The method of determining F is described later in this paper and is identical to the definition given by the U.S. Army Corps of Engineers. In this study a more specific relationship between frost penetration and air freezing index was developed for Ontario highways. A revised freezing index map of the province that was created from 30 years of air temperature records taken at 224 locations is also presented.

Another method of predicting frost penetration, which is becoming more readily applicable because of advances in computers, is through calculation of heat flows given the soil parameters and air temperature regime.

Both methods are examined in this paper and compared with actual frost penetration measurements.

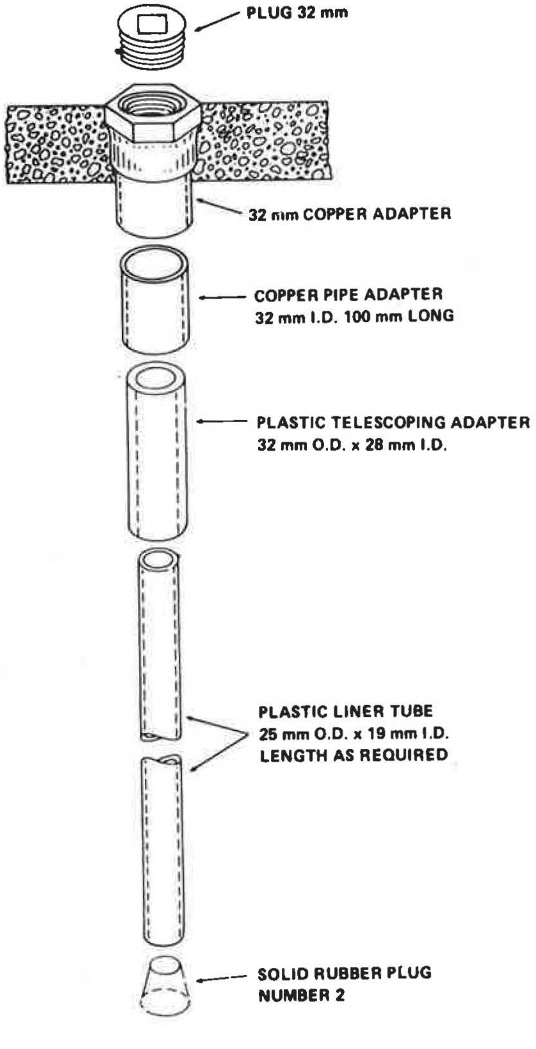
FROST INDICATORS

The frost indicators used by the Ontario Ministry of Transportation and Communications (MTC) to measure frost depth (Figures 1 and 2) are adapted from the Swedish (Gandahl) design and the U.S. Army Cold Regions Research and Engineering Laboratory (CRREL) design.

The Gandahl-type indicator consists of a rigid transparent plastic tube with blue indicator solution contained in an annular space created by a soft rubber insert in the tube. The dark blue indicator fluid (0.05 percent methylene solution) turns white when frozen. The indicator tube is inserted in a close-fitting, telescoping casing buried in the pavement. The length of tube required is estimated from the freezing index at the location of the installation.

To read the depth of frost penetration, the covering cap is unscrewed, the indicator tube withdrawn, and the depth of the frozen white solution measured. The depth of thaw can also be measured in

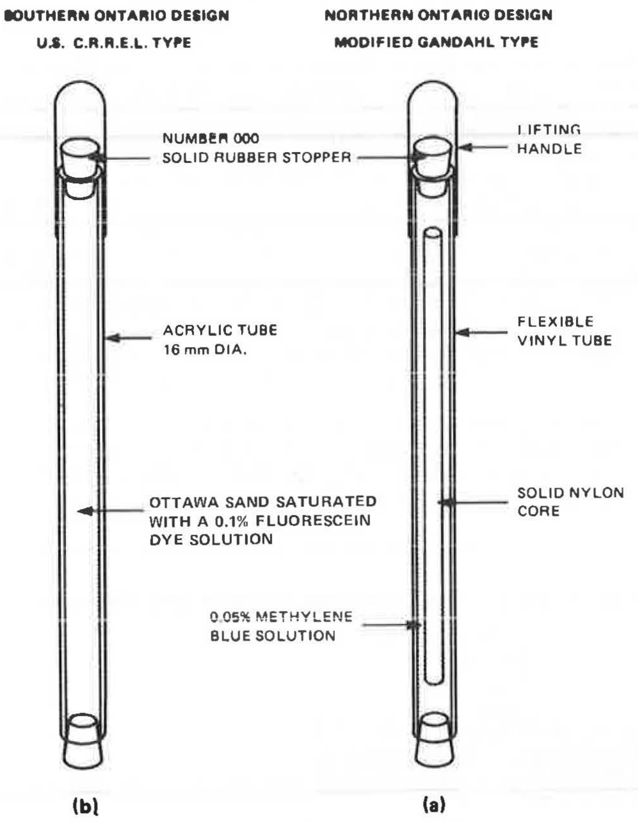
Figure 1. Gandahl-type frost depth indicator casing assembly (MTC design)



the spring, when the melted indicator solution at the top regains its blue color.

In the two northern regions of Ontario, a modified design (Figure 2a) is used because the lengths of acrylic tubing needed for the indicator tube are usually too short. The rigid acrylic plastic tube with a soft rubber insert is replaced by a soft transparent vinyl tube with a solid nylon insert. The same methylene blue indicator solution is used.

Figure 2. Gandahl-type frost depth indicator assemblies (MTC design)



In 1975, an indicator designed and developed by CRREL (Figure 2b) was used in three Ontario regions. This indicator consisted of a rigid acrylic plastic tube filled with a saturated mixture of Ottawa sand and a fluorescein dye solution. The dye, a natural lime green color, turns brown on freezing. This type of indicator more closely parallels natural soil conditions and is now used in the southern regions of the province.

FROST DEPTH MEASUREMENT PROGRAM

In the fall of 1970, 33 frost depth indicators were installed in 15 districts in the five regions of the province. During the next 2 years, an additional 29 frost depth indicators were installed, which increased the distribution to 17 districts in the five regions. Indicators were installed near district patrol yards for convenience.

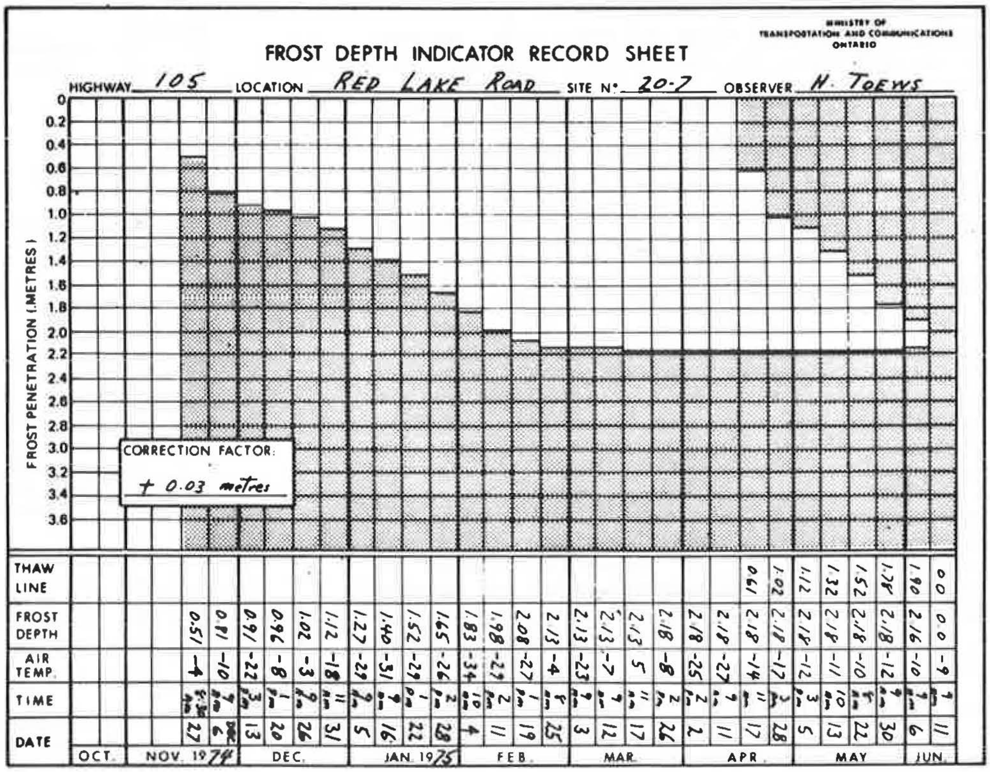
An example of the form used to record frost penetration depths measured at different dates is shown in Figure 3.

Details of site locations for frost depth indicators are given in Table 1. The results of frost penetration measurements taken over five seasons from 1970 to 1975 are summarized in Table 2. These frost measurements were correlated with the air freezing index calculated from air temperature records at the nearest weather stations. Sites not situated close to a weather station were not used in the correlation.

ESTIMATION OF FROST PENETRATION USING AIR FREEZING INDEX

During the 5 years that measurements were taken, Ontario experienced one of the mildest winters in more than 100 years. Weather conditions during the re-

Figure 3. Example data sheet from northern region of Ontario.


MINISTRY OF TRANSPORTATION AND COMMUNICATIONS ONTARIO

FROST DEPTH INDICATOR RECORD SHEET

HIGHWAY 105 LOCATION RED LAKE ROAD SITE Nº 20-7 OBSERVER H. TOEWS

CORRECTION FACTOR: + 0.03 metres

THAW LINE														
FROST DEPTH					0.51	0.81	0.91	0.96	1.02	1.12	1.27	1.40	1.52	1.65
AIR TEMP.					-4	-10	-22	-8	-3	-18	-29	-31	-29	-26
TIME					8:30 am	9 am	3 pm	1 pm	9 am	11 am	9 am	9 am	1 pm	2 pm
DATE					27	6	13	20	26	31	5	16	22	28
	OCT.		NOV. 1974				DEC.				JAN. 1975			

THAW LINE											0.61	1.02	1.12	1.32	1.52	1.78	1.90	0.0
FROST DEPTH	1.83	1.98	2.08	2.13	2.13	2.13	2.13	2.18	2.18	2.18	2.18	2.18	2.18	2.18	2.18	2.18	2.16	0.0
AIR TEMP.	-34	-27	-27	-4	-23	-7	5	-8	-25	-27	-14	-17	-12	-11	-10	-12	-10	-9
TIME	10 am	2 pm	1 pm	8 am	9 am	9 am	11 am	2 pm	2 pm	9 am	11 am	3 pm	3 pm	10 am	8 am	9 am	9 am	9 am
DATE	4	11	19	25	3	12	17	26	2	11	17	28	5	13	22	30	6	11
	FEB.				MAR.				APR.				MAY				JUN.	

maining years in which measurements were taken ranged from below-normal to near-normal temperatures.

Frost penetration depends on climatic factors and soil conditions. However, this study was primarily concerned with the major variable of air freezing index as a basis for estimating maximum frost penetration. By using the data collected from various locations throughout Ontario, frost penetration (P) in meters for cleared asphalt pavement was plotted versus the corresponding air freezing index degree-days below 0°C. The complete set of data gathered during the 5-year study was analyzed by a regression analysis program that showed a correlation equation of

$$P = -0.328 + 0.0578\sqrt{F} \qquad (1)$$

where P is the frost penetration in meters and F is the freezing index in degree-days Celsius. This regression equation line is plotted in Figure 4. The negative values at the lower freezing indices indicate that the freezing index must reach a minimum value before freezing in the road structure will occur.

The variation in frost penetration caused by different soils and moisture conditions, as measured in this program, is not so great as might be expected from theoretical considerations, as is shown by Sanger in Figure 5. A plot of frost penetration

Table 1. Details of site location for frost depth indicators.

Region	District No.	Site No.	Location	Pavement Thickness (mm)	Soils Log, Granular Depth (mm)	Subgrade Material
London	1	1-1	Harrow	83	460	Fine sand
	1	1-2	Chatham	83	610	Fine sand and silt
	1	1-3	Port Franks	83	460	Sand
	2	2-1	Wallacetown	83	460	Silty sand
	2	2-2	Elginfield	83	460	Clay
	2	2-3	Ayr	83	460	Sand and fine gravel
	2	2-4	Langton	83	460	Sand
	3	3-1	Arthur	76	990	Sand
	3	3-2	Wingham	83	610	Clay, loam
	3	3-3	Guelph	100	460	Sand and gravel
	3	3-4	Clinton			
	3	3-5	Fordwich			
	3	3-6	Conn			
	5	5-1	20 South Barrie	76	710	Sand
	5	5-2	Cookstown			
	5	5-3	Clavering	83	460	Sandy loam
	5	5-4	Elmvale			
Toronto	6	T35	Brampton	140	610	Clay
	4	T6	Brantford	140	230	Gravelly sand
	4	4-1	Welland	76		Clay
	7	7-1	Bowmanville	230		Clay
Kingston	8	8-1	Millhaven	102	360	Clay
	9	9-1	Iroquois	76	740	Clay
	9	9-2	Perth	102	660	Clay
	9	9-3	Carp	76		Sand
	9	9-4	Morrisburg	76		
	10	10-1	Bancroft	76	380	Gravelly silt
	10	10-2	Whitney	76	230	Sand
	10	10-3	Bancroft	76		Sand
North Bay	11	11-1	Bracebridge	76	205	Sand
	11	11-2	Dunchurch	102	410	Sand
	13	13-1	Sunridge	102	180	Sand
	13	13-2	Deep River	102	460	Sand
	14	14-2	New Liskeard	180	690	Clay
	14	14-2	Cobalt	102	660	Sand
	14	14-3	Matheson	102	76	Sand
	14	14-4	Timmins			Clay
	17	17-1	Britt		205	Sand
	17	17-2	Little Current	51	380	Sand
	17	17-3	Cartier	25	1090	Sand
Thunder Bay	16	16-1	Cochrane	102	360	Silty clay
	16	16-2	Nagagami	152	510	Sand
	16	16-3	Shekak River	140	485	Sand
	16	16-4	Val Gagne	76	915	Clay
	16	16-5	Iroquois Falls	76		Clay
	18	18-1	Wawa	65	725	Sand
	18	18-2	Marathon	76	150	Silty clay
	18	18-3	Sault Ste. Marie	115	950	Clay
	19	19-1	Thunder Bay	51	510	Clay
	19	19-2	Nipigon	102	1170	Silty clay
	19	19-3	15 miles north of Nipigon	65	850	Sand
	19	19-4	10 miles east of Nipigon	140		Heavy clay
	19	19-5	Thunder Bay	260	760	Clay
	19	19-6	31 miles west of Atikokan	130	1090	Light clay
	20	20-1	Rainy River	40	570	Silty clay
	20	20-2	Ear Falls	65	420	Sand
	20	20-3	Dryden	115	800	Silty clay
	20	20-4	Dryden	130	710	Sand
	20	20-5	Sioux Lookout	65	395	Silty clay
	20	20-6	Sioux Lookout	65	420	Sand
	20	20-7	Red Lake Road	—[a]		
	20	20-8	30 miles east of Kenora	130		Sand and gravel

[a] No data.

predicted by use of the correlation equation (Equation 1) versus measured frost penetration shows that 80 percent of the measured points fall within ±0.3 m of the prediction (see Figure 6).

Because the 62 locations cover a wide range of subgrade types, it appears that for design purposes one can accept a depth calculated by adding 0.3 m to the frost depth penetration predicted from Equation 1. Perhaps a somewhat greater allowance needs to be made for very thick granular structures.

FREEZING INDEX MAP OF ONTARIO

Ontario covers a large, diverse territory, ranging in the south from the same latitudes as Northern California and north to the subarctic shores of Hudson Bay. The associated temperature regimes and their related depths of frost penetration also vary considerably. Freezing index maps previously used were published by the National Research Council of Canada; however, maps of smaller scale cannot show

Table 2. Results of Ontario frost penetration measurements—1970-1975.

Site No.	Degree-Days Celsius (from map)	Predicted Frost Penetration (m)	1970-1971		1971-1972		1972-1973		1973-1974		1974-1975	
			Degree-Days Celsius	Maximum Frost Penetration (m)	Degree-Days Celsius	Maximum Frost Penetration (m)	Degree-Days Celsius	Maximum Frost Penetration (m)	Degree-Days Celsius	Maximum Frost Penetration (m)	Degree-Days Celsius	Maximum Frost Penetration (m)
1-1	300	0.62	Indicator installed summer 1971		400	0.71	190	0.53	300	0.61		ND
1-2	300	0.62				0.84		0.74		0.79	170	0.56
1-3	450	0.88				0.89		0.48		ND		0.58
2-1	400	0.78				0.81		0.51		0.66		0.43
2-2	500	0.93				1.05	← Damaged →		520	0.94	415	0.79
2-3	600	1.06				1.32		1.19		1.22		1.02
2-4	450	0.88				0.91		0.76		0.81		0.61
3-1	900	1.36		1.46	830	1.36	640	1.27	750	1.27	705	1.19
3-2	600	1.06				0.94		0.94		0.94		0.74
3-3	600	1.06				1.57		1.24	705	1.45	650	1.22
3-4	550	1.00			Installed fall 1972			0.91		0.98	← Cancelled →	
3-5	700	1.16			Installed fall 1972			1.51		1.56	← Cancelled →	
3-6	900	1.36			Installed fall 1972		640	1.42	750	1.50	← Cancelled →	
5-1	700	1.16		1.51		1.36	← Cancelled →		← Cancelled →		← Cancelled →	
5-2	700	1.16				1.04		0.99		1.07		0.91
5-3	600	1.06			580	1.07	420	0.99	530	1.02	400	0.83
5-4	700	1.16			Installed fall 1972			1.04		1.16		1.07
T35	500	0.93	720	1.32	670	1.12	480	0.99	580	1.02	← Cancelled →	
T6	450	0.88		1.40		1.27	← Cancelled →		← Cancelled →		← Cancelled →	
4-1	400	0.78							360	0.71	175	0.64
7-1	500	0.93								1.14		1.14
8-1	650	1.12	890	1.24	No measurements		555	0.94	660	0.94		0.81
9-1	700	1.16		1.45	Indicator damaged		← Cancelled →		← Cancelled →		← Cancelled →	
9-2	900	1.36	Indicator damaged			1.29		1.22		1.07		ND
9-3	1000	1.45			1110	1.35	870	1.27	930	1.17	770	1.14
9-4	700	1.16			Installed fall 1972			1.12	← Damaged →			1.02
10-1	1000	1.45		1.07	1080	1.40	790	1.09	945	1.36		ND
10-2	1100	1.53	Indicator damaged			1.85		1.98		1.90		1.88
					Full depth of indicator		← New indicator →					
10-3	1000	1.45	New indicator		1080	1.68	790	1.65	945	1.59		ND
11-1	900	1.36		1.50		1.35		1.14	920	1.27		1.24
11-2	1000	1.45	Indicator damaged			1.54		1.21		1.25		1.27
13-1	1000	1.45	1335	1.51	1390	1.47	1050	1.31	1330	1.38	1120	1.27
13-2	1100	1.53		1.90		1.93		1.74	1090	1.78		1.71
14-1	1400	1.80		2.22	1670	2.18	1360	2.03	1720	2.01	1500	1.79
14-2	1400	1.80		2.39	1670	2.36	1360	2.23	1720	2.34	1500	2.06
14-3	1800	2.10		1.98		2.06		2.01		2.07		1.88
14-4	1750	2.08			Installed fall 1972			2.06		2.03		2.10
17-1	1050	1.50		1.62		1.55		1.50		1.47		1.42
17-2	1050	1.50		1.45		1.32		1.27		1.42		ND
17-3	1400	1.80		1.85	Indicator paved over					1.88		1.70
16-1	1850	2.15	2050	2.37	2170	2.48	1800	2.48	2200	2.49		ND
16-2	2050	2.27		2.61	2440	2.78	2000	2.62	2390	2.73		ND
16-3	2050	2.27			2440	2.56	2000	2.39	2390	2.51		ND
16-4	1800	2.10			Installed fall 1972			2.39		2.49	1660	2.31
16-5	1800	2.10							2100	2.26		ND
18-1	1400	1.80		2.06		2.27		2.01		2.25		ND
18-2	1200	1.64		2.06	Indicator damaged		← Cancelled →		← Cancelled →		← Cancelled →	
18-3	1000	1.45		1.38	1110	2.17	780	1.37	← Damaged →		← Cancelled →	
19-1	1350	1.78	1550	1.60	1780	1.70	1280	1.50	1580	1.60	1240	1.35
19-2	1500	1.88		2.01		2.49		2.18		2.16	← Cancelled →	
19-3	1600	1.96		2.26		2.61		2.16		2.44	← Cancelled →	
19-4	1500	1.88				2.17		1.83		ND	← Damaged →	
19-5	1350	1.77			1780	1.90	1280	1.73	1580	1.80	← Damaged →	
19-6	1600	1.96				2.39		2.01		2.16	← Cancelled →	
20-1	1700	2.04		2.08		2.11		1.93		1.98		1.78
			Full depth of indicator		Full depth of indicator							
20-2	1900	2.18		1.90		1.98		1.88	2140	1.89	1680	1.78
20-3	1850	2.15	1920	2.09	2050	2.03	1610	2.03	2055	2.01	1650	1.90
20-4	1850	2.15	1920	1.96	2050	2.08	1610	1.96	2055	2.06	1650	2.46
20-5	1900	2.18		1.98	Indicator damaged		← Damaged →		2210	1.85		ND
20-6	1900	2.18		2.64		2.83		2.56	2210	2.63	1755	2.51
20-7	1850	2.15				2.39		2.18		ND		2.18
20-8	1750	2.08			Installed 1972			2.03		2.15		ND

Note: ND = no data.

Figure 4. Frost penetration in Ontario 1970-1975.

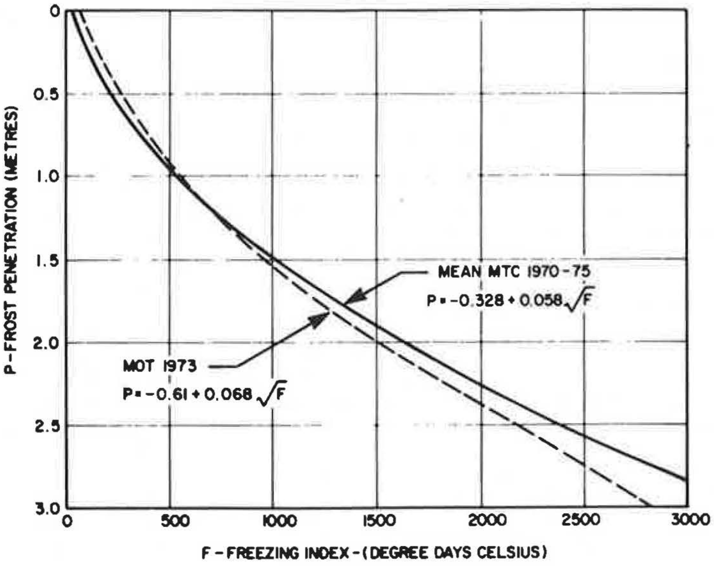


Figure 5. Design frost penetration curve.

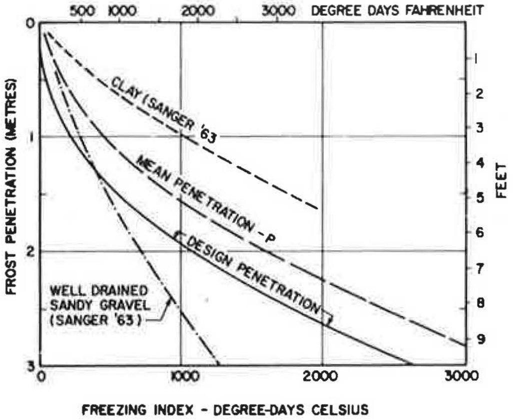
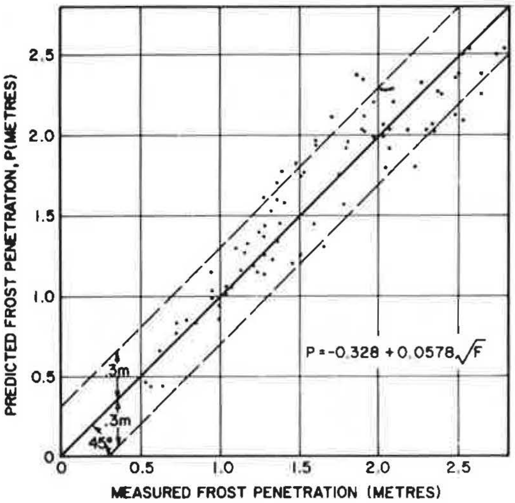


Figure 6. Observed and predicted frost penetration.



local variations of freezing index, which can often be significant. Also, since 1975, all temperature data are in degrees Celsius, and it was felt that an up-to-date freezing index map that used degree-days Celsius was needed.

To construct this map, climatological data for more than 200 stations in Ontario, available from the Atmospheric Environment Services of Environment Canada (2), were used. The data were used in conjunction with a method described in a report by the National Research Council of Canada (3) by which reasonably accurate calculations of air freezing index can be made using monthly mean temperatures. This method, briefly described below, was used to calculate the normal freezing index of stations in Ontario that were not included in the report published in 1973 (4).

Method of Calculation

Because soil freezing depends largely on the extent and duration of depressed air temperatures, it is relatively easy to measure time and temperature by degree-days. One degree-day is defined as a difference of 1°C of the mean daily temperature from the freezing point of water (0°C or 32°F).

The total seasonal freezing index was calculated from average monthly temperature records by a method proposed by Boyd (4). Fahrenheit was used in calculating the freeze index for the stations in the Boyd report. Therefore Fahrenheit was used for the additional stations and converted to Celsius.

The error of estimate for normal degree-days based on a 30-year monthly mean temperature would be about 9 degree-days Fahrenheit in the annual totals. However, it should be noted that, because of differences in elevation and topography, nearness to large population centers, and proximity to large bodies of water or other sources of heat, variations may be found in annual air temperature of as much as 1°F or 2°F at stations only a few kilometers apart. This could lead to a difference of as much as 100 to 200 degree-days Fahrenheit in the air freezing index over a relatively small geographic area. Thus, no matter how accurate readings are from any one station, a probable error of up to 100 degree-days Fahrenheit is likely for sites located within a few kilometers of that station. Such variations may be significant enough to affect a pavement design, especially in areas with a low freezing index.

Constructing the Map

The calculated normal freezing index for all 224 stations in Ontario (data from Environment Canada) was plotted on two large-scale maps of northern and southern Ontario. The location and freezing index for each station was converted to digital form and the data changed to degree-days Celsius by applying a factor of 0.5555. Several key points on the map were digitized to enable subsequent plots (overlays) to be transferred accurately back to the original maps.

An IBM 375 computer connected to a plotter was used to interpolate the points and draw isopleths at intervals of 100 degree-days Celsius for southern Ontario and at 200 degree-days Celsius for the northern Ontario map. The maps of Ontario and the isopleth plots were then matched and redrawn as shown in Figures 7 and 8. These maps are sufficiently detailed to enable the research and design engineer to establish his site location and to determine an appropriate freezing index.

A test of accuracy of the map was carried out by reading off the freezing index at each frost depth indicator location and comparing it with the freezing indices observed from 1970 to 1975.

The comparison, plotted in Figure 9, indicates that the majority of observations fall within ±300 degree-days of the map values. The winter of 1973-1974 was the coldest in the past 10 years, and 1974-1975 was a very mild winter. The map therefore reproduces mean conditions very well and can be used with a fair degree of confidence.

PREDICTION OF FROST PENETRATION BY COMPUTER SIMULATION

The traditional analytic estimation of frost penetration is frequently based on a number of empirical relationships and formulas developed over the years. Such methods used either air or pavement freezing index but take no account of the other key variables, such as soil type and moisture content. The most common method used is the modified Berggren equation (5) which has been adapted to layered systems such as those found in pavement structures. However, these analytic solutions have weaknesses and restrictions, such as the simplifying assumption that all materials have homogenous soil properties or that all soil moisture freezes at 0°C. An alternative approach for predicting frost penetration is by computer simulation.

A project recently carried out for MTC by Carleton University (6) has resulted in a computer program to predict the depth and time pattern of frost penetration beneath pavement structures. The computer simulation program involves the creation of a numerical, finite-difference, heat-transfer model of the soil and a stepwise digital computation in which actual weather data are used. Computer simulation not only provides detailed predictions of frost depth and ground temperature conditions but also predictions of complex and important future events.

Computer Model

The model as described by Chisholm and Phang (6) is

Figure 7. Freezing index map of southern Ontario.

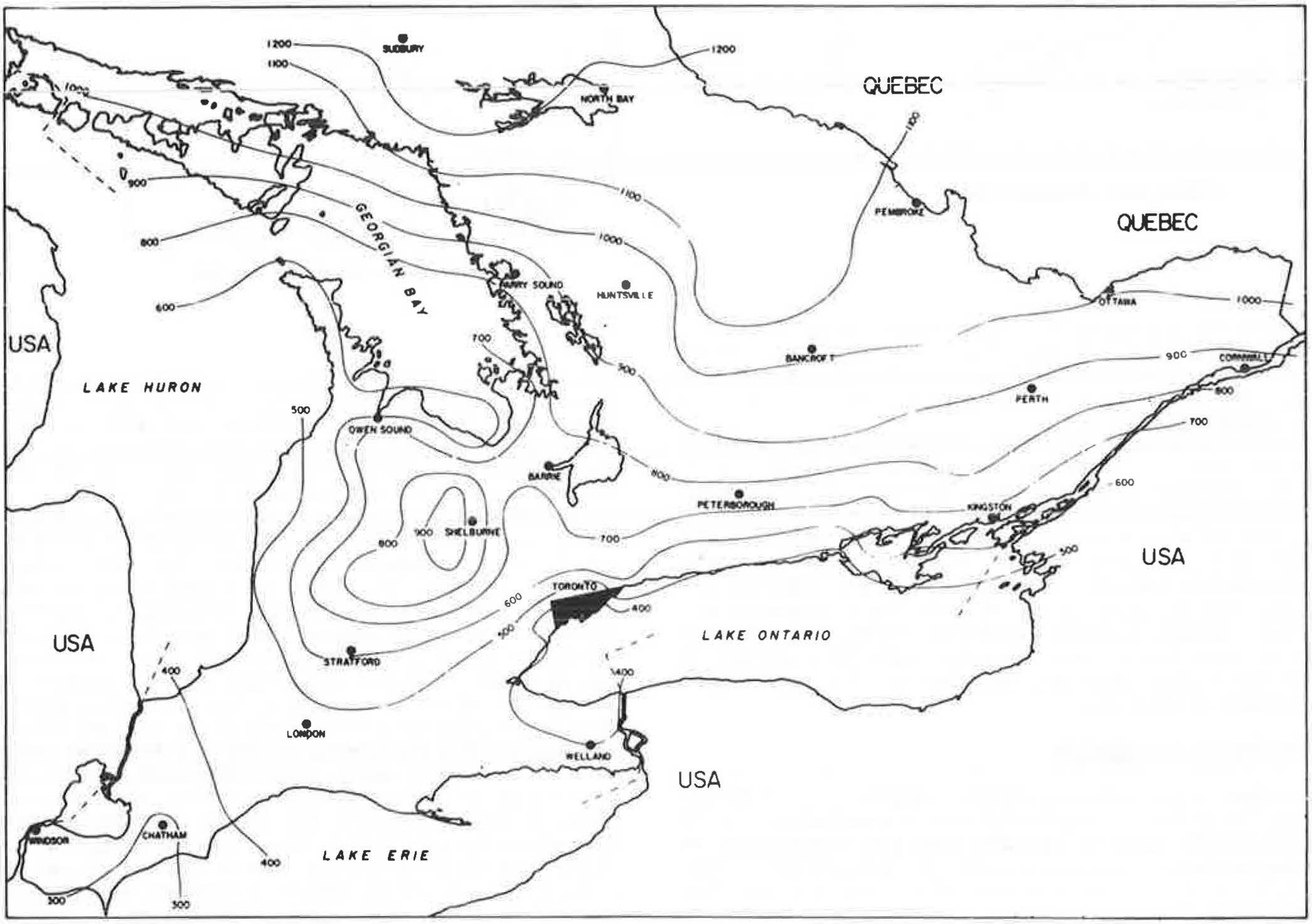


Figure 8. Freezing index map of northern Ontario.

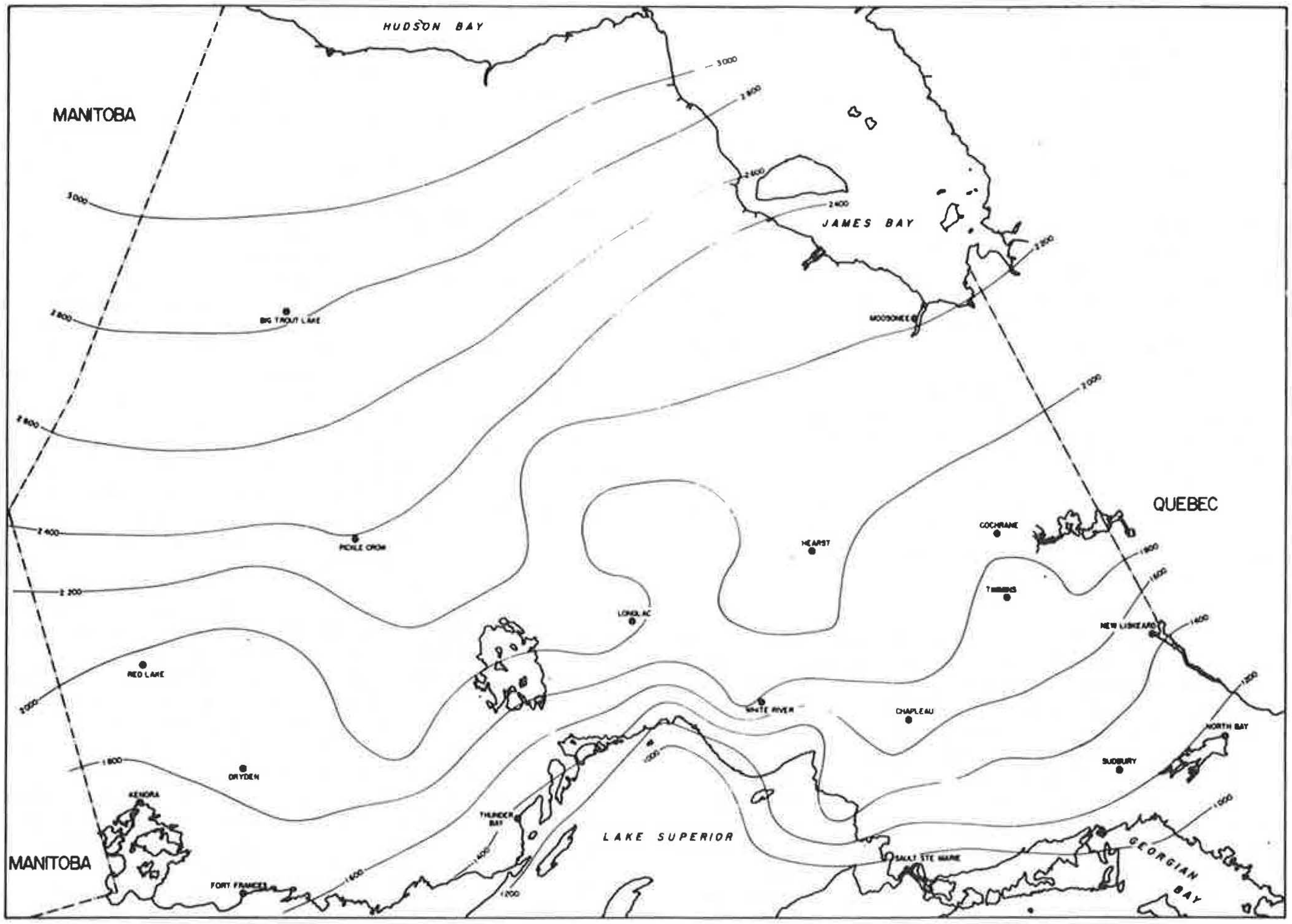


Figure 9. Observed and predicted freezing index.

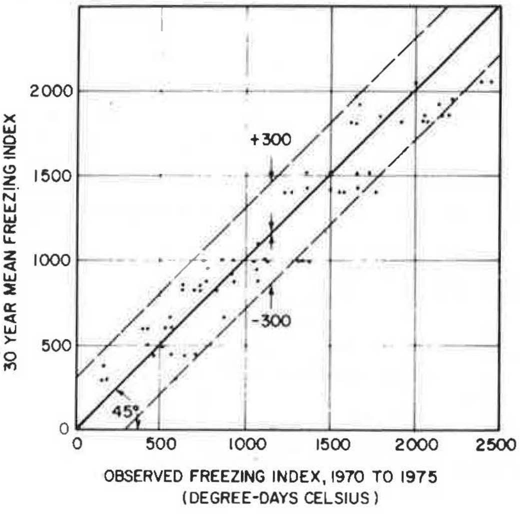
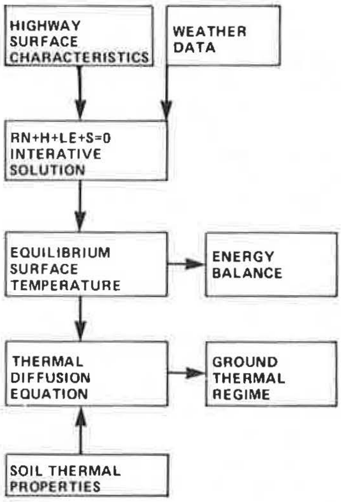


Figure 10. Simplified program flow chart.



based on the strategy developed by Outcalt (7). The computer program simulates the ground temperature and surface energy regimes for paved surfaces using synoptic weather data. A simplified flowchart is shown in Figure 10. The main structural elements of the program are as follows:

1. Weather data (solar radiation, cloud cover, air temperature, wind speed, and atmospheric pressure), together with certain highway characteristics (albedo and aerodynamic roughness), are used to solve the surface energy balance. In general, this is written as

$$RN = H + S(+ LE) \quad (2)$$

where

RN = net radiation balance of incoming and outgoing radiation,
H = convection,
S = heat conduction into or out of the ground, and
LE = evaporation (assumed to be zero for a highway surface).

2. This equation is solved to derive the prevailing surface temperature, which is not routinely available anywhere. To do this, the components of the energy balance equation are each expressed as functions of surface (highway) temperature. Iterative solution of this equation leads to the equilibrium surface temperature.

3. The equilibrium surface temperature is then used as the boundary condition, together with the ground thermal properties, to predict the ground temperature pattern via the heat conduction equation. An implicit finite-difference solution is used (8) that accommodates complex stratigraphy (including frozen and unfrozen states) and freeze and thaw energetics. No account is taken of moisture migration during freezing.

The solution is one-dimensional and thus ignores the finite width of the highway. However, because the depth of frost penetration is considerably less than highway width (approximately 1:10), this is not a serious limitation. Predictions may be viewed as being at the centerline of the highway.

The program is organized to produce output for each day, using either actual daily weather data or daily data interpolated from the monthly data. The latter is adequate for the general prediction of frost penetration; but, if accurate prediction of the timing of freezing and thawing is required, actual daily data must be used. Ground thermal properties may be input directly (where available) or calculated in a subroutine on the basis of physical information supplied by the user. This option is specified separately for each soil layer (up to a maximum of nine layers). The initial ground temperature profile may actually be specified where data are available or simply preset to arbitrary values, although the former is preferred. The bottom grid is necessarily kept at a fixed temperature in the finite-difference calculations. A depth of 6 m is generally suitable for this.

Input Information

The program uses information that in most cases is widely available. Soil thermal properties either are input directly or may be calculated by a subroutine. If limited soils information is available, typical values may be used.

An initial soil temperature profile must be provided. The data may be direct results from thermocouples or thermistors; or, if no information on soil temperature is available, an arbitrary temperature may be set that is based on the mean annual air temperature at the nearest meteorological station.

Climatological data constitute a large part of the input needed for the program. Records published by the Atmospheric Environment Services provide all the information needed for simulations. The weather data required are solar radiation, cloud cover, cloud type, air temperature, wind velocity, and atmospheric pressure. In most cases, it will be necessary to use more than one station to assemble all the data required.

Computer Prediction Versus Measured Frost Depth Penetration

Model predictive capabilities were tested on two specially instrumented sites in the Ottawa area. The sites were instrumented for the measurement of ground water and temperature in a previous study (9). Soil samples were available from the sites: one site was predominantly a clay subgrade and the other mainly sand. Weekly measurements of temperature and ground water provided the data for the program. The observed and simulated frost lines (6) are shown in Figure 11 for the winter of 1975-1976.

Although the prediction model is not perfect, the pattern of frost penetration and soil isotherms is realistically produced at both sites. The worst error encountered in predicting the maximum frost penetration was about 10 percent (15 cm). According to Smith, this disagreement may be due in part to the fact that predictions were based on mean daily temperatures, whereas the measurements were all taken in the afternoon when the surface layer would be warmer. Even though the prediction model used accurate soils information, part of the error may also be due to assigning the soil moisture conditions at the two test sites.

Part of the testing for the model included comparing the results from the frost indicator study with the computer prediction. Four sites were selected from the Ontario network (10) and the necessary weather data were obtained from local weather stations. Because only minimal soils information was available, average values were derived from the literature and used in the program. The observed and simulated frost lines for the four sites are shown in Figures 12 and 13. Agreement is reasonable: only 1 percent error appears in the predicted frost depth for Carp, 13 percent for Millhaven, 15 percent for Guelph, and 24 percent for New Liskeard. Although the available soils information is limited, the prediction model correlates reasonably well with the frost depth indicators. It is highly desirable to input accurate soils data; nonetheless, the predictive capabilities of the model are still good even if this knowledge is not available to the research and design engineer.

Discussion of Results

Because soil conditions are such an important factor in determining the frost penetration in pavement

Figure 11. Observed and simulated frost lines for clay and sand sites, Ottawa, 1975-1976.

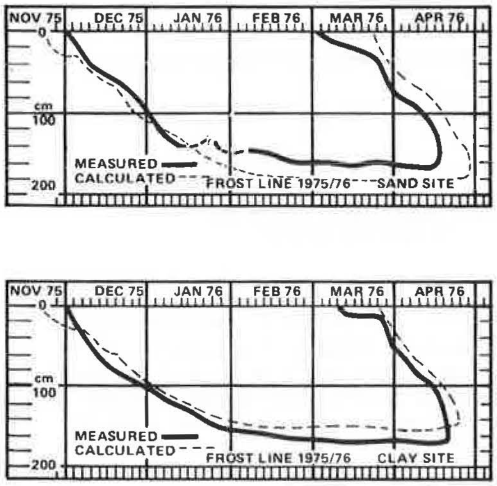
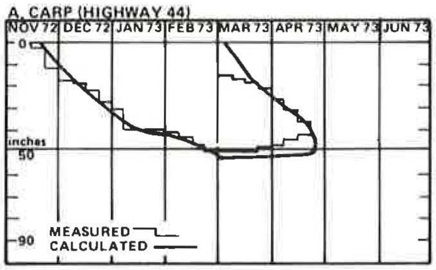


Figure 12. Observed and predicted frost lines, (a) Carp and (b) Millhaven.

A. CARP (HIGHWAY 44)



B. MILLHAVEN (HIGHWAY 133)

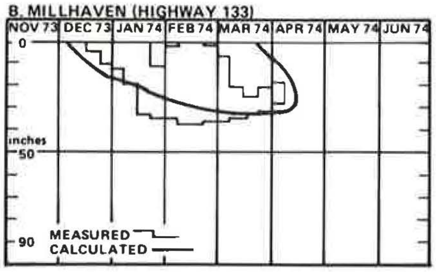
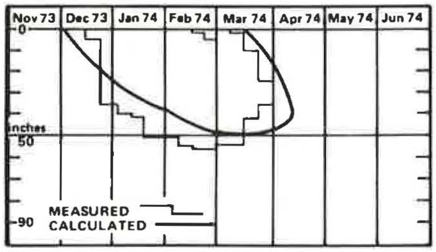
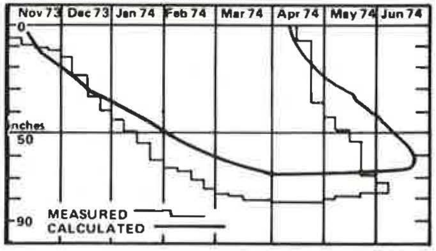


Figure 13. Observed and predicted frost lines, (a) Guelph and (b) New Liskeard.

A. GUELPH (HIGHWAY 7)



B. NEW LISKEARD (HIGHWAY 11)



structures, estimates based on calculations rather than on the relationships shown in Figure 4 are more accurate. The graph in Figure 4 is useful, however, for comparing calculations against the estimated average frost penetration based simply on a knowledge of the site air freezing index. These indices can be easily obtained from the maps for any location in Ontario.

In trying to predict frost penetration for an area where construction of a highway is projected, it must be remembered that the depth of frost penetration will vary from year to year in relation to the extent and duration of the freezing temperatures experienced. In addition, the soil properties and moisture content will vary throughout any stretch of highway, and thus the depth of frost penetration will also vary. The advantage of computer simulation is that it is able to predict complex future events that have not actually been experienced in a field situation.

This program makes possible more accurate time-temperature profiles for use in evaluating the optimum designs for new pavement structures by using experimental materials such as tree bark or sulfur foam. The program could also be used to design for the worst possible situation.

The simulation program requires considerably more data and time before it can be used to predict frost penetration; for specific project applications, however, the program can be a major tool for the pavement design engineer.

CONCLUSIONS

This paper summarizes the results of 5 years of observations of frost penetration in pavement structures across Ontario. The following conclusions have been made:

1. The modified Swedish-type frost depth indicator is an inexpensive and reliable instrument for measuring frost penetration.
2. The relationship between air freezing index and frost penetration was found to be

$$P = -0.328 + 0.0578 \sqrt{F}$$

where

P = frost penetration in meters, and
F = freezing index in degree-days Celsius.

3. Frost penetration at two nearby points may vary significantly depending on the soil and moisture conditions at the site. However, for design purposes, an additional 0.3 m would cover this variation at the 80 percent confidence level.
4. An up-to-date metric freezing-index map of Ontario is presented that is based on data from 224 climatological stations in Ontario. The mean freezing index from the map is within ±300 degree-days of actual observations.
5. A computer program has been developed that is capable of predicting the depth and time pattern of frost penetration beneath pavement structures. The program will enable research and design engineers to fully evaluate techniques such as frost heave treatments or new insulating materials that are now being experimented with in highway construction.
6. The computer simulation program should be used for specific project applications. The relationship based on air freezing index can be used where only a reasonable estimate of frost penetration is needed.

ACKNOWLEDGMENT

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A Device for Evaluation of Thaw Weakening of Frost-Susceptible Soil

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As a soil freezes unidirectionally, water is drawn up to the freezing front and, under appropriate conditions, ice lenses form. As thawing progresses downward, water, which formerly constituted an ice lens, remains perched above the still frozen subsoil. These localized zones exhibit shear resistances below their prefreeze values. A direct simple shear (DSS) device used to investigate this phenomenon on a thawed sample is described. The sample is the upper layer of a large cylindrical specimen that has been thermally conditioned under a carefully controlled laboratory environment. The controlled environment is produced by a frost cabinet with two independent refrigeration units to cool both the air above the specimen and a water supply to the base of the specimen. Either an open or a closed water supply system can be used. After the desired thermal history has been created and the specimen is completely frozen, sequential thawing and simple shear testing begins from the top downward. A carefully controlled heating element thaws the specimen from the top, leaving a thin shear sample. The top surface of the sample is approximately parallel to the bottom surface (the freeze-thaw interface). Undrained, shear testing is then performed. The frozen sublayers inhibit downward drainage, and a reinforced rubber membrane inhibits lateral drainage, thereby effectively duplicating field conditions. The sample is then removed, and the moisture content is determined. Shear testing continues at various elevations down through the specimen. The shear strength and moisture content versus depth profile is obtained for the initially created thermal history. Results from such tests using the DSS device performed on a frost-susceptible silty sand are presented.

Many areas of the world are subjected annually to freezing temperatures. The consequent freeze and thaw of soils often create severe problems for structures constructed on or near the ground surface. Because of these problems, engineers and researchers tend to agree that a more stringent treatment of all parameters associated with the freeze and thaw phenomenon is needed. This is particularly true if safe, efficient, and economical use of in situ soils is desired. Also, a greater knowledge of the freeze and thaw phenomenon is necessary for the development of a scientific approach to solving engineering problems associated with the behavior of thawed ground.

Present techniques for solving engineering problems associated with thawed ground are expensive and quite often wasteful. Thus there is a need for a more thorough understanding of the strength loss of soil subjected to different thermal histories and moisture conditions.

Described in this paper is a direct simple shear testing device, designed and fabricated at Worcester Polytechnic Institute, that is used to measure the post-thaw shear strength of a soil subjected to frost heaving in the laboratory. This direct simple shear device permits evaluation of post-thaw shear strength at different elevations in a previously frozen specimen. The shear sample dimensions permit investigation of minimal shear strength through the localized zones of high water content at the sites of thawed ice lenses. Results from two test series performed on a frost-susceptible silty sand (Ikalanian sand) are presented.

EFFECTS OF THAW ON SHEAR STRENGTH

The phenomenon of frost heaving occurs when a soil-water system, consisting of frost-susceptible soil with access to an unfrozen water supply, is subjected to a freezing thermal gradient. Then, as the least stressed water at or near the ground surface crystallizes, the heave process begins. If the proper quantity of heat is being removed, so that the frost front remains almost stationary and a continuous supply of unfrozen water is available, the ice crystals enlarge to form an ice lens. In frost-susceptible soils, significant heave is attributed to crystal growth while water is transferred to the frost front. In soils that are not frost susceptible, water does not move to the frost front.

As soil thaws from the top downward, ice within the soil melts creating zones that have a higher water content than at the prefreeze condition. This water remains perched above the still frozen sublayers. Bishop (1) indicates that soil shearing resistance for saturated soils is inversely proportional to water content when all other factors, such as stress history, are equal. This is true for undisturbed and remolded cohesionless and cohesive soils. Therefore, a thawing soil with excess water caused by the melted ice will contain thaw-weakened zones exhibiting minimal, possibly zero, strength. After freezing, the continuity of the soil structure will have changed and the ability of the soil grains to resist shearing stresses will be reduced.

Alkire (2) conducted triaxial tests on thaw-weakened soil that had been frozen with access to water and demonstrated an increase in water content and a decrease in post-thaw shear strength. Skempton (3) demonstrated that when a saturated, slowly draining soil is sheared in an undrained mode, the behavior is representative of a material whose strength consists of only a cohesive component.