Journal of Natural Disaster Science, Volume 1, No. 2, 1979, pp. 1-9

FROST PENETRATION DEPTH IN HOKKAIDO, JAPAN*

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(Received 30 November, 1979, and in revised form 30 January, 1980)

ABSTRACT

Serious damage may occur on structural foundations and buildings when ground froze in winter. Frost penetration depths had been measured at various sites throughout Hokkaido in the winter during 1974-75. The experimental results are presented graphically.

1. INTRODUCTION

As a result of the frost penetration and ground freezing during the winter in Hokkaido, the northernmost island of Japan, the ground surface may heave upwards by a remarkably large amount, thus causing serious damage to structural foundations and buildings on it. This phenomenon has often been experienced in Hokkaido. The depth of frost penetration and the heave amount depend largely on the ground surface conditions, such as snow covering and vegetation. If the covering snow would not be removed from the ground throughout the winter, then, only the eastern part of Hokkaido would undergo ground freezing where the depth of frost penetration is about 60cm at most [1]. This can be attributed to the fact that there is not much snowfall in winter in this area, hence the snow cover does not serve as a good thermal insulator.

Recently snow removal work has been widely employed throughout the island, thus exposing ground surface directly to the cold air, whereby promoting the frost penetration deeper into the ground. In this connection, the frost penetration depths were measured at every two or four days intervals at various locations during the winter of 1974-75 in Hokkaido. These measurements had been carried out at schools by students as part of their extracurricular activities, and at observatories by scientists, using rather simple but proper apparatus.

Contour maps, showing the depths of frost penetration and freezing index, are then tentatively illustrated from using the experimental data obtained. In correlating these contours, a mean constant value (a) about 3 was incidentally found in all districts throughout Hokkaido. This would infer that Hokkaido is a uniform land mass as a whole when the relationships between frost penetration depth and the freezing index is considered.

2. FROST PENETRATION SEQUENCES

Detailed and systematic observations of frost heaving were conducted using field basins

*Part of this work was published in the Journal of Analytical Researches on Data of Natural Disaster, Vol. 6, 1977 (in Japanese).

KEY WORDS: Ground freezing, Frost penetration, Cold region

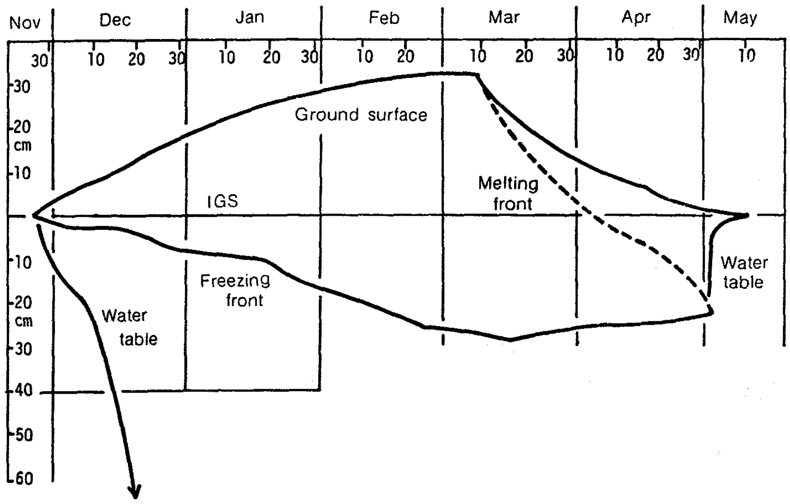

Fig. 1 Frost penetration sequence as functions of time and depth measured from the initial ground surface (IGS), showing ground surface heave, melting front, freezing front and water table. From November 1976 to May 1977, at Tomakomai field site.

at Tomakomai where the test soils had been buried every winter since 1968 by the scientific groups from the Institute of Low Temperature Science. Whenever there was a snowfall, the surface of the test soils was soon cleaned thus making it directly accessible to the cold air. The maximum thickness of the snow covered had reached some 40cm every winter at most places when snow was not removed. An example representing the frost penetration sequence at this site in the winter of 1976-77 is shown in Fig, 1 [2, 3]. It is seen that ground freezing began around November 27. After that ground surface rose continuously and reached the highest level of 32cm above the initial ground surface (IGS) on March 8. Both the freezing front and the water table level were sunken progressively, with the latter reaching the bottom of the basin (230cm below IGS) on January 15. By this time the freezing front had reached only about 10cm below the IGS, while the ground surface heaved 24cm upwards. A considerably large heave ratio, the heave amount to the initial thickness of the frozen layer, at 240% was observed. Heaving occurred by the growth of ice lenses segregated into the freezing front. The water which initiates and promotes these ice lenses had been supplied from the water table far beyond, proving probably that free groundwater could rise more than 220cm through silty soil.

The heaving speed was about 5mm/day from November 27 to January 15, but it decreased to some 2.5mm/day thereafter, because the basin had virtually no free groundwater and a soil-water movement took place as a consequence of the drying of the unfrozen soil below freezing front. On March 8 the freezing front reached the deepest level of 28cm below the IGS; the total heave ratio was then about 118%. However, this ratio constituted only 44% to the whole freezing cycle from January 15 to March 8.

Melting began about March 9 from ground surface. Finally the frozen layer was completely thawed around May 2, while the ground water tabel returned to its original level. The freezing cycle in this case was about 157 days in total.

3. SIMPLE APPARATUS FOR MEASUREMENTS

The frost level beneath the IGS was determined by using a small transparent pipe filled with the solution of 0.01% methylene-blue dye in water, which remained blue in an unfrozen state and turned colorless when frozen. This inner probing pipe was sheathed vertically downwards from the top of an outer pipe having a slightly larger diameter. The latter with its top end open had been embedded vertically in the soil, thus protruding out from the ground surface. Hence, the probing pipe could be raised upward, whenever necessary during operation to record the level along the probing pipe where the solution became frozen and colorless when it was surrounded by frozen soil. As the solution in the pipe would inevitably increase its volume when frozen, a fine but soft vinyl tube was placed alongside within it to serve as a buffer [4].

More than 50 of this apparatus were set up on various sites at schools and observatories, wherein students and scientists measured the frost penetration depths at every two or four days intervals throughout the winter. A coverage area of 2m×2m at each experimental plot was kept clear from snowfall for conducting experiments.

4. RESULTS

The results obtained on frost penetration depths and other items are summarized under the name of districts throughout Hokkaido in the winter of 1974-75, each designated by alphabetic character, as tabulated in Table 1. The first column in Table 1 refers to the district where the sites were located, as also illustrated in Fig. 2. Each row in the table shows the dates when frost began and completely thawed, frost penetration depths plus its maximum, freezing period and freezing index, for each site concerned. Frost began generally around mid-November till early December, and disappeared after mid-April or by the end of May. The freezing period was normally more than 100 days, with the longest being 209 days at Kamishihoro in District I (Tokachi). The maximum depth of frost penetration occurred around mid-March, the largest being 94.5cm at Rikubetsu of District I. At Toyokoro of District I the frost penetration depth had reached 95cm on January 16. If observations had continuously been conducted through the full season, a larger value would have been obtained.

Some data were missing at sites when it was difficult to take measurements due to

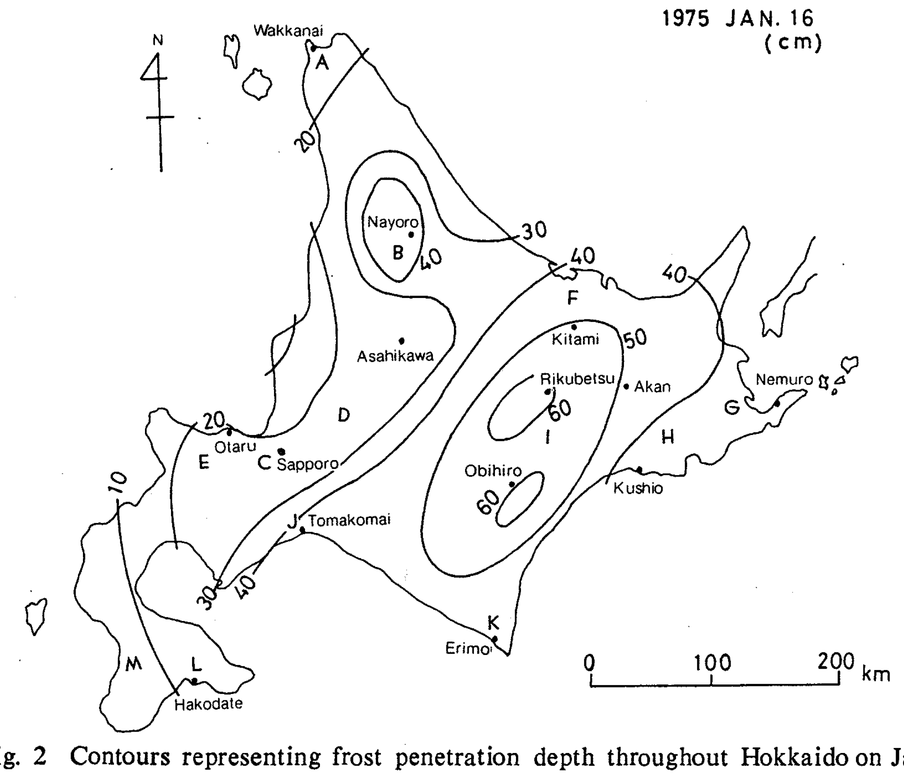

Fig. 2 Contours representing frost penetration depth throughout Hokkaido on January 16, 1975, with alphabets indicating various districts as shown in Table 1. Units in centimeters.

Table 1. Summary of data for frost penetration sequences

District	Site	Date of frost begun	20 Dec. cm
A Sōya	Wakkanai	16 Nov.	
	Wakkanai Higashi School		18.5
B Kamikawa	Furen Nisshin School		25.3
	Kamikawa Shirakawa School		11.3
	Bie School	24 Nov.	18.2
	Nakafurano Nitta School		
C Ishikari	Sapporo, Inst. Low Temp. Sci.	3 Dec.	6.5
D Sorachi	Iwamizawa Komazawa School	25 Nov.	23.0
E Shiribeshi	Otaru Futaba School		
	Kucchan Fujimi School	24 Nov.	
F Abashiri	Monbetsu Komukai Observatory		
	Bihoro	10 Nov.	19.3
	Kitami Technical College	25 Nov.	34.5
	Kunneppu		27.8
	Saroma		33.0
G Nemuro	Nakashibetsu Agriculture Obs.	27 Nov.	19.8
	Nemuro	22 Nov.	
	Rausu Harumatsu School	19 Nov.	
	Shibetsu School	10 Nov.	
H Kushiro	Kushiro University	27 Nov.	18.0
	Kushiro Toyoura		
	Akan Kamitetsubetsu School	30 Nov.	21.0
	Shibecha School	20 Nov.	
	Shibecha Kamiosobetsu School	7 Nov.	19.0
I Tokachi	Rikubetsu School	10 Nov.	44.7
	Shimizu Mikage School	28 Nov.	24.0
	Taiki School		35.0
	Toyokoro Yudo School		44.0
	Kamishihoro Nukabira School	1 Nov.	45.0
	Kamishihoro Mitsumata School		49.0
	Memuro School	4 Dec.	30.3
	Nakafushiko School	12 Nov.	33.0
	Otofuke High School	11 Nov.	23.5
	Obihiro University	27 Nov.	27.0
	Obihiro Shirakaba School	12 Nov.	30.0
	Obihiro W3 S27		31.7
J Iburi	Tomakoami Frost Heave Obs. (silt)	25 Nov.	35.0
	(sand)	25 Nov.	37.0
K Hidaka	Erimo Shono School		
L Oshima	Hakodate Matoba School	15 Nov.	2.5
M Hiyama	Kaminokuni Experiment Forest	15 Nov.	2.0

at various sites throughout Hokkaido in the winter of 1974–75.

Frost penetration depth			Date of complete melting	Freezing period days	Freezing index °C days
16 Jan. cm	Maximum cm	Date of maximum			
	41.0	10 Mar.	22 Apr.	163	560
18.8	34.0	4 Mar.			
48.8	66.4	12 Mar.			
28.2	47.1	26 Mar.	2 May		960
28.0	56.0	11 Mar.	20 Apr.	147	
30.1					
20.0	42.2	5 Mar.	7 Apr.	126	430
25.2	41.5	7 Mar.			620
22.5					390
	46.0	5 Mar.	12 May	163	690
	58.7	7 Mar.			690
35.0	70.0	23 Mar.	4 May	175	880
50.3	77.7	17 Mar.	24 May	181	1020
47.5	64.0	20 Mar.	4 May		
51.5	71.0	20 Mar.	20 May		
39.1	61.1	14 Mar.	15 Apr.	154	480
	42.0	22 Mar.	29 Apr.	158	500
	41.0	12 Mar.	18 Apr.	150	540
	51.0	27 Mar.	20 Apr.	151	
38.0	55.1	11 Mar.	25 Apr.	152	680
35.6	44.0	17 Mar.			
47.0	68.0	7 Mar.	11 May	162	
35.4	62.0	10 Mar.	29 Apr.	160	
39.5	57.0	23 Mar.	13 Apr.	157	1070
65.4	94.5	12 Mar.			1230
50.0	64.5	8 Mar.			
55.5	65.5	26 Feb.			940
95.0					1060
65.0	85.0	4 Apr.	29 May	209	1180
56.7	70.0	10 Mar.			
51.0	65.0	10 Mar.			
51.0	70.0	8 Mar.			
55.0	86.0	21 Feb.	8 May	163	840
49.0	65.6	17 Mar.			
60.3	76.1		3 May		
50.0	62.0	10 Mar.	30 Apr.	157	730
60.0	78.0	2 Mar.	16 Apr.	143	730
41.0					280
13.7					230
4.5					

adverse climate, Upon comparing the data in Table 1, inconsistent variation was seen among sites in the same district, because the frost penetration depends mainly upon various factors such as soil type, water content in soil, groundwater level and degree of snow removal work on the ground surface.

5. CONTOURS OF FROST PENETRATION DEPTHS

The frost penetration depth differs from each other at two different sites, having the same coldness but different in other factors, thus making it impossible to be compared. However, two contour maps, showing tentatively the distributions of frost penetration depth, were prepared as shown in Figs. 2 and 3. The former gives contours of penetration depths on January 16, 1975, and the latter for the maximum penetration depths from data presented in Table 1. The southern part of Hokkaido, especially in Hiyama of District M was the warmest, with the maximum frost penetration about 10cm in depth.

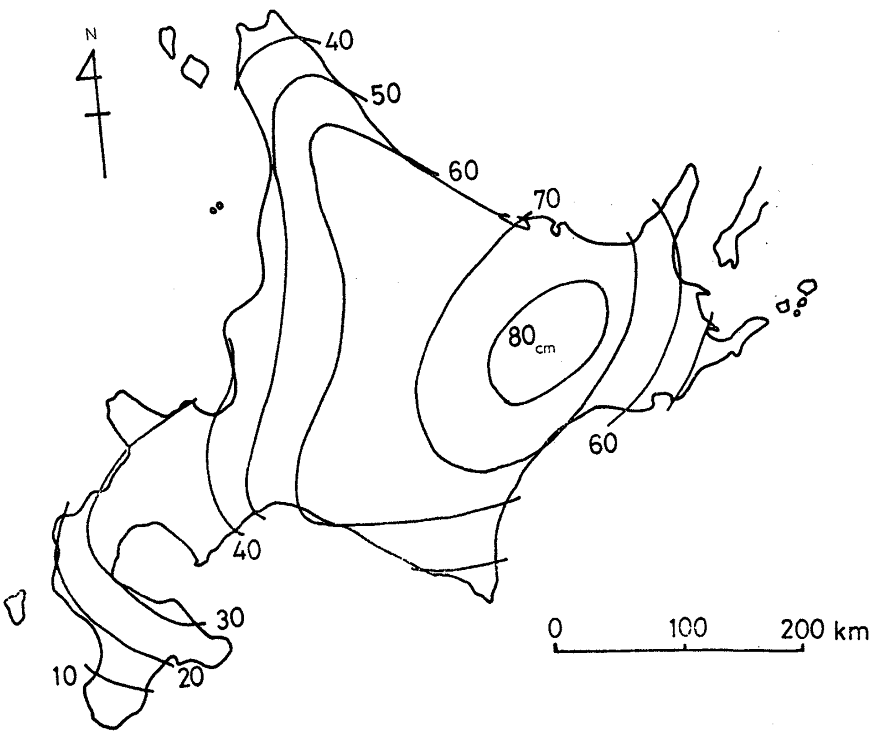

Fig. 3 Contours showing maximum frost penetration depth throughout Hokkaido in March 1975. Units in centimeters.

6. FROST PENETRATION DEPTHS VERSUS SNOW COVERING

As compared with the snow-free ground, the frost penetration depth decreases significantly when covered with snow [5]. As an example, Fig. 4 depicts the result obtained at the campus of Obihiro University, where volcanic ash exists. Snow began accumulating in mid-December and remained at a thickness of 20-40cm till the end of March. In the snow-covered area the frost penetration was flatly decreased but with the depth reaching its maximum at 41. 5cm, comparing with 83. 2cm while in the snow-free area. Nevertheless, the snow covers vary in thickness throughout the winter. Given a snow cover with a constant thickness d and also having homogeneous property, the frost penetration depth D can be expressed by $D=D_f-\frac{k_f}{k}d$, where D_f is the frost penetration depth free from snow cover, k_f and k the thermal conductivities of the frozen soil and the covering snow respectively

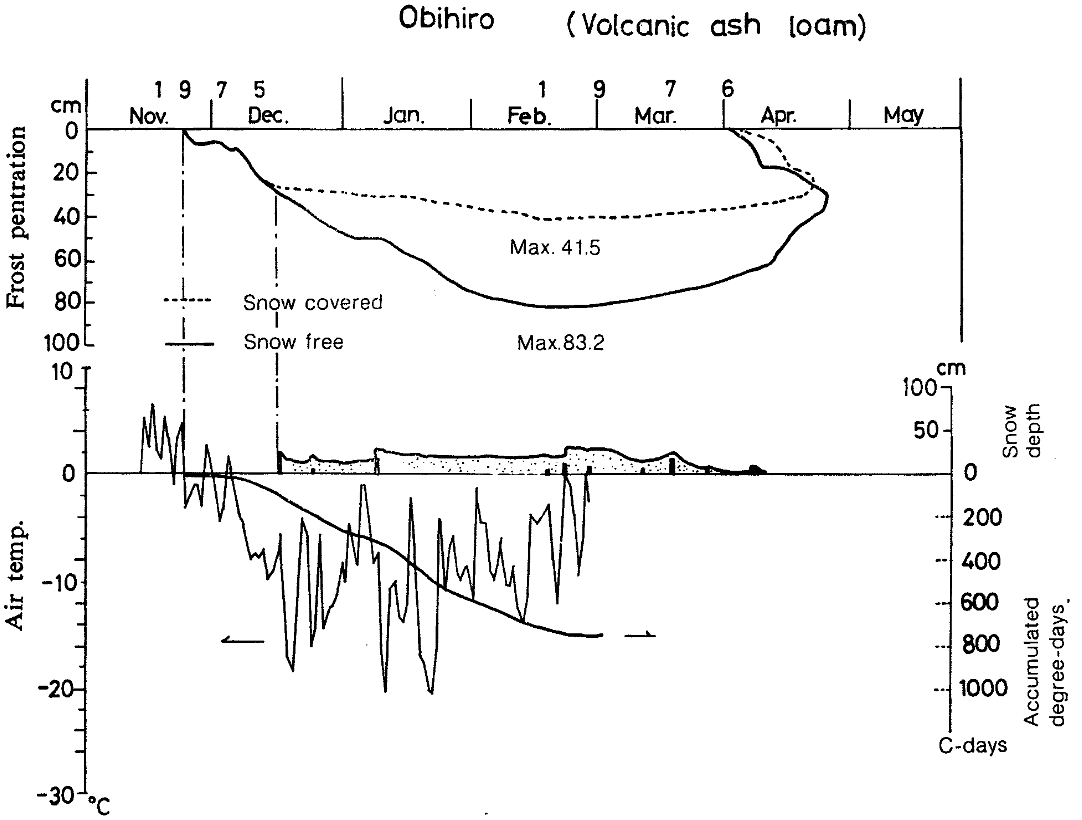

Fig. 4 Frost penetration sequence as function of time at campus of Obihiro University, showing snow covered and snow free cases, plus snow depth, daly mean air temperature and accumulated degree-days.

[6]. The equation indicates a decrease in frost penetration depth by an amount of $\frac{k_f}{k}d$, i. e., the thermo-resistively equivalent thickness of the snow cover d to the frozen soil.

If the thickness of the snow cover was assumed at a constant mean value of 20cm in the case described in Fig. 4, the thermo-resistively equivalent layer of it would be 41. 7cm in thickness, as calculated from the equation above. Therefore, the thermal conductivity of the covering snow was about one half that of the frozen soil. This simple fact explains fairy well the relation of both thermal conductivities reported by Akitaya [7].

7. FROST PENETRATION DEPTH VERSUS FREEZING INDEX

The freezing index, an expression of the accumulated number of degree-days (the difference between daily mean temperature and 0°C, a negative value), has a close correlation to the frost penetration depth. The relation is given by $D=a(F)^{1/2}$, where F is the freezing index, and (a) is a constant value. According to Stephan (as quoted by Jumikis [6]), (a) equals to 3. 5 for the freezing pure water such as in a lake, when D and F are expressed in the units of cm and °C·days respectively. In the case of ground freezing, (a) decreases with increasing ground surface heave due to the release of latent heat in ice segregation while freezing; for a large heave amount such as at Tomakomai field site as shown in Fig. 1, a value of (a) equals 2 was reported. However, if the ground surface has no heave and the soil material has a larger thermal conductivity than silty soil (frost susceptible), (a) would yield a larger value, say 4 or 5, so the frost can penetrate further into a deeper level.

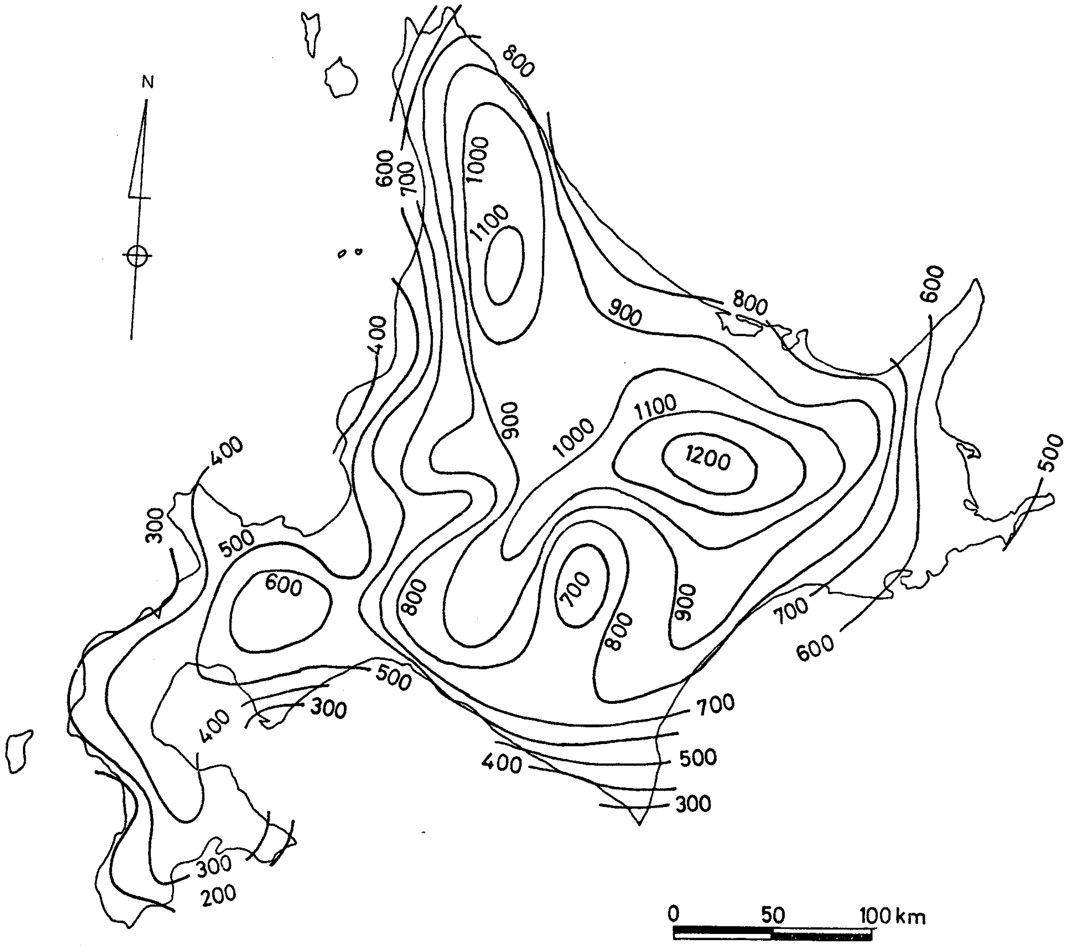

Fig. 5 Contours showing freezing index throughout Hokkaido in the winter of 1974–75.

A contour map of freezing index in the winter of 1974–75 is shown in Fig. 5, using data obtained from various meteorological observatories [8]. The coldest area was found around the boundary between Kitami and Tokachi, corresponding to that of the frost penetration depth in Figs. 2 and 3. These common pattern of contours can be observed from Figs. 2, 3 and 5. Employing these figures, the values of (a) are calculated and found to be about 3 for all districts in Hokkaido, thus suggesting a uniform mean value throughout Hokkaido.

8. CONCLUSIONS

The frost penetration sequences throughout the winter of 1974–75 were systematically observed using simple apparatus at various sites over the whole districts of Hokkaido, Japan, by keeping them clear from snow on the ground surface. However, variation in pattern occurred even in the same district, because the frost penetration depends largely upon the factors such as soil type, water content in soil and ground water table etc. The data so obtained are summarized in Table 1. A contour map, such as Fig. 2 for the mean frost penetration depths, can tentatively be drawn by using data from each district. When snow covers the ground surface, the frost penetration depth decreases by an amount of the thermo-resistively equivalent thickness of the covering snow to the frozen soil. The freezing index can be related to the frost penetration depth. If the freezing index F and the frost penetration depth D are expressed in the units of °C·days and cm respectively, the coefficient a would yield a value about 3 for all districts, thus sufficiently suggesting a mean value throughout Hokkaido.

ACKNOWLEDGEMENTS

The authors wish to express their heartfelt thanks to all observers at each field site throughout Hokkaido for conducting measurements, to Dr. Kondo of Obihiro University for providing valuable data, and to all colleagues at the Frost Heaving Section of the Institute of Low Temperature Science for their assistance in preparing this paper.

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