NRC Publications Archive
Archives des publications du CNRC

Proceedings of the First Canadian Conference on Permafrost

Brown, R. J. E.

For the publisher's version, please access the DOI link below./ Pour consulter la version de l'éditeur, utilisez le lien DOI ci-dessous.

Publisher's version / Version de l'éditeur:
https://doi.org/10.4224/40001156

Technical Memorandum (National Research Council of Canada. Associate Committee on Soil and Snow Mechanics); no. DBR-TM-76, 1962-04-17

NRC Publications Archive Record / Notice des Archives des publications du CNRC :
https://nrc-publications.canada.ca/eng/view/object/?id=ab7ecd93-bdb4-4f35-8c41-319c55f59d38
https://publications-cnrc.canada.ca/fra/voir/objet/?id=ab7ecd93-bdb4-4f35-8c41-319c55f59d38

Access and use of this website and the material on it are subject to the Terms and Conditions set forth at
https://nrc-publications.canada.ca/eng/copyright
READ THESE TERMS AND CONDITIONS CAREFULLY BEFORE USING THIS WEBSITE.

L'accès à ce site Web et l'utilisation de son contenu sont assujettis aux conditions présentées dans le site
https://publications-cnrc.canada.ca/fra/droits
LISEZ CES CONDITIONS ATTENTIVEMENT AVANT D'UTILISER CE SITE WEB.

Questions? Contact the NRC Publications Archive team at
PublicationsArchive-ArchivesPublications@nrc-cnrc.gc.ca. If you wish to email the authors directly, please see the first page of the publication for their contact information.

Vous avez des questions? Nous pouvons vous aider. Pour communiquer directement avec un auteur, consultez la première page de la revue dans laquelle son article a été publié afin de trouver ses coordonnées. Si vous n'arrivez pas à les repérer, communiquez avec nous à PublicationsArchive-ArchivesPublications@nrc-cnrc.gc.ca.

The Associate Committee on Soil and Snow Mechanics is one of about thirty special committees which assist the National Research Council in its work. Formed in 1945 to deal with an urgent wartime problem involving soil and snow, the Committee is now performing its intended task of co-ordinating Canadian research studies concerned with the physical and mechanical properties of the terrain of the Dominion. It does this through subcommittees on Snow and Ice, Soil Mechanics, Muskeg and Permafrost. The Committee consists of about twenty-five Canadians appointed as individuals and not as representatives, each for a 3-year term. Inquiries will be welcomed and should be addressed to: The Secretary, Associate Committee on Snow and Snow Mechanics, c/o Division of Building Research, National Research Council, Ottawa, Ontario.

NATIONAL RESEARCH COUNCIL OF CANADA

ASSOCIATE COMMITTEE ON SOIL AND SNOW MECHANICS

PROCEEDINGS
OF THE
FIRST CANADIAN CONFERENCE ON PERMAFROST

17 AND 18 APRIL 1962

Prepared by

R. J. E. Brown

TECHNICAL MEMORANDUM NO. 76

OTTAWA

JANUARY 1963

FOREWORD

This is a record of the First Canadian Conference on Permafrost which was held at the National Research Council, Ottawa, Ontario, on 17 and 18 April 1962. The Conference was sponsored by the Associate Committee on Soil and Snow Mechanics of the National Research Council. A list of those in attendance is included as Appendix "A" of these proceedings.

The overall theme of the Conference was permafrost in relation to northern development. A wide variety of topics was considered, including phases of basic research, design and practice as they pertain to a variety of problems arising from permafrost: geology, climate, vegetation, soil, heat flow, economics, site investigations and construction. In Session I, under the chairmanship of Mr. T. A. Harwood, five papers were presented. Session II was chaired by Dr. T. Lloyd and five papers were presented. The Chairman of Session III was Dr. J. R. Mackay; five papers were presented. The chairman of Session IV was Dr. R. F. Legget, at which four papers were presented. The Conference was concluded with a showing of the colour film "Building in the North" produced for the Division of Building Research, National Research Council by the National Film Board of Canada. Of the 19 papers presented at the Conference, 13 are reproduced in their entirety in this proceedings and 6 are presented in summary form.

The attention of the reader is directed to the maps immediately preceding the first paper showing the distribution of permafrost in Canada, the U. S. S. R., and the northern hemisphere.

TABLE OF CONTENTS

Wednesday, 18 April

Morning Session:- Site Investigations, Construction, Properties

Afternoon Session:- Construction, Heat Flow

INTRODUCTORY REMARKS

Dr. R. F. Legget, Director of the Division of Building Research, National Research Council, cordially welcomed delegates to Ottawa on behalf of Dr. E.W.R. Steacie, President of the National Research Council, who was unable to attend. Dr. Legget pointed out the importance of the Conference being the first one on permafrost to be held in Canada. He reviewed briefly the development of permafrost investigations in this country during the past decade and noted with satisfaction the present widespread interest as evidenced by the attendance of more than 150 delegates. It was his hope that the Conference would prove interesting and valuable to those present.

Mr. T. A. Harwood, Chairman of the Permafrost Subcommittee, Associate Committee on Soil and Snow Mechanics, welcomed those present and encouraged the delegates to contribute to the discussion at the end of each paper. He drew attention to the photographic displays which were set up outside the auditorium in which the Conference was held and hoped that delegates would avail themselves of the opportunity to view these displays. Announcements were made pertinent to luncheon arrangements, etc.

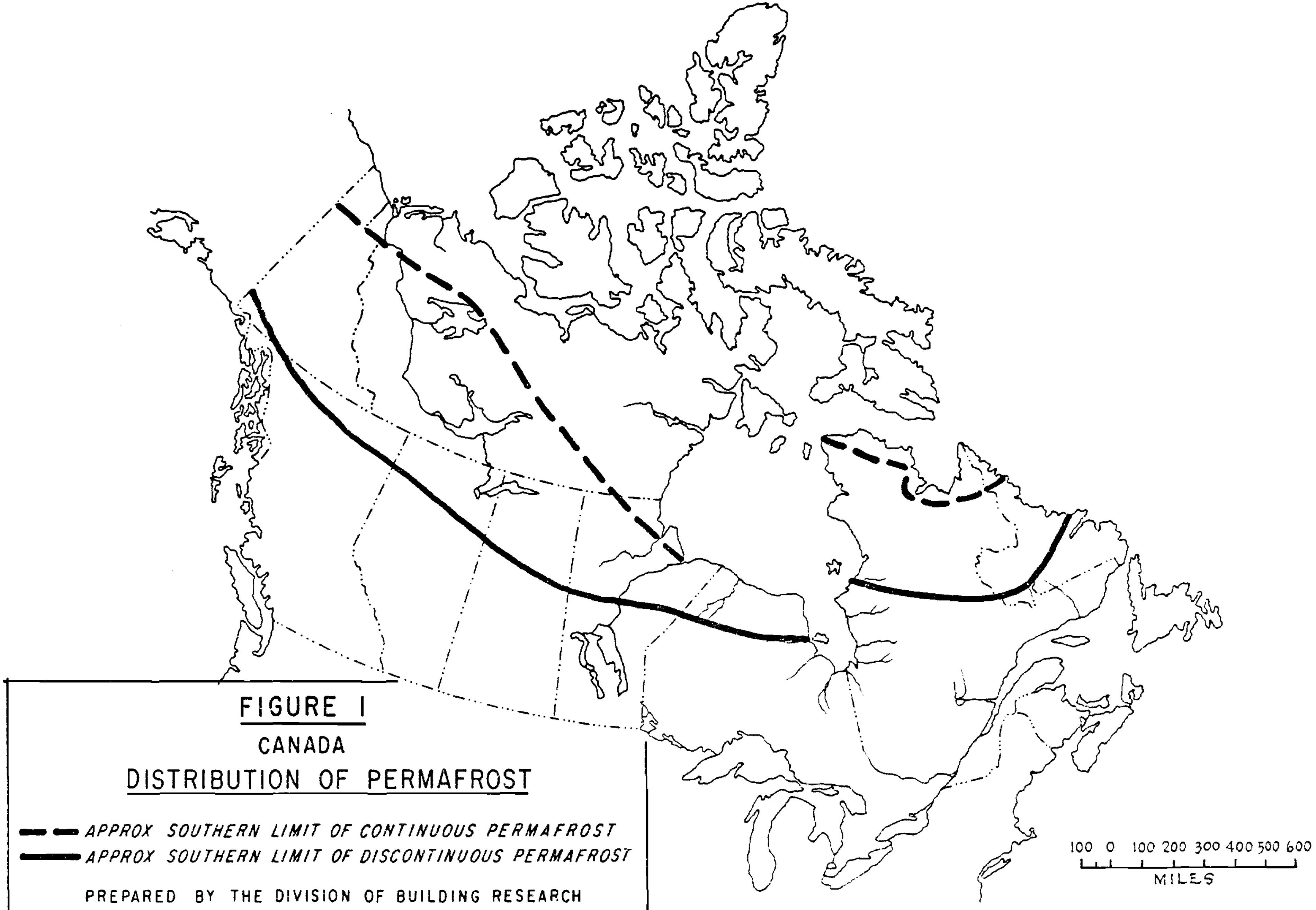


FIGURE I

CANADA

DISTRIBUTION OF PERMAFROST

PREPARED BY THE DIVISION OF BUILDING RESEARCH
NATIONAL RESEARCH COUNCIL
CANADA 1962

BR 2836

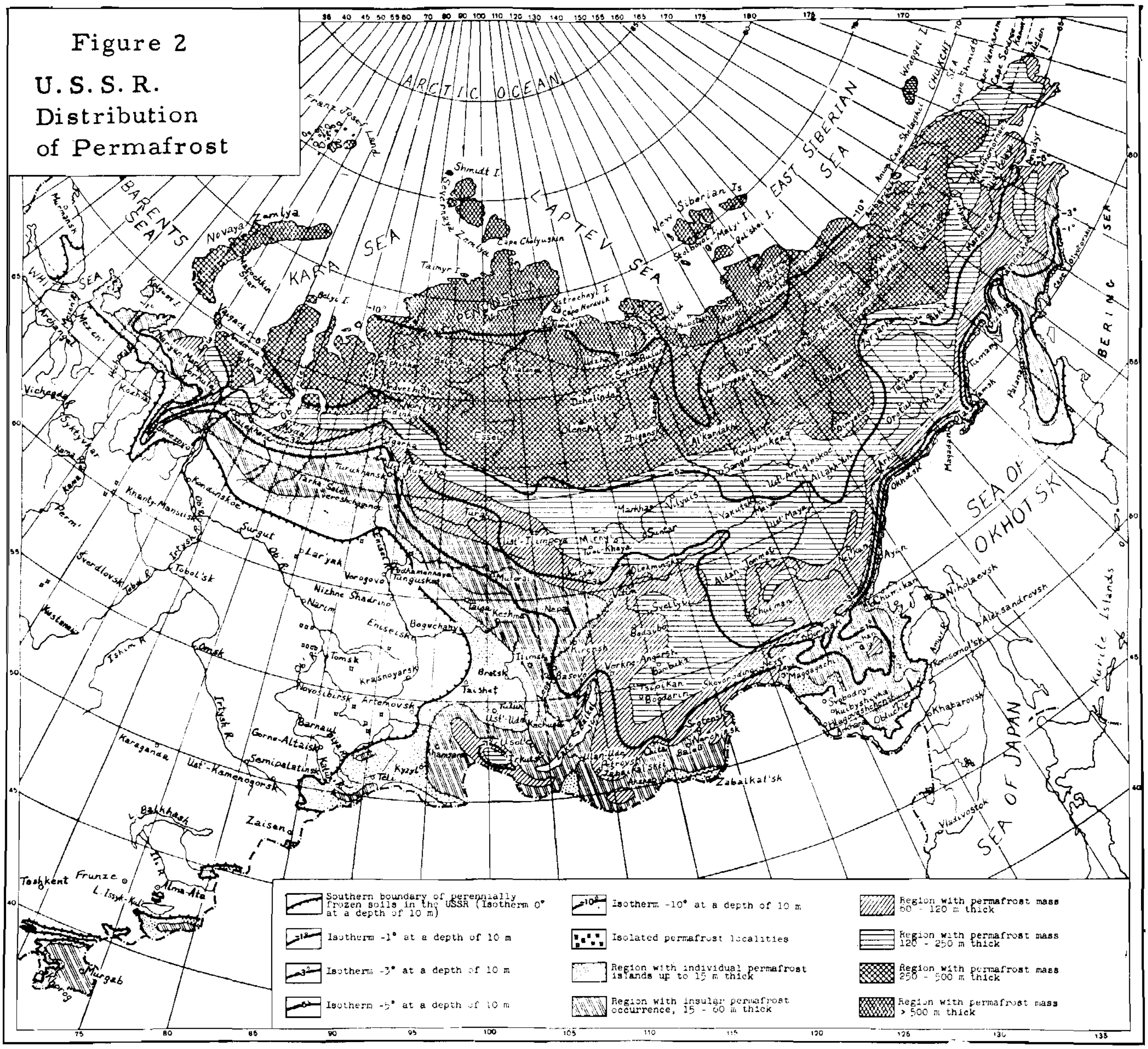
MAP OF PERMAFROST DISTRIBUTION IN CANADA

Explanatory Note

Lines on the map indicate the approximate southern limits of continuous and discontinuous permafrost in Canada. The distribution of permafrost varies from continuous in the north to discontinuous in the south. In the continuous zone, permafrost occurs everywhere under the ground surface and is generally hundreds of feet thick. Southward the continuous zone gives way gradually to the discontinuous zone where permafrost exists in combination with some areas of unfrozen material. The discontinuous zone is one of broad transition between continuous permafrost and ground having no permafrost. In this zone permafrost may vary from a widespread distribution with isolated patches of unfrozen ground to predominantly thawed material containing islands of ground that remain frozen. In the southern area of this discontinuous zone permafrost occurs as scattered patches and is only a few feet thick.

It is emphasized that the lines on the map must be considered as the approximate locations of broad transition zones many miles wide. Their locations may be changed on future maps subject to the obtaining of additional observations. Permafrost also exists at high altitudes in southern Labrador-Ungava and in the mountains of western Canada a great distance south of the limit of discontinuous permafrost shown on the map.

FIGURE 2



From: "Technical Considerations in Designing Foundations in Permafrost".
State Committee of the Council of Ministers (U.S.S.R.) for
Building Problems. State Publishing House of Literature on
Building, Architecture and Building Materials, Moscow, 1960.

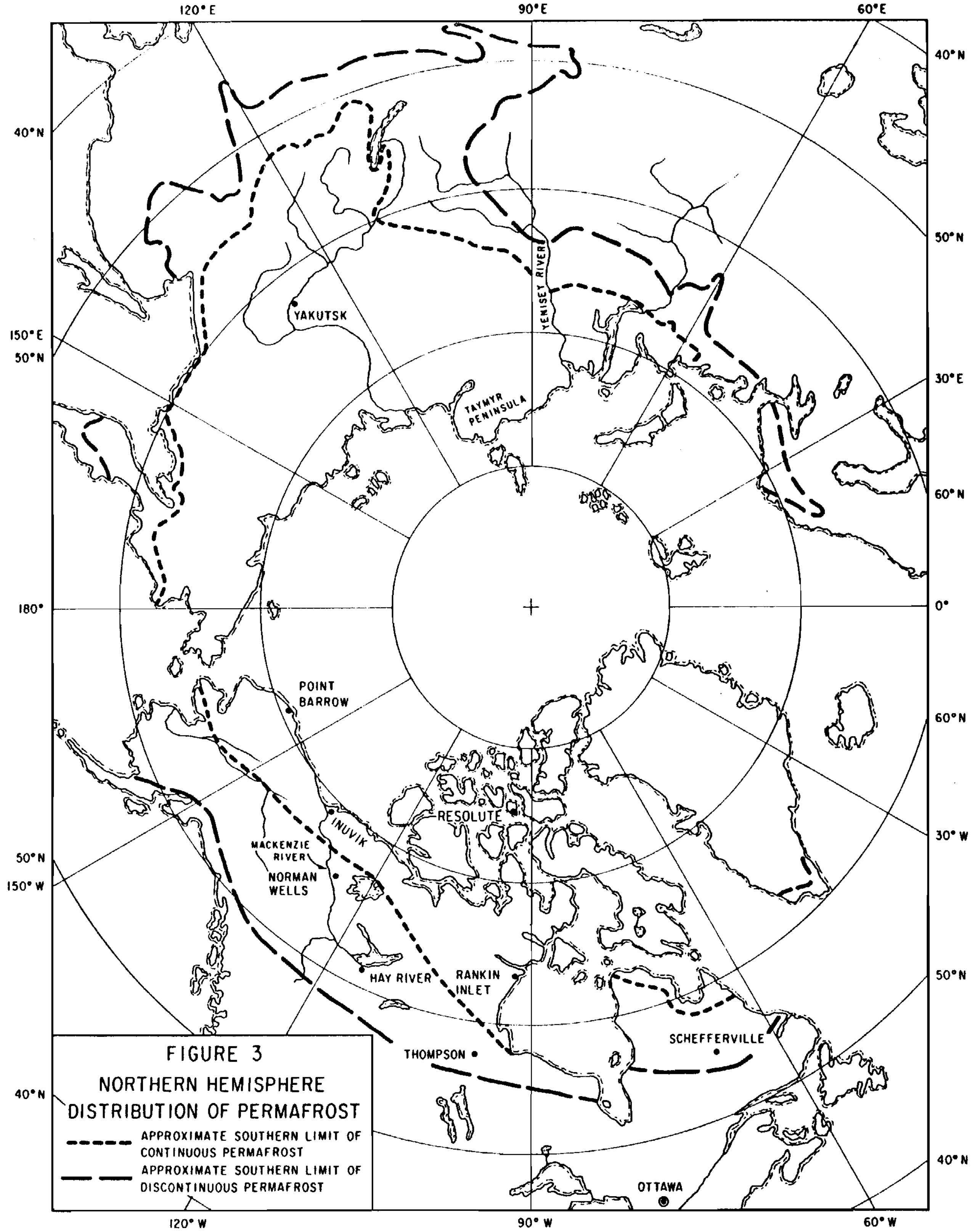


FIGURE 3
NORTHERN HEMISPHERE
DISTRIBUTION OF PERMAFROST

I. 1. THE INFLUENCE OF PERMAFROST ON NORTHERN DEVELOPMENT

T. Lloyd*

INTRODUCTION

The expansion of settlement from man's early home in the fertile, friendly and protected river valleys of the Middle East has been marked by conquest of one natural obstacle after another. Broad seas, hot, dry deserts, mountain ranges and dense forests each in their turn arrested his progress until new techniques were devised and perfected, and became common knowledge. His invasion of the tropical rainforests was delayed by diseases, and his ventures into the far north - what Stefansson has termed "The Northward Course of Empire" (1) - were handicapped by severe cold and snow, and by the heavy ice which impeded and damaged his ships. In his long and frequently frustrated efforts to make a home in even the remotest parts of the earth, man has encountered, and eventually learned to deal with, an enormous variety of natural hazards.

Perennially frozen ground in the polar regions is one of his most recent natural obstacles. It has become of major importance only in the past few decades, although its existence has long been known. Alexander Mackenzie mentioned it and Jules Verne wrote a novel (2) based in part on it, while the quick-frozen mammoths of Siberia have been a cause of wonder for generations.

How was it that such a widespread phenomenon, covering about one-half of Canada and almost as great a proportion of the Soviet Union, should nevertheless have attracted so little attention that until a few years ago it even lacked a commonly accepted English name and is only now being honoured in Canada by a national symposium?

The world population map demonstrates that man has as yet barely reached in any numbers the southern limit of that one-fifth of the land surface underlain by permafrost.

As a significant factor in northern settlement, permafrost problems arise on a serious scale only when man erects heated buildings and other elaborate structures. In North America at least, this is a comparatively recent event, so there is no long, traditional mastery of the technical skills needed to deal with it. Even today one

---

* See Appendix "A" for affiliation

hears of contractors and engineers, discomfitted on encountering permafrost for the first time, searching for quick and ready-to-hand means for extricating themselves from its consequences. There must be among arctic folk a diverting repertoire of anecdotes about the calamities of others who did not take seriously the need for handling permafrost gently. One hears tales of undulating airfields, collapsing foundations, detached porches, disappearing furnaces, shattered water lines and sway-backed or rippled roof lines.

There is a popular misconception that in such matters the Russians have been spared our trials. Yet, despite their long experience and remarkable skill in northern operations, Soviet engineers are not proof against similar catastrophes (3, 4). In the early days of northern settlement many mistakes were made and even today criticism is heard of occasional blunders. Older photographs show the effect on small buildings of disregarding the permafrost, and there are more recent illustrations too.

Referring to the early years of the Norilsk mining community at 69°30' N. east of the Yenesei River, one writer states (5):- "A two storey house is to be built. The hardest available spot on the flowering tundra is selected.... Everybody is satisfied that a two storey house on light foundations would be supported. But no sooner did the inhabitants get their stoves going than the frozen mud thawed, cracks appeared in the walls and one corner of the house tilted and collapsed.... In the hut settlement, a kitchen built of bricks disappeared into the ground. It had gone with all its equipment, the potatoes and the cook". The first railway built from Norilsk to the Yenesei River during one winter, disappeared over long stretches in the following summer – taking wagons and locomotive with it. "No wonder people are frightened of the tundra" as one reporter said.

All the difficulties are not in the past. Writing of Yakutia in 1960 one author states -- "Various industries are developing at a rapid pace in the Yakut ASSR. This requires construction projects which must be carried out in severe climatic conditions and on permafrost. Difficulties are encountered because of a lack of building experience in the north". As will be demonstrated later, there have also been notable successes.

THE PROBLEM

To the architect, the contractor, the engineer and the scientist permafrost offers many and complex problems still needing intensive study and discussion. For the geographer who may be concerned with extending settlement into the northland, the problem is less formidable. The question to which he is seeking an answer is, put simply, "To what extent does the presence of permafrost restrict or inhibit development of an area, or so increase the economic cost of doing so as to make it prohibitive?". In answering this he needs to know the extent of permafrost, in general and, whenever possible, in great detail, what its effects may be on selected activities, and the degree to which techniques exist for circumventing it, or at least lessening its consequences when they are unfavourable.

Much remains to be done to determine the extent of permafrost in North America. In this as in so many other cases, Canadians have access to more information about the physical conditions of the Soviet Arctic than they do about their own country. A useful beginning might be preparation of a chart of ignorance indicating those regions of this country where we do not know all we should about permafrost distribution, in area and thickness. Another useful tool would be a permafrost distribution map similar to one recently published in the Soviet Union (6).

It has been stated that about one-fifth of the world's land surface is underlain by permafrost. In seeking to achieve greater precision, one encounters the important differences between areas where it is continuous, discontinuous or sporadic. Furthermore the depth to the upper surface of permafrost varies from place to place as does the total thickness. South of Point Barrow, Alaska, for example, it is more than 1,000 feet thick. At Resolute Bay, N.W.T. on Cornwallis Island somewhat more; east of the Yenesei River in the Taymyr Peninsula of Siberia it is about 1,600 feet; at Sveagruva, a mine in West Spitsbergen, it is a little less than 1,000 feet. While its extent under the seas is rarely known, there is evidence that it extends for some distance off the northeast coast of Siberia.

The limits of permafrost are of course liable to change because of modifications in climate. Human influence is also significant though on a much smaller scale -- as in the clearing of land for cultivation, which usually lowers the permafrost surface, the draining of water-covered areas such as lakes or estuaries, where the level may rise - as it has also in mining dumps in Siberia. Even in temperate climates it may be induced by "leakage of cold" through the bottom of cold storage plants.

INFLUENCE ON MAN'S ACTIVITIES

The more or less direct influence of permafrost on man's activities in the north will now be discussed.

Paramount is transportation, essential to gain access from the south, to explore the area and to carry on economic or military activities. It calls for roads, bridges, airfields (including hangars and other facilities), railroads (and provision of water for steam locomotives), docks and harbours, towers for radio and electrical transmission. Under industrial activities we may include mining and mineral processing, oil drilling, refining and storage, construction of factories, warehouses and office buildings.

Communities call for housing - whether individual or in apartment blocks - streets, water and heat, and the disposal of industrial and commercial wastes, including warm water, and power plants, both thermal and hydro. To all of these may be added miscellaneous public works requiring excavation and earth moving. These and many more may be influenced by the existence of permafrost at the site.

Defence requirements are today in many ways not unlike those of civilian life, except that the sites may be more remote, the projects are planned and executed more urgently, and the cost is usually not a determining factor.

Very considerable experience has been accumulated in railroad and highway building under permafrost conditions. The C.N.R. line to Churchill, Manitoba built a generation ago was a pioneer undertaking in a then unfamiliar environment, and has proved successful (7). The Alaska Railroad from Seward to Fairbanks crosses in one section almost forty miles of permafrost terrain and requires constant attention because of its high ice content (8). It will be interesting to learn whether corresponding problems are encountered in building the Great Slave Lake railway. The Pechora railway in northern European Russia, which extends across the Urals to the Ob River, is probably the longest line yet built on permafrost.

Construction of the Alaska Highway during World War II encountered permafrost and ran into particular difficulty in cuts and on side slopes because of disturbance of the previous heat balance and the drainage system. There is now a network of long distance roads in eastern Siberia linking the seacoast, the Lena River valley, and the Trans-Siberian Railway. Other roads follow the northward flowing rivers. The usual difficulties with permafrost have been reported. In the Thule area of Greenland, there are several miles of highgrade roads on the Air Base itself, and one stretch of about 20 miles which gives access to the ice-cap. The whole system lies on permafrost and has been used by the U. S. Corps of Engineers for research and testing purposes.

Airport construction is in principle not unlike that of a modern highway and employs some similar techniques. Construction of large airfields in the north was rare before World War II when an expanded programme started in Alaska. A few fields were built in northern Canada (originally in the central and eastern parts and later in the Mackenzie River valley), and three large ones in Greenland. The Soviet Union was similarly engaged in part of northeastern Siberia. Since the war there has been widespread construction of civilian airports in Alaska, as well as modernization and expansion of military fields, and in Canada reconditioning of earlier ones and construction in entirely new areas - such as at Resolute Bay, N.W.T. and Inuvik, N.W.T., and in connection with DEW line sites. Thule is the majór modern airport in Greenland, but smaller ones have been built at Nord in Pearyland and at Kulusuk in south-east Greenland. The runway at Søndrestrøm has been greatly expanded as have the facilities there, including a large hotel. All this demonstrates that there is now a considerable accumulation of technical experience in airport construction under varied arctic conditions, with permafrost usually an important factor (9). The modern airport in the arctic is now often associated with a townsite, and the inter-relationship of the two may be critical, if only because settlements have much excess heat to dispose of. For example, poor siting may allow warmed water to drain from the town toward the airstrip. In any event utilities are needed, as are fuel storage, housing and barracks, hospitals, operational buildings, repair shops, warehouses, community centres, churches, schools and so on. These each raise their special problems both in relation to the frozen foundation and to one another.

Docks and harbours combine some of the difficulties of onshore construction with the uncertainties of conditions under tidewater. In each particular project, care is needed to determine the precise extent of permafrost under the foreshore and the sea itself. The port of Churchill, Manitoba, with its large grain elevator, is an example of skilled engineering based on such careful study. However there is still relatively little experience of port construction under permafrost conditions. None of the northern defence undertakings in Alaska, Canada or Greenland has called for anything of this sort. There are understood to be several large river ports and some seaports in the permafrost areas of Siberia.

It is in the construction of communities that many of the major problems have arisen and most experience has been gained. Single dwellings of wood in small villages raise no unexpected difficulties. They are subject to displacement from seasonal movement in the active layer and also suffer at times from thawing of the permafrost. Occasionally, there are dramatic bursts of underground water that fill a basement or even a house with ice, but the usual consequences are more prosaic saggings, heavings and crackings. Construction and maintenance of northern cities is another matter. Alaska and the Soviet Union have the greatest experience here since there have as yet been no large towns in northern Canada, with the exception of Inuvik. Greenland settlements have avoided serious problems until recently through being built on rock, following the biblical injunction to stay away from sand! The consequences of the recent widespread erection of schools, hospitals, warehouses, apartments and other large buildings in west Greenland settlements has yet to be seen. There have already been some minor difficulties due, it is understood, to insufficient care in the first few years to take precautions against permafrost. There are many Soviet settlements, some now of considerable size, within the permafrost zone. They include Vorkuta, Igarka, Irkutsk, Bratsk, Chita and Yakutsk and many sites of new power plants, mines and river ports.

Fairbanks, Alaska, though small (15,000), has some of the attributes of a large city - with a university, public and commercial buildings, a central business district, suburbs and three large air bases in the vicinity. Thule, already referred to, though an airbase, is in effect a small town.

What has been the outcome in these and other urban centres of more than thirty years of trial and error, of systematic research and extended practice? A recent Soviet report (10) draws attention to the serious effects of thawing of permafrost following construction:

> "In Chita (on the Trans-Siberian Railroad) for example settlement caused three storey residential buildings to be condemned 4 to 7 years after completion. The outer part of one of the buildings settled more than one meter in relation to the central part and only settlement joints saved it from total destruction. In the Vorkuta mining region about 130 out of 165 buildings inspected from 1948-1950 were found to be more or less deformed and some were totally destroyed as a result of thawing of the permafrost to great depths. . . . The deformation of buildings is often due to the heat given off and to the discharge of water from sanitary installations."

The same source names five stations on the Amur railroad in eastern Siberia where thawing of the ground beneath dams led to leakage of reservoirs, which quickly become catastrophic, and some installations had to be abandoned.

A comparable statement from Alaska (11), in this case Fairbanks, reads:

> "Heated buildings on the alluvial fans and colluvial slopes are severely distorted unless special engineering techniques are

> employed. Buildings with heated basements or buildings that allow heat to enter the ground in other ways have subsided differentially 1 to 2 feet or more, cracking walls and preventing windows and doors from opening. Some buildings are jacked up periodically to maintain a level position."

As a consequence of such conditions, older communities in Russia have been said to have a drunken appearance, and Nome, Alaska has been likened to a scene by a contemporary artist! Yet real success has been achieved both in North America and in the U.S.S.R., usually by strict adherence to now-recognized construction practices. Some of these are:

1. Selection of site. Places with large amounts of buried ice are to be avoided to prevent subsidence when the ground becomes warmed.
2. Preservation whenever possible of the site as it exists, even to the extent of avoiding unnecessary vehicle movement and destruction of the natural cover.
3. Precautions to ensure that the ground will remain frozen e.g., by burying the original surface under a pad of dry, coarse material (as was done with the right-of-way of the Hudson Bay Railroad), and by preventing the escape downward of heat or waste water. Buildings may also be placed on piling with a ventilated space beneath.
4. By allowing in certain cases for the building to settle in a predetermined manner as the ground thaws. This is sometimes unavoidable in the case of buildings with high heat output - e.g., metal refineries.
5. In general guarding against transfer of additional heat to the ground - including transmission of the sun's heat by conduction, and heat from buried water and sewage lines.

NEED FOR EXCHANGE OF INFORMATION

One of the surest ways of improving construction techniques in all such cases is through widespread interchange of experience - even though it may at times have been embarrassingly unsuccessful. As literature concerning North American practices is more readily available, it would seem most useful for me to cite examples from the Soviet Union. I shall refer specifically to the case of Norilsk, certainly the largest community in the zone of continuous permafrost and firmly and successfully established (12). The Soviet Census states that in 1959 it had a population of 108,000. It is an important centre of mineral production and processing. It mines coal, uranium, nickel, copper, cobalt and platinum, in fact fifteen metals are refined there. It is linked by railroad to the port of Dudinka on the east bank of the Yenesei River in latitude 69½° N. - about the same as Point Hope, Alaska; Cambridge Bay, N.W.T. ; and Disko Island and the Mestersvig mine in Greenland.

The settlement was started in 1935. Now more than 25 years old, it is regarded as a model for the study of large-scale construction in permafrost areas. Although in operation at the outbreak of World War II, the plant was expanded rapidly in the early 1940's because of the urgent need for nickel. The mine site lies in a hilly basin separated from the Yenesei River by eighty miles of swampy tundra. The climate is very severe with high winds and heavy snow in winter, together with a long period of darkness. The coal in the underground mine is of course frozen. The ore is mined by open pit methods.

Initially, it was decided that the only hope of constructing large buildings securely, including the smelters, would be by placing them on rock foundations. This required digging pits as much as 20 metres deep through frozen ground. Traditional wooden houses were built and located wherever it was convenient. Elaborate snow fences were necessary to make it possible to move within the settlement during winter.

There is no doubt that the town as first built, apart from the industrial units themselves, was of a make-shift character and left much to be desired. Apparently there has been a complete reconstruction since the early 1950's and a modern city has replaced the old mining camp. Excavation of large foundation pits has ceased. The earlier practice of placing piles in holes steamed in the ground has been discarded. Reinforced concrete piles are now frozen into holes made with a standard mining percussion drill. The piles are about twenty metres long and produced in a local plant at a rate of 500 a day. Buildings are generally of brick and precast concrete. Photographs (13) suggest that the city is now much like others of the same size in the U.S.S.R. - apartments are of six to eight storeys, there are broad thoroughfares, parks and the usual community enterprises – medical clinics, libraries with 600,000 books, a professional theatre, a very active full-time and part-time educational programme - thirty schools with an enrollment of about 1,300 students and, in addition, a mining and metallurgical technical school with 1,250 day and evening students. The headquarters of the Agricultural Institute of the Far North is there, together with a permafrost research centre. There are also neon signs and a T.V. station. The city claims to be built on two foundations – the mining operations and the permafrost. It is also a centre for study of construction methods by specialists from as far away as Yakutsk and Magadan in eastern Siberia and Salekhard and Vorkuta in the west.

The principles governing construction are said to be these:-

1. Very careful study of the terrain.
2. Foundations are excavated in winter and are laid in winter.

3. Piles are installed in drilled holes.
4. Bricks are laid in summer, but concrete slab construction goes on throughout the year.
5. Utilidors are employed for outdoor piping. They are periodically ventilated by air blown through them.
6. Buildings have a cold, vented basement or lower storey.
7. All buildings and other works are re-examined constantly. For example, the Permafrost Institute has 150 city houses and 20 village houses under observation, along with 100 industrial buildings and other structures, and 75 miles of outside pipelines. The "dynamics of permafrost" are under continuous study; it has been found that temperatures under the townsite are falling.

Research is continuing into such subjects as more efficient and economical types of utilidors (the present ones are double decked - with sewage pipes below, and steam, water and electric lines above); cold floors are complained of so that improved insulation is needed, and radiant heating of floors is being tested; there is need of a flexible seal of some sort to close gaps which may occur between walls and floors or elsewhere. Better pipeline insulation is required. There remain many problems in the efficient disposal of waste water (14).

NATURAL VEGETATION AND CULTIVATION

The distribution of natural vegetation, which is influenced by the presence of permafrost, is of indirect importance to northern settlement. A local supply of timber for construction and fuel is desirable. The comparatively luxuriant vegetation in some areas is in part made possible because the frozen ground does not permit the usual subsurface drainage, so that the modest precipitation becomes more effective. On the other hand, shallowness of the soil restricts the roots and in some cases stunts the growth of trees.

Agriculture is of considerable importance to settlement in some northern areas and is strongly influenced by permafrost (15). As already suggested, vegetative growth may be aided by retention of water near the root system. However, account must also be taken of the disadvantage of a "reserve of cold" retained near the surface where the roots are affected. Fortunately after two or three years of cultivation the permafrost table is lowered until it is usually below the depth reached by most plants. This can be encouraged by retaining snow drifts on the land and by heavy manuring in Spring. These techniques have assisted production of early ripening barley at Igarka in the U.S.S.R. The existence of permafrost may, under some circumstances, be a very considerable handicap to agriculture – notably when the ground contains large quantities of ice. Cultivation leads to thawing and settling – with the resulting hummocky appearance which in extreme cases is termed "thermokarst" from its superficial resemblance to limestone eroded by solution. There may be deep pits, trenches and gullies, as much as five to twenty-five feet across. The only long-term solution is to select areas where the ice content of the ground is low.

Despite the existence of permafrost in addition to a severe climate, small-scale agriculture has become significant in Alaska, northwestern Canada and parts of Siberia and northern Europe, when a local demand exists for the produce.

THE NEED

What should be done so that settlement of the far north, in any case likely to be slow, is not to be further delayed because of inability to operate efficiently and economically in permafrost areas? The following lines of action are suggested:-

1. The exact extent of permafrost distribution by area and depth in Canada is not yet known. Such ignorance should no longer be condoned. There is need for small-scale permafrost mapping of the whole north and of larger-scale mapping of selected areas. This, which is an obligation of the public service, is less a scientific problem than a technical one. In part it requires detailed field work, in part the assembling of existing data.
2. There is need for a freer interchange of information. The first essential is for this to be done within Canada itself, then with the United States. I do not refer here so much to the needs of scientists and other specialists but to the working contractor, engineer and architect, the administrator and the student in training. There is also an urgent need for far greater availability of recent information from the Soviet Union. The literature is now easier to obtain but few can use it in the original Russian. It should be translated on a comprehensive scale. Canada would seem to be a logical place for much of this to be done (16).
3. Literature is useful, the direct exchange of expert personnel is even more so. How many Canadians have been in the famous Obruchev Permafrost Institute in Moscow? Or that at Yakutsk? How many have personally seen and examined modern Soviet projects built on permafrost? Are there any? The barrier to such visits is in part a financial one but is also a political one. Tours should be made by Canadian students of permafrost to such sites as Norilsk, the mining centre of Vorkuta in the Pechora region, Yakutsk now a considerable research centre, and to some of the large new hydro projects scattered throughout Siberia.

4. Finally there is need within Canada for closer contact between the research scientist in university or government and the men who day by day are faced with practical problems. Those of us who have had contacts with Soviet arctic scientists have been impressed by the obviously close ties between them and those concerned with development and production. The practical man seems to turn spontaneously to the scientist for aid, and the scientist is constantly aware of the developments and discoveries made in the field.

Northern Canada will without doubt develop more rapidly in the next few decades than it has since 1930. The tempo of this development will depend upon the enterprise of industry and the attitude of governments. The cost of it, the success of the various undertakings and the comfort and happiness of those who will operate them and live in the new settlements, will depend greatly upon research done well in advance of the immediate need.

The science of geocryology – the study of frozen ground – and its many applications should take a leading place in northern research. It is to be hoped that government agencies, industries, the universities and such organizations as the Arctic Institute will, as a result of this First Canadian Conference on Permafrost, devote greater attention to the subject. The practical returns will more than justify this.

It may not be inappropriate to end by quoting from the distinguished Russian scientist S. P. Suslov, who wrote in his monumental study of Siberia (17):-

> "The geographer, climatologist, hydrologist, soil scientist, geomorphologist, botanist, entomologist, zoologist, agriculturalist, geologist, biochemist, engineer, architect, geophysicist, palaeontologist, archaeologist - all may find much to study and ponder in the regions where permafrost is found. Perhaps the time is not far off when the obstacle that permafrost places in the way of utilization of territories will, dialectically turn into its opposite, and become a powerful productive force that man can control and regulate."

REFERENCES

1. Stefansson, V. The Northward Course of Empire. New York, 1924. pp. 1-19.
2. Verne, Jules. The Fur Country; or, Seventy Degrees North Latitude. New York, 1876. A tale of "Fort Hope" on "Victoria Island" in the western Arctic.
3. Suslov, S. P. Physical Geography of Asiatic Russia. San Francisco, 1961. pp. 148-149.

4. Bondarev, P.D. "A general engineering - geocryological survey of permafrost regions of the U.S.S.R. and Methods of Construction in Permafrost Areas". Problems of the North, No. 3, 1959, pp. 23-47.
5. Znamya. 1407, 1958.
6. See Priroda. Feb. 1962 for coloured insert map.
7. Charles, J.L. "Permafrost Aspects of the Hudson Bay Railroad". Proc. Am. Soc. Civ. Eng. Soil Mechanics and Foundations Division, Vol. 85, No. S.M. 6, Dec. 1959, pp. 125-135.
8. Péwé, Troy L. "Permafrost and its Effect on Life in the North" in Arctic Biology. Corvallis, 1957. pp. 12-25.
9. See for example Sebastyan, G.Y., paper presented at First Canadian Conference on Permafrost. 1962.
10. Bondarev. op. cit. p. 25.
11. Péwé. op. cit. p. 22.
12. This account is compiled from various Soviet sources including articles in newspapers and magazines.
13. For example those in - Grafsky, Yuri "In the Land of Permafrost". Soviet Union Today, Jan. 1962, pp. 8-13. Moyev, Vitaly "Norilsk, Polar Night on the Calcutta Meridian". Soviet Union, No. 145, 1962. pp. 5-11. For a photograph of the main metallurgical plant see Kutaf'iev, S.A. (ed) Russian Soviet Federal Socialist Republic Economic Geography. Moscow, 1959. p. 722.
14. For a summary of the experience gained during construction of Inuvik in the Canadian Arctic, see Pritchard, Gordon B. "Inuvik, Canada's New Arctic Town." The Polar Record, Vol.II, No. 71, May 1962. pp. 145-154.
15. Suslov. op. cit. pp. 138-142.
    Péwé. op. cit. pp. 19-21.
16. An excellent beginning in the translation of polar literature from Russian to English is Problems of the North, published by the National Research Council in Ottawa.
17. Suslov. op. cit. p. 150.

N.B. The following photographs have been contributed by the Division of Building Research, National Research Council to illustrate construction techniques and problems in permafrost areas.

Fig. 1 Slump in gravel pit caused by melting of ground ice after removal of surface vegetation.

Fig. 2 Thawing of permafrost has caused house foundation to settle unevenly.

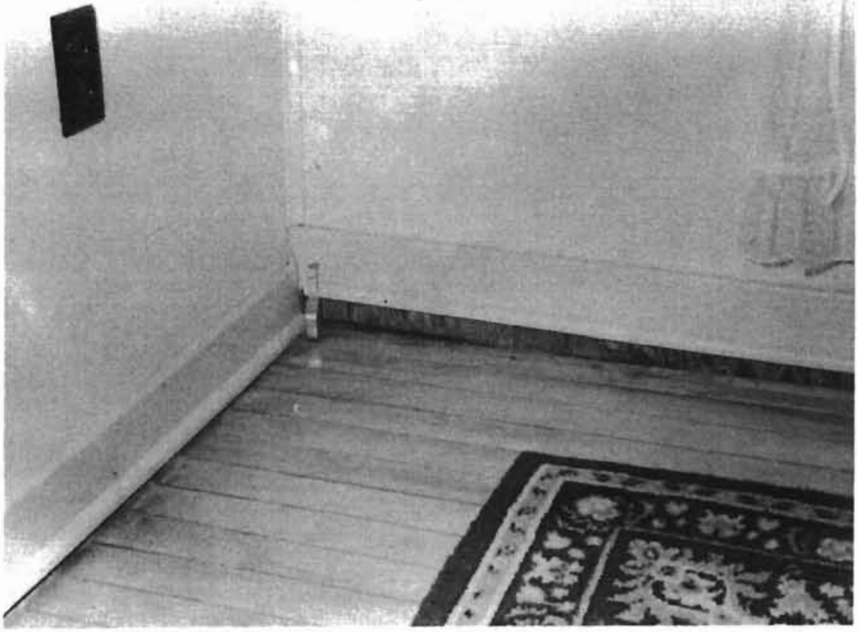


Fig. 3 Settlement of floor in room of house caused by thawing of permafrost.

Fig. 4 Pile steaming and driving on gravel pad for building foundation in continuous permafrost zone.

Fig. 5 Two-storey wood frame school on pile foundation in continuous permafrost zone.

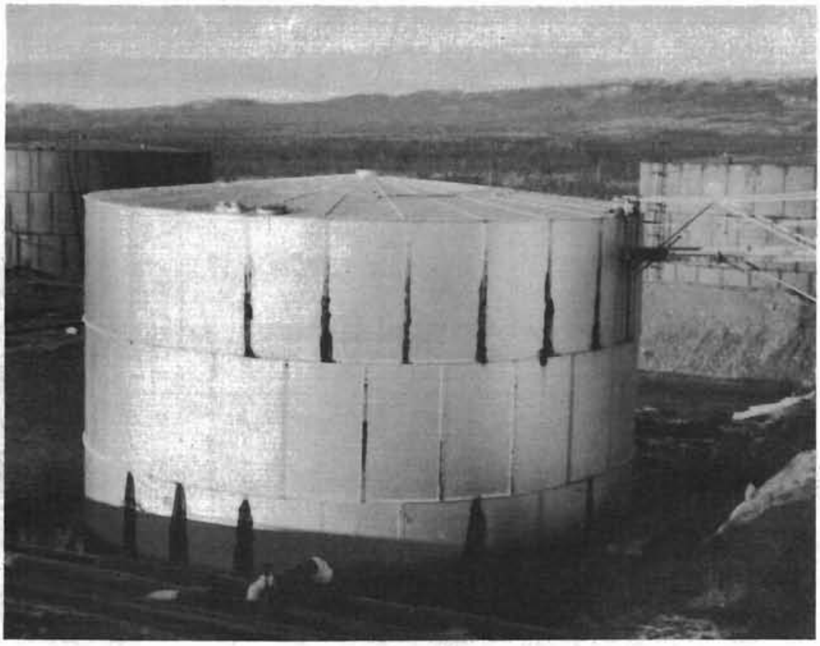


Fig. 6 Thawing of permafrost has caused oil tank to settle unevenly. Oil is leaking between buckled plates.

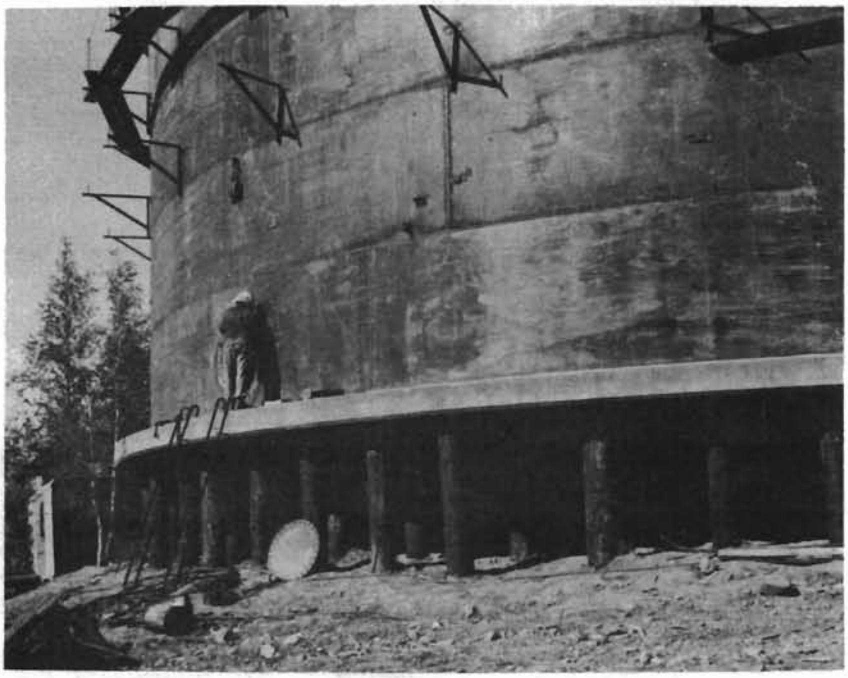


Fig. 7 Pile foundation prevents thawing of permafrost under large oil tank.

Fig. 8 Aluminum sided utilidors on piles in continuous permafrost zone.

Fig. 9 Aerial view of utilidors on piles carrying services to buildings in continuous permafrost zone.

Fig. 10 Construction of road has caused thawing and outflow of underlying perennially frozen silt containing ice near southern limit of permafrost region.

I. 2. FREEZING AND THAWING INDICES IN NORTHERN CANADA*

H. A. Thompson

INTRODUCTION

The degree-day approach has been used successfully for many years to relate temperature data to heating requirements for buildings. Monthly publications of the Meteorological Branch list cumulative seasonal and monthly heating degree-days below 65°F for about fifty representative stations in Canada, while annual summaries include an additional one hundred stations. The growing degree-day concept is familiar to many as a convenient method of linking temperature variations, during a growing season, with plant growth. Calculated normal monthly and annual growing degree-days are listed for about eighty stations in Canada in a paper by Boughner and Kendall (2).

The freezing degree-day and thawing degree-day are logical developments of the degree-day technique, and, as the names imply, are used to relate climatic effects to frost action. Crawford and Boyd (6) mention that, as early as 1930, an empirical relationship involving degree-days below freezing air temperature, and frost penetration into the ground, was used in highway design in the United States.

FREEZING AND THAWING DEGREE-DAYS AND INDICES AS RELATED TO FROST ACTION

Frost action in soils is a problem in practically all sections of Canada in highway, airport and building design. The problem has increased during the past ten to fifteen years with the northward extension of exploration and development into areas of widespread permafrost. To assist in the development of modern engineering techniques in the north, research has been increased in such fields as ground temperature studies, frost penetration, and retreat, in soils, and permafrost distribution and behaviour. During the same period the increasing importance of water transportation in the north has fostered the development of new techniques for forecasting the formation, growth, dissipation and movement of ice in the seas, lakes and rivers. While all elements of climate are interrelated in their effects on each of these manifestations of frost action, temperature is probably the most closely related and temperature data most readily available (10). The most useful expressions of temperature values as they affect soils subject to frost action (7), and influence

---

* Published with the approval of the Director, Meteorological Branch, Department of Transport, Toronto, Ontario.

ice growth and dissipation in waterways (11), are thawing and freezing degree-days. Their accumulations during respective thawing and freezing seasons are known as thawing and freezing indices (16).

Whether it is used in determining the heat requirements of buildings or plant growth, the temperature of the ground, the depth of frost penetration, the depth of thaw in permafrost, or the growth and dissipation of ice in waterways, the degree-day method is based entirely on temperature and neglects such variables of climate as wind, solar radiation, precipitation, etc., not to mention the numerous soil and water factors that are involved. However, in most of these fields, the method does represent this climatic parameter in a convenient, simple form, suitable for use in many engineering and design studies.

Workable empirical relationships exist between accumulations of freezing degree-days and depth of frost penetration in the ground (7), and between thawing degree-days and depth of thaw in permafrost (12). In areas of Canada where temperature data are not available, the freezing index map may be used, with empirical curves, to provide first approximations of frost penetration. The rate at which frost enters or leaves the ground has considerable bearing on frost damage to ground installations (6). This, in turn, is measured by the accumulation of degree-days during the first few weeks of freezing or thawing seasons.

Brown (3) notes that, although the occurrence of permafrost is influenced by many climatic, surface, and geothermal factors independent of the temperature regime, there is a very broad relationship between the boundary of permafrost in Canada and the mean annual air temperature. Since the formation and persistence of permafrost depends as much on the frost retreat during the thawing season as on the frost penetration during the freezing season, thawing as well as freezing indices must be considered.

The degree-day method is commonly used to relate air temperature to ice formation, growth and dissipation. Empirical relationships involving ice thickness and accumulated freezing degree-days are used to predict the rate of ice growth (11). Similar formulae using melting degree-days provide break-up information. According to Markham (11), these degree-day relationships are used at the Ice Forecasting Central to determine the effects of temperature on the ice regime of the coastal waterways of Canada. Burbidge and Lauder (4) tested the degree-day technique to link temperature data to dates of break-up and freeze-up of lakes and rivers. At selected stations, it was possible to relate the date of break-up to the number of melting degree-days prior to break-up. There did not, however, appear to be any connection between the date of break-up and the severity of the past winter season as measured by the freezing index.

PREVIOUS WORK ON FREEZING AND THAWING INDICES

During the last decade, freezing degree-day accumulations and freezing indices have been computed for a number of stations in Canada, in connection with special investigations of frost action (3, 4, 6, 13).

In 1954, as part of a runway evaluation programme of the Department of Transport, Wilkins and Dujay (13) used freezing degree-day accumulations for more than one hundred stations, averaged during the ten freezing seasons 1941-1950, to construct a freezing index map of Canada. The degree-day computations were based on mean daily temperatures. In 1959, a map of average thawing indices in Canada was prepared by the Division of Building Research, National Research Council (3). In this case, the thawing indices were calculated from mean monthly temperature data.

SCOPE AND METHOD

Due to the rather sparse climatological station network in northern Canada at the start of the 1941-1950 decade, Wilkins and Dujay (13) did not attempt to extend their freezing index map into the Arctic. As a result of the northward expansion during the late forties, an additional number of stations in northern Canada now have climatological records of more than ten years. This study is an attempt to fill the northern gap in the freezing index map of Canada, to present a thawing index map of northern Canada, and to provide freezing and thawing degree-day accumulations for specified periods of time during each year of the latest decade, for about forty stations. Maps of northern Canada are also presented which indicate the average dates of the start of the freezing season (mean daily temperatures generally below 32°F after this date), and the average dates of the start of the thawing season (mean daily temperatures above 32°F).

In view of increasing requirements for degree-day information on short period, monthly or annual fluctuations of temperature about a daily mean temperature of 32°F, it was decided to use machine methods to prepare degree-day tabulations for selected stations throughout Canada. The northern stations were given priority on this project, and the data presented here summarize the degree-day computations for about forty stations in northern Canada.

Degree-day data were computed for practically all stations in northern Canada which have continuous climatological records during the period from July 1949 to December 1959. This period, which covered ten freezing seasons and ten thawing seasons, represented the most recent decade of observations available at the time on punched cards. While a single decade of observations cannot be considered entirely representative of normal climate, this period does provide a standard for the comparison of degree-day statistics for individual stations.

The definitions used in these calculations are from the Engineering Manual, Corps of Engineers, U.S. Army (16). On the understanding that the degree-days for any one day are the difference between the average daily air temperature and 32°F, freezing degree-days are accumulated when this value is below 32°F, and thawing degree-days occur when it is above 32°F. In the machine tabulations, freezing degree-days are considered to be minus values, and thawing degree-days are plus values. For these computations, the degree-day totals for each day were derived from mean daily temperatures (in whole degrees F), based on the average of daily maximum and daily minimum temperatures. Three hundred and sixty-five punched cards per station-year were machine processed to give algebraic summations of degree-days measured from 32°F. The degree-day total for each day, and the summation total from January 1st, were indicated in the tabulation. The degree-day totals were cumulative from January 1st to December 31st of each year. It was possible to determine rates of accumulation of degree-days during specified periods of days or months from the time summation tabulation, or from the slope of the time summation curve.

Where the freezing season is considered to include that period of time when the mean daily temperature is generally below 32°F, the Freezing Index may be defined as the number of degree-days between the highest and lowest points on a curve of cumulative degree-days versus time, for one freezing season (16). The Thawing Index measures the number of degree-days between the highest and lowest values on the summation curve during a thawing season. These indices indicate the duration and magnitude of temperatures (with respect to 32°F) during freezing or thawing seasons.

The method used in determining the changeover date between freezing and thawing seasons may be illustrated by referring to the May 1950 degree-day tabulation for Fort Chimo (Table 1). It will be noted that, although the mean daily temperature reached 33°F on May 10th, the maximum accumulation of freezing degree-days did not occur until May 14th. Thus, May 15th was taken as the start of the thawing season.

TABLE 1

Fort Chimo degree-day tabulations - 1950

Date	Mean daily temperature	Degree-days (w.r.t. 32°F)	Degree-day accumulation from January 1st
May 9	28	-4	-4528
" 10	33	1	-4527
" 11	30	-2	-4529
" 12	23	-9	-4538
" 13	20	-12	-4550
" 14	27	-5	-4555
" 15	36	4	-4551
" 16	33	1	-4550

Graphical representations of the duration of freezing and thawing seasons, and the magnitude of freezing and thawing indices, are shown in Figure 5. The cumulative degree-day statistics for Whitehorse during the 1955-56 and 1957-58 thawing and freezing seasons are plotted against time. To facilitate comparison of the curves, the degree-day values of each curve have been adjusted so that they are cumulative from the zero point at the start of each thawing season.

FREEZING INDICES

Figure 1 shows the areal distribution of freezing indices in northern Canada during the period 1949-1959. The map was constructed by averaging the degree-day totals of the ten freezing seasons. Isolines on the map are spaced at 500 degree-day intervals.

As a measure of the combined duration and magnitude of below freezing temperatures during a freezing season, the freezing index is made up of degree-day contributions from several months. Since the months of January, February and March contribute substantially to the freezing index, it would be expected that the mean daily temperatures during these months would be reflected in the pattern of the freezing index map.

Comparison of the freezing index map with mean daily temperature maps for January or February shows a marked similarity in pattern over the Arctic Islands and in the northern continental interior. The dominating cold centre over northern Ellesmere Island, and its southward extension into the Barrens northwest of Hudson Bay, is a feature of both maps. Eureka, the coldest station in Canada during most of the winter months, also has the highest freezing index. The tempering marine influences along Hudson Strait and the east coast of Baffin Island show up as areas of abnormal warmth on each map. Clyde, on the east coast of Baffin Island, has an average freezing index of 8671 degree-days, compared to a figure of 11,093 degree-days at Spence Bay, at roughly the same latitude, but with a more continental type climate. At Resolution Island, near the eastern entrance to Hudson Strait, the average freezing index is only 4434 degree-days.

The freezing index distribution along the east coast of Hudson Bay demonstrates the influence on the freezing index of the open water months of October, November and December. While the mean temperature maps for February and March show only two or three degrees temperature difference between Churchill and Port Harrison, the average freezing index is nearly 1000 degree-days higher at Churchill than at Port Harrison.

The southward bulge of cold air into the Barren Lands to the west of Hudson Bay, as indicated on the January and February mean temperature maps, is considerably modified in southern sections on the freezing index map, where account is taken of the shorter freezing season and the higher temperatures during the Spring and Fall transition months. The influence of the length of the freezing season on the freezing index is further illustrated by the areas of lower indices along the Mackenzie River (Fig. 1), in a section of northwestern Canada where mid-winter temperatures are low. Spring is about two weeks earlier along the Mackenzie River valley than at stations at the same latitude two or three hundred miles further east (Fig. 4).

FREEZING AND THAWING DEGREE-DAYS

While average values of degree-day data may be employed in broad-scale studies of frost action, figures for individual months or seasons are more useful in local investigations. The degree-day statistics for individual years are not included in this paper; however, summaries of the freezing and thawing indices, and of thirty-day accumulations of degree-days at the start of each freezing and thawing season, illustrate, in Tables 2 to 5, the range of these values at each station.

It is interesting to note, in Table 2, that, of the 39 stations, all but 10 reported the lowest freezing index during the 1952-53 freezing season. There is considerable year-to-year variation in the freezing index. Examination of the highest and lowest seasonal values shows that the greatest range may be expected at stations in the Yukon and around Great Slave Lake. To illustrate the magnitude of the variation, the cumulative degree-day curves for Whitehorse, Y. T., covering the 1955-56 and 1957-58 thawing and freezing seasons, are shown in Figure 5. The freezing indices of 5105 degree-days in 1955-56 and 2852 in 1957-58, were respective maximum and minimum figures during the decade. The thawing indices during the preceding thawing seasons were also lowest and highest values. It may be seen from this comparison that, while freezing indices at Whitehorse covered a wide range of degree-days from 2852 to 5105, the variation in thawing indices was considerably less, and ranged from 2865 degree-days in 1955 to 3607 in 1957. During the period April 14th 1957 to March 30th 1958, the thawing index exceeded the freezing index, to show a net accumulation of 755 thawing degree-days. In contrast, during the thawing and freezing seasons in 1955-56, there was a net accumulation of 2240 freezing degree-days.

The cumulative freezing degree-days during the first thirty days of each freezing season are summarized in Table 4. These figures provide a measure of the rate of growth of ice in waterways, or the rate at which frost enters the ground during this period(6, 11). Similar statistics for thawing degree-days are listed in Table 5. It is apparent from these tables that the extreme values are of more interest than the average figures, since they indicate the large year-to-year variation that may be expected in rate of freeze or rate of thaw. Reference to Table 4 and Figure 3 shows that, in general, the highest thirty-day accumulations of freezing degree-days occur in late freezing seasons, while low values usually occur when the start of the freezing season is earlier than the average date.

THAWING INDICES

The map of the average thawing indices in northern Canada during the period 1949-1959 is presented in Figure 2. This map has a pattern similar to the mean daily temperature map for July.

Over the Arctic islands, where temperatures in summer are controlled by the presence of large areas of ice-filled water and where the length of the thawing season varies only a few days with latitude, thawing indices and mean daily temperatures during a typical summer month (July) are closely related. Almost everywhere north of the continental coastline, Foxe Basin and Hudson Strait, the distribution of thawing indices is very uniform with values mostly in the 500 to 1000 degree-day range.

Along the July 50°F isotherm, which extends from the Mackenzie delta to Baker Lake, southern Hudson Bay and Ungava Bay and which is often termed the southern boundary of the Arctic (14), thawing indices average about 1500 degree-days.

Since the zone of higher summer temperatures along the Mackenzie River valley also has a longer thawing season than adjoining areas (Figs. 3 and 4), thawing indices along the Mackenzie are high. Average values of 3476 at Fort Simpson and 2908 at Fort Good Hope contrast with thawing indices of 2465 at Fort Reliance and 2220 at Port Radium at about the same latitudes and only four hundred miles further east.

FREEZING AND THAWING SEASONS

The average dates when the mean daily temperature rises to 32°F in the Spring, and when it falls to 32°F in the Autumn, are charted in Figures 3 and 4. At most stations, the earliest date of the start of the freezing season was about 10 days ahead of the average date. The range was much the same at the start of the thawing season. Latest starting dates were 10 to 12 days after the average starting date.

SUMMARY

The degree-day tabulations for selected stations in northern Canada are summarized in the tables of average and extreme values of freezing and thawing degree-days. The more detailed seasonal and monthly degree-day figures for an increased number of stations will be listed in a future report.

ACKNOWLEDGEMENTS

The assistance of Mr. B.S.V. Cudbird, Head of the Data Processing Section, Climatology Division, Meteorological Branch and his staff is gratefully acknowledged.

REFERENCES

1. Boughner, C.C. Degree-days for Selected Canadian Stations. Canada Department of Transport, Meteorological Branch, CIR-2830, CLI-14, October 16, 1956.
2. ______________ and G.R. Kendall. Growing degree-days in Canada. Canada Department of Transport, Meteorological Branch, CIR-3203, TEC-303, May 25, 1959.
3. Brown, R.J.E. The Distribution of Permafrost and its Relation to Air Temperature in Canada and the U.S.S.R. Arctic, Vol. 13, No. 3, September 1960.
4. Burbidge, F.E. and J.R. Lauder. A Preliminary Investigation into Break-up and Freeze-up Conditions in Canada. Canada Department of Transport, Meteorological Branch, CIR-2939, TEC-252, July 2, 1957.

5. Crawford, C.B. Frost Penetration Studies in Canada as an Aid to Construction. Canada National Research Council, Division of Building Research, Technical Paper No. 20, February 1955.
6. ______________ and D. W. Boyd. Climate in Relation to Frost Action. Canada National Research Council, Division of Building Research, Technical Paper No. 28, January 1956.
7. ______________ and R. F. Legget. Ground Temperature Investigations in Canada. Canada National Research Council, Division of Building Research, Paper No. 33, December 1955.
8. Holmes, Robert M. and G. W. Robertson. Heat Units and Plant Growth. Canada Department of Agriculture, Publication 1042, January 1959.
9. Lee, Owen S. and Lloyd Simpson. A Practical Method of Predicting Sea Ice Formation and Growth. U. S. Navy Hydrographic Office, Technical Report TR-4, September 1954.
10. Legget, R.F., H.B. Dickens and R. J.E. Brown. Permafrost Investigations in Canada. Geology of the Arctic, Vol. 11, 1961.
11. Markham, W.E. Freezing and Melting Degree-day Computations in Spring and Fall Months. Canada Department of Transport, Meteorological Branch, CIR-3350, TEC-325, June 8, 1960.
12. Sebastyan, G.Y. Department of Transport Procedures for the Design of Pavement Facilities and Foundation Structures in Permafrost Subgrade Soil Areas. First Canadian Conference on Permafrost, Associate Committee on Soil and Snow Mechanics of the National Research Council of Canada, April 1962.
13. Wilkins, E.B. and W.C. Dujay. Freezing Index Data Influencing Frost Action. Canada National Research Council, Associate Committee on Soil and Snow Mechanics, Proceedings of the Seventh Canadian Soil Mechanics Conference Technical Memorandum No. 33, September 1954.
14. Thomas, M.K. Canadian Arctic Temperatures. Canada Department of Transport, Meteorological Branch, CIR-3334, CLI-24, May 9, 1960.
15. ______________ Heating Degree-days and Winter Design Temperatures in Southern Ontario. Canada Department of Transport, Meteorological Branch, CIR-3159, CLI-18, February 11, 1959.
16. Engineering Manual, Part XV, Arctic and Sub-Arctic Construction. U.S. Department of the Army, Corps of Engineers, October 1954.

TABLE 2

Average and extreme values of freezing index (degree-days) - 1949-1959

Station	Ten-year average	High	Season	Low	Season
Aishihik A	5302	6291	1955-56	4114	1952-53
Aklavik	8037	8594	1954-55	6811	1949-50
*Alert	12093	12544	1950-51	11397	1952-53
Arctic Bay	9923	10674	1953-54	8849	1952-53
Baker Lake	9422	10072	1949-50	8891	1952-53
Brochet	6216	7040	1949-50	5417	1952-53
Cambridge Bay	10860	11311	1957-58	10302	1952-53
Cape Hopes Advance	5443	6309	1956-57	4562	1955-56
Chesterfield	8750	9449	1956-57	8151	1952-53
Churchill A	6718	7755	1949-50	6253	1952-53
Clyde	8671	9365	1956-57	7943	1952-53
Coppermine	8882	9439	1957-58	7869	1952-53
Coral Harbour A	8539	9510	1953-54	7666	1952-53
Ennadai Lake	8130	8840	1949-50	7660	1953-54
Eureka	13322	14243	1956-57	12519	1952-53
Fort Chimo A	5381	6176	1949-50	4518	1957-58
Fort Good Hope	7860	8638	1950-51	6877	1949-50
Fort Reliance	7172	7726	1956-57	6337	1952-53
Fort Resolution	5776	6354	1951-52	4618	1952-53
Fort Simpson	6040	6895	1950-51	4916	1952-53
Fort Smith A	5613	6235	1951-52	4567	1952-53
Frobisher Bay A	7052	8096	1956-57	6226	1955-56
Hay River	5548	6332	1955-56	4287	1952-53
*Holman Island	9015	9677	1955-56	7931	1952-53
Isachsen	12753	13486	1955-56	11983	1952-53
Mayo Landing	5881	7020	1950-51	4480	1952-53
Moosonee	3790	4626	1949-50	2810	1952-53
*Mould Bay	11912	12529	1953-54	10987	1952-53
Norman Wells A	7220	7973	1950-51	6137	1952-53
Nottingham Island	6401	7227	1953-54	5547	1952-53
Port Harrison	5804	6527	1949-50	5165	1952-53
Port Radium	6982	7776	1955-56	5713	1952-53
Resolute A	11204	11591	1956-57	10292	1952-53
Resolution Island	4434	5483	1956-57	3791	1952-53
*Spence Bay	11093	11578	1956-57	10524	1954-55
Teslin A	4048	5224	1955-56	2931	1957-58
Watson Lake A	5402	6510	1955-56	4515	1954-55
Whitehorse A	3861	5105	1955-56	2852	1957-58
Yellowknife A	6623	7159	1950-51	5318	1952-53

*Indicates period of record less than ten years.

TABLE 3

Average and extreme values of thawing index (degree-days) - 1949-1959

Station	Ten-year average	High	Year	Low	Year
Aishihik A	2412	2715	1951	2035	1955
Aklavik	2261	2859	1958	1761	1959
*Alert	387	612	1956	141	1955
Arctic Bay	808	990	1954	699	1955
Baker Lake	1515	1947	1954	1193	1950
Brochet	2935	3412	1955	2525	1959
Cambridge Bay	1016	1406	1954	767	1959
Cape Hopes Advance	974	1198	1955	822	1958
Chesterfield	1321	1673	1954	1098	1957
Churchill A	2056	2380	1955	1764	1958
Clyde	655	795	1957	550	1959
Coppermine	1362	1620	1954	954	1959
Coral Harbour A	1175	1487	1954	1021	1959
Ennadai Lake	1979	2483	1954	1620	1950
Eureka	701	847	1954	417	1953
Fort Chimo A	2206	2501	1955	1787	1956
Fort Good Hope	2908	3214	1958	2385	1959
Fort Reliance	2465	2924	1955	1768	1959
Fort Resolution	3176	3571	1953	2633	1959
Fort Simpson	3476	3777	1953	2995	1959
Fort Smith A	3365	3685	1955	2806	1959
Frobisher Bay A	1262	1541	1955	1073	1959
Hay River	3171	3472	1952	2573	1959
*Holman Island	1100	1660	1954	820	1959
Isachsen	402	649	1958	136	1953
Mayo Landing	3168	3475	1953	2816	1959
Moosonee	3611	4365	1955	3053	1950
*Mould Bay	422	691	1958	129	1953
Norman Wells A	2996	3354	1958	2531	1959
Nottingham Island	928	1131	1958	780	1950 & 1959
Port Harrison	1677	2293	1954	1288	1959
Port Radium	2220	2799	1954	1582	1959
Resolute A	536	888	1958	322	1955
Resolution Island	552	686	1958	429	1959
*Spence Bay	973	1150	1958	833	1959
Teslin A	2991	3354	1957	2568	1955
Watson Lake A	3388	3683	1953	2965	1959
Whitehorse A	3271	3607	1957	2865	1955
Yellowknife A	3079	3354	1955	2483	1959

*Indicates period of record less than ten years.

TABLE 4

Accumulation of freezing degree-days during first 30 days of freezing season - the period 1949-1959

Station	Average	Highest	From date	Lowest	From date
Aishihik A	289	615	Oct. 14/53	31	Oct. 1/54
Aklavik	314	604	Oct. 5/50	159	Sept. 18/54
Alert	330	597	Sept. 5/58	173	Aug. 13/53
Arctic Bay	255	376	Sept. 19/51	122	Sept. 4/55
Baker Lake	287	617	Sept. 28/56	96	Sept. 17/51
Brochet	419	782	Nov. 4/58	142	Oct. 3/50
Cambridge Bay	338	549	Sept. 28/54	178	Sept. 11/57
Cape Hopes Advance	160	242	Nov. 3/55	98	Sept. 30/54
Chesterfield	296	620	Oct. 9/51	83	Sept. 25/54
Churchill A	356	536	Oct. 30/58	206	Oct. 3/50
Clyde	199	273	Sept. 23/57	72	Sept. 8/55
Coppermine	310	580	Oct. 13/53	73	Sept. 13/57
Coral Harbour A	262	501	Sept. 27/56	32	Sept. 8/55
Ennadai Lake	249	672	Oct. 9/51	25	Sept. 23/53
Eureka	407	564	Sept. 9/58	210	Aug. 22/49
Fort Chimo A	254	442	Oct. 23/54	75	Sept. 29/51
Fort Good Hope	356	749	Oct. 13/53	144	Sept. 26/52
Fort Reliance	357	643	Oct. 29/58	34	Sept. 23/52
Fort Resolution	339	594	Nov. 3/58	141	Oct. 6/49
Fort Simpson	326	570	Oct. 10/56	39	Oct. 6/54
Fort Smith A	346	615	Nov. 3/58	102	Oct. 1/57
Frobisher Bay A	321	713	Nov. 4/55	146	Sept. 20/53
Hay River	362	680	Nov. 3/58	66	Oct. 6/49
Holman Island	290	507	Sept. 22/56	71	Aug. 28/52
Isachsen	334	611	Sept. 7/58	144	Aug. 12/53
Mayo Landing	395	745	Oct. 23/53	138	Oct. 22/52
Moosonee	252	519	Nov. 7/56	36	Oct. 29/53
Mould Bay	211	352	Sept. 6/58	115	Aug. 12/53
Norman Wells A	339	645	Oct. 13/53	92	Sept. 27/52
Nottingham Island	143	210	Sept. 23/52	51	Sept. 21/49
Port Harrison	260	395	Oct. 23/54	104	Oct. 1/58
Port Radium	301	509	Oct. 16/55	64	Sept. 23/52
Resolute A	311	471	Sept. 14/51	129	Aug. 26/57
Resolution Island	119	242	Nov. 5/55	57	Sept. 29/49
Spence Bay	279	493	Sept. 27/54	135	Sept. 6/55
Teslin A	325	451	Oct. 26/53	74	Oct. 6/58
Watson Lake A	444	691	Oct. 20/55	66	Oct. 14/49
Whitehorse A	345	584	Oct. 20/55	148	Oct. 5/58
Yellowknife A	357	508	Oct. 10/56	79	Oct. 6/58

TABLE 5

Accumulation of thawing degree-days during first 30 days of thawing season – 1949-1959

Station	Average	Highest	From date	Lowest	From date
Aishihik A	232	307	May 13/52	168	April 14/51
Aklavik	236	383	May 27/51	72	May 11/59
Alert	162	315	June 15/56	22	June 14/55
Arctic Bay	243	384	June 15/56	157	June 4/55
Baker Lake	272	362	June 9/58	190	May 28/54
Brochet	201	312	April 12/52	83	April 27/57
Cambridge Bay	258	520	June 16/56	139	June 3/53
Cape Hopes Advance	169	270	June 18/58	33	May 5/52
Chesterfield	227	316	June 9/51	167	May 28/54
Churchill A	254	518	June 4/51	108	April 23/52
Clyde	153	263	June 15/56	15	May 21/50
Coppermine	243	529	June 12/56	69	May 14/55
Coral Harbour	201	309	June 8/56	97	May 28/54
Ennadai Lake	289	515	June 4/51	86	May 25/54
Eureka	247	350	June 5/57	120	June 4/55
Fort Chimo A	242	450	May 25/51	85	April 27/59
Fort Good Hope	325	537	May 11/55	207	April 28/56
Fort Reliance	254	448	May 12/55	89	April 28/50
Fort Resolution	305	430	May 3/58	169	April 22/55
Fort Simpson	334	574	May 3/58	81	April 14/57
Fort Smith A	309	480	May 3/54	90	Mar. 24/58
Frobisher Bay A	138	334	June 8/56	51	May 15/59
Hay River	279	455	May 3/58	162	April 26/57
Holman Island	239	563	June 12/56	60	May 11/53
Isachsen	160	346	June 12/57	57	June 1/52
Mayo Landing	267	444	May 4/59	83	Mar. 24/58
Moosonee	211	426	May 7/50	53	April 15/53
Mould Bay	164	281	June 12/57	42	June 17/53
Norman Wells A	307	500	May 10/55	133	April 21/52
Nottingham Island	143	238	June 7/58	50	May 19/50
Fort Harrison	183	345	May 17/55	3	May 10/58
Port Radium	247	543	May 23/54	103	May 11/59
Resolute A	191	270	June 15/56	120	June 15/55
Resolution Island	67	124	June 8/58	15	May 20/53
Spence Bay	297	364	June 17/56	225	June 13/59
Teslin A	210	364	April 30/54	96	April 9/52
Watson Lake A	267	449	April 30/54	165	April 13/56
Whitehorse A	186	373	April 29/54	98	Mar. 30/51
Yellowknife A	348	546	May 11/55	107	April 26/57

Discussion

J. R. Mackay asked if it is possible to give the approximate relationship which might be expected between freezing and thawing indices measured in a weather screen and those for the ground surface, for example, at a depth of one centimeter. The author replied that all the temperatures used in the computation of freezing and thawing indices were obtained from weather screens. There is no information available on the expected relationship. T. A. Harwood commented that micro-meteorological complications, which are evident at the ground surface, are ironed out at a height of 4 feet above the ground. Therefore, air temperature measurements from the weather screen are a more reliable indicator of meteorological conditions.

In reply to an inquiry by T. A. Harwood on the correspondence existing between mean annual air isotherms and the southern limit of permafrost in Canada, the author replied that there are not enough meteorological stations at present in the area to give a precise answer. The paper by R. J. E. Brown (The Distribution of Permafrost and Its Relation to Air Temperature in Canada and the U.S.S.R., Arctic, Vol. 13, No. 3, Sept. 1960, pp. 163-177, NRC 5941) shows only a broad relationship. Thawing indices, in addition to freezing indices, must be considered, the final result being a consideration of mean annual air temperature. R. J. E. Brown remarked that a broad relationship exists between mean annual air temperature and the southern limit of permafrost. Our present knowledge of the southern limit in Canada indicates that it lies in the zone bounded by the 25°F. and 30°F. mean annual air isotherms. Because of the complex energy exchange regime operative at the ground surface which results in the mean annual ground temperature being several degrees (about 6) warmer than the mean annual air temperature, there is no known instance of the permafrost lying south of the 30°F. mean annual air isotherm. Fluctuations across the country and local variations in permafrost within a small area appear to be influenced by terrain and subsurface features such as vegetation, soil, and others.

N. W. Radforth wondered if it is possible to reconcile the differences existing between isolines of freezing and thawing indices to permafrost. It appears that thawing indices, in addition to freezing indices, should be considered before any comparison can be attempted. Also, the degree day method considers temperature only, as one of many factors of climate affecting the distribution of permafrost. The snow on the ground, vegetation, type of soil, and other features affect the southern boundary considerably.

******

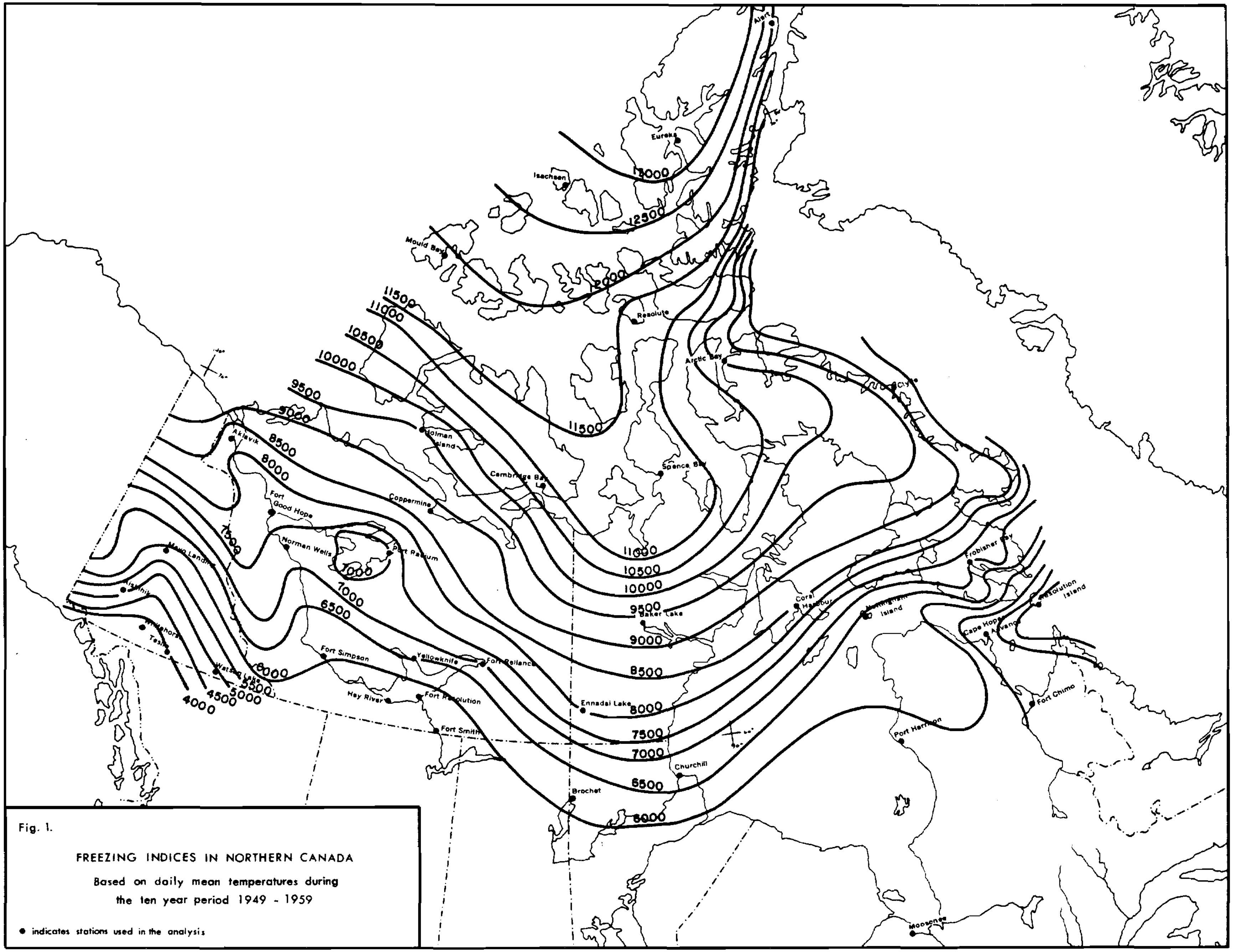


Fig. 1.

FREEZING INDICES IN NORTHERN CANADA

Based on daily mean temperatures during the ten year period 1949 - 1959

● indicates stations used in the analysis

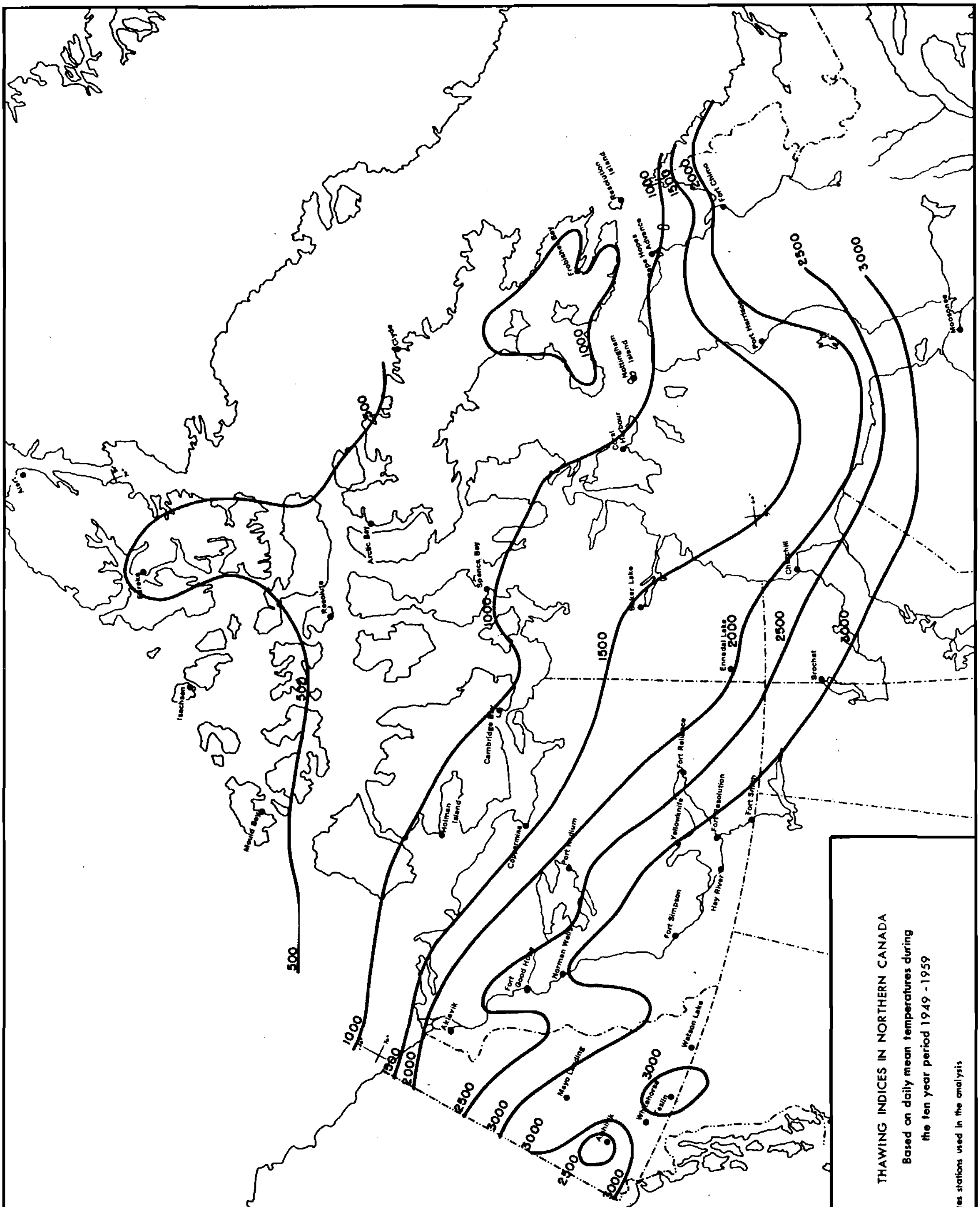


Fig. 2.

THAWING INDICES IN NORTHERN CANADA

Based on daily mean temperatures during the ten year period 1949 - 1959

● indicates stations used in the analysis

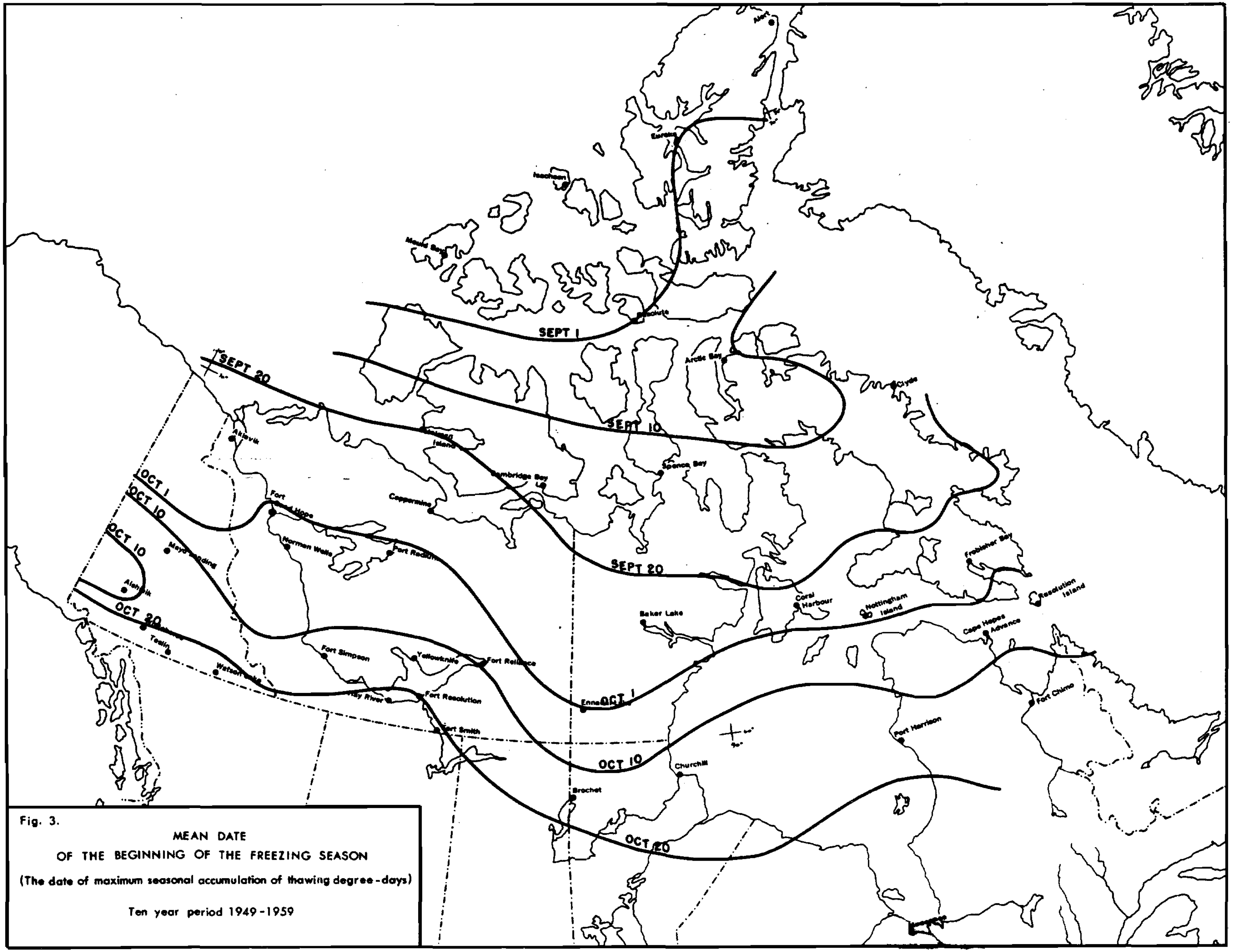


Fig. 3.

MEAN DATE
OF THE BEGINNING OF THE FREEZING SEASON
(The date of maximum seasonal accumulation of thawing degree-days)

Ten year period 1949-1959

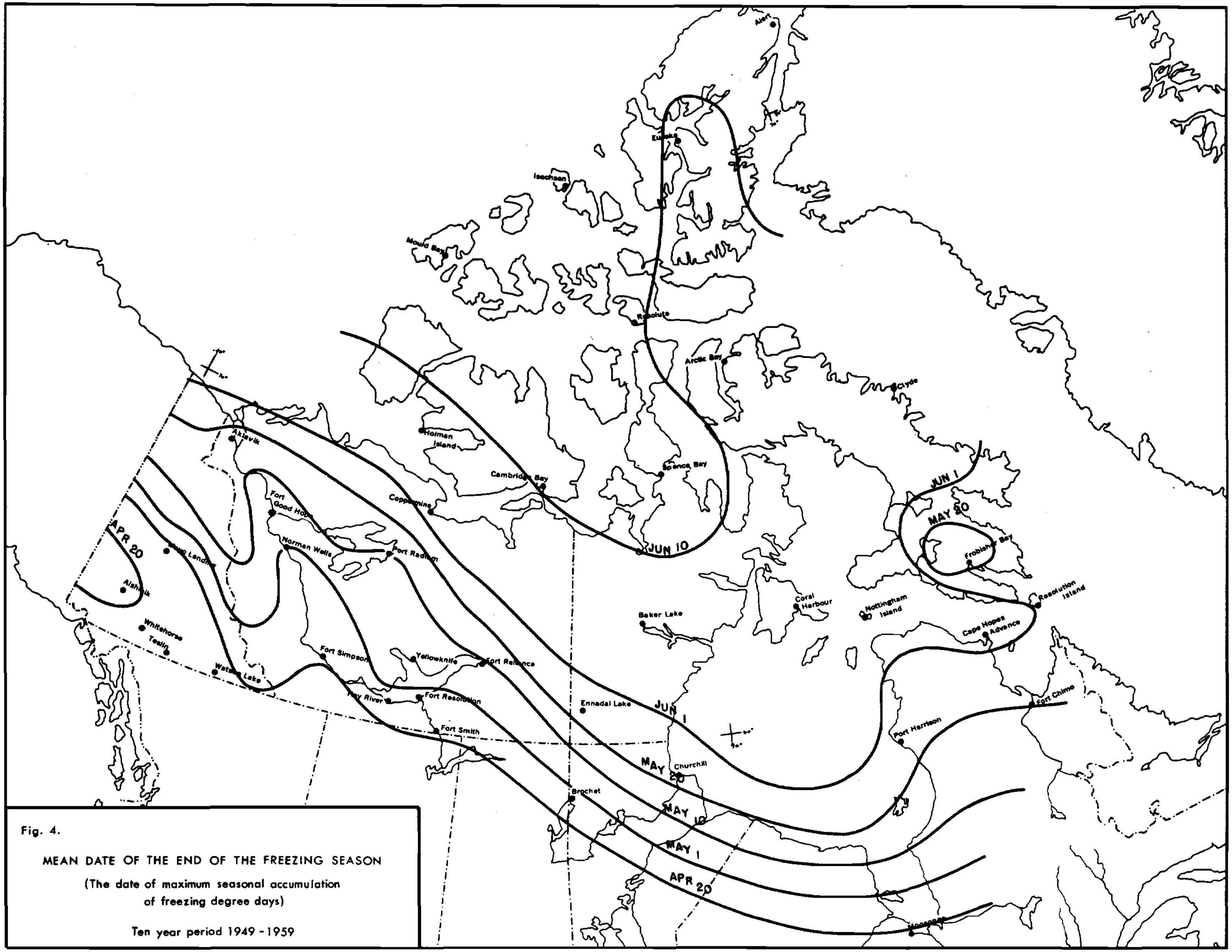


Fig. 4.

MEAN DATE OF THE END OF THE FREEZING SEASON

(The date of maximum seasonal accumulation of freezing degree days)

Ten year period 1949 - 1959

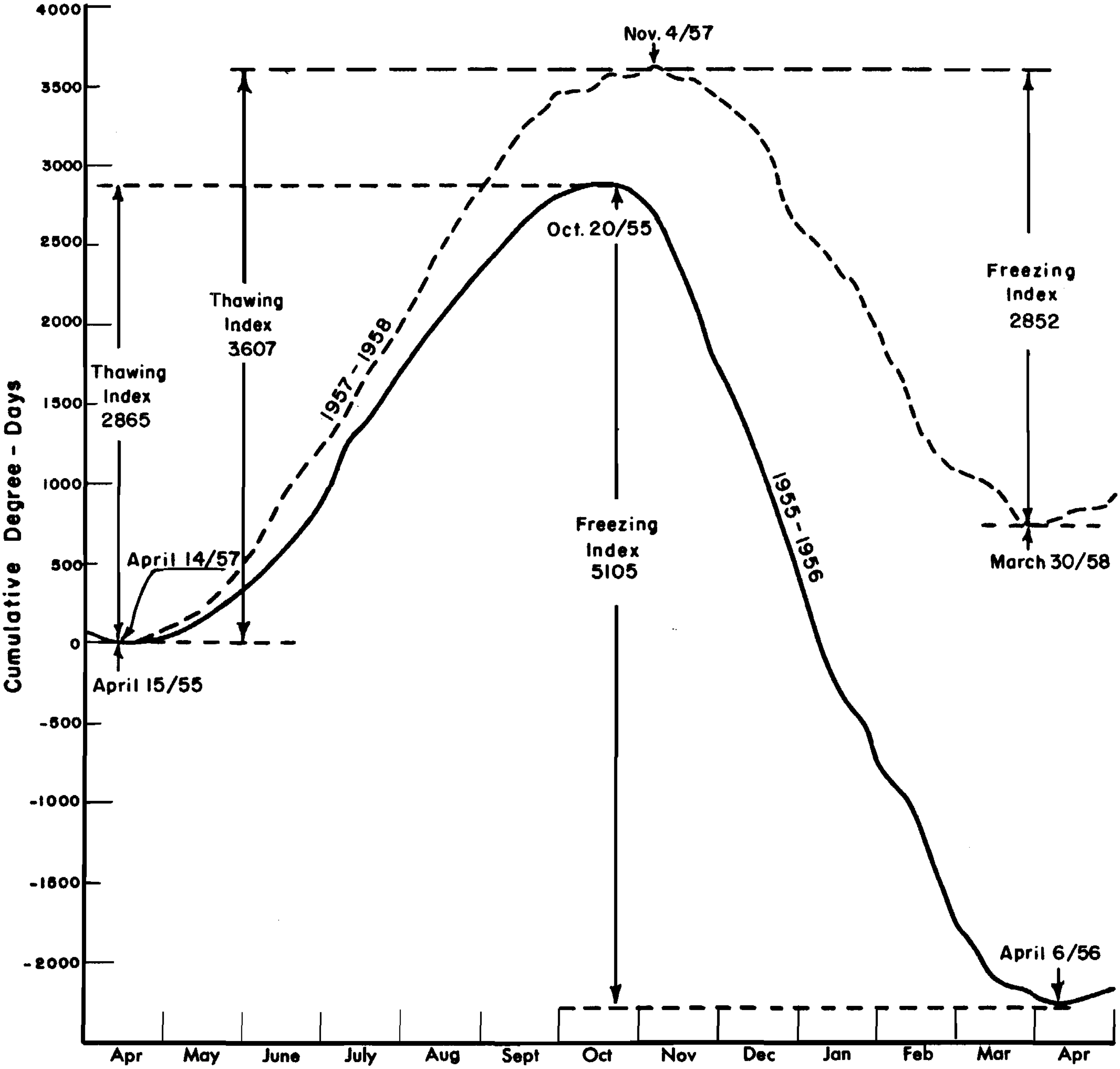


Fig. 5 - Degree-day Accumulations at Whitehorse, Yukon. (Base temperature 32 deg. F.)

I.3. PEDOGENIC STUDIES ON SOILS CONTAINING PERMAFROST IN THE MACKENZIE RIVER BASIN

J.H. Day

In this paper, the Mackenzie River basin is defined as the portion that lies north of the approximate southern limit of discontinuous permafrost, east of the main mass of the Cordillera, and west of a line joining Fort Smith, Yellowknife, Fort Franklin at the western end of Great Bear Lake and Tuktoyaktuk on the Beaufort Sea.

In this region the rocks are mainly of Palaeozoic, Ordivician, Devonian and Cretaceous age; they are sedimentary and include limestone, dolomite, shale and sandstone. The region is mainly low-lying, heavily wooded for the most part, poorly drained with many lakes and widespread muskeg, but the surface here and there is broken by a number of hills or higher plateaux which rise from 1,000 to 3,000 feet above the level of the surrounding country.

The region was glaciated by the Wisconsin-Laurentian ice sheet which left large moraines and thick drift on much of the area. During the final retreat of the ice sheet, lakes were widespread. Probably the largest lake that was formed was that in the Great Slave Lake -Great Bear Lake basins, and along the topographic low that lies between them (1). A southward extension of this lake extended along the Slave River valley, in which direction the lake drained during its early stages. Draining of these lakes during deglaciation, followed by isostatic changes and siltation, has considerably altered some of the lakes; siltation is still in progress in Great Slave Lake.

The following paragraphs outline briefly the history of soil investigations in this region, and summarize the characteristics of the great soil groups that have been described.

In 1944 Dr. A. Leahey and Mr. F.S. Nowosad, of the Canada Department of Agriculture, traversed the Fort Nelson and Liard rivers between Fort Nelson, B.C., and Fort Simpson, N.W.T. Observations were also made by Leahey between Fort Simpson and Waterways, Alberta (5). In 1945 Leahey traversed the route between Waterways and Aklavik, N.W.T. (3). The observations in this and the preceding year necessarily were confined to a narrow strip of land adjacent to the rivers. In 1952 Leahey examined the soils adjacent to that portion of the Mackenzie Highway within the Northwest Territories (4). In 1955 Leahey and the author mapped the soils of the Slave River lowland on a broad reconnaissance scale (2). In 1957 the Alberta Research Council initiated the exploratory soil survey of the northern area of that province. The programme is nearly completed and so far 63 million acres have been mapped, using helicopters for transport. In 1960 the author visited Reindeer Depot, Inuvik and Norman Wells, all situated in the Northwest Territories, spending only one month in the field. In 1961, the author conducted a broad reconnaissance survey in the Fort Simpson area and along the Laird River to the British Columbia border.

In this region, most of the parent materials are youthful, but generally the alluvium along stream channels is the youngest deposit. Young soils lack horizons, or at best, the surface horizon is an accumulation of organic material. The profile has lost nothing less soluble than calcium carbonate. This type of profile is called a Regosol.

Older parent material that has had time or conditions permitting more intense weathering usually show brown colours at the mineral soil surface. This infers weathering, in the upper horizons, of the clay minerals with liberation of sesquioxides, leaching of bases from the clay complex and removal of calcium carbonate. These profiles are called Brown Wooded.

As the weathering process continues, more bases are removed from the clay complex, clay is mobilized and translocated, organic matter destruction is accelerated and conspicuous eluviated (Ae) and illuviated (Bt) horizons develop. Such profiles are called Gray Wooded.

As the weathering process continues, the eluvial (Ae) horizon becomes more siliceous as sesquioxides are leached from it, and the sesquioxides are deposited, mainly just below the eluvial horizon, forming a new illuvial horizon (Bf). The clayey (Bt) horizon present in the Gray Wooded profile is broken down and more or less completely destroyed. Such a profile is called a Podzol.

In this chain of events some stage may be bypassed, for example, some Regosols go directly to Gray Wooded, while some Brown Wooded soils go directly toward the Podzol.

Organic soils, which have one foot or more of peat over mineral material, may be associated with any of these groups.

At the southern limit of the region, as here defined, many soil inspections have been made by the Alberta Research Council. In the first two areas covered (essentially that between 56° N and 58° N) only a few occurrences of frozen organic soil were reported. In the third area (between 58° N and 59° N) frozen organic soils were more frequent. In the fourth area (between 59° N and 60° N) nearly all organic soils were frozen at shallow depths, but very few, if any, mineral soils contained frozen material within three feet of the surface. Prof. W. Odynsky, Head of the Soils Division, Alberta Research Council, states that about 80 per cent of the land adjacent to the Alberta border is covered by organic soils with permafrost. In the remaining area, the presence of Brown Wooded soils with Gray Wooded soils is interpreted by Odynsky as a retarding of soil development by the presence of ice conditions at depth.

In the Slave River lowland, the soils are mostly peaty Meadow soils, with Regosols on the better drained ridges. In the northern portion of the area, permafrost was general but any conclusions as to whether or not its presence had retarded soil development were prevented by the youthfulness of the soil material in the whole area.

In the Mackenzie Highway - Hay River area, most of the recent alluvial soils are Regosols, but on the higher alluvial terraces and on the upland above the escarpment Brown Wooded and Gray Wooded soils are the dominant mineral soils. Organic soils are common everywhere and are frozen at shallow depths.

In the Fort Simpson area, upland mineral soils are mainly Brown Wooded and Gray Wooded. Permafrost is present at shallow depths in the sphagnum-black spruce bogs, on east-facing slopes along the riverbanks, and at greater depth on Simpson Island and probably elsewhere in the area. In the Liard River valley from the British Columbia border to Fort Simpson, Regosols occupy the lowest position and Brown Wooded the highest position where the soil material is inferred to be the oldest. Organic soils with permafrost were found with both Brown Wooded and Gray Wooded soils; the presence of permafrost in the area was not considered to have had any influence on the associated well-drained mineral soils. Organic soils with permafrost probably occupy 80 per cent of the area between the Liard River valley and northern Alberta.

In the area from Camsell Bend to Arctic Red River, N.W.T., and in the Mackenzie River delta, permafrost is present in practically all soils, excepting those that flood annually. It is the opinion of the author and his colleagues that the continuous permafrost boundary should be placed further south to include most of this area. Here the land generally has a continuous cover of mosses and patterned ground is common, whereas to the south the moss cover is discontinuous and patterned ground is uncommon. Regosols with permafrost occupy the lowest land, Brown Wooded with permafrost the higher land on well-drained locations. In poorly drained sites, peaty Dark Gray Gleysolic with permafrost, peaty Gleysol with permafrost and Organic soils with permafrost are present. Organic soils cover most of the land back from the Mackenzie River.

The Brown Wooded soil with permafrost is essentially the same as the orthic Brown Wooded in more southerly areas. The Dark Gray Gleysolic soils are characterized by a thin peaty horizon, by a high organic-matter content in the mineral surface horizon, by high base saturation, and by dull colours and mottling in the subsoil.

The boreal forest changes to the essentially treeless tundra both on the west and east sides of the Mackenzie River delta. On the west side, Leahey described a well-drained soil that had a slightly acid surface mineral horizon high in organic matter, a brown, slightly basic subsoil horizon, and a lower horizon that contained streaks of organic matter. Since then, Mackay has shown that this buried organic matter resulted from the progressive burial of the organic tongues that extend downward in the depressions between the hummocks. Mackay and others in Canada, and Tedrow and others in Alaska, have shown that the buried organic layer is common to most soils of the tundra (6, 7, 8, 9).

At Inuvik, soils examined under the tundra-forest transition vegetation were similar to those examined under tundra vegetation at Reindeer Depot. Both areas had hummocky topography although the hummocks apparently were higher and more frequent at Reindeer Depot. At Reindeer Depot the centres of some hummocks had a profile with little or no expression while others had a relatively well expressed profile that had a brownish surface over a gleyed subsoil. All the profiles had acid, unsaturated, surface horizons that became less acid or slightly alkaline with depth. They all had uniform textural profiles with no signs of clay translocation and all profiles were uniform in clay mineralogy. However, the tundra profiles had buried organic horizons while the forest profiles did not. The author examined these profiles in mid-July, when the depth to frozen ground under the knolls was two to three feet. These layers were not observed in the field because in one case the mineral material was very dark coloured, and in the other the layer was frozen. These layers in the tundra profiles were detected by chemical analysis.

At Inuvik on the gravelly outwash fan of Boot Creek, a Podzol with permafrost was sampled. While the profile was thin, the eluvial (Ae) and illuvial (Bf) horizons common to Podzols were reasonably well developed. Probably the degree of development expressed in this profile was possible because of the porous, gravelly nature of the material, which is not so susceptible to frost-heaving as the clayey glacial till on the upland area. It is also probable that this Podzol represents the maximum stage of soil development under the prevailing climate.

At this time, our observations are too few to permit revision of the classification scheme to accommodate the few soils studied at Inuvik and Reindeer Depot.

REFERENCES

1. Craig, B.G. and Fyles, J.G. Pleistocene Geology of Arctic Canada. Geological Survey of Canada, Paper 60-10. 1960.
2. Day, J.H. and Leahey, A. Reconnaissance Soil Survey of the Slave River Lowland in the Northwest Territories of Canada. Experimental Farms Service, Dept. of Agriculture, Ottawa, Canada. 1957. 44 pages.
3. Leahey, A. Characteristics of Soils Adjacent to the Mackenzie River in the Northwest Territories of Canada. Amer. Soil Science Procs., Vol. 12, 1947. pp. 458-461.
4. ―――――― Preliminary Soil Survey of Land Adjacent to the Mackenzie Highway in the N.W.T. Experimental Farms Service, Dept. of Agriculture, Ottawa, Canada. January 1953.
5. ―――――― Report of an Exploratory Soil Survey made along the Water Route from Fort Nelson, B.C. to Waterways, Alta., via Fort Simpson, N.W.T. Experimental Farms Service, Dept. of Agriculture, Ottawa, Canada. 1945.
6. Mackay, J.R. A Subsurface Organic Layer Associated with Permafrost in the Western Arctic. Geographical Branch, Ottawa. Geographical Papers No. 18, 1958. 21 pages.
7. Tedrow, J.C.F. and Cantlon, J.E. Concepts of Soil Formation and Classification in Arctic Regions. Arctic, Vol. 11, 1958. pp. 166-179.
8. ―――――――― Drew, J.V., Hill, D.E. and Douglas, L.A. Major Genetic Soils of the Arctic Slope of Alaska. Soil Science, Vol. 9, 1958. pp. 33-45.
9. ―――――――― Harries, H. Tundra Soil in Relation to Vegetation, Permafrost and Glaciation. Oikos, Vol. 11, 1960. pp. 237-249.

******

Discussion

N. W. Radforth asked if one can make any generalizations concerning the genesis and morphology of soils in the permafrost region of Canada, to which the author replied that it is impossible at present because only a limited number of profiles have been examined. Considerable work has been done on the arctic brown soils in Alaska and this has been reported in numerous papers by Tedrow and other investigators.

R. E. Beschel commented that this paper seems to discuss mostly stable soils and it is surprising to have such a large number of these. In reply to his question of what proportion of the soils are unstable, the author answered that if the term "unstable" refers to disturbances caused by frost action, then the profiles described in the paper are disturbed. Nevertheless, there are evidences of weathering which means that frost action effects are slow. There was no evidence of newly formed soils.

A question was asked whether any brown wooded soils were encountered, to which the author replied that they were encountered in the south which lacked permafrost. Brown wooded soils were encountered also at Norman Wells in permafrost and showed some effect of frost action.

A. Corte enquired firstly if any soil sampling was undertaken laterally from hummocks, secondly, if the soil was uniform throughout the hummocks, and, thirdly, if grain size analyses were made of any of the soils. The author replied in the negative to the first question and in the affirmative to the second. The reply to the third question was that a number were done in a vertical section. As an example, one imperfectly drained tundra soil showed the following grain size distribution:

Depth	Sand (%)	Silt (%)	Clay (%)
0" - 5"	7	41	52
5" - 9"	6	39	55
9" - 23"	8	45	47
23" - 28"	6	37	57

N. W. Radforth asked what was the temperature at the 18 inch depth in organic terrain at Norman Wells, for example. The author replied that permafrost was encountered there at a depth of 16 inches. Radforth added that the present and past vegetation has an effect on the freezing index line.

******

I. 4. OBSERVATIONS ON THE TIME FACTOR IN INTERACTIONS OF PERMAFROST AND VEGETATION

R. E. Beschel

INTRODUCTION

During three summers in the Arctic mainly devoted to studies of plant growth in glacier forelands, the author made incidental observations concerning the relation of vegetation and frozen ground.

Numerous relations of plants and frozen ground phenomena have been summarized by Benninghoff (3). Many problems have still to be solved to understand vegetation patterns in periglacial regions of which areas with permafrost form the main part (19) and to clarify the importance of frost action as an environmental factor. Likewise, the surface structures resulting from cryopedological processes can not be adequately interpreted unless vegetation is considered as an essential modifier. The actual time of the formation of periglacial vegetation and surface patterns is only known in rare instances. Radiocarbon dating gives the best results for longer time periods. The possibilities to date changes of shorter duration will be discussed here based on personal observations.

CLOSE-UP PHOTOGRAPHS

For any future determination of changes in vegetation and surface patterns the importance of photographic documentation is self-evident. Nevertheless, most photographs are taken without adequate indications of the location and the relocation of the exact place, not necessarily by the same observer, becomes very time consuming or impossible. Vertical photographs offer better chances of measuring changes accurately but the relocation is especially difficult. If one does not have time for accurate surveying or the placing of permanent, conspicuous markers, future work is aided by combining vertical photographs with pictures of the landscape in one or more directions from the same spot. The intersection of various ridges or hills on the horizon permits a rapid orientation during a revisit. A matching of the landscape in intermediate distances finally brings the observer back to the identical place.

The second major disadvantage at present concerns the availability of photographs. Only a fraction of photographs will ever be published and their exact location is rarely given. The bulk of photographs remains scattered with the persons who have taken them. It would be in the greatest interest of geomorphologists and plant ecologists to assemble archives containing close-up photographs arranged on the basis of geographical co-ordinates. Government agencies conducting or supporting research in periglacial regions could further stipulate that prints or negatives of relevant photographs be deposited in such archives. The availability of copies for field work, especially from the vicinity of settlements and weather stations in the Arctic, would aid all studies of surface and vegetation changes greatly.

The present difficulty of finding old photographs is reflected in the rareness with which such documented changes are reported. Mattick (9) repeated in 1951 a photograph of 1938 of an elongated sorted stone ring in the vicinity of Ny-Ålesund, Spitsbergen. The structure was first thought to be active as the plant cover succeeded from the bare centre through an incompletely colonized zone of crustose earth lichens on the fines into a ring of fruticose lichens (Cetraria delisei, Stereocaulon arcticum) on the inner edge of the raised stone ring with scattered cushion plants between, and small crustose lichens on the stones. The repetition showed, however, stability of all but very few stones on the margin as well as in the centre and barely visible changes in the plant cover restricted to very few places. Mattick concluded that patterned ground in this area had formed quite rapidly in the past while colonization of the stabilized ground proceeds very slowly. Continued frost heaving in the centre of the stone ring may have hindered plant growth although further sorting did not occur.

In 1961 Anker Weidick and the author had the opportunity of taking photographs from the same locations as Steenstrup (17) had done in 1898 on the western slope of Blaesedalen in the vicinity of the three southeastern outlet glaciers of the Lyngmarksbrae on Disko Island, West Greenland (69° 18' N, 53° 30' W). Two of these photograph pairs are shown in Figures 1-4. (Copies of the old photographs were kindly provided by the Greenland Geological Survey.) The photographs were taken on 2°-10° eastward inclined basalt plateaux above the shoulder of the valley at 450 metres above sea level. The depth to frozen ground varied from 30 to 60 centimetres on July 19, 1961. Between basalt boulders of 10 to 100 cm diameter and scattered gneissic erratics the ground consists of unsorted, sandy silt. The substrata is a mixture of predominantly local ground moraine and basalt bedrock weathered in situ. Patterned ground is weakly developed in the form of scattered sorted stripes. Amorphous solifluction is not represented by lobes or terraces but could be active as a gradual creep. The plant cover consists of an open Cassiope tetragona - Salix glauca - Cetraria nivalis heath. Lichens cover only about 20% of the surfaces on boulders. The vegetation could indicate instability, especially when contrasted with the nearly complete cover on basalt ledges in the vicinity,or on the moraine, at least 1500 years old, in the middle distance of Figures 3 and 4. Changes related to the shrinkage of the glaciers are obvious. The second glacier (Figs. 1 and 2) retreated about 1 kilometre and the third glacier (Figs. 3 and 4) nearly 2 kilometres in the past 63 years. A lateral moraine of the third glacier (Figs. 3 and 4-right hand side), formed around 1850, and has decreased 3 to 5 metres in height in the last 63 years as its ice core melted. The slumping is still continuing. The flank of the old moraine outside, however, still has boulders in identical positions. Even more surprising is the stability of the terrain in the foreground during the time interval. Most stones are still in the same places. Cracks in frost-shattered stones (Figs. 1 and 2-foreground) have not widened measurably. The same Umbilicaria thalli grow on the boulders with either no measurable growth or increases up to 2.5 centimetres in diameter. In addition only a few Umbilicaria thalli less than 2.5 centimetres in size became visible and some have vanished. The vascular plant cover has altered to a higher degree. Cassiope cushions have grown anew or have expanded greatly while many willows have disappeared, but the same percentage of cover remained open. Another photograph pair with a 10°-20° south facing slope in the foreground showed, however, movement of some big boulders by several metres and the smaller stones of the foreground could not be relocated.

HISTORICALLY DATED SUBSTRATES

When the position of retreating ice margins in the past is known or inferred from other evidence, the maximum time available for the formation of surface features in a glacier foreland can be ascertained. Between slumping moraines and shifting meltwater channels lie areas in which patterned ground appears to be forming particularly rapidly (20, 9). On the other hand shrinking perennial snow patches may only re-expose patterns formed long ago. Ice and snow cover have remarkably little influence on the underlying ground in the high Arctic. The advancing Crusoe Glacier on Axel Heiberg Island, N.W.T. (79° 22' N, 90° 50' W) has eroded mainly lateral meltwater channels while sod lies still undisturbed under the base of the 15 metre high lateral ice cliff. Retreating glacierets on Axel Heiberg Island expose occasionally undisturbed plant cushions at their margins (5). Under such conditions surface forms may also persist unchanged. J. D. Ives and G. Falconer of the Geographical Branch, Department of Mines and Technical Surveys, Ottawa, have observed ice-wedge polygons emerging under wasting ice masses in central Baffin Island (personal communication). Caution is therefore necessary to separate new surface forms from old ones.

Older patterns may also persist during continued sedimentation.

The formation of ice wedges at a depth of 30 metres is not necessarily related in time with the formation of permafrost as Shvetsov (14) and Taber (16) inferred. Trapping of windblown dust by open tundra vegetation may raise the soil level as well as the top of an ice wedge. Sedimentation in alluvial fans could work in a similar manner. The deposition of silt from weathering shale during snow melt and during the superficial thaw of permafrost is building a flat cone into the Colour Lake at the Base Camp of the Jacobsen - McGill Expedition on Axel Heiberg Island (79° 25' N, 90° 30' W). This alluvial fan and others in the vicinity are nevertheless patterned by large ice-wedge polygons which persist despite the sedimentation. Popov (12) gives clear evidence for this continued growth. He even claims that ice wedges increase only in conjunction with sedimentation and that they cease growing when silt and peat deposition stop on the polygons.

After disturbances, changes can be very rapid in periglacial regions. Williams observed extensive sorting and the origin of stony earth circles within one year after dwarf shrubs were removed in Rondane, Norway (22). Thermokarst often results from disturbances of the vegetation cover in areas with ground ice within a few years. Five kilometres northeast of the weather station at Eureka, N.W.T. an airstrip was constructed in 1947 by scraping the surface of a clayey silt plain at 125 metres above sea level. In 1951 this strip was abandoned. Sim mentions unfavourable cross winds for the landing and take-off of aircrafts as a reason (16). The extensive melting of ice wedges was related by station personnel to the author as another factor. This old airstrip (Fig. 5) stood out strikingly in 1960 by its much denser vegetation cover (5). P. F. Bruggemann observed this in 1953 (personal communication). There is no difference in level between the old airstrip and the surrounding area. The border has in parts a low ridge 30 centimetres high and a few metres wide which is very likely the material scraped from the runway. Ice wedges in the airstrip have melted and the polygons 20 to 30 metres in diameter are often separated by ditches 2 to 3 metres wide and 1 to 2 metres deep in contrast to the furrows outside the runway which are depressed only 20 centimetres. The new ditches possess already a well developed vegetation cover consisting mostly of Carex stans, Eriophorum scheuchzeri, Deschampsia brevifolia, and Equisetum arvense, while the only common species in the shallow furrows outside of the airstrip is Deschampsia. Colonization of a different habitat by additional species is to be expected, but the increase in plant cover on the flat polygons is surprising. Puccinellia angustata, Festuca brachyphylla, Alopecurus alpinus, Deschampsia brevifolia, and Salix arctica are much more vigorously developed on the airstrip and cover 30 to 40 per cent of the ground in sharp contrast to a scarce growth of the same dominant species covering only 5 to 10 per cent of the area outside the airstrip. Benninghoff mentions a rapid growth of cultivated plants the first year after ground above permafrost has been stripped of its original vegetation and relates it to a better water supply when the frozen ground thaws to greater depth. In later years, however, the productivity decreases (3). At Eureka the same relationship should prevail. The unexpected continuing rapid growth may be caused by the removal of accumulated salt in the top layers of the soil by scraping. Under the very arid conditions of this area salt crusts are common on bare soil and may be more disadvantageous to plant growth than the low precipitation. Water supply from melting snow and the thawing surfaces lasts over a month to keep the Eureka airstrip soft (16). Continuing thaw under the drying and hardening surface provides moisture to the deeper rooted plants for most of the growth season. Delayed thawing caused by a denser vegetation cover reduces the run-off and distributes the water supply over a longer period. The denser vegetation may also retain more snow. Whatever the interaction of the various factors may be, the old airstrip at Eureka demonstrates that minor initial changes may produce substantial alterations in a few years where permafrost and vegetation interact.

Evidence from historical information is rare and has to be supplemented with other time indications in many cases.

DENDROCHRONOLOGY

The number of whorls in spruces above the tilt in the stem resulting from caving in over thawing permafrost on lake margins permitted Wallace to estimate the recession rate of the shores (21). Palmer and Miller used the number of terminal bud scars on branches of dwarf willows to date the most recent colonization in front of a retreating glacier in the Alps (11). This method helps only to determine time spans up to 30 years because the scars become obliterated through the development of bark. In _Salix_ _arctica_ Beschel and Webb found further that branches are usually shed after a few decades and only the central burl, the half buried main stem of the shrub, reaches an age up to a century (6). The annual growth rings are thus age indicators for a longer time, although the rings are often discontinuous which makes counting difficult. Raup was able to use the age of dwarf willows to determine the rate of formation and regeneration of turf hummocks in Northeast Greenland (13). Growth ring studies of arctic dwarf shrubs are still very rare but give very useful results for time periods up to a century. The inferred stability of the substrate applies only for these sections of patterned or moving ground where the plants are rooted. Stability may differ greatly over a few centimetres.

LICHENOMETRY

Reindeer lichens (Cladonia subgen. Cladina) branch once a year at their tips (1, 2). The number of dichotomies from tip to base of the fruticose thallus equals the age of the living parts. Because of slow decay at the base, it is not possible to determine the total age of the plant. For a number of decades, up to a century, Cladinae can be used for dating. As the reindeer lichens establish themselves, in most cases only after a humus- or peat layer has developed, the relative stability of the substrate must have lasted for a multiple of the time these lichens are able to indicate.

Annual growth rhythms are unfortunately not expressed as distinct structures in other lichens. The diameter of circular thalli or of cushions is roughly proportional to their age (4). The rate of growth varies greatly with the climate and optimum growth rates have to be determined with the aid of otherwise dated substrates first. Growth rates differ greatly between various common species. The relationships of the largest measured diameters of different species give a multiple check of the estimated age of an undisturbed substrate within the life span of lichens and cushion plants. One of the slowest growing plants is Rhizocarpon tinei, a crust lichen of almost ubiquitous distribution in polar and alpine regions. Its optimum increase in diameter per century varies from 10 to 20 millimetres in many of the visited areas in the Arctic, with extremes of 4 to 90 millimetres in the driest parts of the Søndre Strømfjord, West Greenland, and very oceanic parts of the Alps respectively. On ground which was just at the ice margin on the first and second Lyngmarksbrae in 1898, the maximum diameters of R. tinei measured in 1961 were 8.5 millimetres. In places where less slumping occurred, the adjacent marginal moraines bear thalli of this lichen with maximum diameters of 11 millimetres. These moraines could have been colonized since about 1890. An indistinct moraine arc lies within the position of the ice margin mapped in 1912 by Mercanton (10) which bears R. tinei thalli dating back to about 1920 and having maximum diameters of 6 millimetres. Using these zones as a base and dividing the maximum diameters of common plants by the years available for colonization, the average annual diameter increments of the most rapidly developing plants can be obtained (Table I, column 1). Dividing the largest diameters of these plants in or near these glacier forelands (column 2) by the annual increments gives an approximate age of these plants until no further increase in diameter occurs (column 3). Fluctuations in the growth rates are not considered in this example. The selected plants established themselves only a few years after the ground became ice-free. These data serve only to give an idea of the range within which plant diameters can be used for dating. The growth rates vary considerably in different

TABLE I

Growth of common plants in the forelands of the first and second outlet glacier of the Lyngmarksbrae, Disko Island

Species	Average annual diameter increase of optimally developed plants in mm	Diameter of largest plants in and near the forelands in cm	Possible maximum duration of diameter increase in years
On soil			
Salix glauca	45.5	320	70
Saxifraga tricuspidata	6.7	65	97
Silene acaulis	7.1	40	56
Stereocaulon alpinum	3.4	26	75
Peltigera rufescens	15.8	33	21
On boulders			
Physcia caesia	1.0	7.0	70
Xanthoria elegans	0.75	8.2	110
Placodium melanophthalmum	0.26	2.6	100
Umbilicaria virginis	0.82	11.4	140
Umbilicaria hyperborea	0.44	6.5	150
Umbilicaria proboscidea	0.50	5.2	105
Alectoria pubescens	0.56	15.5	275
Aspicilia cf. *arctica*	0.30	15.3	510
Lecidea cf. *lapicida*	0.35	33.0	940
Rhizocarpon tinei	0.15	21.7	1550

climates and remain only roughly proportionate among themselves. The observed maximum diameters fluctuate also. Under more adverse microclimatic conditions, growth may be very much slower. Many of these plants may also retain a constant final diameter for a long time because of inherent characteristics or if they are in competition with other plants. The age estimates are thus conservative, but nothing can be said about the duration of persistence with unchanged size. Stone surfaces, completely covered with slow growing crust lichens and diameters of individual thalli of several centimetres, indicate stability of the surface for at least many centuries. More extensive nivation in the last centuries has killed this old cover in local depressions as remnants of large lichen thalli often indicate. Even then, these lichen corpses denote a stable position of the boulders. Limestones, dolomites, shales, soft sandstones, and soft schists do not possess an old lichen cover because of their fast weathering. Lichen crusts on bare soil seem to be fast growing and have not been used for dating thus far. Lichenometry is useful in interpreting the rate of surface changes if hard rocks are present. The time interval for which the method can be applied exceeds dendrochronology in the arctic by an order of magnitude. The accuracy is lower, however, especially when dating of areas below 100 metres square is desired.

SUCCESSION AND TOTAL PLANT COVER

A rough indication of the activity of patterned ground and solifluction is generally gained from the degree of plant cover on soil. Successions for the formation of non-sorted patterns are interpreted only with very crude time estimates (8). Zoned vegetation on many types of patterned ground or on solifluction lobes simulates successions. This is not necessarily the case because the various zones are also influenced by different microclimates, different length of snow cover, great differences in soil structure and water supply, besides the commonly assumed differences in stability of the surfaces. Other factors contribute at least to accentuate a pattern related to frost action. Vegetation may in turn preserve the patterns and even be responsible for their origin. Freezing and thawing cycles progress at rates which vary with the type and amount of vegetation cover. These differences produce instability and maintain it in turf hummocks and tussock rings. Patterns, whose development extends over decades to centuries, may change at a fairly constant rate which preserve the overall pattern for millennia without the development of vegetation to a complete and homogeneous cover as Sigafoos has shown (15). Trends towards uniformity cannot be used to give a time estimate because frost action may cause the plant cover to become more diversified.

Ice-wedge polygons on the higher parts of the flood plain of the Expedition River on Axel Heiberg Island vary in diameter from 10 to 30 metres. The separating furrows are shallow trenches between the raised edges of the polygons, which are about 20 centimetres high. A few points have been raised up to 60 centimetres above the centres of the polygons. The base of these hills consists of fine silt. Their bulk is made of raw humus, a dense tangle of rhizomes, roots, and partly decayed mosses. The hills have become perches for long-tailed jaegers and snowy owls as regurgitated pellets and bird manure indicate. Excess fertilization permitted a better development of plants. The dead plant parts and the raw humus act as an excellent insulator of the frozen ground after the outer few centimetres have thawed. The permafrost table rose in the hummock preserving its shape. The birds became more attracted by the hummocks rising highest which permitted still better growth on these.

A part of the polygons mentioned above has been undercut by the outbreak of ice-dammed lakes (5). Although the most recent disturbances caused splitting and collapsing of polygons on the shore of the river, earlier erosion resulted in a differential melting of ground ice and ice wedges. The bulk of each polygon has maintained its height because a dry carpet of moss peat on the surface permits only a seasonal thaw to 20 centimetres in contrast to the ground in inorganic or wet organic soil which thaws usually to 70 centimetres in the vicinity. Instead of shallow furrows the polygons are separated, however, by gullies up to 5 metres wide and 4 metres deep with flat bottoms. The gullies decrease gradually in size away from the river and continue into the normal shallow furrows about 100 metres from the shore. In contrast to the sparse and xeric vegetation on top of the marginal polygons the gullies possess dense mats of sedges and mosses. The presence of ice wedges together with the insulating effect of the dry moss layer could produce these intense relief forms. Slumping continues on the edges of the polygons but the presence of organic layers below the surface maintains the steep sided walls of the gullies. Organic matter at depths of 130 to 140 centimetres gave a radiocarbon date of 2900 ± 120 years (7). Sedimentation must have continued many centuries until the gullying began. The erosion probably proceeded rapidly at first and has now approached an equilibrium. The erosion may have lasted for centuries but the rapid colonization as shown in the ditches of the old airstrip at Eureka makes it rather futile to look for evidences of the lapsed time period in the stage of succession.

SUMMARY

In the complicated interaction of vegetation and frozen ground phenomena the time scale of changes is rarely known. Surface forms may change rapidly within a few years or may persist practically unchanged for many centuries. Repetition of photographs will provide the best evidence in the future. Frequently, vegetation provides useful time indications and can be used through dendrochronology or lichenometry for a better understanding of the processes. Rock surfaces are colonized very slowly but the succession on soil is a much less reliable time indicator as great changes in the total cover of plants can occur within a few years, while the same patterns of incomplete cover may last for centuries under the limiting conditions of the arctic environment. Local differences of the environment persist over long periods and the vegetation is not able to change the environment towards more mesic conditions. Contrarily, differences in the environment may be accentuated through the vegetation. Trends towards a climax cannot be observed in regions with permafrost.

ACKNOWLEDGEMENTS

The work was supported by the Arctic Institute of North America, the Jacobsen - McGill Research Expedition, the National Research Council of Canada, and the Greenland Geological Survey.

In discussions in the field the author profited greatly from the helpful criticism of Dr. Fritz Müller and cand. mag. Anker Weidick.

REFERENCES

1. Ahti, T. Studies on the Caribou Lichen Stands of Newfoundland. Ann. Bot. Soc. Zool. Bot. fennicae Vanamo, Vol. 30, No. 4, 1959. pp. 1-44.
2. Andreev, V.N. O priroste kustistykh lishainikov. Dokl. Akad. Nauk SSSR, Vol. 85, 1952. pp. 909-912.
3. Benninghoff, W. S. Interaction of Vegetation and Soil Frost Phenomena. Arctic, Vol. 5, 1952. pp. 34-44.
4. Beschel, R. E. Dating Rock Surfaces by Lichen Growth and its Application to Glaciology and Physiography (lichenometry). In: Geology of the Arctic, G.O. Raasch Ed. (University of Toronto Press), 1961. pp. 1044-1062.
5. ____________ . Botany; and Some Remarks on the History of Vegetation and Glacierization. In: Jacobsen - McGill Arctic Research Expedition to Axel Heiberg Island, Preliminary Report 1959-1960. B.S. Müller Ed. (McGill University), Montreal, 1961. pp. 179-199.
6. ____________ and D.E. Webb. Preliminary Growth Ring Studies. (manuscript).
7. Hegg, O. Preliminary Report on the Palynological Field Work of 1960 Including Two Radio-carbon Datings. In: Jacobsen - McGill Arctic Research Expedition to Axel Heiberg Island, Preliminary Report 1959-1960. B.S. Müller Ed. (McGill University), Montreal, 1961. pp. 201-208.
8. Hopkins, D.M. and R.S. Sigafoos. Frost Action and Vegetation Patterns on Seward Peninsula, Alaska. U.S. Geol. Surv. Bull., No. 974-C, 1951. pp. 51-101.
9. Mattick, F. Steinringbildung und Pflanzenwachstum auf Spitzbergen. Ber. Deutsch. Bot. Ges., Vol. 65, No. 2, 1952. pp. 41-46.
10. Mercanton, P.L. Les glaciers du Blaesedal (Disco). In: A. de Quervain and P.L. Mercanton. Resultats scientifiques de l'expéditions Suisse au Groenland 1912-13. Medd. om Grønland, Vol. 59, No. 5, 1925. pp. 255-257.
11. Palmer, W.H. and A.K. Miller. Botanical Evidence For the Recession of a Glacier. Oikos, Vol. 12, 1961. pp. 75-86.
12. Popov, A.I. (The Origin and Development of Massive Fossil Ice. Acad. Sc. USSR, V.A. Obruchev Inst. Permafrost Studies, Moscow, 1955). Transl. in: Natl. Res. Council Canada, Techn. Transl. 1006, 1962. p. 5-24.
13. Raup, H.M. Turf Hummocks in Northeast Greenland. (Paper read at AAAS meeting, Denver, Colo., Dec. 1961).
14. Shvetsov, P.F. Permafrost and Engineering-geological Conditions in the Anadyr' District. GUSMP, 1938.

15. Sigafoos, R. S. Frost Action as a Primary Physical Factor in Tundra Plant Communities. Ecology, Vol. 33, 1952. pp. 480-487.
16. Sim, V. W. Geographical Aspects of Weather and Climate at Eureka, Northwest Territories. Geogr. Bull. Vol. 10, 1957. pp. 37-53.
17. Steenstrup, K. I. V. Beretning om en Undersøgelsesrejse til Øen Disko i Sommeren 1898. Medd. om Grønland, Vol. 24, No. 3, 1901.
18. Taber, S. Perennially Frozen Ground in Alaska: Its Origin and History. Geol. Soc. Amer. Bull., Vol. 54, 1943. pp. 1433-1548.
19. Tedrow, J. C. F. and H. Harries. Tundra Soil in Relation to Vegetation, Permafrost and Glaciation. Oikos, Vol. 11, 1960. pp. 237-249.
20. Troll, C. Strukturböden, Solifluktion und Frostklimate der Erde. Geol. Rundschau, Vol. 34, 1944. pp. 545-694.
21. Wallace, R. E. Cave-in Lakes in the Nabesna, Chisana, and Tanana River Valleys, Eastern Alaska. Journ. Geol., Vol. 56, 1948. pp. 171-181.
22. Williams, P. J. The Development and Significance of Stony Earth Circles. Skr. Norske Vidensk. Akad. Oslo I. Mat. Naturv. Kl. No. 3, 1959. pp. 1-14.

******

Discussion

T. A. Harwood asked how lichens are used for dating to which the author replied that in a glacial foreland, for example, the diameters of the largest and fastest growing plants are measured. The later and slower growing plants are not considered. The growth rates of different species of established lichens must be related for dating purposes. It is possible then to compare growth rates in different moraine areas.

In replying to a further question by T. A. Harwood asking if any rock glaciers have been excavated, the author stated that none had been excavated and it was possible to say only how long the surface had been stable.

G. H. Johnston requested information on the rate of deposition of sedimentary material on the ice wedge polygons. The author remarked that as much as 4 metres of sediments have been observed overlying ice wedge polygons. C-14 dates gave an age of 4,000 years at a depth of 2 1/2 metres and 2,900 years at a depth of 1 metre indicating a very slow rate of accumulation of material. T. A. Harwood commented that the dating of areas can be facilitated with the use of aerial photographs. The National Air Photo Library has photographs taken in 1949 on which young polygons are visible. Now, 13 years later, it is possible to examine present photographs and therefore follow the changes in these polygons.

Fig. 1 Blaesedalen, Disko Island, West Greenland; 2nd outlet glacier of Lyngmarksbrae seen from south; August 1898.

Fig. 2 As Fig. 1; July 1961.

Fig. 3 Blaesedalen, Disko Island, West Greenland; 3rd and 4th outlet glaciers of Lyngmarksbrae seen from south; August 1898.

Fig. 4 As Fig. 3; July 1961.

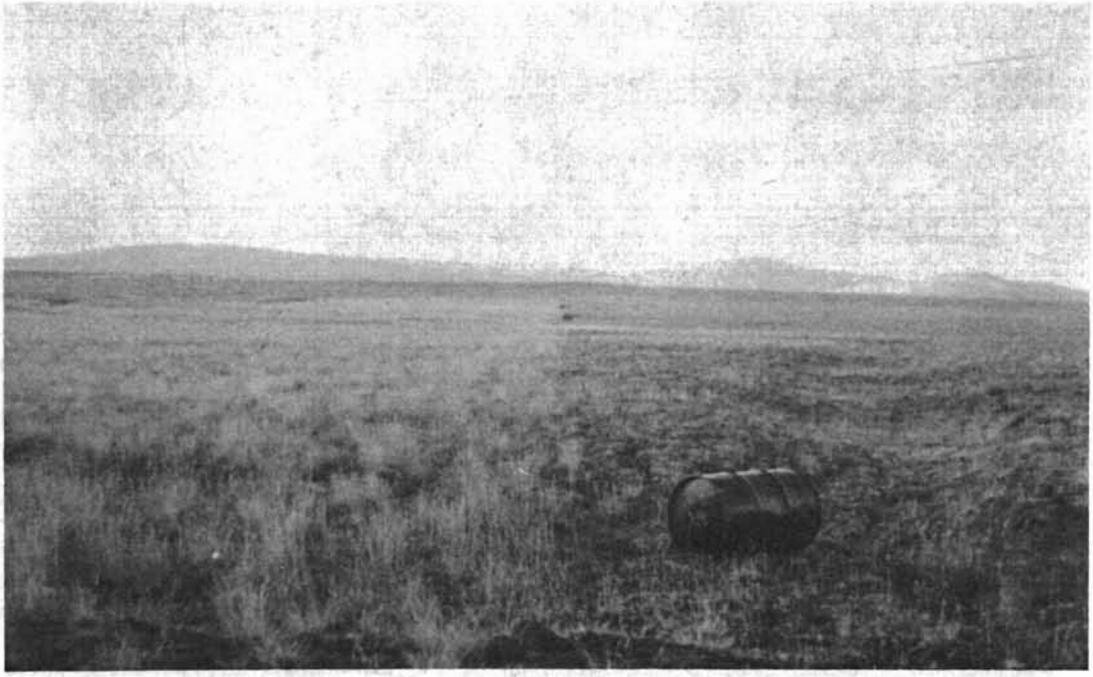


Fig. 5 Eureka, Ellesmere Island, N. W. T.; dense plant cover on the 1951 abandoned airstrip on the left.

I.5. THE ICE FACTOR IN MUSKEG

N. W. Radforth

INTRODUCTION

Perhaps because of engineering and scientific experience in the north, the presence of ice as a component in northern terrain is being viewed with increasing attention. Sometimes the ice factor is an aid in engineering application because it affords increased strength and cohesion in terrain that would be otherwise too weak to bear specified traffic. On the other hand, the high amplitudes of unevenness of the ice-surface, the differentials in the deterioration rates incurred in melting and the variation in structure of ice usually provide secondary barriers to successful off-road mobility. Also, now that foundation designers are better able to cope with the permafrost factor, the importance of seasonal frost conditions is coming to the fore.

The author has been associated particularly with disclosing and identifying ice phenomena in organic terrain. In one account (4) emphasis was placed on the suggestion that subsurface ice constitution in organic terrain was related to biological factors in frozen peat and its living cover. In another paper (2) an attempt was made to relate subsurface ice conditions (using contour pattern type) to the system of reference used in classifying organic terrain. Also, some consideration has been given to the importance of ice as a palaeoecological and physiographic factor influencing the development or evolution of organic terrain (1).

In each of these cases, emphasis was given to the development of either principles or hypothetical reasoning. Much research remains to be done before the phenomena involved can be fully accounted for and explained.

The main object of the present account is to reassess the accrued information pertaining to the ice factor in muskeg in order to give special consideration to the seasonal factor.

THE MECHANICS OF ACCUMULATION OF ICE

It is now generally known that organic terrain may be found in which ice occurs when no ice exists in the surrounding mineral terrain. This condition was noticed in Parry Sound District in Ontario at least as early as the first week in April 1962. This is not likely to occur the next year. Ice was not always present in all the organic terrain of the District even this year. When present, it differed as to thickness, shape of the local mass, depth of the mass from the surface of the terrain, quality of the ice and amount. It showed variation in the contour of its surface. Differences in melting rates were apparent. One might wonder whether this complexity can ever be accounted for. It is important that it should be if prediction of terrain conditions is an objective in terrain interpretation.

The problem becomes considerably more complicated when the geographic entity involved is not merely a Provincial District such as Parry Sound, but is instead half a continent. The reason is no doubt wider environmental influence. How this affects complication is a matter for examination.

In northern North America, because of permafrost, ice persists at the base of the peat - the fossilized component of the organic terrain. Where this condition is found, the ice may remain indefinitely, or it may disappear at the end of one summer. At the end of the summer when freezing temperatures commence, new ice forms at the top of the peat and eventually persists and deepens. In time, top ice and basal ice meet and the entire organic overburden is then frozen until the following early summer.

There are therefore three conditions of ice formation associated with the temporal factor; ice which is permanent, produced as an element of the permanently frozen condition (permafrost), ice which is temporary, which lasts more than a year and which is apparently caused in part by the permafrost condition, and finally, ice which comes and goes with seasons within the year. Because the three conditions have separate implications for biological, structural and mechanical relations in organic terrain, the author and his associates have given them different names. The permanent kind of condition (N.B. not the ice itself) is permafrost. The temporary condition which outlasts a year is climafrost. The third condition, the seasonal one, is called active frost.

For obvious reasons it will not always be possible to distinguish between these conditions through the manifestation of mode of ice formation. The temporal factor makes the condition elusive. To claim that climafrost is active frost, as indeed the author has done (4), is not at all wrong if the inference alludes to the ice rather than to the condition, for climafrost ice is undoubtedly active. On the other hand, the genetic meaning and distinction that active frost and climafrost convey is not exemplified in the claim unless the inference is appreciated.

DISTRIBUTION OF ICE FORMATIONS

Northern North America perhaps lacks geographic precision in the author's present connotation. Those who are concerned with the ice factor and with frost temperatures in the terrain, often use the southern limit of the permafrost as a means of separating north from south. The usefulness of this arbitrary method cannot be denied. It becomes troublesome only when one tries to locate the southern limit, and the southern limit is most significant for the engineer and the ecologist.

Near Wabowden, Manitoba, thought to be south of the limit of permafrost (7), John Stewart, an associate working under the author's direction, found active frost which outlasted the summer of 1960 - clearly climafrost. Lest the reader should assume that the presence of this ice arose out of the undetected existence of permafrost, the writer must advise that, beneath the ice mass, temperatures higher than 0°C existed for as far down as the observer could probe.

Thus, climafrost ice does not depend necessarily upon permafrost for its existence. How far south of the permafrost it exists is a matter for study and exploration. Beyond its southern limit, active frost, on the basis of the temporal factor, remains as the sole ice-forming condition and is found in muskeg well south of the United States boundary.

In randomly chosen samples of organic terrain, the average depth-to-ice (18 to 20 inches in August) is no greater at the Wabowden area than it is about twenty miles south of Churchill, Manitoba. Indeed, right at Churchill, soundings showed that it was more usual to find the ice surface about 10 inches further down. Thus, the presence of permafrost is not necessarily a criterion of less rapid recession of the ice surface.

Although climate has its influence on ice formation and persistence, the phenomenon of large isolated ice masses shows that the climatic factor, though primary. is not the only factor governing the control of ice formation. Whatever the localized secondary factor may be it is present in many places, at Hay River, N.W.T. and Wabowden, Manitoba, for example, where climafrost is common; or at Prince Rupert, B.C., Edson, Alberta, on an axis commencing 40 miles north of Kapuskasing, south through Parry Sound and terminating near Dundas, Ontario, at Huntingdon, P.Q. and into the Atlantic Provinces. At the latter locations, the feature can be demonstrated in terms of isolated active frost, in many instances well into the summer months.

ICE-FORM

The subsurface ice-form patterns reported elsewhere (1) by the author are partly in the nature of micro-patterns of ice topography. Several of them contribute a macro-effect when considered over a wide expanse of landscape.

Polygons contribute to a fissured contour (Fig. 2). In the early part of the summer, the ice surfaces within the polygons are flat. Later they become concave and the irregularity of contours over a traverse is enhanced. Although it is reasonable that polygons should appear south of the permafrost limit, there is as yet no knowledge whether the ice form in climafrost and active frost conditions is similar to that in permafrost country.

Perforations (loc. cit.) in active and climafrost ice, and invaginations in permafrost ice provide another kind of subsurface conformation. This is a common kind of feature and occurs both north and south of the permafrost limit.

Ice knolls (Figures 1 and 4) have also been recorded elsewhere. Collectively they form still another common kind of subsurface topography. They are prevalent in the islands of the Canadian arctic archipelago and are just as common in southern confined muskeg.

There are other aspects of contours on subsurface ice which have no direct relationship to specified micro-features. North or south of the permafrost limit raised ice masses occur in both regular and irregular peat plateaux (Figure 11)(2). Sometimes the top of the ice mass is 8 to 10 feet higher than the top of the surrounding ice. Also, there are the ice-forms that arise as a result of the effect of secondary geomorphic aspects in the organic terrain and others that occur through the action of water (1). It is questionable whether these can be defined as forms as yet because conformation is highly variable and somewhat fortuitous.

Elsewhere, the writer has noted that ice is a factor in controlling the topography of organic terrain (loc. cit.). It is perhaps more obvious that the reverse may also occur. In any case, when drainage ensues (Figure 14) ice erosion follows.

INSTABILITY OF ICE CONFORMATION

The temporal effect, the availability of water and inherent variability in ice-form and structure, combine with the climatic factor to make subsurface ice conformation evolve. Upon this, annual change is rhythmically superimposed. Accordingly, imponded arrangements may change and shallow ponds may migrate and change in size.

Also, the process of melting is on a differential basis as the results in Tables I and II illustrate. The amount and rate of melt varied from one station to another. All the readings were taken within the peat. The same situation occurred at the Lamprey site (Table II).

TABLE I

Differential melt in seasonal ice-surface shown by depth-to-ice measurements; Mile 472.5, near Hudson Bay Railway south of Churchill, Manitoba (1949).

	Depth-to-ice (inches) at 9 locations								
	1	2	3	4	5	6	7	8	9
July 9	12	10½	11½	10	9½	10	10½	8½	9½
July 22	12	10½	14½	12	10½	11½	13½	8½	13
Aug. 11	18	16	18	15	14	15	16	12	15
Aug. 27	20	18½	20	18	15	17½	19	13½	17½
Sept. 6	22	20	22	18	16	19	19	14	18
Sept. 15	22½	19	25	20	18	16	20½	15½	21

Inspection of the measurements in the tables shows that the subsurface ice contour profile is different for each date in the traverse connecting the locations. It is not surprising therefore that the areas of free water in the muskeg are constantly changing in position even within a season. Also, ponding pattern (Figure 15), shape and size of ponds would understandably vary from year to year.

ICE AND AIR FORM PATTERN

Certain type patterns predominate as one examines organic terrain from the air. Attributes of the ground have different emphasis as elements of pattern, depending upon the altitude at which inspection is made. This principle has been explained elsewhere (2,3). At 30,000 feet the Air Form Patterns have been designated as Marbloid, Terrazzoid, Reticuloid, Stipploid and Dermatoid (6).

For obvious reasons, especially when most areas of Canada have been photographed from 30,000 feet, it would be useful to know what the ice relations are with reference to the Air Form Patterns.

Marbloid

In Marbloid, because of ice knolling, ice contour of the type depicted in the diagram (Figure 1), is universally common. The polygoid condition is much less common but more prevalent than for other air form patterns. Raised ice masses with eroded edges are extensive and basic to any configuration that arises secondarily, viz., ice ridges from coalescing knolls.

TABLE II

Differential melt in seasonal ice-surface shown by depth-to-ice measurements; Mile 477, near the Hudson Bay Railway south of Churchill, Manitoba (1949).

	Depth-to-ice (inches) at 13 locations												
	1	2	3	4	5	6	7	8	9	10	11	12	13
July 6	26	18½	10	10	10	10	9	8	13	10	13	14½	18½
July 22	36	25	14½	10½	11	11½	13	11	15½	14	17½	21	25
Aug. 11	41	31	22	15	17	14½	15	13½	18	15	25	22½	29
Aug. 27	48½	45½	28	20	18	17	17	18	22½	19	29½	25	35
Sept. 6	46	49	33	23½	19	17½	19	19	26	21	33	46	47
Sept. 15	62	49½	35	24	19½	18	19	19	25	20	34	47	51

The depth to ice is less on the whole for Marbloid than for other air form patterns. Where there is permafrost the shallow depth persists into mid-September as compared with mid-July for active frost.

Marbloid is not confined to regions of permafrost and climafrost ice. Figure 9 shows an area of permafrost and climafrost ice; Figure 6, an area with permafrost-free climafrost ice; Figure 7, an area with active frost ice. On the other hand, Marbloid is very infrequent where active frost alone occurs, much more frequent where permafrost-free climafrost occurs and of highest frequency in permafrost country. From this it might be construed that the ice conditions noted as prevailing for Marbloid are distributed accordingly. Apart from the fact that the polygoid ice configuration has not been studied south of the permafrost limit, the inference would be valid.

Terrazzoid

The ice conditions described for Marbloid occur for Terrazzoid in less exaggerated fashion but in separated areas and with the polygoid feature seldom arising. In the organic terrain adjoining these areas, the frequent ice-form is the highly perforated condition. Figure 12 shows the surface of the terrain.

Active frost ice alone and climafrost and permafrost may occur in Terrazzoid but in climafrost country Terrazzoid is less common than Marbloid.

Reticuloid

Both the knoll and polygoid conditions are rare in Reticuloid although knolls sometimes appear when the reticulations are coarse.

Within the reticulations, the amplitude of change in the depth to ice is high and irregular. Walking is difficult because one moment one foot may be submerged to ankle depth whereas the other foot, a pace away, may sink three feet down with only the hips to check the subsidence.

Beyond the reticulations, ice recedes from the surface rapidly. The conformation produced resembles that shown elsewhere (4), and ponding ensues. The ice at the edges of reticulations usually recedes sharply leaving an almost vertical bank (steep pond margin) unless the reticulations are very broad in which case the ice-surface is less steep and conforms roughly to the slope of the pond margin (2).

The ice conditions described are similar for active climafrost and permafrost country. In the latter, the permafrost ice is found well below the level of the organic overburden, and in the reticulations usually it is likewise within the mineral sublayer. So far as the writer knows, the same applies for climafrost although exceptions may almost certainly be expected to occur (e.g. near Hay River, N.W.T.).

Stipploid

Ice-knolling is common in Stipploid but the knolls are in patches of up to 20 or 30 knolls per traverse across each patch. Neither polygoid nor perforated ice-forms have been found. Erosional patterns, mostly dendritic, are very common and there is great variability in the depth to ice.

In northern Canada, residual ice occurs in Stipploid well into the onset of seasonal frost in the permafrost country. Because this ice is at different depths in different years and occasionally recedes to the lower limit of the organic matter, the author is of the opinion that it is all climafrost ice rather than permafrost ice. South of the permafrost limit climafrost and active frost ice both appear (e.g. Wabowden vicinity).

In the south, where Stipploid is as common as Marbloid is in the north, the ice forms are similarly complex and with marked differentials as to melt (e.g. near Kapuskasing, Ontario).

When snowfall is heavy, it may occur that no ice arises in Stipploid (e.g. Parry Sound District, 1962) whereas it may, and usually does, form in Dermatoid.

Dermatoid

Ice-knolling is common and continuous in Dermatoid (Figure 4). The polygoid condition occurs but is rare. Perforated ice is very common, the condition being similar to that found in the reticulations of Reticuloid but on an extensive and continuous scale (Figure 13). Where this condition is extreme, "shifting" ponds arise in the course of ice recession (Figure 15) but this condition has been noted to date only in permafrost country.

Erosional features (Figure 14) are common (more so than for Stipploid) and are variable but not as abruptly so as with Stipploid. Although erosion is common, it is not usually dendritic and leads to imponding. Ponds, which are a feature in the Dermatoid south of the permafrost limit are permanent, occur with less frequency and usually have steeper (more abrupt) banks than their counterparts in permafrost country (e.g. Peace River in Alberta, Prince Rupert, B.C. and Newfoundland). Where the banks are steep, the ice-contour conforms.

Both north and south of the permafrost limit hummocking (Figure 3) (2) is common in Dermatoid and this is associated with perforated ice.

ICE-FORM AND VEGETAL COVER

The author has reported elsewhere (4) on subsurface ice with specific reference to muskeg cover. Although the work and reporting in this field is still generally incomplete, emphasis here has been placed on the importance of a single cover class designated earlier by the writer as Cover Class H (2).

Normally, Cover Classes are not defined on the basis of species composition but on morphological features (loc. cit.). Thus Classes A and B both may be constituted of Picea and Larix but they fall within different characteristic ranges of stature when referred to in the sense of Class. In Class H it happens that the structural attributes on which the Class is designated are such that they can only apply to species of lichen. Therefore Class H as it appears in formulae (loc. cit.) designating muskeg cover always connotes lichens.

The cover formulae which recur in the permafrost region frequently are: H, HE, HEI, EH, HEB, EHB and BEH. Their frequencies diminish in the order listed but it must be appreciated that H, the pure Cover Class, usually shares the cover with another class unless the unit of cover is small, say, the size of a metre quadrator less. Therefore H will seldom be referred to as occurring alone wherever large ice-masses are concerned.

The literature already demonstrates that the H factor in cover formulae applies generally in the north (2) and that it arises in association with Classes E, I and B. It has never been explained however, that these associations usually occur where high-table ice-form is established (Marbloid and Terrazzoid) where ice-knolls persist and frequently where polygons occur.

For low-table ice the H factor does not show, e.g., the vegetal cover for the background terrain of Terrazzoid or northern Dermatoid. If the H factor appears in northern Stipploid again there is a high ice-table present though usually not so high as for the Marbloid condition.

Sometimes Classes E and I gain prominence in the cover formulae. When this occurs, irregularities in the ice contour of the raised table are prominent and there is marked erratic micro-relief in both the terrain surface and the ice contour beneath.

The only exception where no high ice-table arises and when the H factor is prominent is where the organic layer is only two or three inches deep and, in these circumstances, the layer thins to zero as, for instance, when an esker or old beach line intervenes across the organic terrain.

Beneath the lichenaceous cover moss exists invariably, sometimes Sphagnum often Hypnum. This constituent predominates in the peat if the cover formula is HE. Thus it appears that the H Class of cover is carried up as a thin layer as the moss grows beneath it. Often through the summer the lichenaceous layer is dry and crisp. Possibly this is why it is never important as a fossilized component of the peat - no water, no fossilization. The H factor is therefore only a symbol designating the presence of a high ice-table, etc. The preservation of low ground temperatures to preserve the ice through summer periods of high atmospheric temperature must be attributed to the living and fossilized moss and the associated components. Doubtless the lichen and the moss are mutually beneficial and biotically compatible. It is reasonable to conclude that this vegetal relationship ultimately controls the formation and maintenance of the conditions producing high ice-table. At Great Whale River, P.Q., at Winisk, Ontario, at Baker Lake, N.W.T., and from the air, across the arctic archipelago one can observe this ice phenomenon arising on scale which diminishes toward the north. It is easy to detect the H factor from the air at any altitude. It appears in summer as a grey to yellow-green mantle (Figure 9); south of Great Slave Lake, N.W.T. (Figure 6) and west of Musgravetown, Newfoundland (Figure 7). The H factor shows white, and the presence or absence of the factor is easy to detect.

It has been observed on a flight commencing near Dawson Creek, B.C., and proceeding north to Fort Nelson, B.C., that the H factor comes into sharp prominence about two-thirds of the distance to Fort Nelson.

A flight from Axel Heiberg Island, southwest to Banks Island and on to Whitehorse, Y.T., revealed HE plateaux south of the snow line beyond Franklin Bay near Horizon R at the end of May 1961. On this traverse the H factor was encountered to within about 25 miles of Whitehorse, Y.T.

On a third flight from Whitehorse to the Edmonton area the H factor reappeared about fifty miles from Fort Nelson.

During the flight northwards from Winnipeg to Churchill the H factor appears about fifty miles northeast of Norway House and becomes plentiful. This region is at about the same latitude as Wabowden, about two hundred miles to the west at which the H factor is also known to occur but where EH is more plentiful than HE.

Finally, the H factor occurs south of Winisk, Ontario on the Hudson Bay coast as observed on a flight from Moosonee, Ontario.

Where a traverse is made in the direction of prevalence of the H factor, Class H is usually first noticed as BEH with H constituting slightly more than 25% of the cover. Within twenty miles in the direction of greater concentration of H, all the formulae involving Class H (loc. cit. p. 11) will have appeared but in reverse sequence. Thus H quickly displaces E as the dominant cover. This phenomenon can be conveniently demonstrated in a flight traverse from Winnipeg, Man. to Churchill.

THE H FACTOR AND THE SOUTHERN LIMIT OF PERMAFROST

An analysis of the positions of initial occurrence of HE shows an approximate coincidence with the southern limit of the permafrost condition. The degree of prevalence of Class H in a secondary position in formulae designating the cover condition to the south of the limit suggests the presence of permafrost-free climafrost (e.g. Wabowden, Man.).

Confirmatory evidence supporting this theory can only be supplied by field inspection. The writer hopes that pertinent data will accumulate during future exploration and invites assistance.

If the theory is substantiated, no doubt there will be important exceptions. One has already appeared. In the Marbloid near Hay River (Figures 5 and 6) and in that near Churchill (Figures 9 and 10), the former in climafrost and the latter in combined climafrost and permafrost country, the situation conforms to the theory. It is assumed on current knowledge however, that in Newfoundland there is neither permafrost nor climafrost ice, despite the presence of the H factor, in significant enough amounts to suggest occurrence of climafrost ice. Although the writer has not had the opportunity to check this example in the field, examination of the ice conditions elsewhere in Newfoundland supports the exception. The climate prevailing in Newfoundland provides strong continuous winds in the summer. Where active frost ice occurs, drying action above it is rapid and persistent. Resulting surficial drought encourages formation of lichens just as it did near Churchill and Hay River. In the latter situations, the drying was slower and the agent was high temperature, not wind.

SUMMARY DISCUSSION

A full accounting for the ice factor in organic terrain will not be expected in this paper for it is too large a topic and in any case it is not yet possible to provide all the evidence and reasoning that comparative analyses require. The information herewith already suggests that perhaps more important than climate are geomorphology and vegetal cover in accounting for ice occurrence and behaviour.

Peat structure if woody and coarse and with many woody erratics harbours much pure ice distributed generally. Woody fibrous peats of a finer texture also contain ice masses but here they are smaller and more numerous than in coarser peats. Where woody and non-woody fibrous components associate, ice masses are often in the form of thin perforated sheets less than a quarter of an inch thick. Where this occurs, the bulk of the peat is incorporated within the ice to interrupt the peat-free laminae. Finally, where granular peats freeze, peat and ice are inseparable.

It will be acceptable to the reader that each ice-peat association as broadly described above will have its own mechanical properties. Frozen peats are sometimes friable, sometimes rubbery and highly elastic. Were it not for the irregularity of contour, generally, frozen peat offers an ideal bearing strength notably resistant to shear and penetration and affords good traction. Construction upon it or within it will be difficult, however, unless the kind of peat-ice mixture is identified and its properties determined. This difficulty is exclusive of that suggested by occurrence of the various subsurface ice micro- and macro-patterns and characteristic differential melt, the order of which would seem to be predictable.

Whether active climafrost or permafrost ice is involved, in engineering development and scientific study, they are each indicative of dynamic states. In organic terrain, active and climafrost ice are more significant because they are more prevalent. Permafrost ice, although inherently static, is inevitably overlain by climafrost which for foundations must be regarded as unstable. The author wishes to emphasize the dynamic concept because of its importance to development in the subarctic and arctic. Long into the summer, the ice factor keeps most of Canada's 500,000 square miles of organic terrain in subtle motion from day to day. The engineering implications of this are obvious. Drainage problems alone, as an example, require special imaginative treatment. In frozen peat in the Prince Rupert area, where woody erratics in the peat are often massive logs one foot and more in diameter occurring at all levels in peat, many 30 to 50 feet thick, the heat conductivity phenomena suggest physical relations that differ from those in the land of "shifting" ponds.

To the academically inclined, there is perhaps need for some supplementary nomenclature. To speak and write of active frost ice, climafrost ice and permafrost ice, each of which is important in its own right, is cumbersome. Why not actakeg, climakeg and the already coined permakeg? Icekeg would serve as an all inclusive expression. Permakeg would then be icekeg but icekeg would not necessarily be permafrost.

The conditions which produce the ice should also be defined as presently named, thus:

Permafrost is a frozen condition existing indefinitely within terrain. Climafrost is a frozen condition existing temporarily but for more than one year within the terrain. Active frost is a frozen condition existing temporarily within the terrain for less than a year.

In this paper too little attention has been directed to the ice factor in confined organic terrain such as is found commonly in the Canadian Shield. Here, Dermatoid and Stipploid are important. Although the ice conditions described for these air form patterns can be expected to be fixed, their distribution will have certain characteristics imposed by reason of the basic geomorphic control that the kettle-hole-like "vessel" imposes on the muskeg it contains. This is a subject for another related account.

ACKNOWLEDGEMENTS

The author acknowledges gratefully the financial and professional support he has received from the National Research Council and the Geophysics Section, Defence Research Board for this and related work.

REFERENCES

1. Radforth, N. W. Organic Terrain. Soils in Canada. Ed. R. F. Legget. Roy. Soc. Canada Special Publications No. 3. Toronto, 1961.
2. ______________ Organic Terrain Organization from the Air (Altitudes less than 1,000 feet). Handbook I. Defence Research Board of Canada. DR No. 95, 1955.
3. ______________ Organic Terrain Organization from the Air (Altitudes 1,000 - 5,000 feet). Handbook II. Defence Research Board of Canada. DR No. 124, 1958.
4. ______________ Palaeobotanical Method in the Prediction of Subsurface Summer Ice Conditions in Northern Organic Terrain. Trans. Roy. Soc. Canada, Series III, Sec. V. Vol. XLVIII, 1954.
5. ______________ Suggested Classification of Muskeg for the Engineer. The Engineering Journal, Vol. 35, No. 11, 1952.

6. ——————— The Application of Aerial Survey Over Organic Terrain. Roads and Engineering Construction, 1956.
7. Thomas, M.K. Climatological Atlas of Canada. Meteorological Division Department of Transport. N.R.C. No. 3151, Ottawa, 1953.

******

Discussion

T. A. Harwood commented that it is important to realize the changes that take place in permafrost. Permafrost is a temperature condition and perennially frozen material does not necessarily contain ice. A distribution map of permafrost in Canada, showing thickness and temperatures of the ground, similar to the one already available for the U.S.S.R., is required. There is a problem of nomenclature here because ground remaining frozen for one or two years can be considered as permafrost. These local variations are caused by micro-climatic changes and variations in vegetation. For construction, each site must be assessed individually. The southern fringe area of the permafrost region is the most difficult for construction and this is where northern development is taking place first. Finally, it must be remembered that permafrost is "perennially frozen ground" not "permanently frozen ground". The author reiterated the usefulness of the "climafrost" concept. In his opinion, there are three types of frozen material associated with the time factor. Firstly, there is the permanent kind of condition which lasts indefinitely called permafrost; secondly, there is the temporary condition which outlasts one year called climafrost; thirdly, there is the seasonal condition called active frost.

J. L. Charles observed that ponds in the tundra beside the Hudson Bay Railroad have been noticeably enlarged through the transmission of heat.

J. A. Pihlainen emphasized that permafrost is defined strictly on a temperature basis. There is no need for the term "climafrost" because it denotes a perennially frozen condition of the ground and therefore can be considered as permafrost.

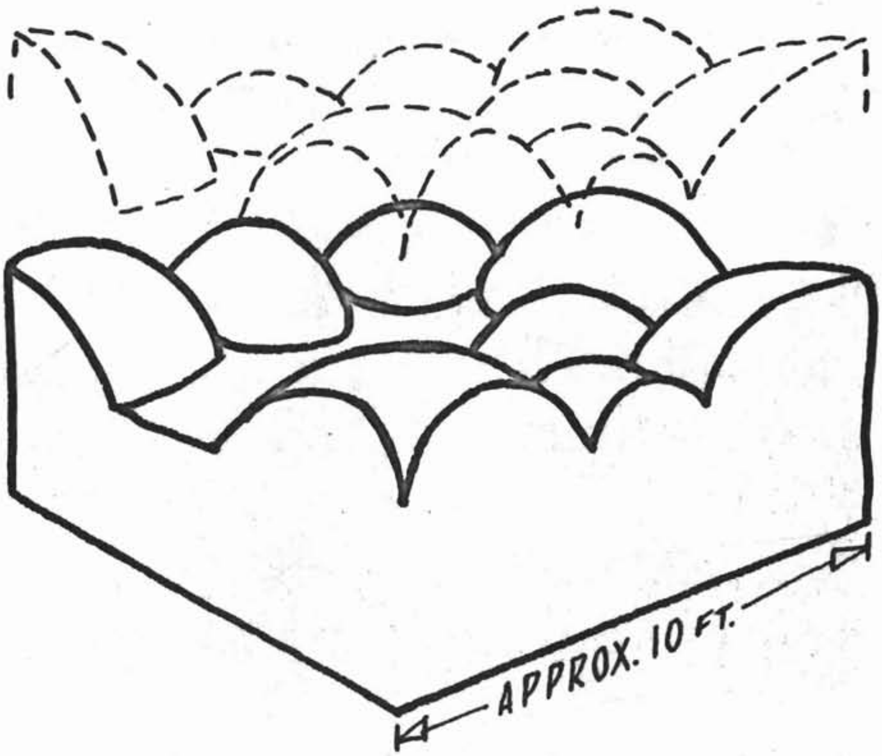


Fig. 1 Diagram showing conformation of ice-surface caused by ice-knolls, a condition common in Marbloid and Stipploid.

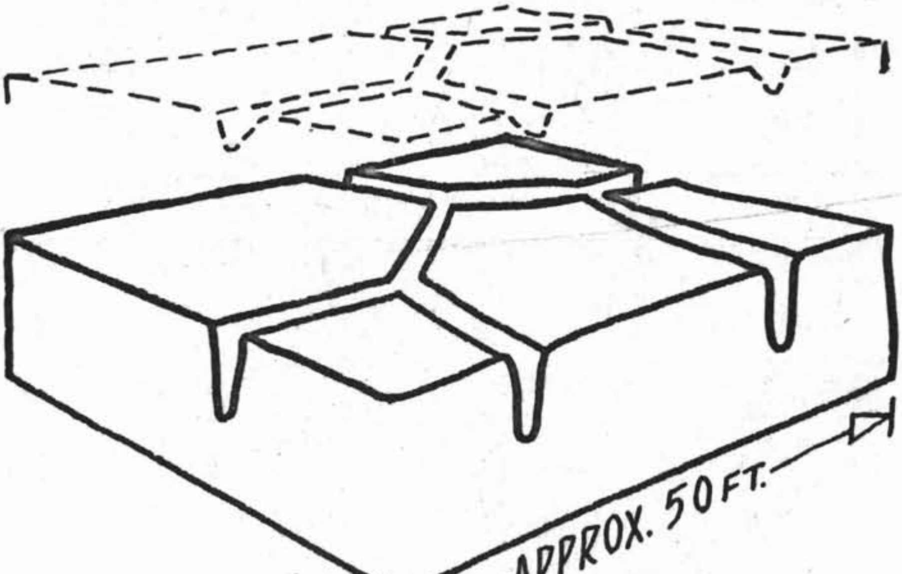


Fig. 2 Diagram showing conformation of ice-surface caused by closed polygons, a condition common in Climafrost of Marbloid.

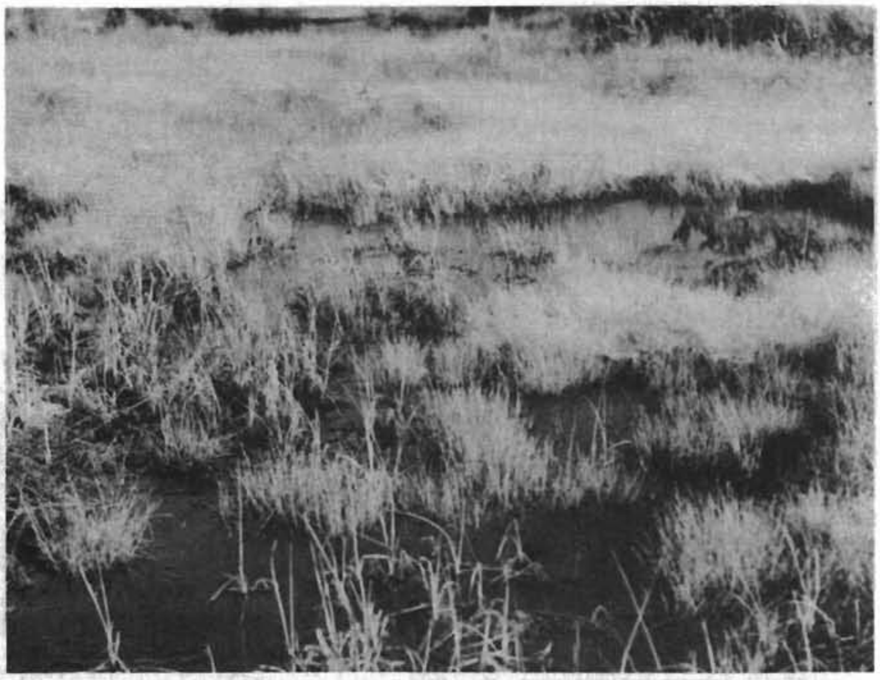


Fig. 3 A photograph showing hummocking ('a') (cf. Fig. 4, mounds ('b')) where perforations occur in active frost of Dermatoid and Reticuloid.

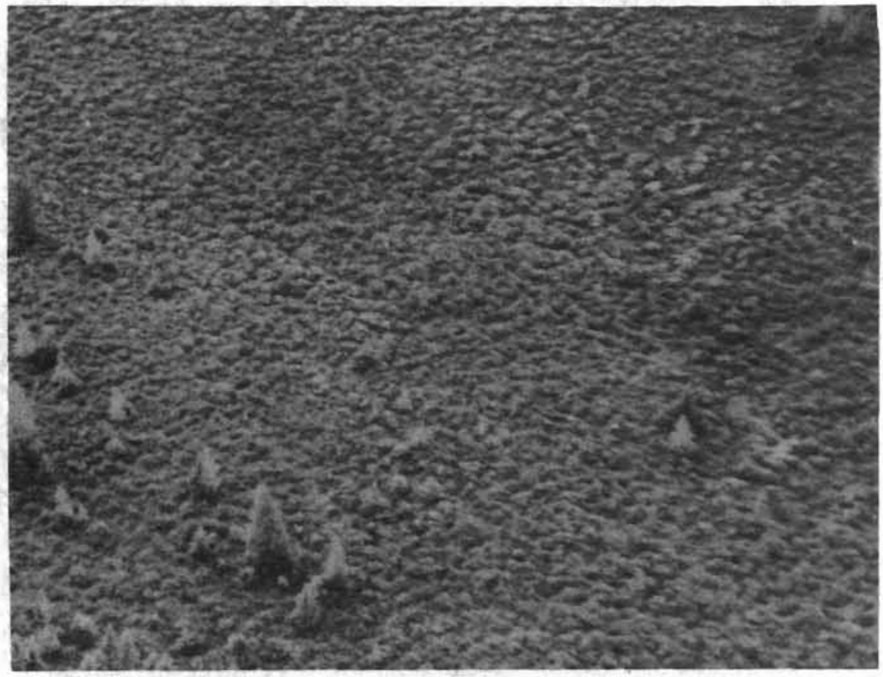


Fig. 4 An association of mounds ('b') (distinct from hummocks ('a') in which ice knolls occur.

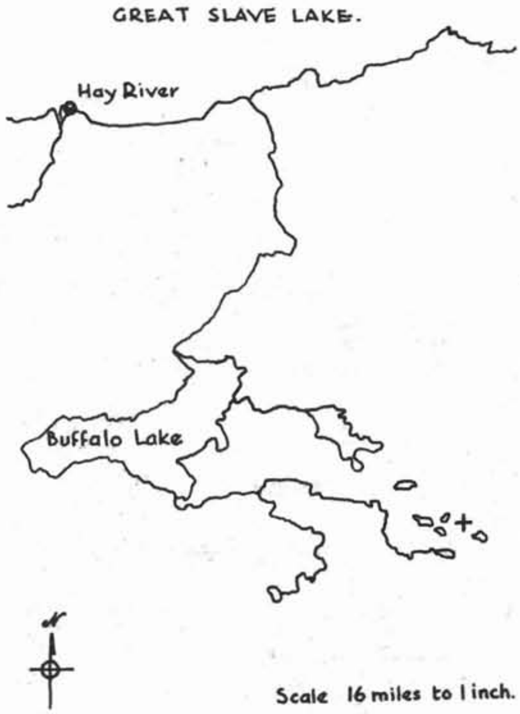


Fig. 5 Map of region south of Great Slave Lake, N. W. T. showing the location of the terrain of which the air photograph Fig. 6 was taken.

Fig. 6 Marbloid near the southern fringe of permafrost where climafrost conditions are common. Light tone marks "H" factor. Scale 1": 1 mile.

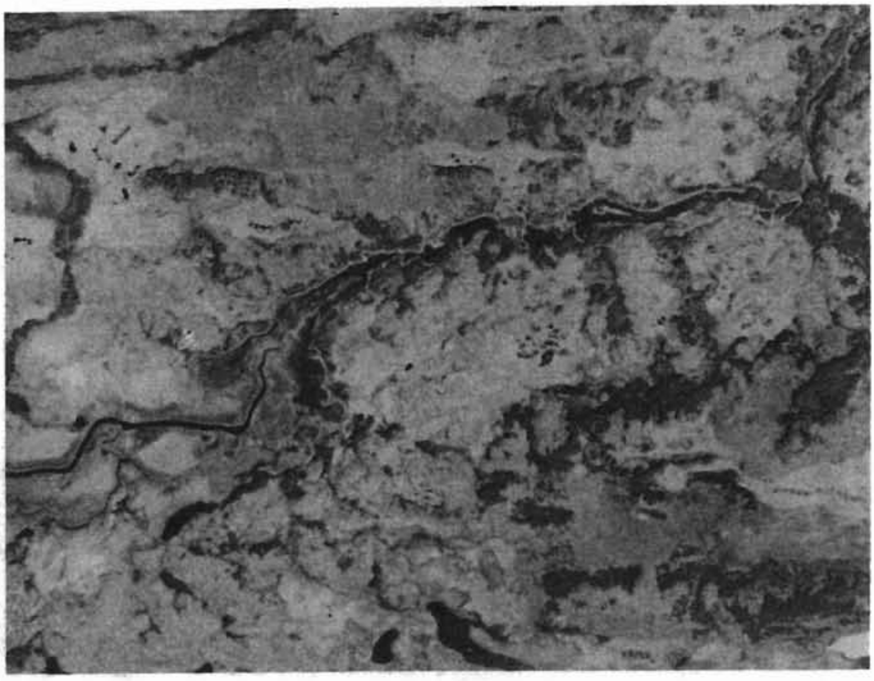


Fig. 7 Marbloid in permafrost-free organic terrain of Newfoundland. Light tone marks "H" factor. Scale 1": 1 mile.

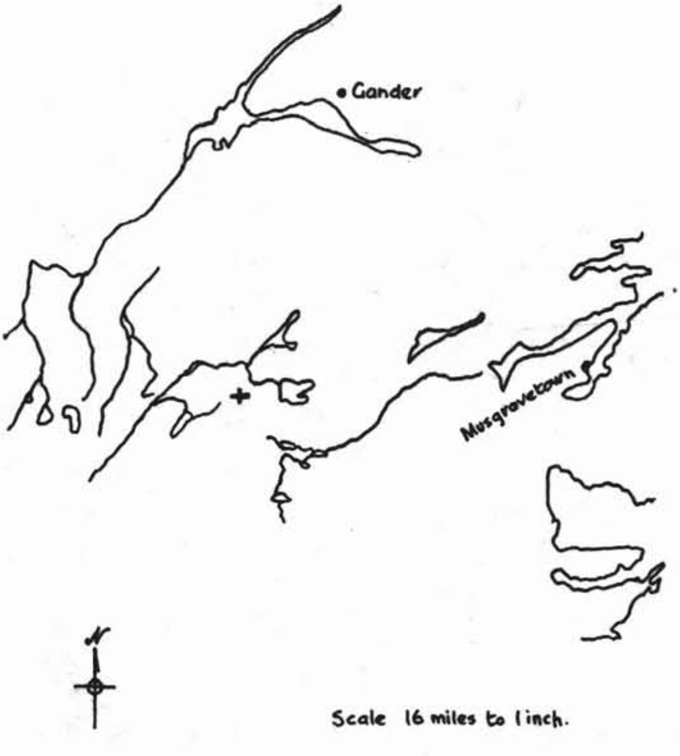


Fig. 8 Map of region west of Musgrave Town, Newfoundland showing the location of the terrain of which the air photograph Fig. 7 was taken.

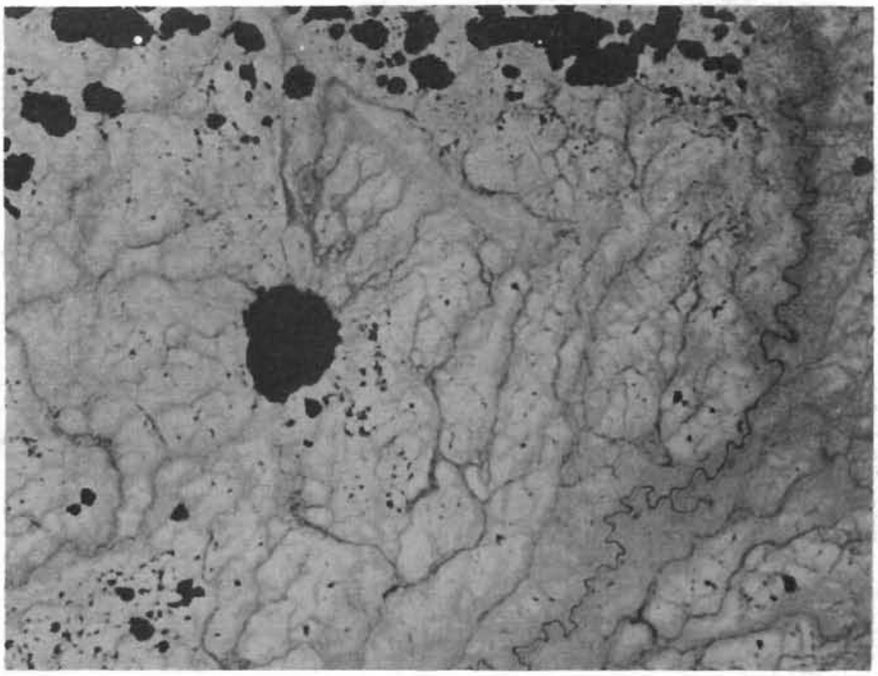


Fig. 9 Marbloid in permafrost area of organic terrain near Fort Churchill, Manitoba. Light tone marks "H" factor. Scale 1": 1 mile.

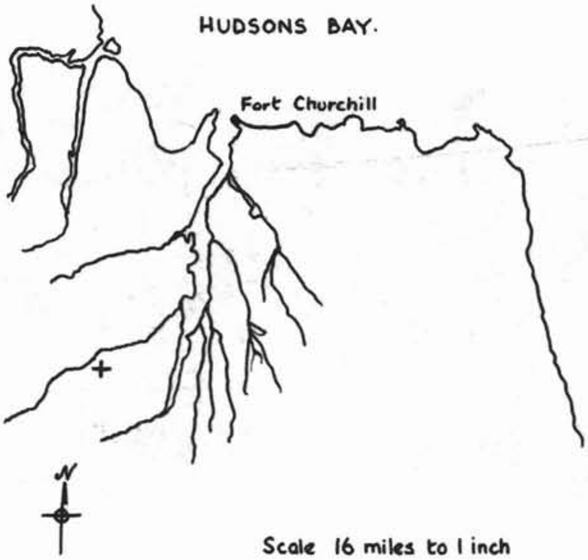


Fig. 10: Map of region east of Fort Churchill, Manitoba showing the location of the terrain of which the air photograph Fig. 9 was taken.

Fig. 11 An irregular peat plateau in which high table ice occurs.

Fig. 12 Depressions in Terrazzoid in which low table, usually active, ice occurs with irregular borders.

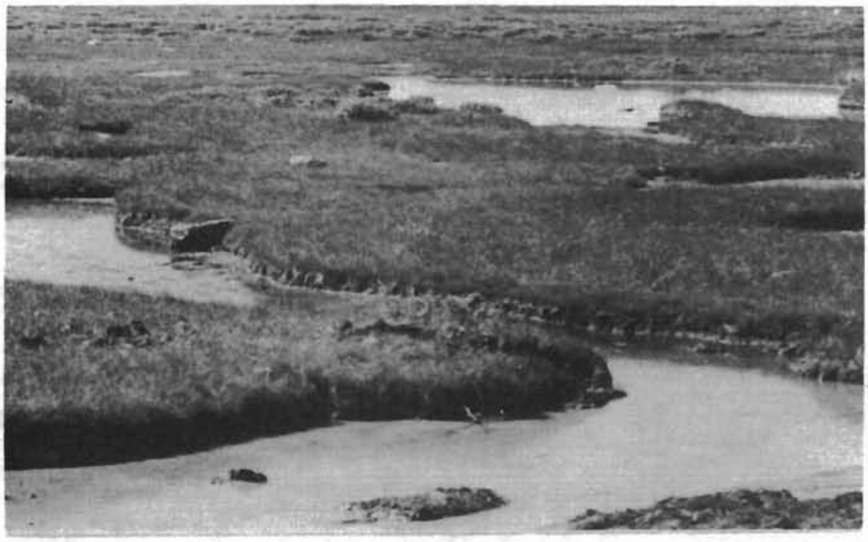


Fig. 13 Depressions in Reticuloid in which, south of the permafrost, low table seasonal ice occurs with regular boundaries.

Fig. 14 Ice erosion caused by summer drainage - a condition common in Dermatoid.

Fig. 15 "Shifting Ponds" - a phenomenon encouraged by Climafrost in permafrost country.

II. 1. ORIGIN OF THE PINGOS OF THE PLEISTOCENE MACKENZIE DELTA AREA

J. R. Mackay

(Summary)*

Pingos are ice-cored hills, which are typically conical in shape. There are over 1,400 pingos in the Mackenzie Delta area. The largest group of pingos, exceeding 1,350, lies in a belt extending east from Richards Island. The pingos are in an area of Pleistocene sands and silts with rolling relief. A small group of pingos, differing in age, size, and method of formation from those of the Pleistocene area, occur in the distal portion of the modern delta. It is the purpose of this paper: to describe the characteristics of the pingos of the Pleistocene Mackenzie Delta area; to discuss theoretical aspects of their origin; and to estimate their age.

The most distinctive terrain characteristic of the pingo is its occurrence in flat low-lying areas which are, with few exceptions, present or former lake basins. The thickness of the sediments over the ice-core varies considerably. It appears to be directly related to the size of the pingo, small pingos having the thinnest cover of sediments, large pingos the thickest. The overburden cover is estimated at one-half to one-third of the pingo height. Some pingos have multiple ice-cores.

Pingos have developed in sandy material too coarse grained to be susceptible to extensive ice lens formation. The thick horizontal ice sheets which are widely distributed in the same region as the pingos have not grown in the sands but in silty material near the surface of the ground. The two types of ice should not be confused.

The most generally accepted origin for pingos of the Mackenzie Delta type has been proposed by Porsild who states pingos "... were formed by local upheaval due to expansion following the progressive downward freezing of a body or lens of water or semi-fluid mud or silt enclosed between bedrock and the frozen surface soil, much in the way in which the cork of a bottle filled with water is pushed up by the expansion of the water when freezing." (4-p. 55). Müller, in his detailed analysis of the Mackenzie Delta type of pingo,

---

* Paper presented with the permission of the Director, Geographical Branch, Department of Mines and Technical Surveys, Ottawa. The full paper will be published in Geographical Bulletin No. 18, Geographical Branch, Department of Mines and Technical Surveys, Ottawa.

has elaborated upon the theory of Porsild (2). In the following discussion, certain modifications and amplifications will be made to the existing theories of pingo origin. There is common agreement that pingos grow as a result of the aggradation of a capping of permafrost, ab initio, over an unfrozen lake bottom.

In view of the paucity of data on permafrost depths beneath lakes, a theoretical approach may give information on permafrost surfaces. Theoretical aspects of the general problem of three-dimensional heat conduction in a semi-infinite medium, disturbed by surface effects, have been considered by many authors. In particular, Lachenbruch has discussed theoretical aspects of three-dimensional heat conduction in permafrost beneath heated buildings (1). The same theory may be applied to lakes.

In the case of pingo formation, two permafrost surfaces are involved. The first permafrost surface is that beneath the lake bottom. This surface had all of post-glacial time, probably 5,000 to 10,000 years, prior to pingo growth to reach equilibrium. Consequently, steady state conditions have been assumed for the position of this surface. The second permafrost surface is that which spread as a seal on the lake bottom at time of pingo growth. In this surface, which is associated directly with pingo formation, transient and latent heat effects are included.

Considering the first surface, if permafrost exists beneath the centre of a lake, and the lake radius is gradually increased, with steady state conditions prevailing, a critical radius will be reached when the permafrost lens beneath the lake "opens" up, so that all the material directly beneath the lake centre is above 0°C.

Considering the second permafrost surface, three factors would seem to operate in combination to produce a dome-shaped lower permafrost surface at the site of pingo growth during the aggradation of permafrost in a lake basin.

Firstly: most lakes are deepest towards the centre, and shallowest near the shores. Thus, if the water gradually shoaled, permafrost will have had a longer time to grow near the shore with a dome-shaped lower surface therefore resulting.

Secondly: any tendency towards ice segregation would result in a downward warping of the permafrost surface around the ice, because saturated soil would freeze faster than water.

Thirdly: once ice segregation caused a mound to grow on the lake bottom, an upward bending of isotherms can be shown to occur.

Consequently, as a result of the three factors discussed above, the penetration of permafrost in a lake basin should be uneven. A dome-shaped lower permafrost surface should form in most basins, the arch of the dome being near the lake centre.

The generally accepted theory for pingo formation depends upon updoming by hydrostatic pressure resulting from volume expansion of water on freezing as permafrost advances on all sides into a closed unfrozen pocket. Laboratory and field experiments carried out by various investigators on the freezing of saturated sands shows that excess pore water tends to be squeezed out if the permeability exceeds about 5 inches per day, provided the surplus water is free to escape.

The development of a closed system whereby expelled pore water is trapped under pressure would seem to require only the growth of a continuous permafrost seal on the lake bottom. Expelled pore water could, therefore, not escape upward through the impermeable permafrost seal; it could not go sideways because of permafrost extending out from the shore, and it could not escape downwards because of the presence of permafrost, saturated soils, impermeable sediments or a combination of them.

The initial rate of formation of permafrost under constant temperature is about proportional to the square root of time. Thus the rate of downward aggradation of permafrost would be relatively rapid when permafrost was thin and the temperature gradient high, but it would slow down when permafrost had extended to greater depths. Therefore the rate of expulsion of pore water, from downward freezing, would gradually diminish. In addition, the volume of unfrozen sediment would normally decrease with depth, so that equal increments of permafrost growth would not contribute equal amounts of expelled pore water.

As an illustration of the probable slowness of permafrost growth, let us consider the freezing of 15 yards of saturated sand of 30 per cent porosity. For a ground surface temperature of -5 °C, it is about 10 to 20 years; for -1 °C, it is about 50 to 100 years; and for -0. 1 °C, it is hundreds of years. Although the figures cannot be more than approximate ones, they do suggest that during prolonged shoaling of a lake, whether through geomorphic or climatic causes, downward penetration of permafrost will be slow, because mean annual lake bottom temperatures will oscillate around 0 °C and then gradually drop below it as lake ice freezes for longer and longer periods to the lake bottom.

The rate of pingo growth cannot be rapid, except in exceptional cases. For example, if the ice core in Ibyuk pingo is assumed to be a right cone 40 yards high with a base 70 yards in radius, the volume of ice would be approximately 200,000 cubic yards. If this represented a 10 per cent volume expansion of sand with 30 per cent porosity, the required volume of unfrozen sand would have been about 7,000,000 cubic yards. If the unfrozen sand were beneath a circular lake and the sediments were in the shape of a right cone with a slope of 45°, the radius and "depth" of the cone would have been 190 yards. The freezing of such an unfrozen cone would have taken many decades.

The great majority of the pingos are probably hundreds, if not thousands, of years old. As long as permafrost is thicker than the height of a pingo, and the surface cover remains intact, a pingo is a relatively permanent feature of the post-glacial landscape. The vegetation cover of pingos attests to an age of at least several hundred years. The patterns of large tundra polygons, with some ice wedges several yards wide, is suggestive of ages in the thousands of years, judging from inferred rates of ice wedge growth elsewhere. Peat, one to two yards thick, flanks some pingos, but feathers out against them, showing, therefore, growth after pingo formation. Two radio-carbon dates for peat deposits suggest a rate of accumulation of about 1 to 1.5 feet per thousand years. On this basis, a number of pingos examined are three to five thousand years old. Wave-cut pingos, which occupy drained lakes whose shapes show a coastal recession of several thousand feet, also indicate a venerable age. Müller estimates the minimum ages of two pingos near Tuktoyaktuk at 7,000 and 4,000 years (3). Such an age would be compatible with a period of cooling following the post-glacial thermal maximum, or even earlier growth.

In conclusion, if we wish to test any theory of pingo growth, it would be an easy matter to artificially shoal a suitable lake by lowering its outlet. We could thus experiment on forming a full-sized natural scaled pingo. A small pingo might even be born in five years, perhaps in time for Canada's centenary!

REFERENCES

1. Lachenbruch, A.H. Three-dimensional Heat Conduction in Permafrost Beneath Heated Buildings. U.S. Geol. Surv. Bul. 1052-B, 51-69, 1957.
2. Müller, F. Beobachtungen Über Pingos. Meddelelser om Grønland, Bd. 153, Nr. 3, 1959. 127 pp.
3. ___________ Analysis of Some Stratigraphic Observations and C_{14} Dates from Two Pingos in the Mackenzie Delta, N.W.T. unpublished manuscript, 1962. 13 pp.
4. Porsild, A.E. Earth Mounds in Unglaciated Arctic - Northwestern America. Geog. Rev. Vol.28, 1938. pp. 46-58.

Discussion

T. Lloyd asked why the largest pingos do not grow larger, to which the author replied that the pingos reach a certain size at which the summit ruptures followed by eventual collapse. Pingo size is also limited by the water supply available in the area. M. Bozozuk added that it appears that the phenomenon of ice accumulation in a house on permafrost would be caused by a mechanism similar to that of pingo formation.

T. A. Harwood wished to know why pingos occur only in the Pleistocene and present deltas of the Mackenzie River. The author gave the reason that these are the areas with the highest amounts of sandy soils which are necessary for pingo formation.

J. S. Rowe enquired if there is evidence of relic pingos in southern Canada, for example, in southern Alberta or the Prairies. The author's reply was that none is known in Canada but there are evidences of relic pingos in France and Belgium. P. J. Williams commented on a collapsed pingo in Sweden where an ice block has melted leaving a crater. The author remarked that the sediments fall into the crater when the ice melts. J. D. Ives described the collapsed pingo to which Mr. Williams referred. It is located in the floodplain of a small stream in the Abisko area being about 20 metres in diameter with a raised rim about 3 metres wide and 1 1/2 metres high.

R. Chevalier asked if the Tuktoyaktuk pingos are growing. The author stated that the word "pingo" suggests growth according to Porsild but there is no record of this. The presence of ice wedge polygons on the sides of the pingos leads one to the conclusion that no growth is occurring.

J. G. Fyles requested information on the location of the youngest pingos to which the author replied that they occur in the outer portions of the Mackenzie delta. From Sir John Franklin's narratives, it is evident that there are some pingos in existence today in areas where they did not exist in his time. A pingo could be formed today by draining a lake.

II. 2. RESEARCH ON FUNDAMENTAL PROPERTIES AND CHARACTERISTICS OF FROZEN SOILS

R. Yong

INTRODUCTION

In the study of soil properties and characteristics, it is often considered useful to obtain fundamental relationships relating measured properties and characteristics with behaviour patterns. For soils existing at temperatures above freezing, of particular interest are such properties as soil strength and compressibility or deformation characteristics, because in the final analysis these have the most direct bearing on engineering structures. The parameters involved in such behaviour characteristics are presently being subject to considerable study and scrutiny. For many clay soils, it is becoming more and more evident that the laws of mechanics applicable to coarse-grained soils may not be as easily applied to such clay soils. The surface forces existing in clay soils must now be considered.

In soil strength, there is evidence that the method of test evaluation plays an important part in the determination of the factors giving rise to soil strength. Between the limits established by coarse-grained soils and clays, it is thought that friction is primarily responsible for strength of the former in the one instance, and "cohesion" is the other prime factor in the strength of the latter. "Cohesion" however is an elusive parameter which seems best interpreted as an inherent property of clay soils dependent upon such factors or variables as:-

a) type of clay mineral and soil mass composition;
b) prestress history;
c) soil structure - particle orientation and arrangement;
d) nature of pore water and degree of saturation;
e) method of test evaluation.

Because of the lack of knowledge of clay soil-water interaction, it is apparent from the interest now shown in this important area of study that, at the present time, it is more a problem of the definition of the term "cohesion" (2, 4, 5).

If the problem of defining and establishing the basic parameters involved in soil strength seems difficult for unfrozen soils, the case for frozen soils is most complex by comparison. Added to the complexities of unfrozen soil are such factors as temperature, ice content, partial freezing of the pore water resulting in the establishment of unfrozen water in frozen soils, number of ice crystals formed, orientation of ice crystals and size of ice crystals. It may be that some of the complexities of unfrozen soils will be obviated, but, on the other hand, they may be multiplied.

EXPERIMENTATION

To obtain an insight into the problem of frozen soil strength and its relationship with conventional measured properties and observed characteristics, three types of soils were used in the study - sand, silt and clay (Figure 1 and Table 1). Two types of strength tests were used to measure shear strength of the frozen soils - unconfined compression test and ring shear test. A schematic representation of the ring shear test method is given in Figure 2. Restraint against axial elongation was provided and, as part of the test technique, the test sample was subject to an axial force prior to application of the shear force.

TABLE 1

Properties of soils used for study

Sand - $\phi = 37°$, $c = o$, $S_s = 2.65$

	Silt	Clay
LL	25.1	67.0
PL	17.0	28.8
S_s	2.68	2.73
Wopt.	16.5	28.5
Opt. dry density	114.5 pcf	87.8 pcf
Mineral content in approx. %		
Chlorite	-	2-3
Biotite	-	10
Amphibole	-	2-3
Feldspar	20	50-60
Quartz	80	25

Test samples were prepared in waxed containers in the case of sand samples, and the silt and clay samples were prepared either by consolidation or compaction. Sand samples in both the dense and loose states were fully saturated and only the consolidated clay samples were completely saturated. Clay and silt samples compacted by the Harvard Miniature method were compacted on the dry side and either frozen in that state or allowed to take up water for three days by controlled soaking prior to freezing.

Evaluation of unfrozen water content was by calorimetric means. Variation of initial water content was achieved only by means of moulding water content - (not by drying out from a uniform initial water content).

RESULTS AND DISCUSSION

Some of the data and results have been presented previously in primarily tabular form (9, 10) for strength tests on laboratory prepared samples. Subsequently, further experimentation has been undertaken on other more fundamental factors such as relationships between temperature, soil type and unfrozen water content. Only results and data pertinent to the discussion on a possible mechanism of shear strength of frozen soils will be presented here.

It seems most appropriate to discuss the philosophy of frozen soil strength along the following lines:

a) What the strength tests indicate;
b) The possible mechanics of the frozen system.

Rate of Loading in Unconfined Compression

Projecting from conventional strength tests on unfrozen soils, the logical procedure would be to determine strength of frozen soils initially in terms of unconfined compression tests. In the general understanding of strength of materials, this reasoning is both valid and sound. From previous studies (1) on frozen soil strength in unconfined compression, the rate of load application was found to be important up to a rate of loading of approximately 400 psi per minute. Beyond this, the strength increase realized from an increase in rate of loading was small and relatively insignificant.

At rates of loading in unconfined compression of approximately 60 and 500 psi per minute, designated as "slow" and "fast" respectively (Table 2), it was noticed that temperature was more effective in causing marked changes in ultimate strengths and stress-strain moduli (Figures 3 and 4). Rate of loading plays a more dominant role at higher temperatures in the realization of ultimate strengths of clays and sands. At these temperatures (approximately -5°C), the higher rate of loading serves to decrease ultimate strength of the frozen sand soils while increasing their stress-strain moduli. On the other hand, while the ultimate strength of the clay soils decreased with the higher loading rate at the same high temperature, the stress-strain modulus of the test samples were increased.

Based upon limited studies of rate of strain loading on clay soils at normal above-freezing temperatures, the decrease in ultimate strength and stress-strain modulus with increased rates of loading experienced at temperatures just below freezing, indicate that it is not possible to

TABLE 2

Summary of unconfined compression results

NOTE: Groups consist of 5 individual samples

Group No.	Sample Nos.	Test Temp. °C	Rate of Test	Av. Density lbs/ft^3	Av. Void Ratio	Av. Water Content W %	Av. Ultimate Strength K.S.F.	Av. Stress strain Modulus K.S.F.
1	LS-31-35	-17.8	Fast	119.3	0.784	29.8	311.2	14300
2	DS-31-35	-17.8	Fast	132.5	0.446	16.9	362.0	16700
3	LS-36-40	-17.8	Slow	118.5	0.810	30.8	269.0	11500
4	DS-36-40	-17.8	Slow	132.0	0.464	17.5	318.7	12600
5	LS-41-45	- 4.7	Fast	123.0	0.679	26.0	124.0	9300
6	DS-41-45	- 4.7	Fast	132.0	0.461	17.5	223.9	11200
7	LS-46-50	- 4.7	Slow	123.2	0.662	25.4	164.8	3300
8	DS-46-50	- 4.7	Slow	130.3	0.488	18.6	259.8	6100
9	CL-1-5	- 4.7	Fast	108.6	1.111	39.7	84.4	1910
10	CL-6-10	- 4.7	Slow	109.7	1.202	43.1	105.2	2570
11	CL-11-15	-17.8	Fast	111.5	1.123	40.3	236.7	6720
12	CL-16-20	-17.8	Slow	111.3	1.153	41.6	208.5	6780

explain frozen clay soil strength using the same model for both frozen and unfrozen soils. While this may seem intuitively obvious, there have been numerous suggestions proposing just such analyses. The decrease in ultimate strength of sand soils with a corresponding increase in rate of loading seems to justify the need for another mechanism or for the search for other factors hitherto unknown concerned with development of frozen soil strength. These will be discussed in the section on "Factors Affecting Frozen Soil Strength".

Ring Shear Test

The ring shear test shown schematically in Figure 2 was used in an effort to learn more about the mechanics of shear failure of the frozen soils. Initially, no restraint from axial elongation was provided for, and under transverse shear, the tendency for axial elongation was noticed. Consequently, the shear test was refined to include axial prestressing - with the hope that more could be learnt about the relationship between confinement and shear stress. It must be pointed out that while this tries to emulate the conventional triaxial test, it in no way pretends to be such, since restraint and confinement can only be controlled positively in the axial direction. Confinement along the radial direction was controlled directly by the fit of the frozen soil specimen in the ring shear apparatus. At extremely low temperatures, this was not too critical, but at temperatures slightly below freezing, it seemed that the tendency for radial expansion induced both by shear and axial restraint could be the cause for some of the irreproducibility of results.

In Figures 5 to 9 inclusive, some test results relating shear strength and final axial pressure for sands, silts and clay soils are given. Although initial axial confinement may be used as a relating factor in reporting the test results, it was felt that because of the axial elongation under shear, the results may be more meaningful if the final axial pressure was used to analyze the inter-relationships. To provide further data in the study of contribution to shear strength from ice strength, Figure 10 shows the influence of axial pressure on the shearing strength of ice. No attempt was made to control the growth or orientation of ice crystals - both for the soil samples and for the companion ice samples.

It may be argued from an examination of the ice curve in Figure 5 and those in Figure 10 that axial confinements above 50 psi would begin to cause crushing of the ice in the soil voids. This cannot be denied. Failure in frozen soils however is not governed solely by the ice component - as witness the curves in Figures 5 to 9 inclusive. Even in the case of ice specimens, while shear strength of the ice specimens averaged around 100 psi with no initial axial confinement at -5 °C, strength increase is noted with increasing axial confinement. It would seem that a "frictional" characteristic does exist in ice which tends to influence ice strength. It would seem obvious that there must be an optimum axial confinement which may be placed on the ice samples at any temperature - beyond which ice breakdown would be too great and failure would occur before any transverse shear can be effected. The curves for ice strength at -5 °C and -8 °C in Figure 10 show just this phenomenon.

How does this affect frozen soil strength? In frozen saturated coarse-grained soils, while it is not possible to separate the frictional characteristic of the ice from that of the soil grains, the evidence indicates that the total mass behaves similarly with frictional material. The slight aberrations from linearity must possibly arise from plastic yield and deformation of the ice phase.

While the clay soil used in the study showed very little frictional characteristic in the unfrozen state, the results shown in Figures 8 and 9 indicate otherwise. It must be concluded from these results that the major frictional contribution is derived from the ice while particle interaction and other undetermined factors could also provide some of this friction characteristic. For incomplete saturation, much remains to be learnt about interparticle action in clay soils in the unfrozen state. This lack of knowledge restricts intelligent speculation on the nature of interparticle action in the frozen state.

The two limits represented by frictional and frictionless soils (sand and clay) both demonstrated that the ice phase in the frozen soils contribute significantly to the development of frozen soil strength. Although there is difficulty in defining the actual contribution from the ice phase, the results obtained by decreasing the freezing temperature show increased strengths.

It would be expected that the frozen silt soils would also reflect the same trends shown in the clay soils. The influence of the ice component seems to be more noticeable when the "dry" and "wet" silt samples are compared. This seems reasonable because it was shown from studies of normal above freezing temperatures that friction is the governing component in the silt soil. Hence, if these same silt soils are prepared in the "dry" state, i.e. dry of optimum and at about 50% saturation, it would be reasonable to assume that increases in strength arising from corresponding increases in axial confinement would result primarily from mobilization of granular friction. By allowing the silt soils to take up water - up to about 90% saturation, the strength increases shown previously in the "dry" samples were not as pronounced in the "wet" samples. While shear strength of the "wet" silt samples did increase with increasing axial confinement and also with decreasing temperature, these increases seem to depend more on the demonstrated strength properties of the pore ice.

Unfrozen Water Content

It became increasingly evident from observations on the behaviour of frozen saturated clay soils under unconfined compression, that some of the demonstrated yield and plastic deformation even at below freezing temperatures must be due to the presence of some water in the frozen samples. It was not clear whether this unfrozen water resulted from local melting at stress concentrations, or whether it existed despite freezing of the samples with no relation whatsoever with imposed radial shear.

In a detailed study on unfrozen water content, some of the results of which are presented in graphical form in Figures 11 to 15 inclusive, it is necessary to define certain limitations and conditions. Williams (8) (personal communication) used the technique of drying out samples from a constant initial high water content as standard procedure for sample preparation. For this study, variation in water content was achieved by varying initial moulding water content. The difference in technique here, although seemingly slight, has resulted in an interesting and meaningful development.

The results presented in Figures 11 to 15 inclusive show that variation in the initial moulding water content results in corresponding variations in the quantity of water remaining unfrozen measured at different subfreezing temperatures. Figure 15 shows this phenomenon. For clays and silts, it is a matter of great importance whether the specimen is prepared at above optimum, optimum, or below optimum water contents. Unfrozen water content decreases as temperature decreases, but the position of the curve depends upon the initial moulding water content. Further to this, unfrozen water content varies at the same temperature dependent upon whether the specimen is frozen to the test temperature or frozen at a lower temperature and allowed to thaw to the test temperature. This is demonstrated by the band lines or curves in Figures 11 to 14 inclusive. The upper limits of the bands represent the unfrozen water content measured as the specimens were frozen directly to the test temperature shown, while the lower limits of the bands represent measurements of unfrozen water content as the specimens thawed to the test temperature from about 2°C lower than the test temperature. Similar hystereses were reported by Leonards and Andersland (3) and Williams (8).

By relating unfrozen water in terms of per cent saturation or per cent of original moulding water content remaining unfrozen, a better understanding of the phenomenon of partial freezing may be obtained.

Williams (8) reports that the quantity of water remaining unfrozen is not dependent on initial water content. On the basis of drying out from a constant initial water content to different water contents prior to freezing, this may be expected. In terms of soil structure or orientation of soil particles, little particle rearrangement occurs under slow drying (within limits) from the reported technique. Hence it would be expected that soil suction measured in terms of pF would not change significantly. It follows then that, with this technique of sample preparation, the quantity of water remaining unfrozen at a constant pF would be dependent on the test temperature and the means of attainment or arriving at the test temperature.

On the other hand, with the technique of variation of initial moulding water content, individual specimen soil structures would be varied and from previous studies (7, 6) pF would correspondingly vary. Consequently, the results given in Figure 15 reflect unfrozen water contents based upon variations in pF's arising from differences in structural orientation.

The factors giving rise to partial freezing and unfrozen water content have been discussed in previous studies (11). As expected, the silt soils prepared and tested do not show the same magnitudes of unfrozen water. However they showed the same inter-relationships between initial moulding water content, temperature, and unfrozen water content.

Factors Affecting Frozen Soil Strength

At the present stage of research on frozen soil properties and characteristics, the evidence indicates that much remains to be done. While it is not possible to give positive results or to draw conclusions, it is possible to examine the factors considered in the development of frozen soil strength.

It is evident that frozen soil strength increases as temperature is decreased and as restraint on axial elongation is increased. Projecting this further, it would seem feasible to suggest (based upon the data) that if normal pressure is increased, shear strength would correspondingly increase or if volume change is restricted, shear strength would be increased. The ice "frictional" characteristic can be used to an advantage to develop greater strength potential in the frozen soil.

The quantity of water remaining unfrozen in partially frozen soils will affect strength development because it is fairly obvious that more unfrozen water means less pore ice present in the soil. Under load application, strength development is thought to depend upon not only shear strength of ice and soil particles, but also on the adhesion of ice to soil particles. Because unfrozen water and the concepts proposed for the existence of unfrozen water suggest that a film of water separates individual soil particles from the pore ice or ice phase, it follows that adhesion between ice and soil particles depends upon the properties of this unfrozen water. No results are available however to allow for any speculation on the properties of the unfrozen water.

Not only temperature, soil type, confinement, and water content affect frozen soil strength, the freezing or thawing history of the frozen soil mass must also be considered. It may be argued that present available test techniques do not measure or yield the necessary properties for interpretation of inherent parameters. However these are the only ones available at present.

CONCLUSIONS

The present stage of knowledge of the mechanics of frozen soil leaves much to be desired. While studies and reports are available detailing strength of frozen soil as a function of soil type, temperature and a few other factors, a clear understanding of the mechanism involved therein is lacking. Much remains to be done and further study is presently underway to determine the more fundamental parameters thought to be important in the consideration of frozen soils.

ACKNOWLEDGMENT

The research work reported in this paper was performed under a continuing research grant from the Defence Research Board, in the form of a Grant-in-Aid of Research to the author (Grant No. 9511-28 [G. and C.]). The Grant was first given in April 1958 with subsequent yearly renewals.

The author wishes to acknowledge his indebtedness to the Defence Research Board for its support and interest without which this research study would not have been possible.

REFERENCES

1. ACFEL Investigation of Description, Classification and Strength Properties of Frozen Soils. SIPRE Report No. 8, 1951.
2. Lambe, T.W. Compacted Clay - Symposium, Trans. ASCE. Vol. 125, 1960.

3. Leonards, G.A. and Andersland, O.B. The Clay-Water System and Shearing Resistance of Clays, ASCE Shear Conference, 1960.
4. Rosenquist, I. Th. Physico-Chemical Properties of Soils. Journal ASCE, Soil Mech. and Founds. Vol. B5, No. SM2, 1959.
5. Schmertmann, J.H. and Hall, J.R. Cohesion after Non-Hydrostatic Consolidation. Journal ASCE, Soil Mech. and Founds. Vol. 87, SM4, 1961.
6. Schofield, R.K. The pF of the Water in Soil. Trans. 3rd Int. Congr. on Soil Science. 1935.
7. Warkentin, B.P. Volume change in Clay Soils - Shrinking and Swelling. Soil Mech. Series No. 2, McGill University. 1962.
8. Williams, P.J. Specific Heat and Unfrozen Water Content in Frozen Soils. Paper for First Canadian Conf. on Permafrost, 1962.
9. Yong, R. Some Physical Characteristics of Frozen Soil. Report DR 123, Directorate of Phys. Res. DRB. 1958.
10. ——— Some Shearing Characteristics of Frozen Soil - Part 1. Report No. D.Phys.R. (G) Misc. G. 2. DRB. 1960.
11. ——— Soil Freezing and Permafrost. Soil Mech. Series No. 1, McGill University. 1962.

******

Discussion

L. W. Gold wanted to know the time of failure of the samples tested. The author stated that failure occurred within 5 minutes. There is no influence by creep if the rate of application of the load is greater than 400 lbs/sq.in/minute.

T. Lloyd enquired whether tests have been made with soil samples containing organic material and with frozen soils containing salt water. Such soils might be encountered particularly in construction sites near the sea. The author replied that the answer to both questions is negative. In the case of soils containing salt there is a problem with the concentration of electrolytes.

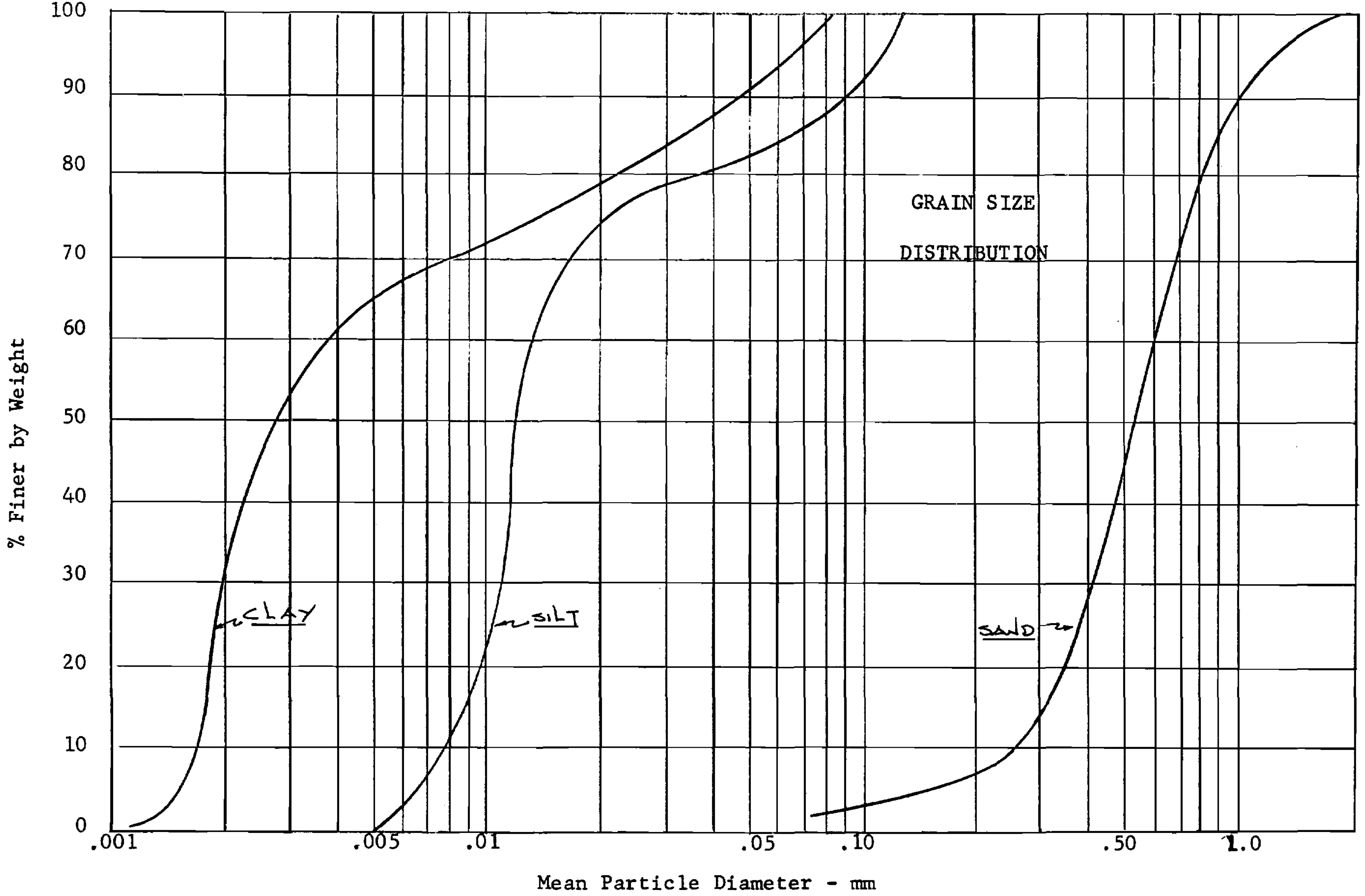

100
90
80
70
60
50
40
30
20
10
0
% Finer by Weight
.001
.005
.01
.05
.10
.50
1.0
Mean Particle Diameter - mm
GRAIN SIZE
DISTRIBUTION
CLAY
SILT
SAND

Figure 1

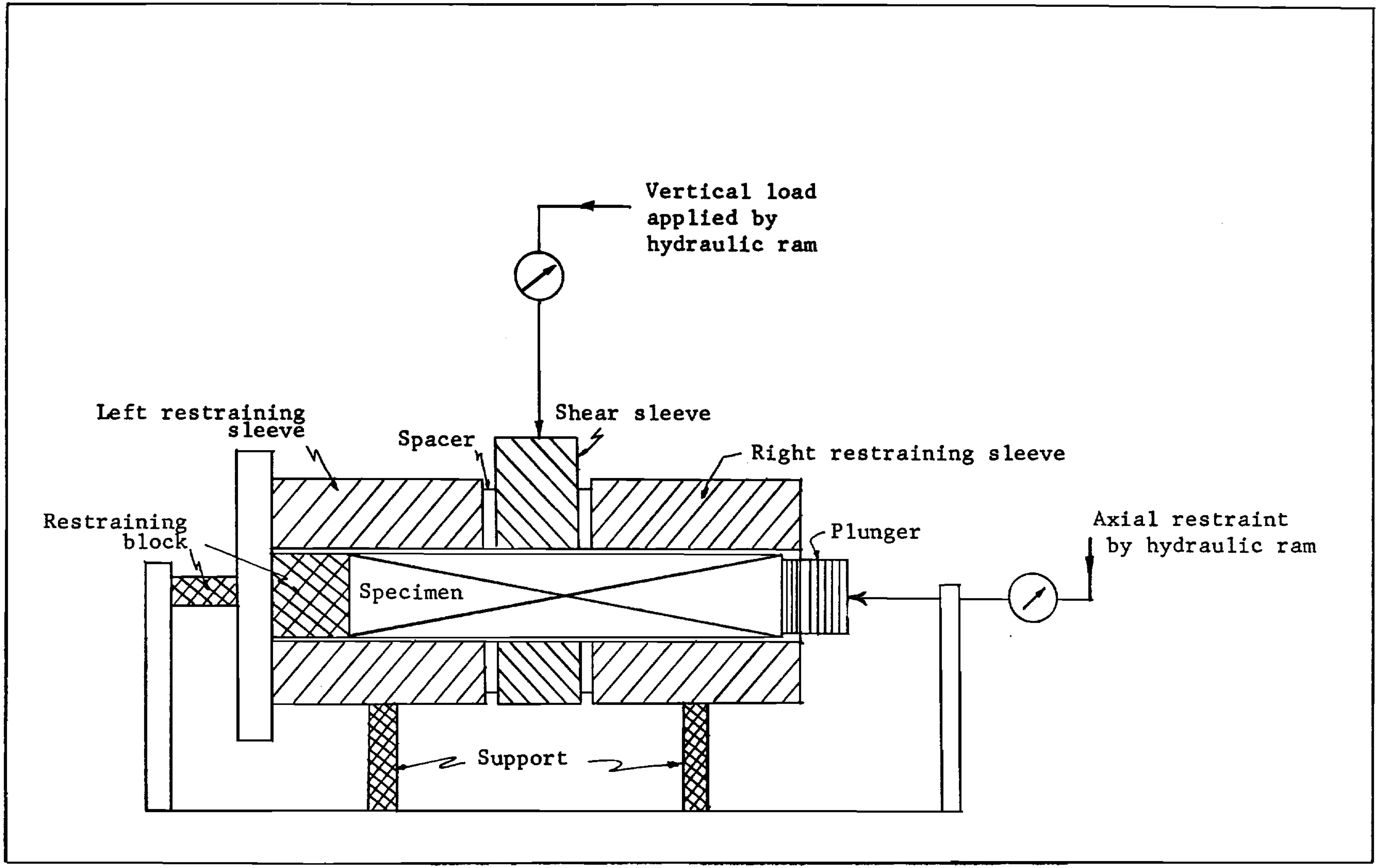


Figure 2

Schematic Picture of Double Shear Test

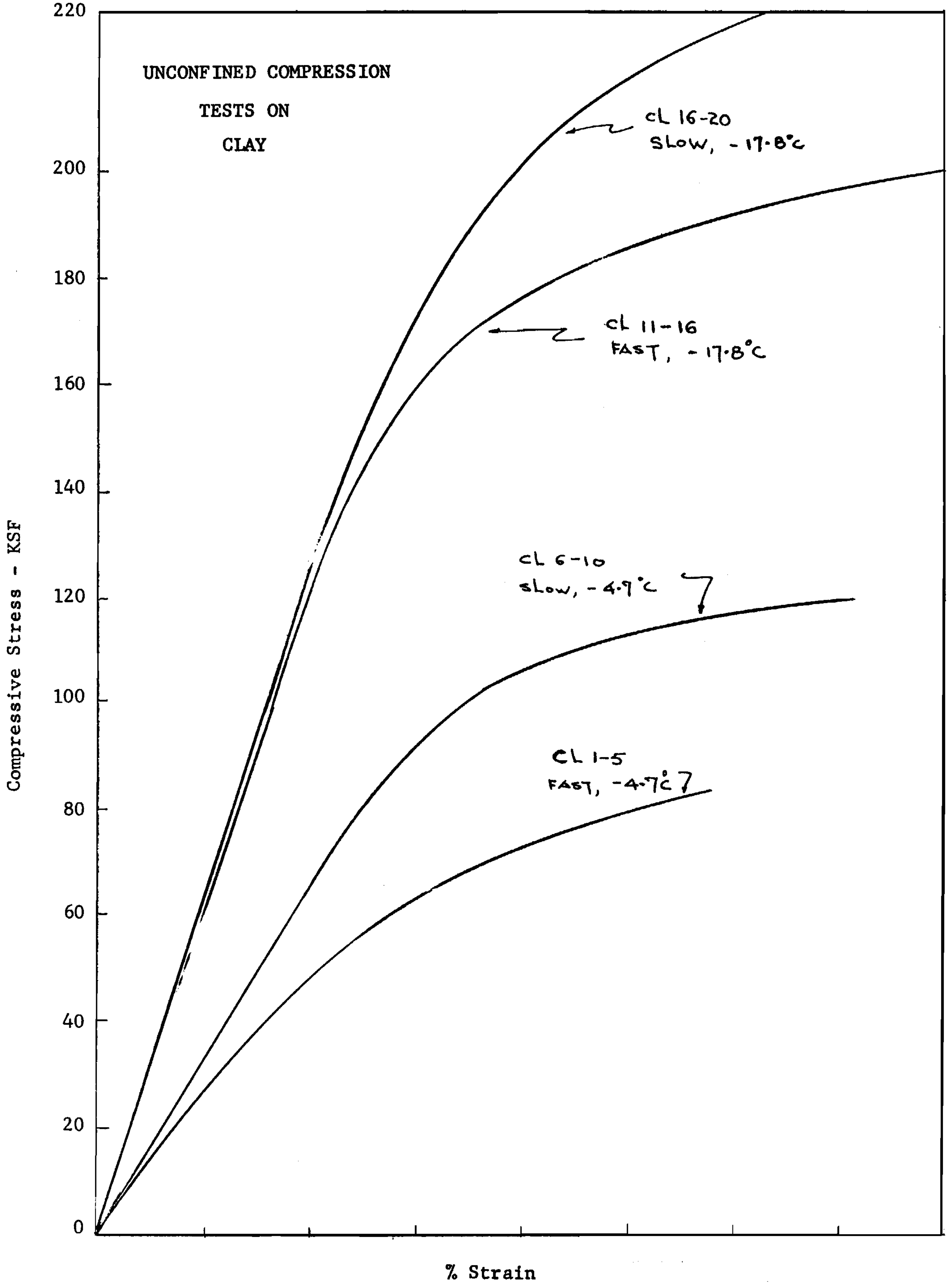

UNCONFINED COMPRESSION
TESTS ON
CLAY
Compressive Stress - KSF
% Strain
0
20
40
60
80
100
120
140
160
180
200
220
cL 16-20
SLOW, -17.8°c
cL 11-16
FAST, -17.8°C
cL 6-10
sLow, -4.9°C
CL 1-5
FAST, -4.7°C

Figure 3

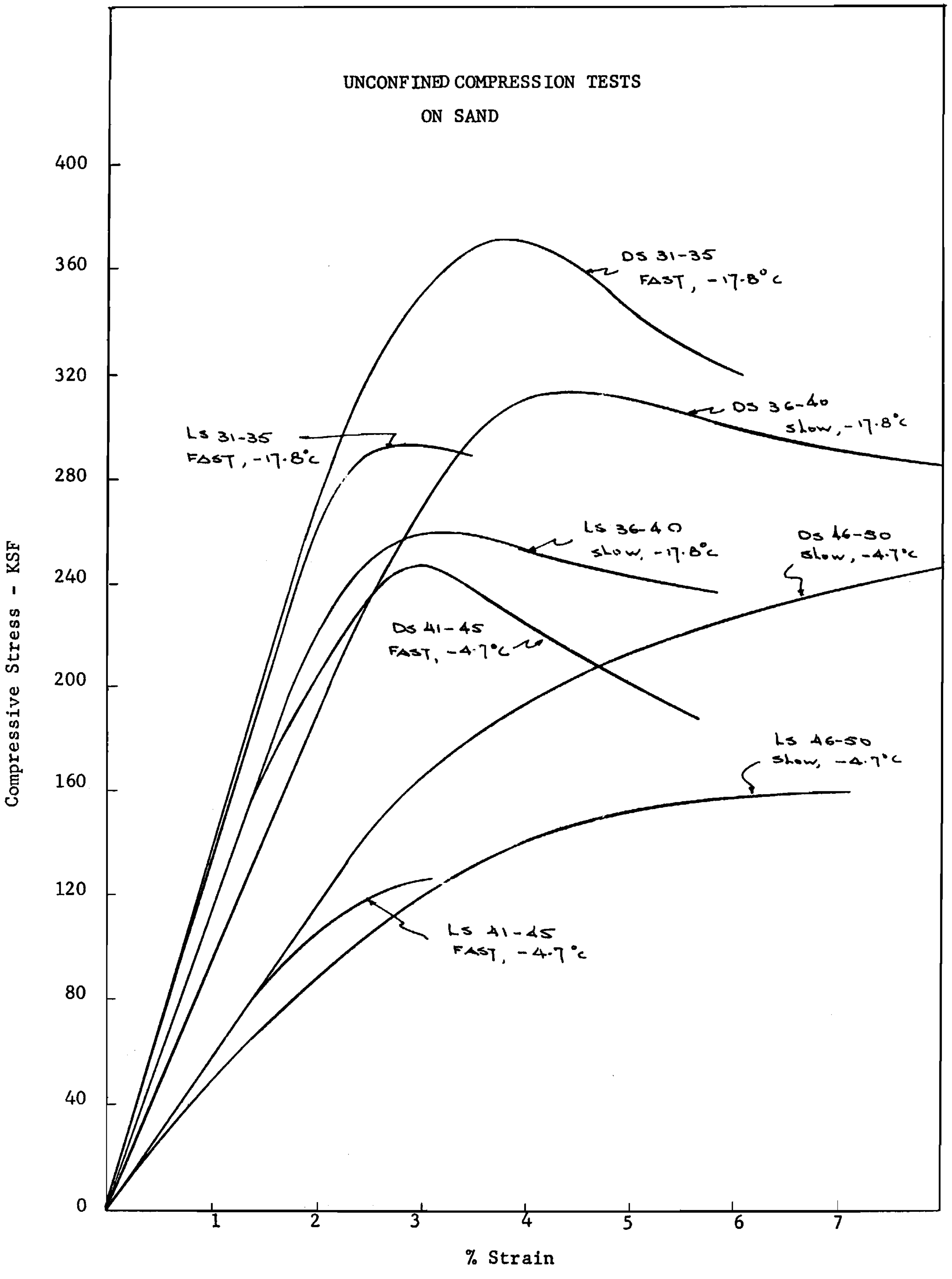

UNCONFINED COMPRESSION TESTS
ON SAND
Compressive Stress - KSF
% Strain
0
40
80
120
160
200
240
280
320
360
400
1
2
3
4
5
6
7
DS 31-35
FAST, -17.8°c
DS 36-40
slow, -17.8°c
LS 31-35
FAST, -17.8°c
LS 36-40
slow, -17.8°c
DS 46-50
slow, -4.7°c
DS 41-45
FAST, -4.7°c
LS 46-50
slow, -4.7°c
LS 41-45
FAST, -4.7°c

Figure 4

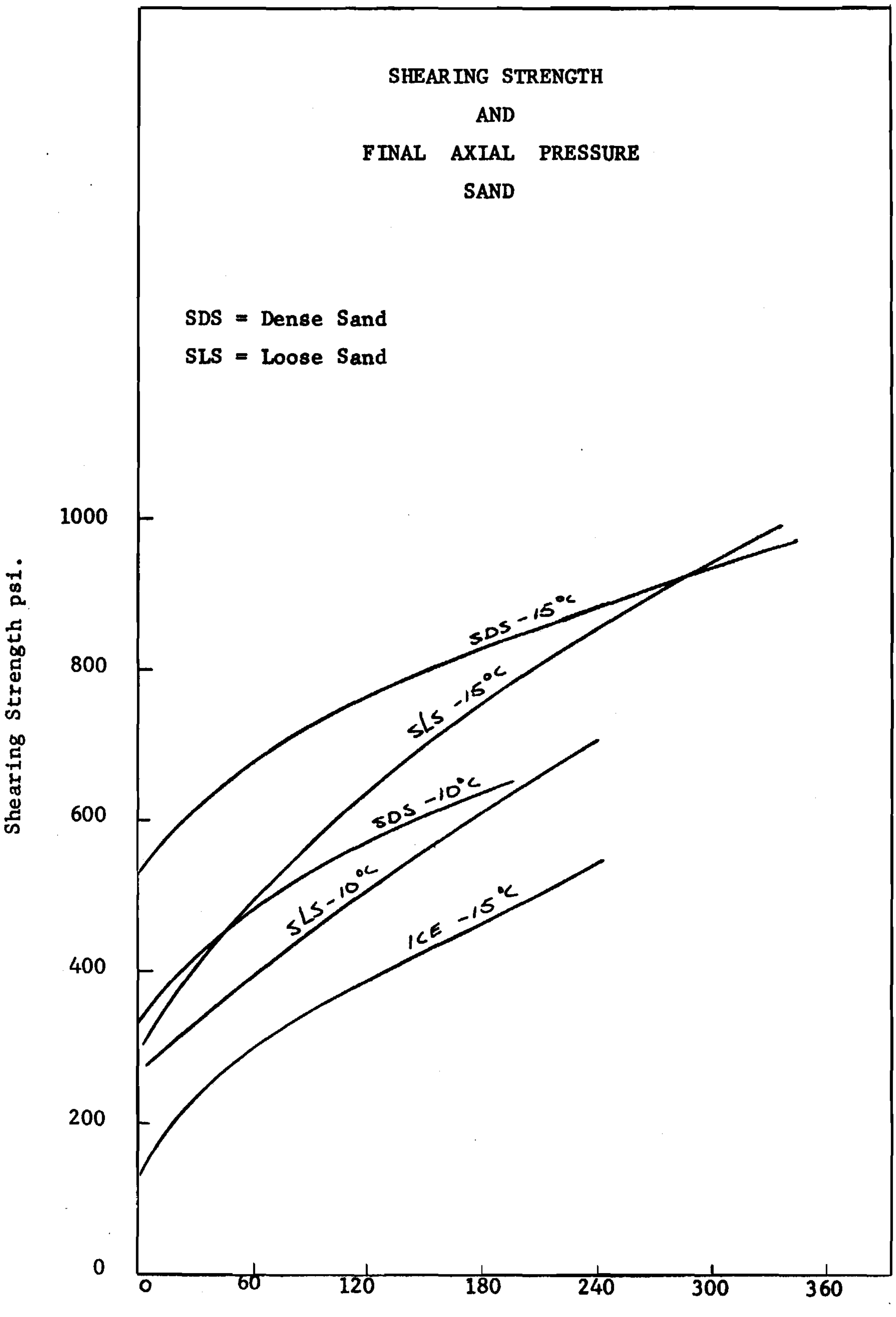

SHEARING STRENGTH
AND
FINAL AXIAL PRESSURE
SAND
SDS = Dense Sand
SLS = Loose Sand
SDS -15°C
SLS -15°C
SDS -10°C
SLS-10°C
ICE -15°C
Shearing Strength psi.
0
200
400
600
800
1000
0
60
120
180
240
300
360
Final Axial Pressure - psi,

Figure 5

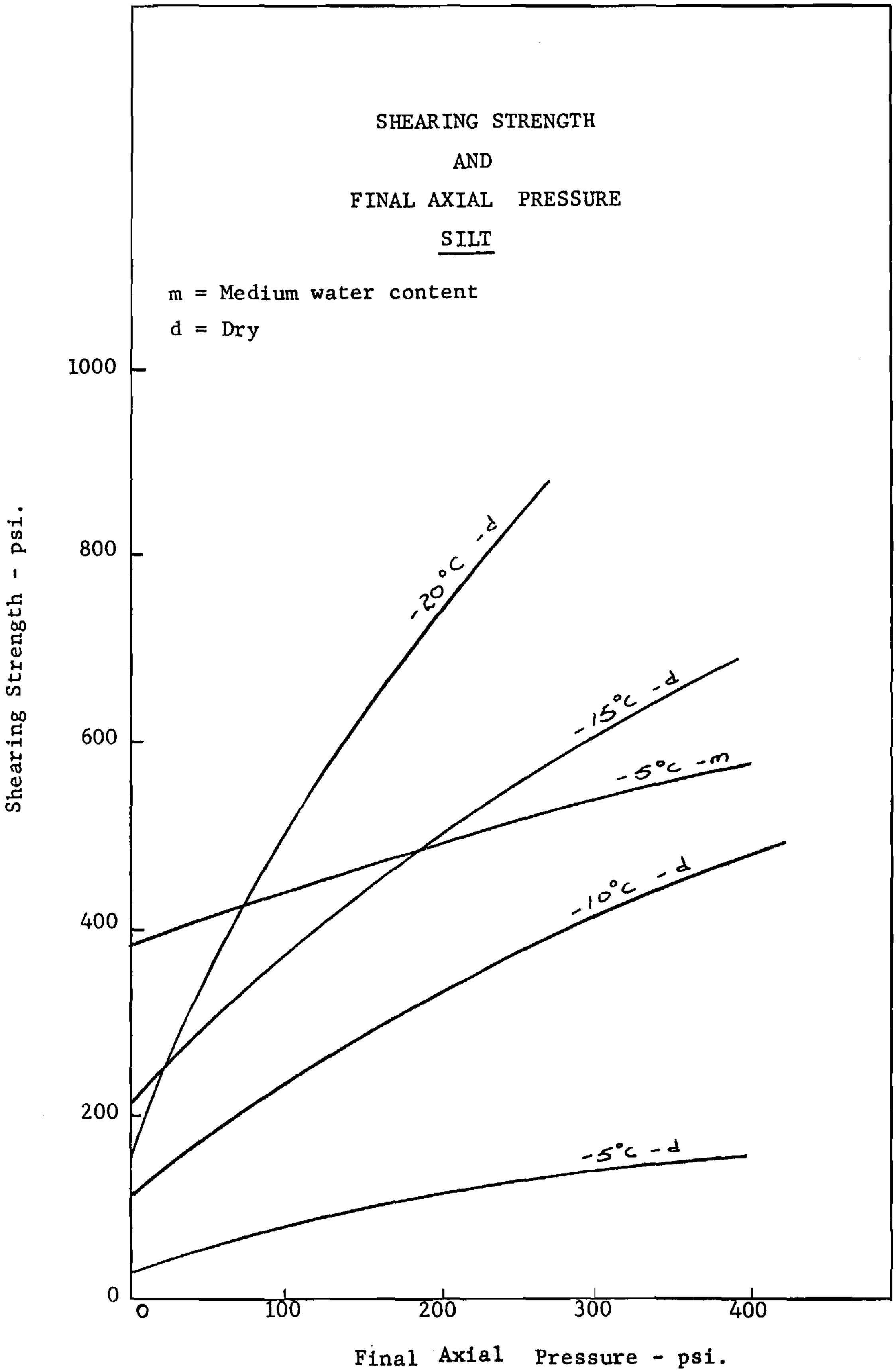

SHEARING STRENGTH
AND
FINAL AXIAL PRESSURE
SILT
m = Medium water content
d = Dry
Shearing Strength - psi.
0
200
400
600
800
1000
0
100
200
300
400
Final Axial Pressure - psi.
-20°C -d
-15°C -d
-5°C -m
-10°C -d
-5°C -d

Figure 6

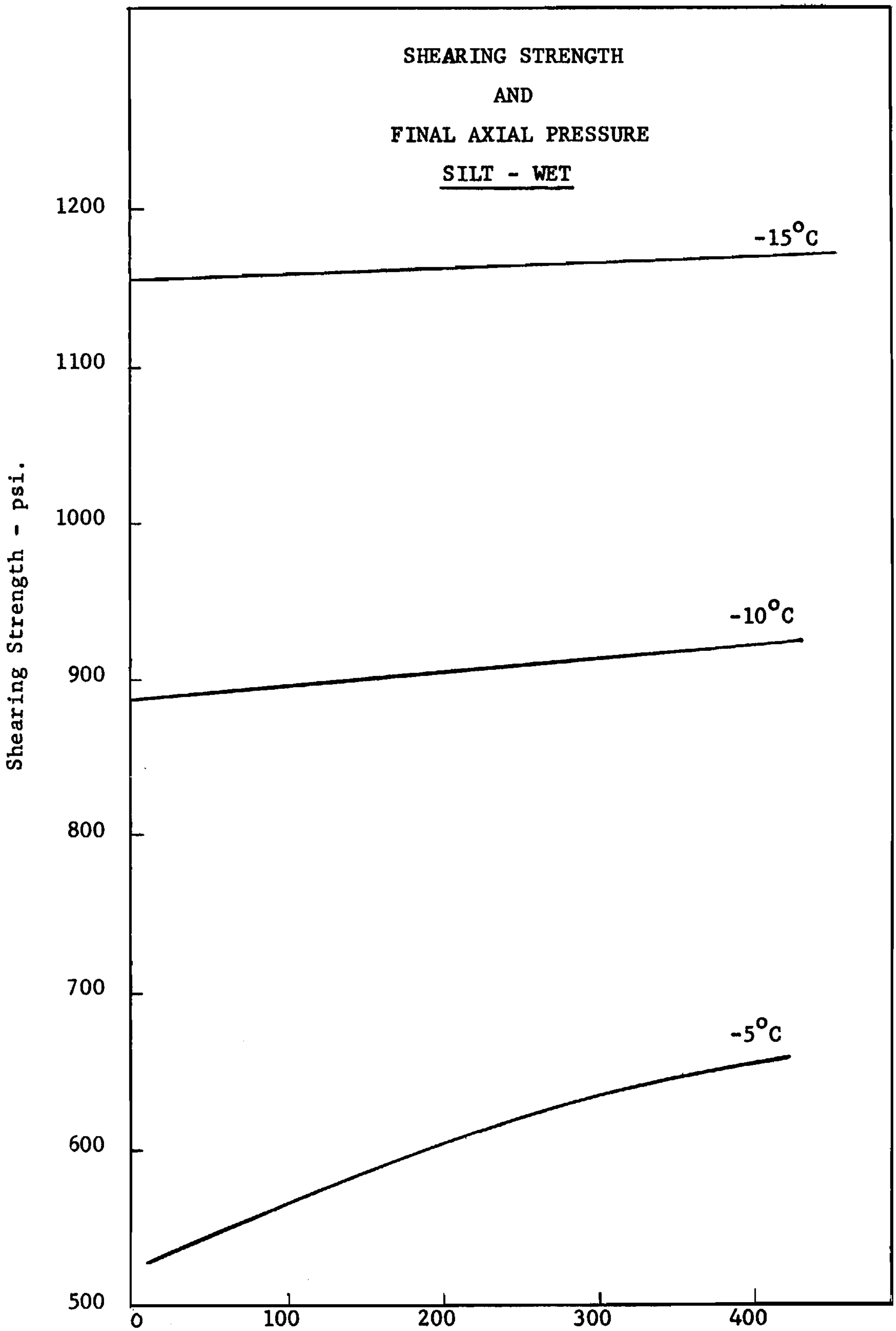

SHEARING STRENGTH
AND
FINAL AXIAL PRESSURE
SILT - WET
Shearing Strength - psi.
1200
1100
1000
900
800
700
600
500
-15°C
-10°C
-5°C
0
100
200
300
400
Final Axial Pressure - psi

Figure 7

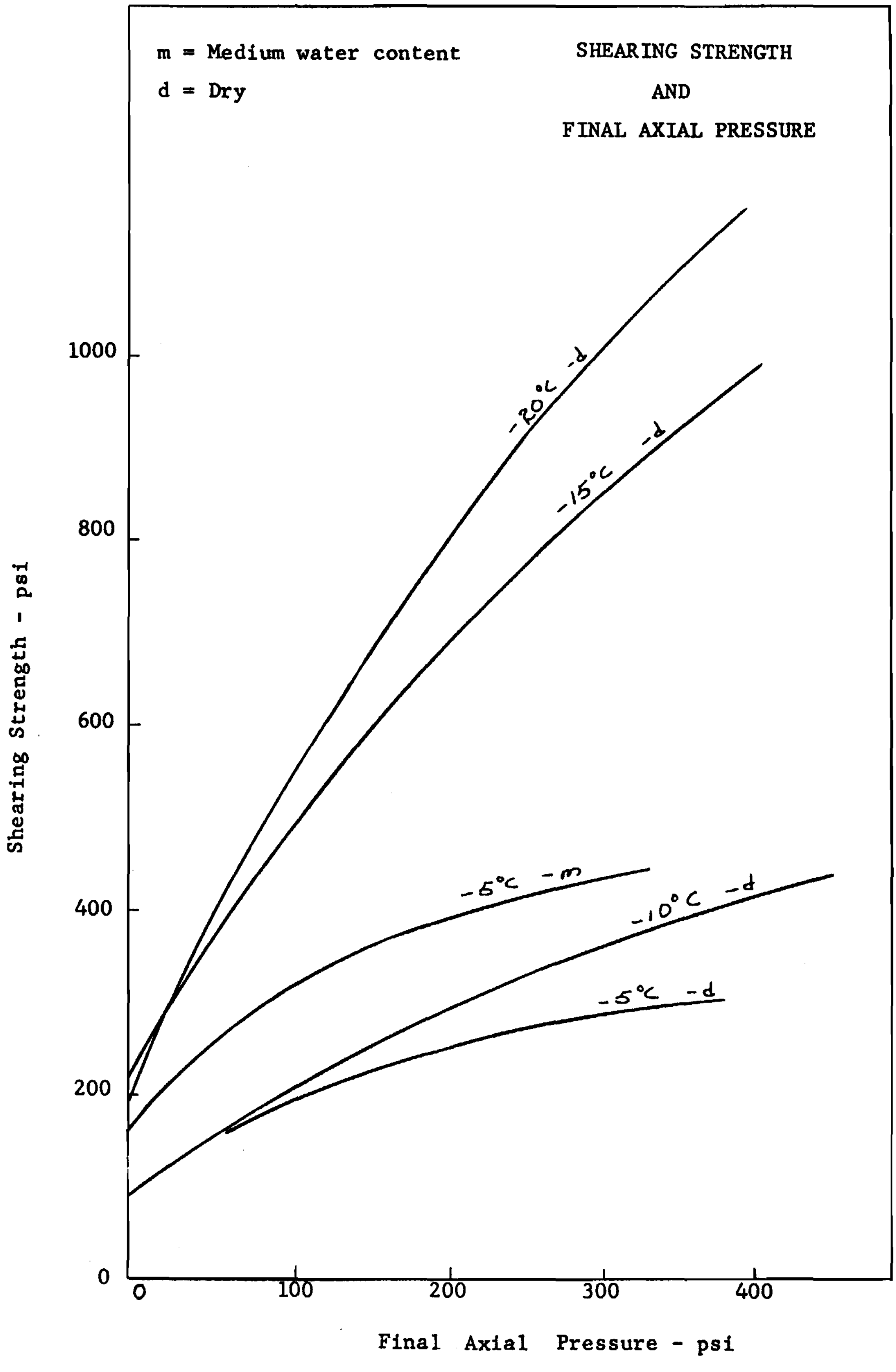

m = Medium water content
d = Dry
SHEARING STRENGTH
AND
FINAL AXIAL PRESSURE
Shearing Strength - psi
0
200
400
600
800
1000
0
100
200
300
400
Final Axial Pressure - psi
-20°C -d
-15°C -d
-5°C -m
-10°C -d
-5°C -d

Figure 8

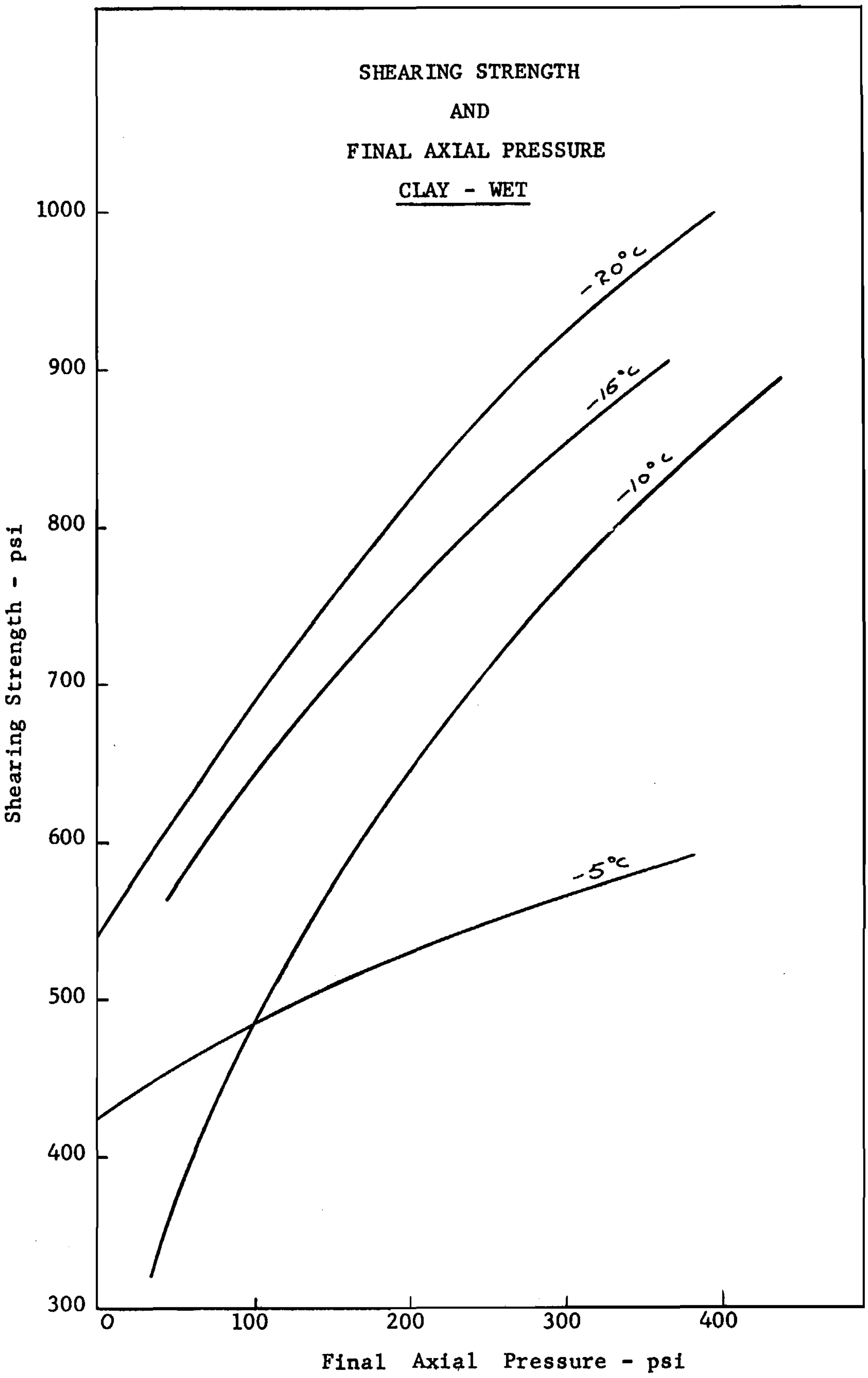

SHEARING STRENGTH
AND
FINAL AXIAL PRESSURE
CLAY - WET
-20°c
-16°c
-10°c
-5°c
Shearing Strength - psi
1000
900
800
700
600
500
400
300
0
100
200
300
400
Final Axial Pressure - psi

Figure 9

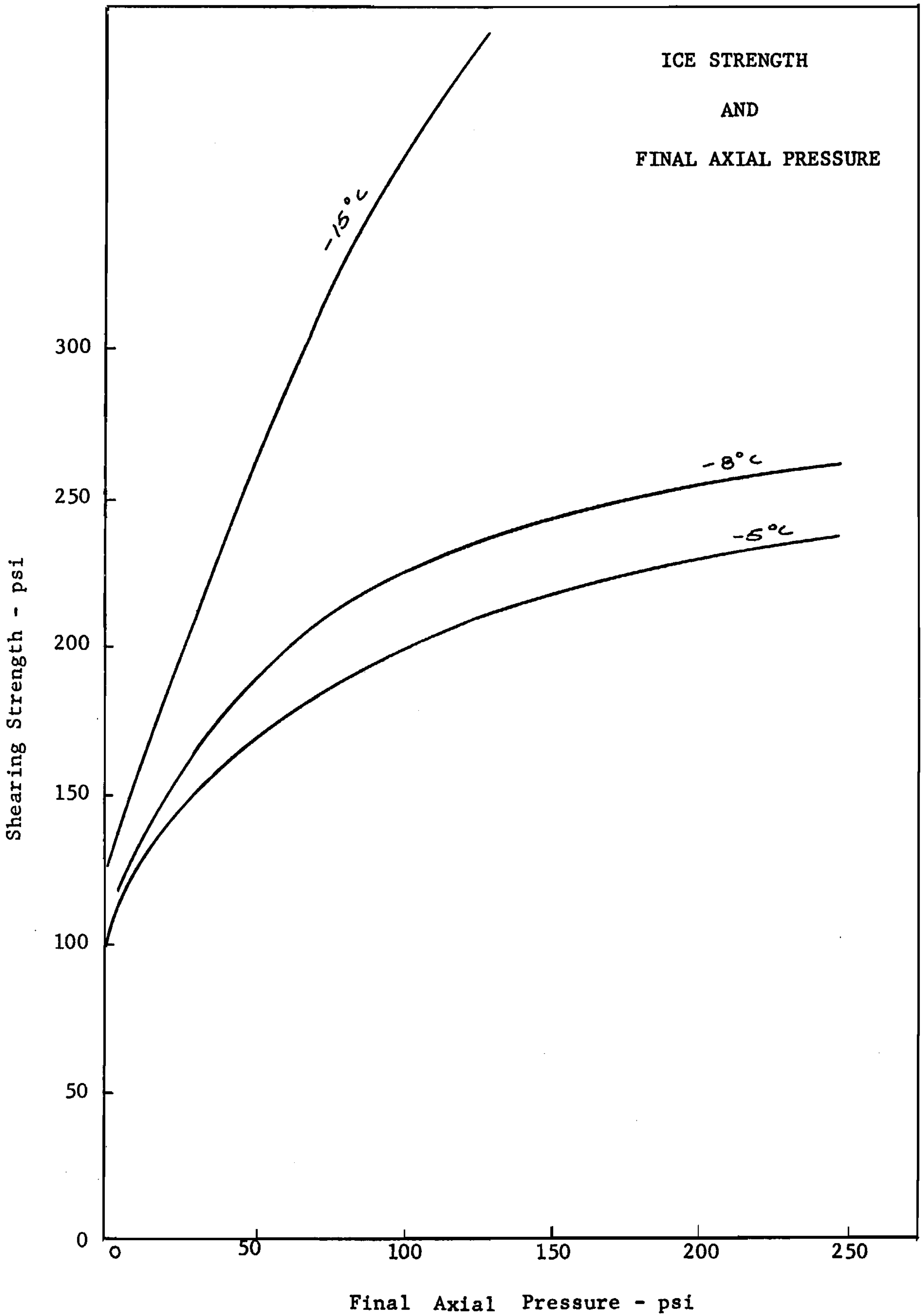

ICE STRENGTH
AND
FINAL AXIAL PRESSURE
-15°C
-8°C
-5°C
Shearing Strength - psi
300
250
200
150
100
50
0
0
50
100
150
200
250
Final Axial Pressure - psi

Figure 10

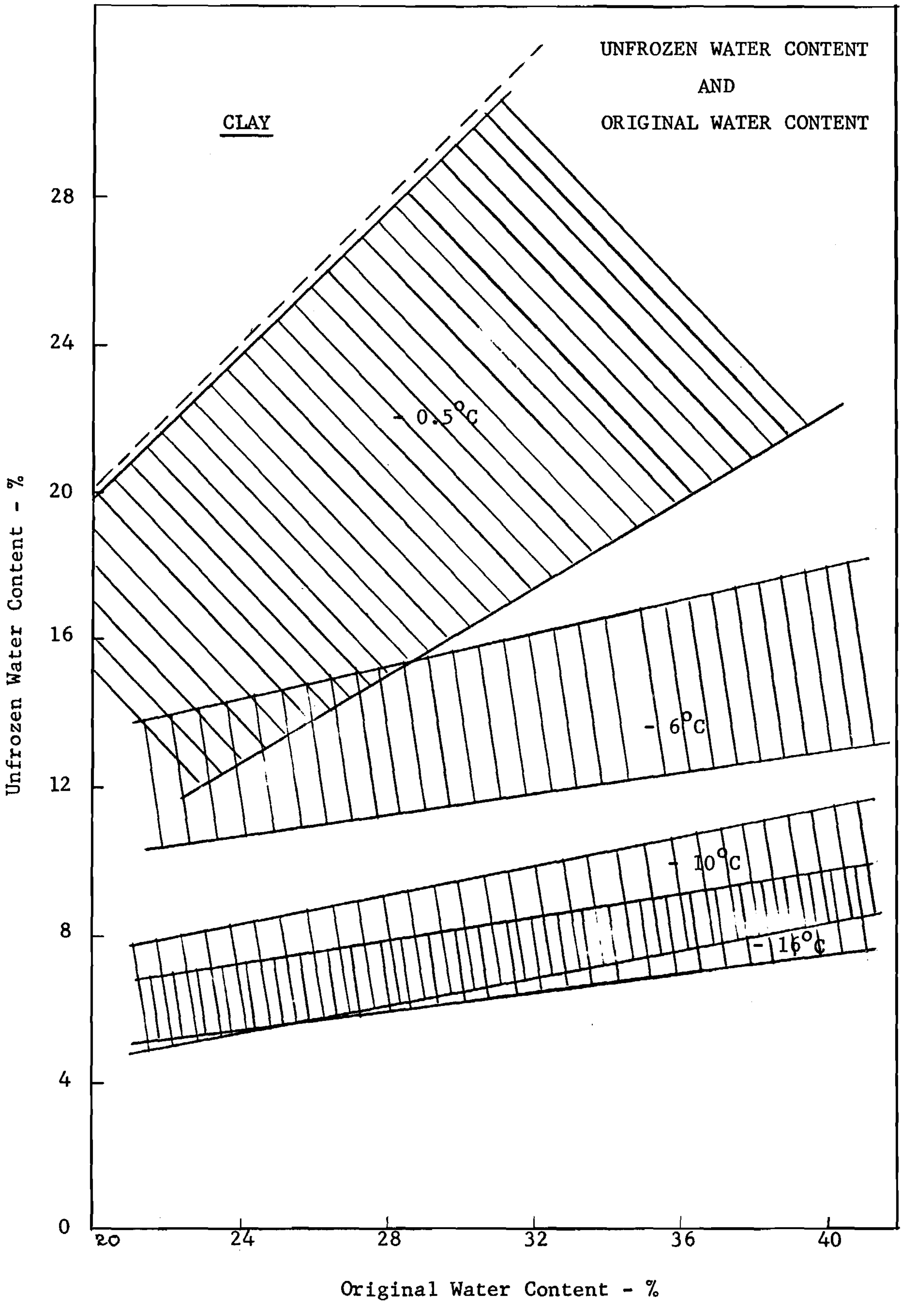

UNFROZEN WATER CONTENT
AND
ORIGINAL WATER CONTENT
CLAY
- 0.5°C
- 6°C
- 10°C
- 16°C
Unfrozen Water Content - %
0
4
8
12
16
20
24
28
20
24
28
32
36
40
Original Water Content - %

Figure 11

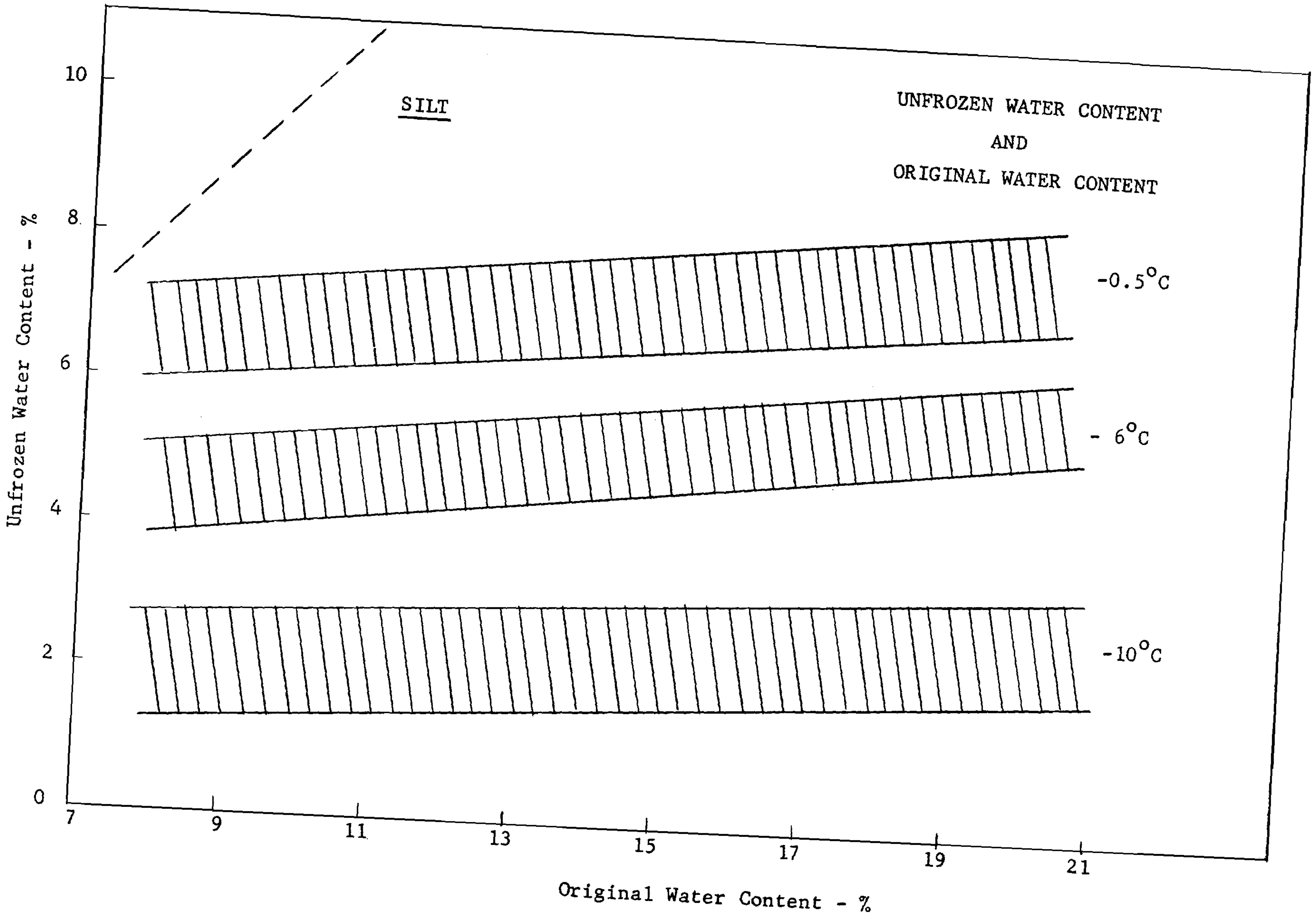

SILT
UNFROZEN WATER CONTENT
AND
ORIGINAL WATER CONTENT
-0.5°C
- 6°C
-10°C
Unfrozen Water Content - %
0
2
4
6
8
10
7
9
11
13
15
17
19
21
Original Water Content - %

Figure 12

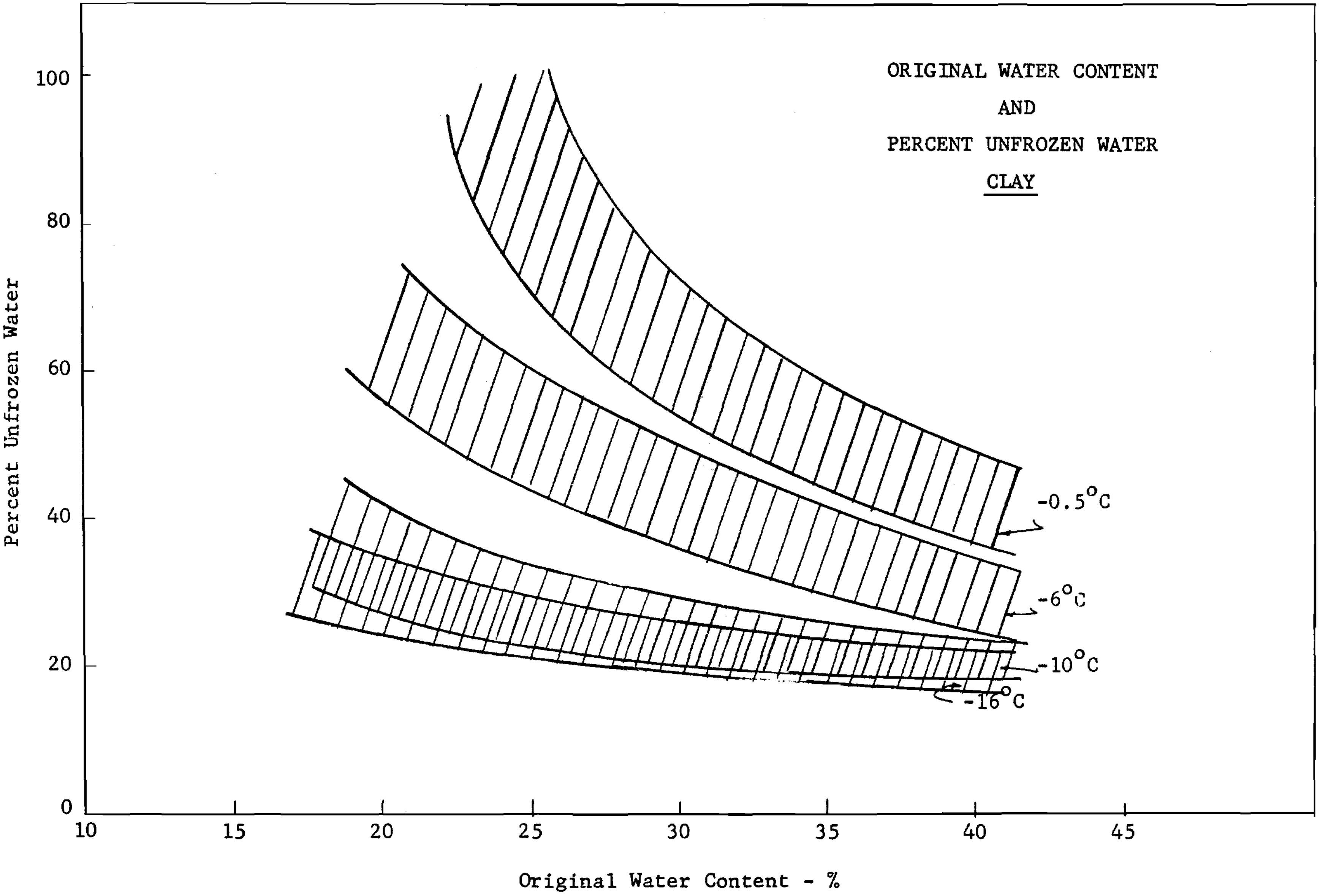

ORIGINAL WATER CONTENT
AND
PERCENT UNFROZEN WATER
CLAY
Percent Unfrozen Water
100
80
60
40
20
0
10
15
20
25
30
35
40
45
-0.5°C
-6°C
-10°C
-16°C
Original Water Content - %

Figure 13

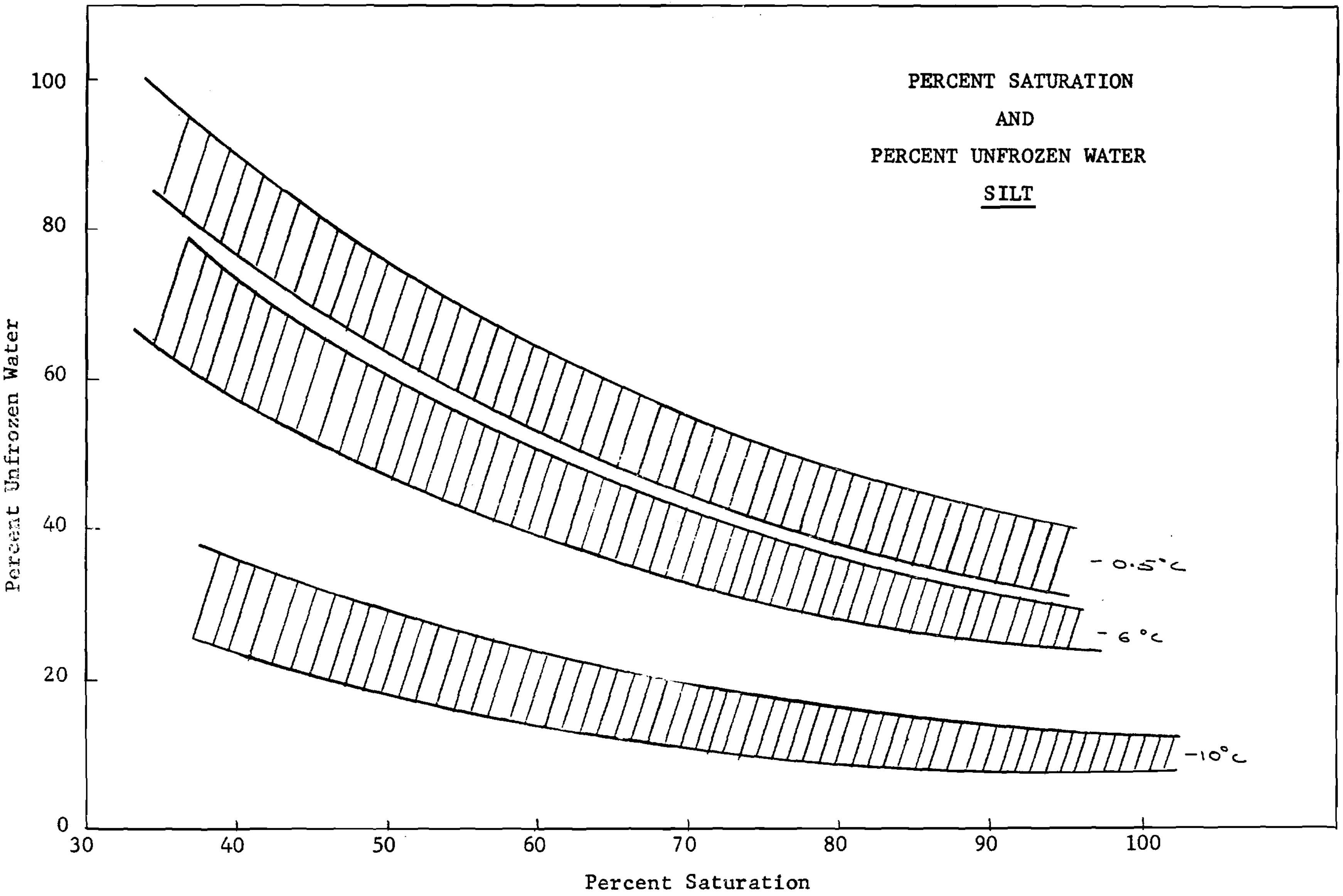

PERCENT SATURATION
AND
PERCENT UNFROZEN WATER
SILT
Percent Unfrozen Water
0
20
40
60
80
100
Percent Saturation
30
40
50
60
70
80
90
100
- 0.5°C
- 6 °C
-10°C

Figure 14

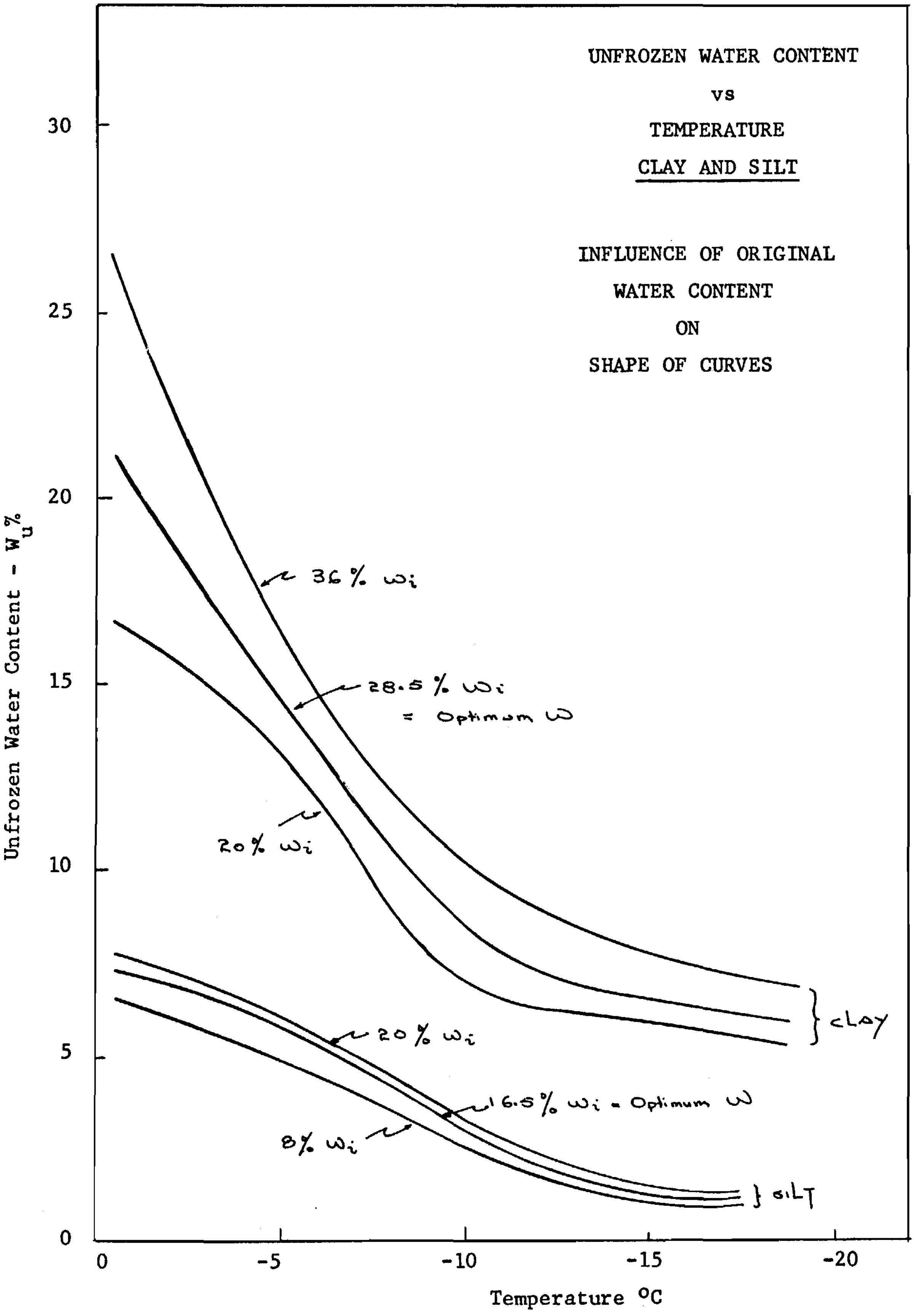

UNFROZEN WATER CONTENT
vs
TEMPERATURE
CLAY AND SILT
INFLUENCE OF ORIGINAL
WATER CONTENT
ON
SHAPE OF CURVES
Unfrozen Water Content - W_u%
30
25
20
15
10
5
0
0
-5
-10
-15
-20
Temperature °C
36% ω_i
28.5% ω_i
= Optimum ω
20% ω_i
clay
20% ω_i
16.5% ω_i = Optimum ω
8% ω_i
silt

Figure 15

II. 3. SPECIFIC HEATS AND UNFROZEN WATER CONTENT OF FROZEN SOILS

P. J. Williams

It was observed many years ago that water in soils did not freeze until the temperature was lowered appreciably below 0°C (11). Subsequent experiments demonstrated that in natural soils there is no single freezing point but that the water freezes progressively as the temperature falls (1, 3). In fine-grained soils one-third of the water may remain unfrozen at several degrees below 0°C (8, 9). The stresses still existing in the soil-water system are generally regarded as the most important cause of this phenomenon.

The changing proportions of frozen and unfrozen water are significant in consideration of the strength and deformation of frozen ground (10, 15), and the freezing and thawing of water in soil at temperatures below 0°C has important effects on its thermal properties. Several soils have recently been studied by calorimetry as part of an investigation by the author of the unfrozen water content. The experimental observations and calculation of unfrozen water content from them are briefly described and discussed in this paper. It will be shown that the application of the results to field problems requires consideration of the factors influencing the freezing of water in soil.

CALORIMETRIC INVESTIGATIONS

A calorimeter has been constructed which permits measurement of the amount of heat added to or removed from a soil sample to raise or lower its temperature by a given amount. Three thermocouples inserted in the sample measure its temperature, which is continuously recorded. Temperature differences within the sample are normally less than 1/10°C.

During the warming of a sample, a measured heat input is supplied electrically by a coil wound around the holder containing the sample (Fig. 1). It is necessary that there be no significant exchange of heat with the soil sample other than that arising from the heating coil. To achieve this, the sample holder is suspended inside a brass container maintained at a temperature almost equal to that of the sample holder. There is thus no significant temperature gradient and negligible exchange of heat between them. The temperature of the brass container is regulated by a heater in the refrigerated ethylene glycol surrounding it. This heater is controlled automatically by a mechanism which operates when a small temperature difference occurs between the brass container and the surface of the sample holder.

From measured values of the time taken for the temperature of the soil to rise a given amount and rate of heat input to the sample, the quantity of heat supplied to cause the temperature rise is calculated. In the thawing curves of Figures 2 to 4 inclusive, results of this type are shown, as the specific heat of the soil (i.e. the amount of heat in calories required to raise the temperature of one gram of soil by 1 °C) for various negative temperatures.

The specific heats during freezing are obtained in a similar way (Figures 2 to 4) except that the brass container is held at a temperature lower by a constant amount than that of the sample holder. The heating coil on the sample is not operated. There is then a steady extraction of heat from the holder, the magnitude of which is determined by prior calibration.

Were all the water to freeze at 0 °C, one would expect that values of the specific heat below 0 °C would be roughly constant and of much the same magnitude as those above 0 °C. In fact, the latent heat released or absorbed as water is progressively frozen or thawed results in specific heats many times as great. For a given sample, the specific heats determined during cooling differ somewhat from those determined during freezing. Not only is the value of specific heat for a given temperature different in the two cases, but for one soil type (Figure 4), the values obtained for the case of cooling repeatedly showed an unexpected rise in the region of -1.1 °C.

Instrumental Accuracy

The accuracy of the curves shown in Figures 2 to 4 inclusive, depends substantially on the quality of the temperature measuring and control equipment associated with the calorimeter. Calibration tests indicate that the specific heat values represented by the smoothed graph are correct to within a few per cent. The periodic fluctuations of points at lower temperatures are probably due to experimental error. The conspicuous peak at -1.1 °C in Figure 4, exceeds by many times the value that would be expected should the curve in fact be smooth, and it cannot be regarded as an experimental error. On the other hand, the variations on the thawing curve at about -0.5 °C represent deviations which, regarded as a percentage, are no greater than those appearing for the lower specific heats at lower temperatures.

CALCULATION OF THE PROPORTION OF ICE AND UNFROZEN WATER IN THE SOIL

The calorimeter results can be used to calculate the ice formation taking place in the soil. By deducting amounts corresponding to the specific heat of the mineral components, ice and water present, from the heat involved in a given temperature change, a value for the heat involved in freezing or thawing water during that temperature change is obtained. Assuming the latent heat of freezing to have the same value as that of free water, a figure is obtained for the amount of ice formed or melted. By a process of summation between the temperature of initial freezing, or completed thawing, and temperatures below them, curves of the type shown (Figures 5 to 7) are obtained.

The finer-grained soils show higher unfrozen water contents. For each soil there is a marked hysteresis, such that the amount of unfrozen water present at a given negative temperature will depend on whether the soil is undergoing warming or cooling. Furthermore, during thawing the amount is also dependent on the lowest temperature reached in that freeze-thaw cycle (Figure 9).

Repeated tests on the same sample, and on different samples of the same soil, give results within 3.5% dry weight for the unfrozen moisture content at -4°C. Various rates of cooling were used. The time taken for cooling from -1° to -4°C was varied from 4 hours to 16 hours, and appeared to have no effect on the results (Figure 8). The unfrozen moisture content is shown to be independent of the total moisture content (Figure 9), so long of course, as it is greater than this.

PHYSICAL PROCESSES RESPONSIBLE FOR THESE OBSERVATIONS

The physical processes giving rise to these observations are incompletely understood, and the calorimetric results by themselves provide only limited information. Discussion of the processes is appropriate because they appear likely to have considerable relevance in the practical application of the calorimetric results.

Hypotheses Involving Stresses in Soil Water

When ice and water exist together under a pressure greater than atmospheric, the freezing point is lowered below 0°C. Edlefson and Anderson point out also that if ice at atmospheric pressure is in contact with water at a pressure lower than atmospheric, this too will cause a freezing point depression (6).

That the water in unsaturated soils is not at atmospheric pressure is shown by the fact that water moves into such soils from a source at atmospheric pressure. This state of stress, or so-called "suction", of the water of soils is greater the lower the water content.

Several authors point out that, as ice forms in a soil, the remaining water will be under an increasingly different state of stress to that of free water at atmospheric pressure. Accordingly, to freeze such water requires progressively lower temperatures.

Different theories have been put forward as to the nature of the stresses in soil water that might be responsible for the lowering of the freezing point. Winterkorn (16), Jung (9) and Edlefsen and Anderson (6), have proposed that the adsorption forces of the soil particles acting on the adjacent water molecules result in pressures in the soil water that are higher than atmospheric. When these pressures exist at an ice/water interface, there will be a lowering of the freezing point. As the particle surface is approached, the pressure due to the adsorption forces increases, and the freezing point becomes lower.

In contrast, others (12) maintain that most of the water in unsaturated soils is because of capillary effects, under tension (subatmospheric pressure, or negative stress). This also can result in a lowered freezing point provided any ice present is under atmospheric or higher pressures (6) (this is also implicit in the equation used by Schofield (14), and Croney and Coleman (4)).

It is not known to what extent different pressures can occur in adjacent ice and water phases in a soil. Nor is it appropriate in this paper to discuss the relative importance in the soil water of stresses, greater, or less, than atmospheric pressure. Either of the situations outlined above can provide a reasonable explanation of the "suction" properties of soils. By using experimentally observed values of soil "suction" for particular moisture contents, values of freezing point depression may be calculated for these moisture contents (6, 14).[1] These freezing point values can then be compared with the temperatures found to give equal contents of unfrozen water in frozen soils. Depending upon which of the two situations discussed is accepted, somewhat different values are obtained for the freezing point depression. With the limited information at present available, both appear reasonable for certain ranges of moisture content. Investigations are at present being carried out to determine more precisely this relation between suction characteristics of soils and the amount of unfrozen water present at various negative temperatures.

---

[1] In this paper a typographical error has apparently occurred in the equation which should read:-

$H = \frac{(Lj)}{(Tg)} \times t$ where H = cm. of water; T = absol. temp.
Lj = latent heat of fusion; t = freezing point depression.

From the present experimental observations, and the observations and discussions of others, it can be concluded that the stresses in the soil in the pore water and solid phases have considerable influence on the course of freezing.

Depression of Freezing Point by Dissolved Salts

Bouyoucos (2) and others believed that the soil water contained sufficient salts such that, as freezing progressed, the concentration would rise sufficiently (because the salts are substantially excluded from the ice) to give lowered freezing temperatures of the magnitude observed. In fact, as pointed out by Edlefsen and Anderson, the salt concentration is far too low for this to be so in most soils. The soil solution extracted from the Leda clay at about 30% moisture content was found to freeze at approximately -0.1°C. When all but 5% moisture content is frozen, the depression of the freezing point on this account will be approximately 0.6°C.

Value Ascribed to the Latent Heat of Freezing

In calculating the amounts of unfrozen water, a value of 79.68 calories/grm was adopted for the latent heat of freezing. This is not strictly correct for freezing occurring below 0°C. Figures are available for the latent heat at freezing below 0°C occurring as the result of a pressure applied equally to both the ice and water (5). Were these figures used, the calculated values of unfrozen moisture content at, for example, -5°C might differ by about 1/2% dry weight from those shown. Values are not known for situations where the pressures on the ice and water phases might differ, but such values are probably of similar magnitude.

When water is added to oven dried soils, measurable quantities of heat are liberated. This "heat of wetting" results, at least in part, from the adsorption of water on to soil particles. Such soil water, from which heat has been lost, might have a substantially lowered latent heat of freezing (7, 13). The heats of wetting have been determined (Figure 10) for the soils shown in Figure 5. The temperature rise occurring when a weighed quantity of the soil was mixed with a greater quantity of water was observed. For samples in which some moisture was already present, the heat liberated was much less than for oven dried soils (Figure 10). Already at quite low moisture contents, the addition of further water does not result in significant heat of wetting. It is reasonable to assume that the water from which significant heat is lost, because it includes the most strongly adsorbed, would only freeze at the lowest temperatures. When Figures 4 to 6 inclusive are compared with Figure 10, it is seen that the quantity of water remaining unfrozen, even at the lowest temperatures recorded, probably includes all the water that is associated with the heat of wetting. The question of latent heat of such water does not therefore arise.

VALIDITY OF THE CALORIMETRIC RESULTS IN FIELD PROBLEMS

The calorimetric observations do not represent exactly the thermal properties of the soil under natural conditions. Especially where the overburden is thick, the stresses within the soil will be different from those in the calorimeter sample. The stresses in both ice and water phases may give rise to corresponding differences in the proportions of freezing and unfrozen water. The specific heats during freezing will often be apparently increased by migration of water and the associated ice lens growth. For many practical problems, however, involving near surface conditions, and where in any case the temperature and soil conditions are not very precisely defined, a useful qualitative evaluation may be obtained from the calorimetric observations.

GENERAL SUMMARY

The unfrozen water of frozen soils has been shown to be a significant and quite complex phenomenon. It is appropriate to summarize those aspects likely to be of general importance.

In most soils the freezing and thawing processes are progressive with the latent heat of freezing being involved through a wide range of temperature. For the sub-zero temperatures occurring in many field situations, a significant proportion of the soil water is unfrozen. At a given negative temperature the amount of unfrozen water present varies considerably with the type of soil, being greater with finer-grained soils. It also depends on whether the soil is freezing or thawing, and in the latter case further depends on the lowest temperature reached during freezing.

In certain field problems the application of the specific heats and unfrozen water contents determined by the calorimetric observations requires consideration of the effects of overburden pressures and moisture supply.

REFERENCES

1. Bouyoucos, G. J. A New Classification of the Soil Moisture. Soil Science, Vol. 9, No. 1, 1921.
2. ——————— Classification and Measurement of the Different Forms of Water in the Soil by means of the Dilatometer Method. Mich. Agric. Coll. Exp. St., Tech. Bull. No. 36, 1917. 48 p.

3. Bouyoucos, G.J. and M.M. McCool. Further Studies on the Freezing Point Lowering of Soils. Mich. Agric. Coll. Exp. St., Tech. Bull. No.31, 1916. 51 p.
4. Croney, D., Coleman, J.D. and Pamela M. Bridge. The Suction of Moisture Held in Soil and Other Porous Materials. Road Research Technical Paper No. 24. Dept. of Scientific and Industrial Research, Harmondsworth, Middlesex. 1952.
5. Dorsey, N.E. Properties of Ordinary Water-Substance. National Bureau of Standards, Washington, D.C.
6. Edlefsen, N.E. and Alfred B.C. Anderson. Thermodynamics of Soil Moisutre. Journ. of Agric. Science, Vol. 15, No. 2, 1943.
7. Grim, R.E. Clay Mineralogy. McGraw-Hill. 1953. 384p.
8. Institut Merzlotovedeniia. Materialy po laboratornym issledovaniiam merzlykh gruntov. Akademiia Nauk SSSR, Izd. Moskva, im. V.A. Obrucheva, Sbornik 1, 2, 3, 1953-57.
9. Jung, E. Weiterer Beitrag zur aggregierenden Einwirkung des Frostes auf den Erdboden. Zeitschr. fur Pflanzenern. Düng. u. Bodenk. A. Wiss. Teil, Bd. 1932. p. 1-20.
10. Lovell, C.W. Temperature Effects on Phase Composition and Strength of Partially-frozen Soil. Highway Research Board, Bull. 168. 1957.
11. Petit, A. Untersuchungen über den Einfluss des Frostes auf die Temperaturverhaltnisse der Boden von verschiedener physikalische Beschaffenheit. Forsch. Agrik. - Phys. LXXII. 1893.
12. Pore Pressure and Suction in Soils. Conf. organized by British National Society of the International Society of Soil Mechanics and Foundation Engineering at the Institution of Civil Engineers, London. 1960.
13. Rosenqvist, I. Th. Investigations in the Clay-Electrolyte Water System. Norwegian Geotechnical Institute, Oslo. Publ. No. 9, 1955. 125 p.
14. Schofield, R.K. The pF of the Water in Soil. International Congress of Soil Science. Third, Vol. 2, 1935. pp. 37-48. Discussion from Vol. 3, 1935. pp. 182-186.
15. Vialov, S.S. Creep and Long-Term Strength of Frozen Soils. Dok. Akad. Nauk SSSR, Vol. 104, No. 6, 1955. pp. 850-853. Translated February 1957, Defence Research Board, Canada, T203 R, 4 p.
16. Winterkorn, H.F. The Condition of Water in Porous Systems. Soil Science, Vol. 56, 1943.

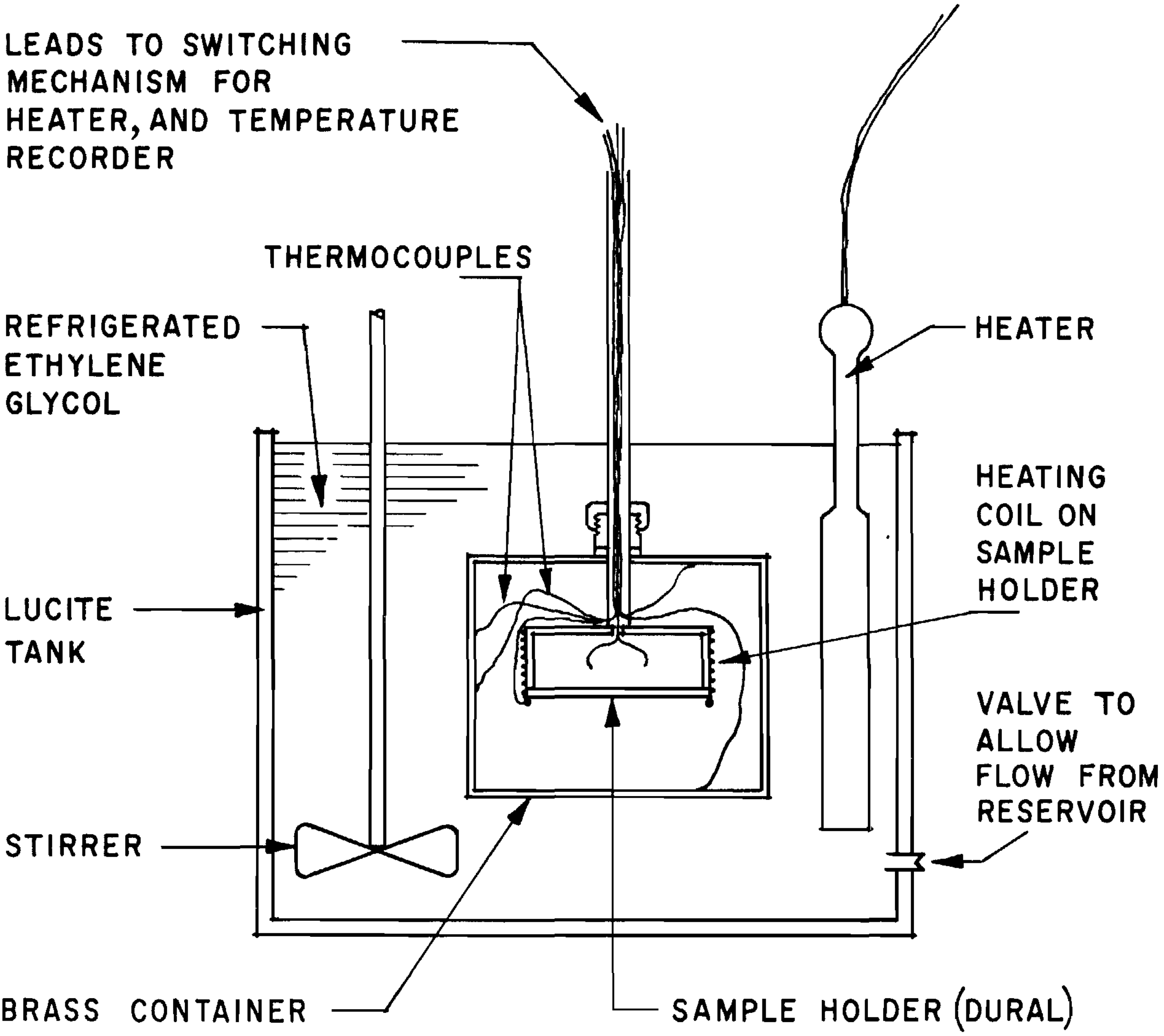
******

Discussion

R. Yong asked, with reference to the unfrozen moisture contents of samples with different total moisture contents, whether the density of such samples differs initially, to which the author replied that it would differ initially. Yong enquired further what mechanisms were considered responsible for the presence of unfrozen water. The author stated his belief that capillarity is responsible at least for the first 1°-2°C below 0°C. Yong's first question might be answered better by saying that although the initial density was changed by changing the initial moisture content, the question was whether the magnitude of the change was significant. Furthermore, as freezing progresses, the unfrozen water content becomes lower and lower, and it is this (decreasing) quantity of water which determines the degree of packing of the particles.

A.E. Corte requested information on the possibility of expressing the results as time/temperature curves for the soils. The author replied that in fact such curves were observed directly with the calorimeter. They were not very meaningful, however, unless the size of the sample was taken into account. Corte said he was interested in more details on supercooling. The author answered that this was shown clearly, the temperature falling slowly to somewhat below 0°C and then rising suddenly to just below 0°C. After that a much slower cooling takes place. Supercooling varied with soil type and with different samples of the same soil. Although hardly statistically significant, it is felt that results of the repeated freezing of the same sample showed less variation than that between freezings of different samples of the same soil.

N.W. Radforth wanted further information as to the "suction properties of the water" which were suggested as the cause of the unfrozen water. The author clarified the question by stating that it would be more precise to say "suction properties of the soil" because the water is regarded as being largely just ordinary water. The suction properties were those often referred to as "moisture potential" or "pF" of the soil. Radforth then asked if the moisture is distributed evenly throughout the sample. The author replied that even in those tests carried out most slowly, the unfrozen moisture content was similar to that found in the other tests. Therefore a state of equilibrium could be assumed to have been reached in the sample. As far as the unfrozen water is concerned, this means the suction properties, or pF, would be uniform throughout (the water having no tendency to migrate). Because each sample is quite uniform, it can be assumed that the unfrozen moisture content was uniformly distributed.



THE CALORIMETER

FIGURE I

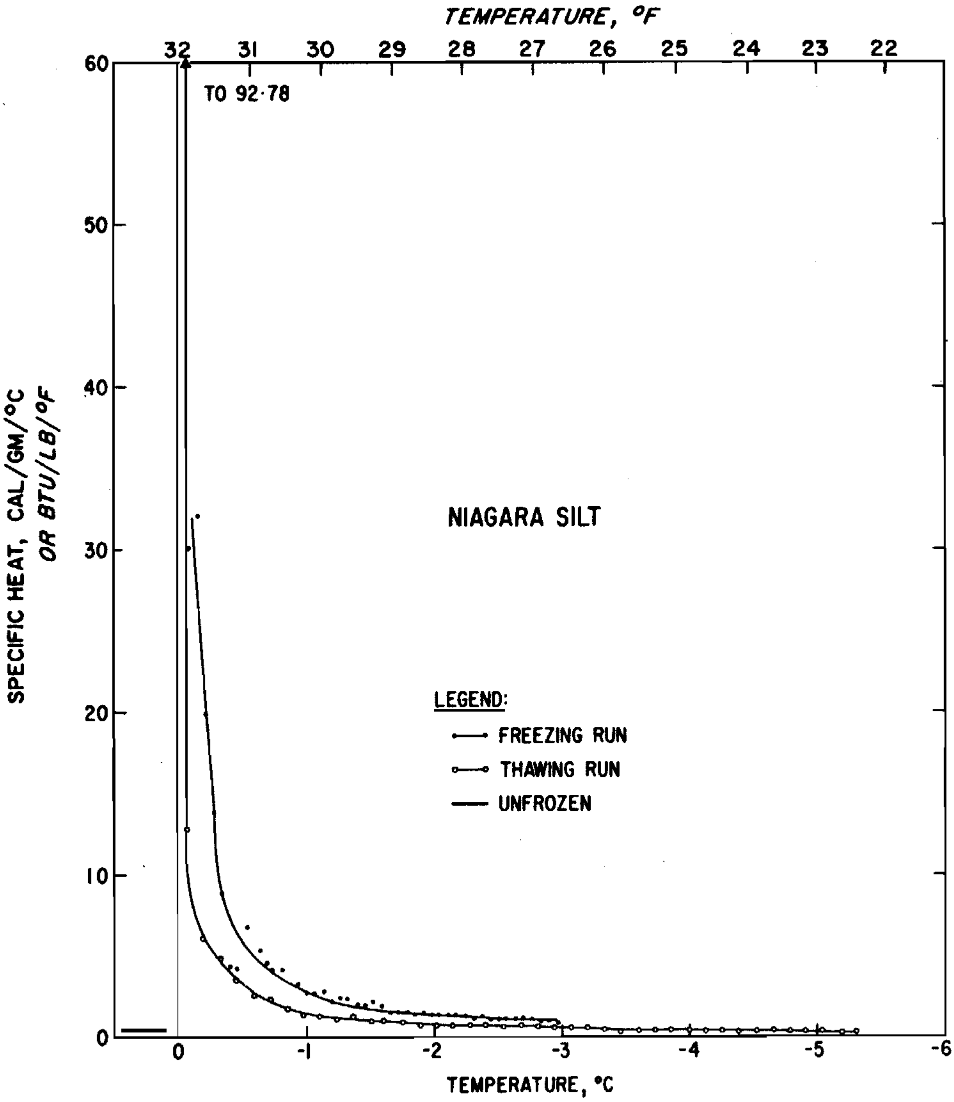


FIGURE 2

SPECIFIC HEAT OF NIAGARA SILT DURING FREEZING AND THAWING.

BR 2640-1

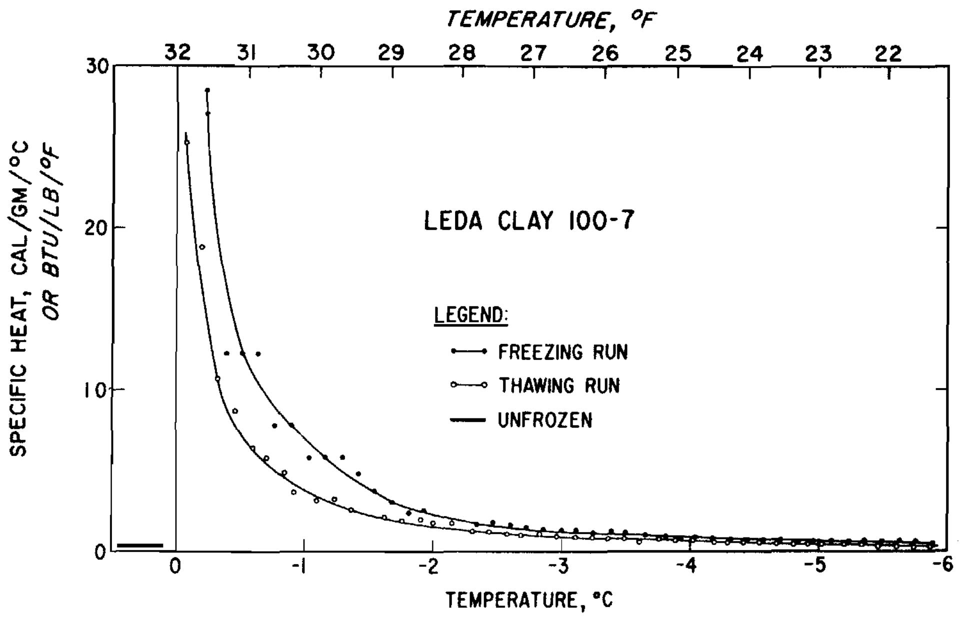


FIGURE 3

SPECIFIC HEAT OF LEDA CLAY 100-7

DURING FREEZING AND THAWING.

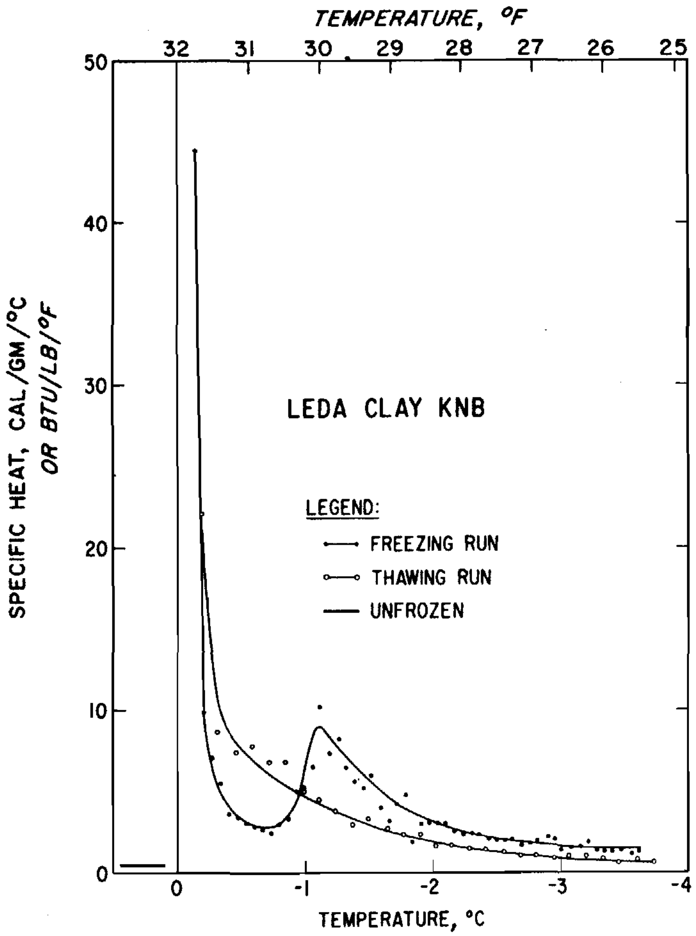


FIGURE 4

SPECIFIC HEAT OF LEDA CLAY KNB DURING FREEZING AND THAWING.

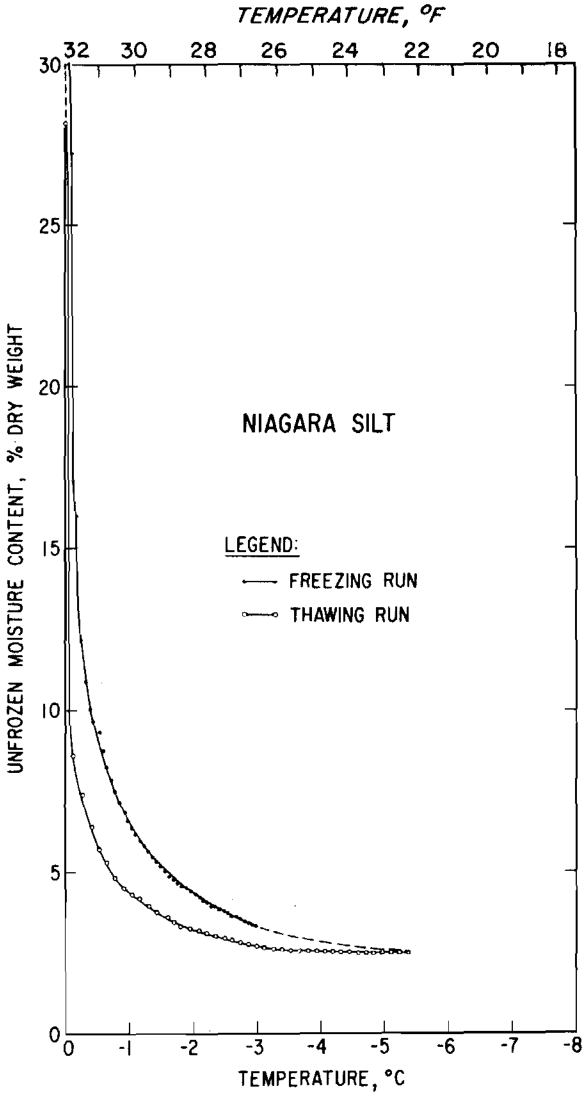


FIGURE 5

UNFROZEN WATER CONTENT OF NIAGARA SILT DURING FREEZING AND THAWING

BR 2640-4

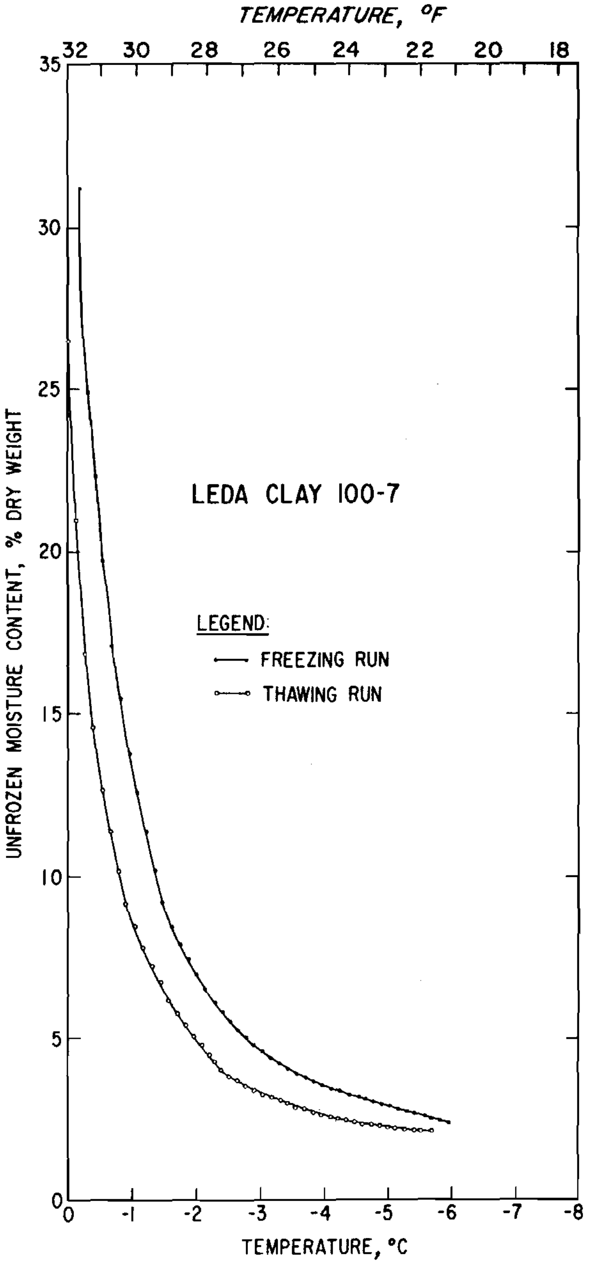


FIGURE 6

UNFROZEN WATER CONTENT OF LEDA CLAY 100-7 DURING FREEZING AND THAWING.

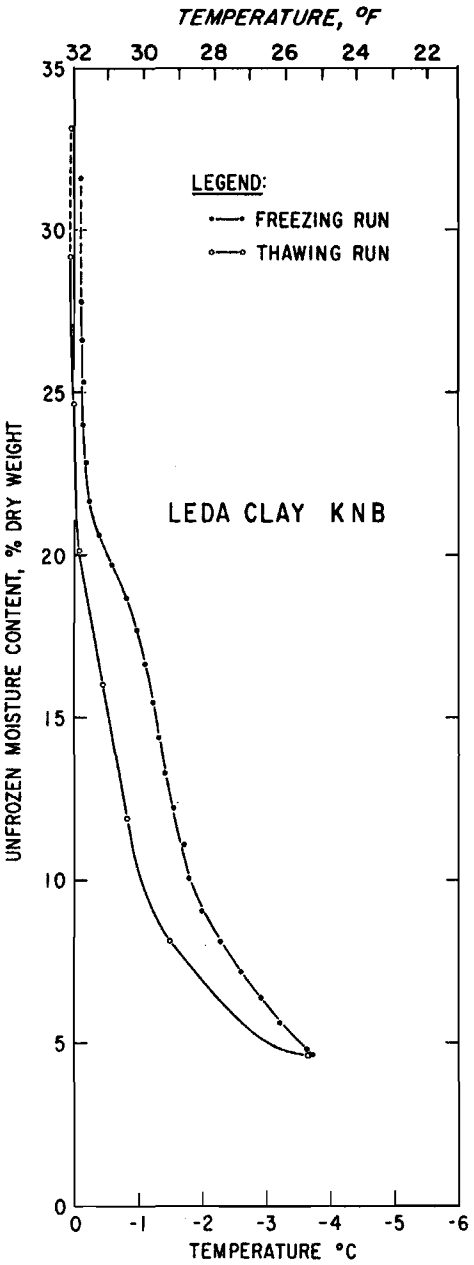


FIGURE 7

UNFROZEN WATER CONTENT OF LEDA CLAY KNB DURING FREEZING AND THAWING.

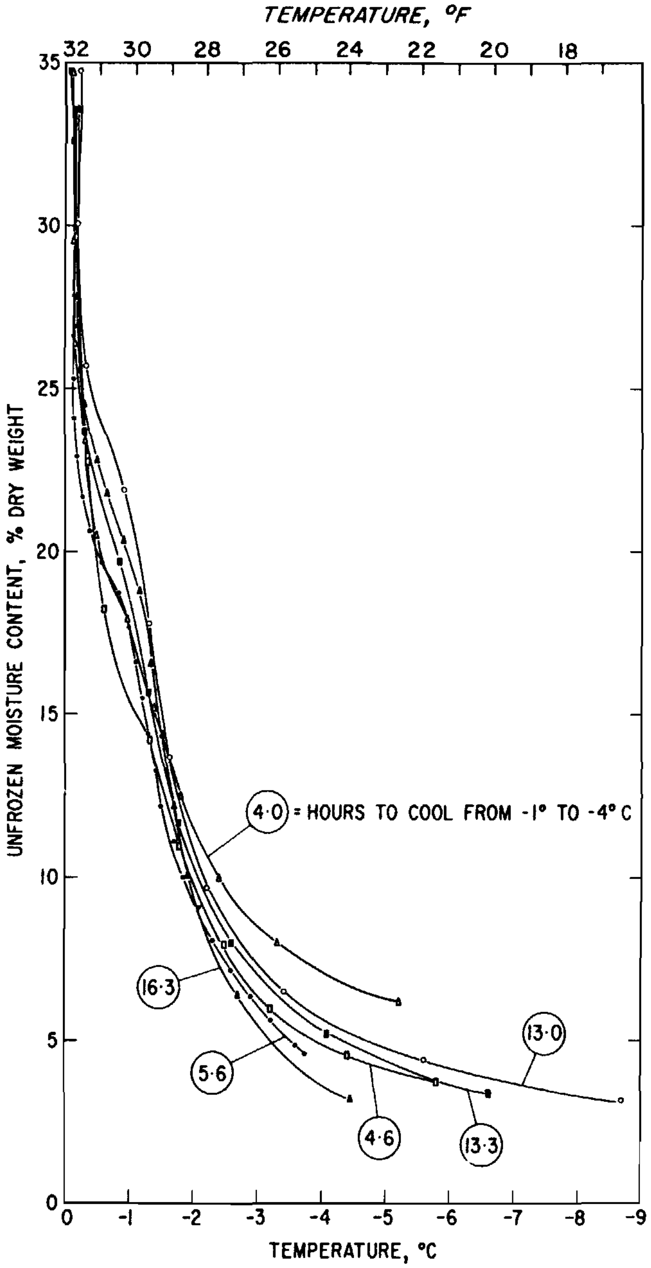


FIGURE 8

THE UNFROZEN WATER CONTENT OF LEDA CLAY KNB APPEARS INDEPENDENT OF THE RATES OF FREEZING SHOWN.

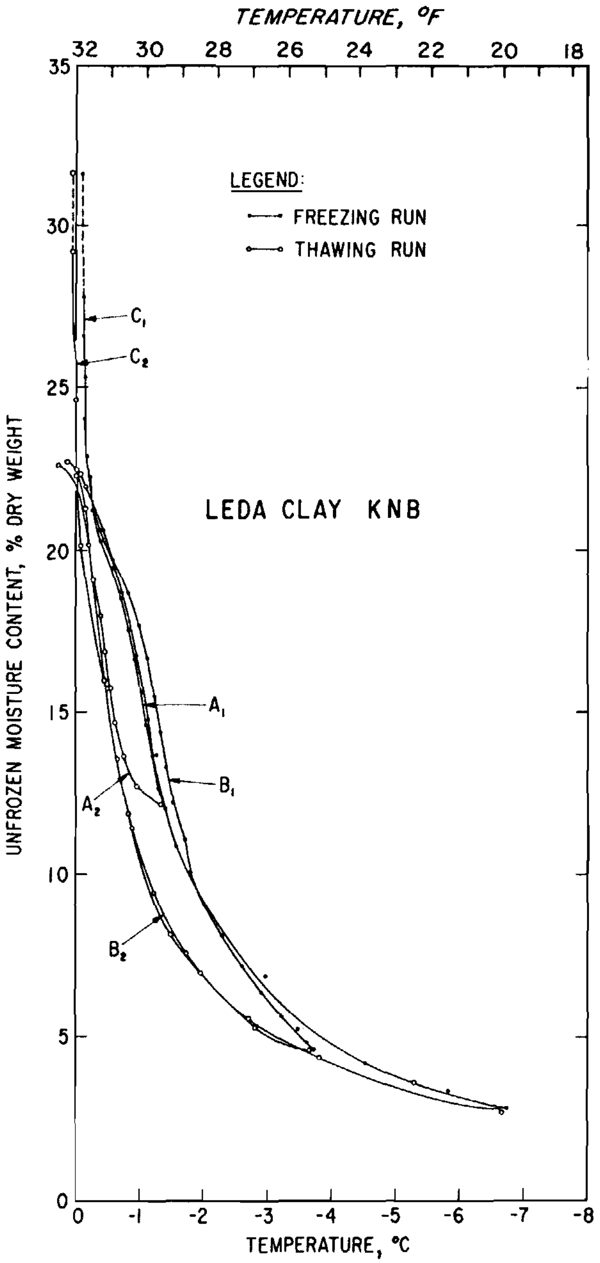


FIGURE 9

UNFROZEN WATER CONTENTS OF SAMPLES OF LEDA CLAY, OF 32 PER CENT MOISTURE CONTENT (CURVES C_1, C_2), AND 22 PER CENT MOISTURE CONTENT, (CURVES A_1, A_2 AND B_1, B_2).

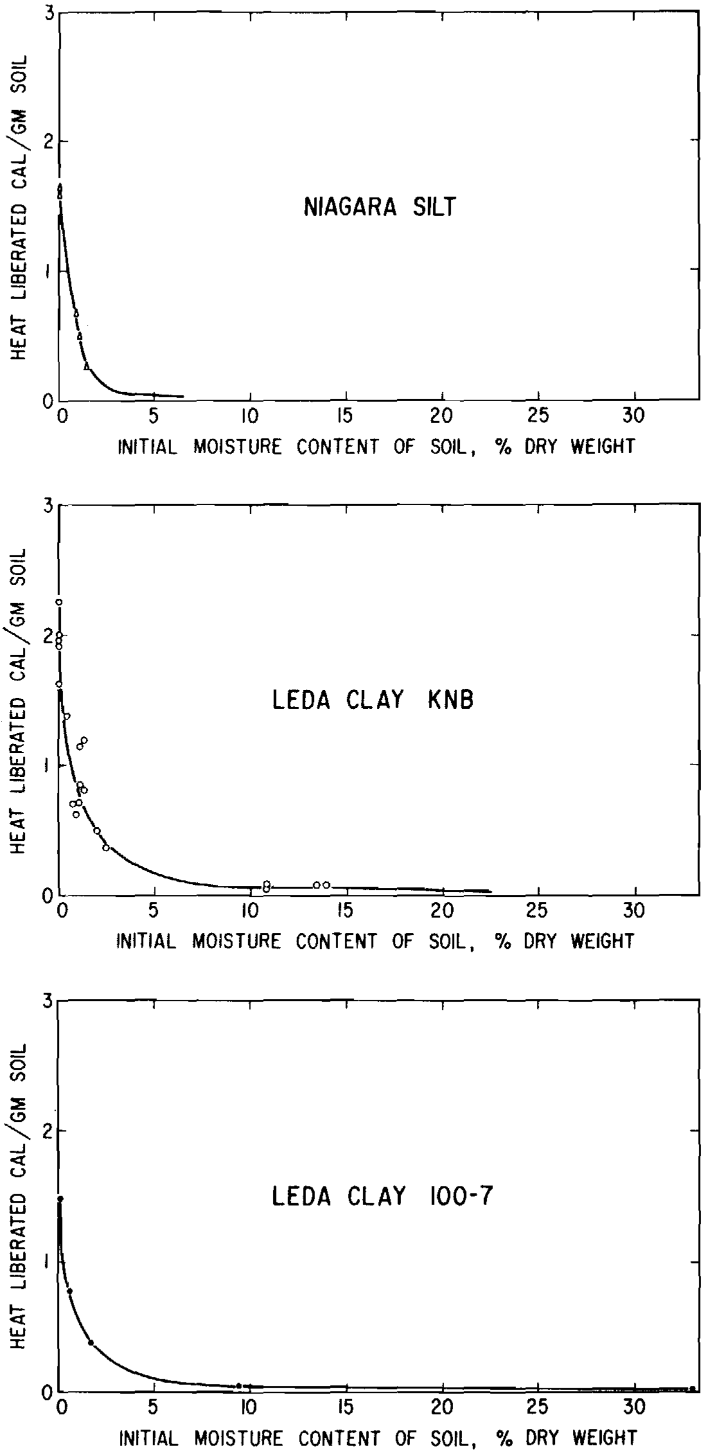


FIGURE 10

HEAT OF WETTING OF SOIL SAMPLES OF VARIOUS INITIAL MOISTURE CONTENTS. IT IS APPARENT THAT THE ADDITION OF WATER AT MOISTURE CONTENTS ABOVE ABOUT 4 PER CENT DRY WT. IS NOT ASSOCIATED WITH LIBERATION OF HEAT.

II. 4. PERMAFROST AS A GEOMORPHIC PROCESS

F. A. Cook

(Summary)*

Geomorphology, as the science of landforms, is both descriptive and interpretative in approach. Recently, increased attention has been paid to geomorphic process in the interpretation of landform development, "process" being loosely defined as any physical or chemical modification of the earth's surface.

Permafrost is a very important northern geomorphic process underlying about half of Canada's total area. It has, however, received only scant attention as a process, per se. Although papers have appeared on individual features, as for example, pingos, there has been little attempt to assess its overall importance. The present summary briefly considers the relationship between permafrost and major geomorphic features and processes. The published paper will endeavour to synthesize present knowledge of permafrost as a geomorphic process in the development of northern landforms.

FEATURES

Pingos

Pingos are among the most spectacular individual geomorphic features attributable to permafrost. Because J. R. Mackay's paper, "Origin of the Pingos of the Pleistocene Mackenzie Delta Area" is included in these Proceedings, the topic will not be developed here. There is no doubt that permafrost is of paramount importance in their development.

Patterned Ground

Patterned ground, a very well known, but little understood, phenomenon of permafrost and other areas, is a group term for a wide range of geometric forms, including: circles, stripes, nets, and the "mark" of the north, the polygon, which in its largest form, the tundra polygon, reaches diameters exceeding 100 metres. A large unorganized body of literature has developed, with little agreement on the relative significance of the several processes involved in the formation of patterned ground, although permafrost is undoubtedly important.

---

* Published with permission of the Director, Geographical Branch, Department of Mines and Technical Surveys, Ottawa. The full paper will be published by the Geographical Branch.

Thermokarst

Thermokarst, a form of karst topography exclusive to permafrost regions, is defined as the settlement of soil over thawing rock or unconsolidated material containing large amounts of ice. Thermokarst relief, determined by structure of the material and quantity of ice contained, forms only when thawing proceeds below the active layer. The resulting settlement of the surface leads to continued thawing which cannot be compensated by seasonal freezing.

Thermokarst seems to be initiated by a number of causes, including climatic change, forest fires, breaks in the surface by animals, and such human activities as deforestation, cultivation, and construction of buildings and highways. Among the commonest landforms produced by thermokarstic processes are: (1) surface cracks or fissures which may be associated with polygonal structure, (2) cave-in lakes or thaw lakes occupying depressions developed by the thawing of ice, (3) thaw-depressions, as above, without water, and (4) thaw-sinks which are closed depressions with subterranean drainage believed to have originated as thaw lakes.

Ground Ice

Ground ice features are widely distributed, although their areal extent is unknown. They may be responsible for rapid gulleying when exposed. A recent study showed that melting of ground ice triggered erosional action bringing about removal of large quantities of unconsolidated material.

Asymmetric Valleys

East-west trending asymmetric valleys are attributed to one-sided stream erosion when the ground is perennially frozen. On the southern slope the active layer thaws slowly permitting little erosion from melting snow cover, and, as a consequence, slopes have a low gradient. On the other hand, the permafrost table is much deeper on the more highly warmed northern slopes, and here rapidly melting snow moves material speedily, producing steep slopes.

Miscellaneous Features

Numerous other features, suchas oriented lakes, altiplanation terraces, rock glaciers, nivation hollows and talus slopes have been described as resulting partly from permafrost, although space does not permit discussion here.

PROCESSES

Solifluction

Solifluction is the most important mass-wasting process in permafrost areas. A very slow gravity movement of mantle over permafrost, it is measurable in centimetres per year. In addition to such minor features as solifluction lobes, fronts and terraces, there is an overall downslope movement on a wide scale. The end result is a levelling of the landscape and a smoothing of the contours producing a subdued, non-angular relief.

Although the processes involved in solifluction are not fully understood, permafrost is important. First, it provides a hard impermeable base or slip-plane on which earth materials move downslope. It concentrates underground drainage near the surface facilitating plastic flow of the soil. Furthermore, it maintains soil temperature near the freezing point, permitting alternate freezing and thawing with resultant displacement of soil particles, and possibly some mechanical weathering.

Running Water and Tides

The work of running water in permafrost regions is chiefly concentrated or restricted to stream run-off. Perhaps the most important point is that both down-cutting and lateral side-cutting of streams are considerably reduced by permafrost which presents a resistant erosion surface to the water. The period of maximum run-off and erosion occurs in late Spring or early Summer when unconsolidated material forming their channels is still frozen or has thawed only slightly. It is thus difficult for the stream to pick up sediment at this time as it is forced to expend its energy on the extremely resistant permafrost. Later, when conditions are more favourable, the volume and erosive power of the stream has decreased. However, the load of sediment may be heavier, resulting in deposition, and the development of braided streams and floodplains common to permafrost areas.

Permafrost along a coastline will also inhibit erosive action of waves and tides, although, if ground ice should be uncovered, erosion may proceed rapidly.

Mechanical and Chemical Weathering

Permafrost influences the rate and type of weathering in northern lands. Mechanical weathering, usually by frost action, is important, almost to the exclusion of chemical weathering, which does occur, however, in some limestone regions, especially if precipitation is heavy.

It has long been assumed that alternate freezing and thawing has been the important mechanism in mechanical weathering in permafrost regions. Recent studies suggest that the diurnal cycle is restricted to the top few centimetres of mantle and may be of less importance than previously thought. The annual range of temperature, however, with its effect on expansion and contraction, may be very significant, particularly in permafrost with high moisture content.

Organisms

Permafrost retards microbiological processes in the active layer, and none whatever occurs in permafrost, although bacteria may be present. Consequently, vegetative residue decomposes slowly, leading to the accumulation of organic material. Peat may be formed, in addition to string and palsa bogs, and a number of other vegetative forms. All of these forms are influenced by this retarded process of decomposition, in addition to the ponding of water and interference with surface and subsurface drainage by permafrost.

Permafrost also places a limitation on the movement of earth worms and burrowing animals as geomorphic agents.

Permafrost is also a physical barrier to the downward growth of roots, acting as a cold shield compelling the roots to spread horizontally on the thin upper strata of its upper layer. Winds and other forces may then cause trees and other vegetation to be tipped or tilted in different directions, resulting in the "drunken" or "dancing" forests sometimes encountered in permafrost areas.

CONCLUSIONS

Permafrost has considerable effect on the landforms and processes present in northern regions. A special type of subdued landscape results, the movement of surface and ground water is confined, and extreme dissection of the earth's surface discouraged. The role of mechanical weathering is accelerated, chemical and biological action is greatly reduced, and a number of minor landforms develop which are peculiar to permafrost regions.

II.5. GROUND WATER IN THE PERMAFROST REGIONS OF THE YUKON, NORTHERN CORDILLERA AND MACKENZIE DISTRICT*

L. V. Brandon

In a discussion of the hydrogeology of a large area comprising the Mackenzie District and the Yukon Territory, it is, at present, possible to make only broad generalizations as to groundwater availability. The presence of permafrost in this area has often deterred engineers from contemplating the use of groundwater as a source of water supply. There are, therefore, little water well drilling data available for use as concrete evidence of the presence and direction of movement of groundwater in particular localities. Data available on climate, run-off, and geology are, however, sufficient to show that groundwater is present throughout areas of discontinuous permafrost and that rocks are saturated in the same manner as in humid temperate regions. It is only in some areas of continuous permafrost that groundwater flow is unlikely.

For descriptive purposes, the northwest can be classified into three type regions; the regional selection being based on geology and climate. The first region is the Precambrian rock region in the east part of the Mackenzie District. The second region comprises two areas of sedimentary plains which are, (a) the Mackenzie plain and (b) the Porcupine plain. The third region is the Cordillera which occupies much of the area west of the Mackenzie River.

THE PRECAMBRIAN REGION

Climatically this is a dry sub-humid region where potential evapotranspiration calculations indicate a moisture deficiency during the summer time (5). Precipitation ranges from 8 inches to 10 inches per year. In common with many other parts of Canada, the only effective period of groundwater recharge occurs during the Spring break-up when the snow melt contributes to infiltration in areas where permafrost is not present. The region is poorly drained as indicated by the abundance of lakes. Streamflow data are non-existent on some of the main rivers, such as the Coppermine, so it is not possible to make any estimates of groundwater flow to rivers or of bank storage.

In the areas where continuous permafrost exists, field

---

* Published with permission of the Director, Geological Survey of Canada, Department of Mines and Technical Surveys. Paper read at Conference by I. C. Brown.

evidence indicates that infiltration of water does not occur. This is apparent after observing the frost-thrusting of jointed rocks in which water has frozen while entering the joint system at the surface and caused heaving of the rocks. Further evidence of the absence of infiltration is provided by the presence of intermittent streams in valleys such as the Coppermine where dry creek beds, typical of an arid land, are visible. These creeks are dry immediately after surface water run-off has been completed because any seepage which could occur in these areas of continuous permafrost is influent. Other evidence for the absence of infiltration is provided by mines which are usually dry, except where fracture zones permit influent seepage of water from surface reservoirs such as nearby lakes.

Locally, in a few places referred to as being within areas of continuous permafrost, there are reports of springs which build up extensive ice-sheets during the winter. Tyrrell commented on these and named them crystocrenes (ice fountains) (8). Douglas and later authors have also observed and described these features (2). It is possible that these springs are the result of seepage from a lake or creek located at a higher level.

The rocks of the region are igneous, metamorphic and sedimentary, and the only possible movement of groundwater is through joints and fissures in rock and by permeation through unconsolidated sands. Fractures rarely extend to a depth of more than two hundred feet; thus any effective groundwater flow must be near surface if present at all. Many of the rocks are unfractured thus preventing groundwater movement. Although rock outcrop is extensive, there are also many areas covered by glacial drift and muskeg.

The Precambrian region may therefore be classified as one where groundwater flow is very small and where the only effective source of groundwater for domestic supply is in alluvial or glacial sands adjacent to streams or lakes. In a few localities, adequate groundwater supplies for a home could be obtained from wells drilled into jointed rocks that are not frozen and which are near a surface water supply. The only wells that have been used or attempted in the region have been at construction camps where sand points have effectively supplied water. A deep diamond drill hole was once put down at Rae, N.W.T. but this was a failure because it was drilled in unjointed granite.

THE PLAINS REGION

(a) The Mackenzie River plain is climatically similar to the Precambrian region in that it is also within a dry sub-humid zone. Precipitation is slightly higher than in the Precambrian region ranging from 10 to 12 inches per year. Run-off data are meagre or non-existent. A groundwater level recorder was recently installed at Pine Point south of Great Slave Lake, which will record the times of groundwater recharge occurring generally at the time of snowmelt.

Geologically the plain is composed of flat-lying sedimentary rocks consisting mainly of limestones, dolomites and shales. The geology of most of the plain has been mapped at the reconnaissance scale. Some of the carbonate rocks locally contain solution channels through which there is considerable groundwater flow; but for the most part groundwater flow is along joint planes. Good local permeability is developed within some limestone reef and sandstone formations. The region differs from the Precambrian region in that overall permeability of the rocks is higher and because groundwater flow can occur at much greater depths in a system of sedimentary rocks.

Data obtained from observation of springs and from chemical analysis of river waters show that lakes and rivers receive groundwater by effluent seepage throughout the entire region except in areas of continuous permafrost. Thus most of the land south of the Arctic Circle has groundwater movement towards the rivers.

A typical area where springs are visible is along the south and northwest shores of Great Slave Lake where seepage of water that is high in sulphates and chlorides is seen at localities such as Sulphur Point, High Point and Windy Point. The temperature of waters in these small springs is 37°F. Groundwater outflow to lakes also occurs along the line of the Palaeozoic-Precambrian contact between Great Slave Lake and Great Bear Lake. This can be seen in Lac la Martre and Lac Tempier, and lakes along this line are the places of natural groundwater discharge. It has not been possible to determine if this seepage occurs north of Great Bear Lake because that area is heavily drift-covered.

Chemical analysis of river waters also reveals the effect of groundwater flow from the near surface muskeg waters and from deeper flow in the underlying carbonate rocks. The near surface flow, known as interflow, is water that has received a typical red colouration from organic matter in muskegs. Many rivers receiving waters from the swampy areas of the Mackenzie plain have this red colouration which is greatest in the summer time. This can be seen in such rivers as the Redknife, Willow, Rabbitskin and Hay. The degree of colouration is measured by comparison with a standard cobalt-platinum colour scale. Hay River has a high colouration throughout the year (6); but the colouration diminishes during the winter with the decrease in interflow, and it is probable that sampling of similar rivers would show a diminution of colour in winter.

The presence of deeper groundwater flow toward rivers is indicated by chemical analyses of such rivers as the Little Buffalo which is high in sulphates, and also by rivers such as the Saline River and Vermilion Creek south of Norman Wells,N.W.T. which are rivers with highly mineralized waters that have been derived from groundwater flow.

Springs are present along the main channels of drainage such as the Mackenzie River; and flowing water wells have been drilled during oil exploration work along the shores of the Mackenzie (3). This phenomenon is to be expected in an area of groundwater discharge.

Water well drilling has been attempted at some settlements in the Mackenzie plain. The most northerly operating well is at Wrigley, N.W.T. airport. Drilling at Fort Good Hope, N.W.T. was a failure because the fine-grained glacial drift was frozen and deeper drilling into the underlying limestone would have yielded saline waters which are difficult to demineralize with the present arrangements in small settlements. Exploration holes further north in the valley have encountered water in unfrozen gravels.

Drilling has also been carried out at Fort Smith, N.W.T. and Hay River, N.W.T. At both places the high mineral content of the groundwater has prevented any extensive development, although a well is used at Fort Smith airport and wells are in use at Hay River.

In general, it may be said that waters in the Mackenzie plain will be high in sulphates at shallow depths, and highly saline at great depth and at places of upward leakage in valley bottoms. The only places where waters of low mineral content are to be found are in the alluvium adjacent to rivers where much of the water is derived from bank storage.

(b) The Porcupine plain is an area about which little information is available. It may, at present, be classified as an area where drainage is poor, permafrost is widespread and thick and the only groundwater potential is at considerable depths where saline waters occur in the sedimentary rocks.

THE CORDILLERAN REGION

Climatically this is a more humid region where precipitation ranges from 12 to 18 inches per year. Excellent run-off data are available on the flow of the Yukon River and some of its tributaries. These data have been obtained because of the interest in hydro-electric development in the region. Good estimates of groundwater baseflow and bank storage are, however, not possible because the rivers drain large lakes and because the precise gauging of river flow in winter is difficult. It is sufficient here to say that river valleys of the Cordilleran region, having deep deposits of till or of river sediments in unglaciated parts, are valleys in which there must be considerable bank storage of water between flood seasons.

The region comprises many mountain ranges, plateaux and valleys. These consist of folded sedimentary rocks in the Franklin, Mackenzie and Richardson Mountains. Towards the west there are various intrusive and altered rocks in the mountains and plateaux which make the geology more complex.

The potential aquifers in the region are glacial sands and gravels and alluvium. Locally some fractured rock formations are aquifers, such as fractured limestones and the Tertiary basalts.

The practical understanding of permafrost and the use of groundwater is of longer standing in the Yukon than in regions to the east. Historically the region has had two periods of development when engineers attended to these problems. The first period was at the end of the 1890's when mining in the perennially frozen gold bearing gravels of the Klondike was begun. The need to remove the muskeg blanket prior to thawing the ground was realized when dredging operations began. The technique of thawing the ground by cold water injection was adapted early in the 1930's. At an early phase in the work in the Klondike it was realized that water under pressure could exist under the perennially frozen gravels at those places where the depth to bedrock was great. Tyrrell commented on this when describing an artesian well in the Klondike (7).

The second phase of permafrost study and groundwater development in the region began in 1942 when the construction of the Alaska Highway was undertaken. Engineers of the U. S. Army realized that water wells would be a much more economic means of obtaining water for maintenance camps than from surface intakes; consequently they requested the U. S. Geological Survey to examine all potential camp sites and to advise where drilling should be undertaken. (The author is very grateful to the U. S. Geological Survey for making available the notes of Dr. C. V. Theis who successfully selected many sites for wells along the highway.) As a consequence of this work, wells were drilled along the highway and along the Canol pipeline route. Most of these wells have been abandoned with the closing of the camp sites; but the use of wells at small settlements has continued. In almost every location these wells obtain water from sand and gravel lenses within the valley bottoms. In the Shakwak Valley there are flowing wells at mileposts 1124, 1095 and at Destruction Bay which are reported to have been drilled through permafrost. The maximum reported thickness of permafrost at these wells is at milepost 1095 where frozen ground was reported to occur from 35 to 125 feet. The temperature in this flowing well was found to be just above 32°F, and the well has a heating coil in it because it is found that a build-up of ice occurs periodically. The heat coil is switched on when this occurs.

The highest capacity wells in the region are at Whitehorse, Y.T., and Dawson, Y.T. In Whitehorse, the wells obtain water which is mainly derived from bank storage in gravels adjacent to the river and this water is reported to vary in temperature from 39°F to 40.5°F. The wells are used in winter because the water is warmer than the river water which is the summer source of supply. The wells at Dawson obtain water by induced infiltration from the Klondike River; the bank of the river being composed of gravels at the location of the wells. The water is steam heated to 39°F prior to distribution along the water lines.

THE USES OF GROUNDWATER

Groundwater may be used for two purposes in these regions. 1. As a source of water supply for communities. 2. As a source of heat for communities.

1. A source of community water supply. There is no place in the north which is inaccessible to well drilling rigs and great advantage could sometimes be taken of the presence of drilling rigs in the north to put down wells where necessary. However, the effective use of wells will best occur when problems of well construction are properly overcome and when demineralization is practical in some locations.

The simplest type of well is the wire-wound stainless steel well point, usually of 2 1/2 inches diameter, which can be drilled or jetted down into alluvial or glacial sand aquifers. Wells of this type are far superior to dug wells; indeed the author has noticed that dug wells eventually deteriorate into nothing more than polluted holes in the ground because they always suffer from surface water contamination. Because surface infiltration in sands is rapid, it is essential to plan sewage disposal with care to avoid contaminating wells. In areas of thin discontinuous permafrost, it is possible to thaw the frozen ground by cold water injection.

Most high capacity aquifers in the north are in sands and gravels and it is essential to realize that wells in sands will require well screens. There are a number of reported well failures which have been caused by fine sands or silts entering a well and plugging the casing. This can be prevented if adequate precautions are taken by the engineer and the contractor to ensure the well is properly developed and made free of sand. This usually requires the installation of a well screen which is designed according to the grain size of the sands in the aquifer; and, in some cases, it is necessary to install a sand or gravel wall around the well screen. The techniques for doing this are standard procedure for experienced well drilling contractors; and although these techniques involve much higher capital costs for the installation of a well, they are nevertheless essential to provide satisfactory operation.

The waters in most glacial aquifers in all three regions can be chemically classified as calcium bicarbonate water which is entirely satisfactory for drinking. There is an increase in sulphate content with depth. All deep rock wells in the sedimentary plains are saline. The author wishes to point out that research into demineralization of saline waters has reached a point now where small domestic demineralizers are coming onto the market, and it may soon be possible to evaluate the use of these machines which may be of great value for treating water all year round in some northern localities. In some locations the high iron content of groundwater may make treatment necessary.

2. A source of heat for communities. The thickness of permafrost at any locality depends on the average annual temperature at the surface and on the geothermal gradient below the surface. The rate of increase of temperature varies with location and the methods of measuring the true geothermal gradient in bore holes are difficult owing to the time-lag before equilibrium is restored after drilling. Temperature logs are obtained in oil well drilling by lowering an electrode which consists of a length of platinum wire that is set in a rubber coating. The platinum is exposed to the mud in the drill hole where it rapidly acquires the temperature of the fluid in which it is immersed. Changes in temperature produce changes in resistance which can be correlated at surface to a change in temperature and this is recorded. The electrode is raised from the bottom of a hole to the top and a log of temperature against depth is recorded. Temperature logs are run in oil wells to distinguish sands from shales because the thermal conductivity of sands is greater than of shales; but these logs are used mainly to determine the top of the cement in a well after cement has been set. This record is obtained because the cement generates heat while setting. Some temperature logs have been run to determine permafrost thickness.

Reference to the temperature logs of some of the exploration wells drilled in the north shows that the thermal gradients are of the order of magnitude of one degree Fahrenheit per 65 feet of depth.

Thermal gradients of wells in the prairies vary from about 50 to 70 feet per degree Fahrenheit. Thus at depths of 5,000 feet temperatures of 130°F are common (1).

In some localities it is unnecessary to drill to these depths for warm waters. These places are the ones where rock faulting or other structural features have permitted groundwaters to percolate down to considerable depths and to emerge again in the form of thermal springs. The term "thermal spring" is used here because it applies to springs where the water has a temperature higher than the mean annual temperature; many thermal springs are hot springs.

Thermal springs rarely occur in isolation; usually there are several springs in one locality where water emerges from a number of rock fractures. At some springs most of the water is discharged into a river below the level of the bank so that most of the discharge is invisible.

All the thermal springs in the north are in the Cordilleran region. Among the best known springs in the Mackenzie District are those near Wrigley where waters ranging in temperature from 70°-80°F emerge from the Roche-qui-trempe-a-l'eau just north of the settlement on the east side of the river. The total flow of these springs is estimated at 70 gpm at the surface; most of the individual springs are, however, only seepages. Other large springs occur on Old Fort Island (mile 336 Mackenzie River); the temperature of these flows was found to be 53°F in August 1960 and the largest flow from one individual spring was estimated to be 300 gpm. Another large spring is at the entrance to the first Canyon of the South Nahanni River where springs emerge from silts, sands and gravels along the river bank. The warmest water recorded there was found to be 98°F. Hot springs occur further up the South Nahanni River in the Selwyn Mountains (4) and up the Flat Creek.

There are also a number of thermal spring locations in the Yukon Territory. The best known of these being the Takhini Springs (temperature 116°F) and various springs in the McArthur Range. In all these places the flow can be expected to be continuous throughout the year and the temperature is fairly constant.

The author has made reference to thermal springs and natural sources of heat within the earth, not only because they prevent the development of permafrost, but because they can be utilized. Although a heat pump does involve much capital cost and design difficulties, it is nonetheless a method of obtaining a lot of heat for a community throughout the year in a cold region. There are many places in western and northern Canada where this heat could be developed.

REFERENCES

1. Beach, Floyd K. Geothermal Gradients in Canadian Plains. Can. Oil and Gas Industries, Nov. 1952. pp. 43-46.
2. Douglas, George M. Lands Forlorn. The Story of an Expedition to Hearne's Coppermine River. The Knickerbocker Press, New York, 1914.
3. Hume, G. S. Lower Mackenzie River Area, N.W.T. and Yukon. Geol. Surv. of Canada, Memoir 273, 1953.
4. Porsild, A.E. The Vascular Flora of an Alpine Valley in the Mackenzie Mountains, N.W.T. National Mus., Canada, Bulletin 171, 1961.
5. Sanderson, Marie. Drought in the Canadian Northwest. Geographical Review, Vol. 38, 1948. pp. 289-299.
6. Thomas, J.F.J. Water Survey Report No. 8. Mackenzie River and Yukon River Basins in Canada 1952-53. Mines Branch, Canada, 1957.
7. Tyrrell, J.B. A Peculiar Artesian Well in the Klondike. Eng. and Mining J., Vol. 75, 1903. p. 188.
8. ——————— Crystophenes or Buried Sheets of Ice. J. Geology, Vol. 12, 1904. pp. 232-236.

******

Discussion

J.M. Robinson enquired whether water occurs in thermal belts in the mountains, to which the reader of the paper replied that there is little information on this but these thermal belts may be a source of hotsprings.

D.R. Nichols asked if the reader developed any hypothesis for the causes of the high salinity of deep subpermafrost groundwater that seems to characterize large areas in permafrost regions, not only in Canada but also in Alaska and Siberia. The reader stated that salt occurs in rocks at depths of several thousand feet as in the Prairies. As the water moves in the ground it should start out as a bicarbonate solution and end up as seawater. There is little salt water in unconsolidated sediments although some has been encountered south of Great Slave Lake. F.E. Crory commented that it is possible to have an aquifer resulting in artesian flow without the existence of a lake, to which the reader added that water occurs in mines beneath the permafrost in Canada's permafrost region. In the Con Mine at Yellowknife, N.W.T., water under high pressure was encountered at the 2,300 foot depth. The pressure which was measured was almost equal to the hydraulic pressure. Drainage was attempted without success and it appeared that the water had moved through thawed zones in the permafrost. Water was encountered also in Eldorado Mine at Port Radium, N.W.T. on Great Bear Lake. T. Lloyd remarked that Porsild reported groundwater in permafrost in the Disko Island area of west Greenland.

III. 1. PERMAFROST OCCURRENCE AND ASSOCIATED PROBLEMS AT THOMPSON, MANITOBA

K. S. Goodman and R. M. Hardy

This paper deals with permafrost conditions at Thompson, Manitoba. This is a new townsite which has been developed since 1957 to house and service the personnel at the mine and smelter operation of the International Nickel Company of Canada. Although extensive investigations had been carried out in connection with the mine and smelter sites, there was no evidence of the existence of permafrost in the area. However, when work was subsequently started in the townsite, permafrost was encountered at many locations.

Included in the paper is a description of the soil profile in the Thompson area, a discussion of the significance of certain test results on soil samples from the site, a brief history of construction at Thompson and finally, a review of the procedures which are being followed in engineering construction at the present time to minimize the effects which are normally associated with permafrost occurrence.

The town of Thompson is located approximately 400 miles north of Winnipeg and 250 miles southwest of Churchill. This places it roughly 150 miles south of the line which approximates the southern limit of continuous permafrost as shown in the Climatological Atlas of Canada (4). It also places it approximately 50 miles north of the southern limit of permafrost as recorded by Charles (2). The mean annual temperature at Thompson is approximately 25°F, which incidentally is close to that at Norman Wells, N.W.T., where widespread permafrost has been encountered. The mean January and July daily temperatures are about -15°F and 59°F, respectively. On the average there are about 140 frost-free days each year.

The soil profile in the Thompson area consists of varved clays overlying glacial outwash deposits of sand and gravel which in turn overlie the bedrock. Two distinct horizons exist in the varved material, differentiated by a colour change from brown to grey. The change occurs at an average depth of approximately 12 feet but has been observed as deep as 17 feet.

In the upper portion of the profile the silt to clay varve proportion is roughly 1/4 inch of silt to 3/4 inch of clay. The proportion of silt gradually increases and below a depth of about 12 feet the layers are approximately equal in thickness. Index and physical properties of the brown and grey varved materials are shown in Table 1. It will be noted that a somewhat higher than usual variation in natural moisture

TABLE 1

Index and Physical Properties

Clay Type	Moisture Content (%) No. of Tests	Moisture Content (%) Range	Moisture Content (%) Av.	Atterberg Limits (%) No. of Tests	Liquid Limit Range	Liquid Limit Av.	Plastic Limit Range	Plastic Limit Av.
Brown	130	28-47	34.2	25	34-80	58.0	19-32	26.0
Grey	183	19-55	31.7	25	20-77	45.2	16-29	19.5

	Unconfined Compressive Strengths No. of Tests	Tons/Sq. Ft. Range	Tons/Sq. Ft. Av.
Brown	15	0.8-2.3	1.48
Grey	25	0.1-2.3	0.66

contents occurs in the clays. This is significant because it suggests that the higher moisture contents occur in sections of the profile where permafrost has only recently receded and subsequent consolidation of the clay is not yet complete.

Routine foundation investigations at several building sites have included laboratory strength and consolidation tests on undisturbed samples of both the brown and grey varved material. Shear strength was determined by means of the unconfined compression test. The average results of some 40 tests on samples from two such sites are shown in Table 1. These are typical of the results from the several sites investigated. The tests consistently showed a reduction in strength with depth. As more and more test results became available it became apparent that the unconfined compressive strength tests did not in all cases accurately assess the strength of the soil in situ. It did not seem logical to accept as valid, strength test results which showed shear strengths of only 300 to 400 pounds per square foot for samples from depths of 30 to 40 feet.

A detailed study of all the available strength data was therefore undertaken. Shear vane tests were conducted at a limited number of sites to secure a check on the in situ shearing strength of the clays, and in addition, penetration tests were run in the form of driving resistance of thin walled Shelby tubes.

No correlation was found between the natural moisture content and the strength of the varved silt-clay soils as determined by the laboratory unconfined compressive strength test. This suggests that the soil derives its shearing strength predominantly from thixotropic bonds between the soil particles, and to only a relatively minor degree from their frictional characteristics. This appears to be the case irrespective of whether or not the soil has been subjected to permafrost conditions in its recent geological history.

Figure 1 shows plots of laboratory unconfined compressive strengths, field penetration tests and in situ shear vane tests each plotted against depth below the surface. Ground temperature readings are also plotted against depth in Figure 1. These data are composite results from several test holes at two typical sites in the townsite area.

It will be noted from Figure 1 that shear vane tests, both ultimate and remoulded, show substantially greater strengths at depth for the soil than is indicated by the laboratory unconfined compressive strength tests. As would be expected the curve for shear strengths indicated by the penetration tests closely match the remoulded vane shearing strength curve over the portion of the depth where the two curves overlap. The plots for the vane shear strength tests appear to reflect the effect of recent thawing of the permafrost in that the minimum strengths occur over the depth where permafrost is known to exist at present in the area of these sites. The laboratory unconfined compressive strengths were all characterized by comparatively high rates of strain at failure stress and by a decrease in modulus of deformation with depth of sample.

The strength-depth relationship from laboratory unconfined compressive strength tests, as shown in Figure 1, is not consistent with currently accepted principles governing the shearing strength characteristics of clay soils. It is recognized that desiccation may produce increased soil strength with a gradual decrease to the depth of undesiccated soil. This factor could only affect the soil strength to a shallow depth of a few feet, however, in view of the location and recent geological history of the Thompson area.

A more valid explanation is suggested on the basis of research done in recent years on Norwegian normally consolidated varved clays as well as work on normally consolidated glacial lake deposits of varved clays in Canada (1). The Norwegian workers found that for the Norwegian sensitive varved clays ordinary sampling procedures produced a partial destruction of the soil structure. This resulted in a loss in strength and an increase in strain at failure as measured in laboratory strength tests. The effect increased with depth of sample and appears to be associated with sample disturbance by the sampling equipment plus rapid release of stress in removing the sample from its natural environment. This latter factor, of course, increases with greater depth of sample. The Norwegian work indicated that "per cent strain at failure" in the laboratory strength tests was a positive measure of the degree of sample disturbance, and "failure strains" exceeding 3 per cent were indicative of appreciable strength loss due to sampling.

Experience during the past few years with normally consolidated glacial lake bottom varved clays at Steep Rock Lake in Western Ontario has shown these same soil characteristics to exist (5). Extensive laboratory strength tests on samples secured by conventional sampling methods showed loss of strength and increased strain at failure with depth of sample. In situ shear vane strength tests indicated that the laboratory strength test results were unrealistic as a measure of the in situ strength, and demonstrated that there was, in fact, an increase in strength with depth. These results have been confirmed by the subsequent performance of dredged slopes in the lake bottom material, which extend to vertical heights of as much as 400 feet. These were designed on the basis of the increase of strength shown by the in situ vane tests, and would not be standing if the in situ shear strengths were only the values indicated by the laboratory strength tests on conventionally extracted samples.

The evidence is, therefore, that the laboratory shear strength test results on samples from the Thompson sites are subject to the same limitations as indicated by the Norwegian findings and the experience at Steep Rock Lake. The fact that laboratory shear strength tests underestimate to a substantial degree the in situ strength of the clays at depth at the Thompson sites is of considerable practical importance. It is significant in the design of foundations that must be carried through permafrost or through zones where the permafrost has only recently receded. The results of in situ vane tests would seem to be more reliable in assessing the true soil strengths below the permafrost or even within the zone of recently thawed permafrost.

It is of some interest to assess the effect of the formation of permafrost in the Thompson varved silt-clays in disturbing the structure of the soil. One might well expect that the cycle of freezing and thawing would produce complete remoulding and therefore result in almost complete loss in strength. However, the available data do not confirm this. While some effect of freezing and recent thawing is evident in Figure 1 it is considerably less than appears to result from soil sampling and rapid stress release. It may be speculated that the reason for this is that the glacial lake varved deposits in the Precambrian Shield area of Canada appear to be subject to comparatively rapid formation of thixotropic bonds between the soil particles (3).

Leaving now the questions of soil types and characteristics, let us consider the nature and occurrence of the permafrost in the Thompson area. Over the course of four separate drilling programmes carried out between November 1957 and February 1962, 171 test borings have been put down in an area approximately 7,000 feet square. Permafrost in one form or another has been encountered in 75 of these borings. A study of a plan showing the location of all borings shows that the permafrost is patchy and occurs in scattered islands, the largest of these permafrost islands being approximately 1,500 feet by 2,500 feet. The transition from permafrost zones to frost-free zones is very abrupt. At one particular location, for example, one boring showed 24 feet of permafrost while another boring only sixty feet away showed no permafrost whatsoever even though there was no great difference in surface topography and tree cover between the two sites.

Not only is the permafrost patchy in occurrence in the horizontal direction but it also varies considerably with depth. In a few cases discontinuities were observed, a portion of the boring showing ice crystals, then unfrozen soil for a few feet, then ice crystals again. These crystals were approximately 1/8 inch on a side and had the appearance of commercial rock salt. Most of the evidence of ice segregation which was found was in the form of clusters although some evidence of the formation of lenses of clear ice was observed. The maximum size of crystal recorded was 3/4 inch and the maximum thickness of ice lenses about 1/4 inch.

Not only did visual observations of the nature of the permafrost indicate that retrogression was taking place, but in the earlier work, where hand auger methods were used, there was a very marked variation in the resistance to penetration encountered in extending the borings. In some cases, augering was relatively easy, but where the frost was continuous progress was very slow.

The maximum depth to which permafrost has been observed is 30 feet but generally it does not extend below a depth of about 14 feet. It is interesting to note that of those borings which were carried beyond a depth of 14 feet the bottom of the permafrost was encountered between depths of 13 and 15 feet in approximately half of them. The maximum depth of continuous permafrost which was encountered was 22 feet.

Since the time when the first investigation was completed in 1957 the town of Thompson has enjoyed a substantial development. There are now over 700 houses, a modern hotel and hospital, a large completely enclosed Shopping Centre, two schools and many other small commercial and service buildings. The foundation performance of the great majority of these has been satisfactory but, at some sites and particularly where no preliminary soil investigations were conducted, foundation troubles have developed. As might possibly be expected the major problems have been in connection with buildings which cover a substantial area. An example of this is the case of the first school building erected. At this school site, where four test borings were put down and where permafrost was found to underlie the entire building area, a heavily reinforced structural concrete slab was used without a foundation wall. Subsequently, extensive settlements have taken place in the building and differential movements of as much as 18 inches have been measured.

Movements have also occurred in a number of house foundations, resulting in extensive damage. It is now a requirement that at least one test boring be put down on each lot before constuction is permitted to proceed to ensure that permafrost is not present.

The history of foundation movements in Thompson is that they occur quickly and this supports other evidence that the permafrost is disappearing very rapidly. Sufficient information is available to suggest that the permafrost will thaw during one summer from a cleared piece of ground, but complete reconsolidation of the soil within the frozen zone may not be complete in this time.

There have been a number of types of foundations used at Thompson. In areas where the dense sand and gravel strata are within economical pile length, point-bearing timber, or concrete piles have been used and have proven satisfactory. In other areas, where permafrost has been encountered, drilled cast-in-place concrete piles are being used, the length of the pile depending on the depth of the permafrost. It has been the general practice to assume no support down to a depth equal to twice the depth of the permafrost and then assume a pile loading capacity equal to between 300 and 500 pounds per square foot of pile surface area. By providing an extra length of pile equal to twice the depth of the permafrost, allowance is made for the negative skin friction effect produced when the permafrost melts and the unfrozen soil begins to consolidate. The comparatively low skin friction values which have been used for design purposes reflect the low values secured in laboratory strength tests.

Spread footings have also been used in the design of a number of structures. An example of this is the shopping centre which covers an area of approximately 90,000 square feet and which is completely enclosed. It is carried on pad footings with adjustable columns being provided to take up any differential movements that may occur. The maximum movement recorded to date is about 6 inches. Spread footings are now being recommended in those areas where the soil moisture content profile does not show any abnormally high values which would indicate very recent permafrost, and where the shearing strength of the varved silt and clay material is not less than one-half ton per square foot.

In areas where recent clearing has resulted in the decay of the permafrost, but comparatively high natural moisture contents still exist due to incomplete reconsolidation in the permafrost horizon, displacement piles such as creosoted timber piles appear to offer advantages. The driving of these piles will have a consolidating effect in the former permafrost zone, and there appears to be no reason to assume that negative skin friction will develop. If the strength of the clay below the permafrost zone is assessed by means of in situ vane shear tests, and the piles are assumed to act as friction piles in the clay, they can be designed very economically. They need not be extended to the depth of the underlying sand and gravel. Where site conditions are such that permafrost thawing has occurred only a few months previous to construction, it is considered advisable to use structural basement floors carried on piles similar to those used for the foundations.

A surprisingly wide variety of foundation types have been successfully used in the Thompson area, but there appears still to be ample scope for further investigations and study. The records and data available at the present time undoubtedly provide a valuable source of knowledge, and even the preparation of this paper, which involved a review of old files, has pointed out new avenues for study. For example, it would be interesting to determine what effect the freezing and subsequent thawing of soil has had on the swelling characteristics of the clays. Detailed studies of the moisture content profiles in recently thawed permafrost areas to determine the moisture migration pattern, as well as studies of the degree of distortion to the soil skeleton resulting from the freezing and thawing cycle would provide data which would be both interesting and of practical value.

There is no question but that the Thompson area can provide a tremendous amount of useful information regarding permafrost conditions, information which will be of great value in the ultimate development of the Canadian North.

REFERENCES

1. Bjerrum, L. Geotechnical Properties of Norwegian Marine Clays. Geotechnique, Vol. IV, 1954. pp. 49-69.
2. Charles, J. L. Permafrost Aspects of Hudson Bay Railroad. A.S.C.E. Paper 2319, 1959.
3. Hardy, R.M. and Legget, R.F. Boulder in Varved Clay at Steep Rock Lake, Ontario, Canada. Bulletin Geol. Soc. of America, Vol. 71, January 1960, pp. 93-94.
4. Thomas, M.K. Climatological Atlas of Canada. National Research Council Public. No. 3151, 1953.
5. Whitman, E.W., Reipas, S.A. and Hardy, R.M. Unusual Problems in the Development of the Caland Mining Operation at Steep Rock Lake. Presented to Annual Meeting E.I.C., June 1960. In press.

Discussion

G. J. Sladek commented that permafrost occurs at Thompson in scattered islands underlying somewhat less than 50 per cent of the townsite area. In some of these frozen areas, it is neither practical nor desirable to maintain the soil in the perennially frozen state. He asked if it is possible, with present techniques of field investigations, to predict the rate at which the permafrost can be expected to degrade either in undisturbed or disturbed areas. The author replied that it is not possible.

R. G. Howard enquired whether any precautions were taken when pouring cast-in-place concrete piles in permafrost to prevent freezing of the concrete. C. A. Nesbitt stated that no precautions were taken. After the holes were drilled, reinforcing steel was installed and then the concrete was placed.

H. G. Dutz wished to know what effect the destructive qualities of permafrost on housing have on the prospective purchasers. C. A. Nesbitt's answer was that under controls enforced by the Central Mortgage and Housing Corporation and the town authorities, the developers have repaired the damage to houses at their own costs in all cases.

The author remarked that the National Research Council has been making ground temperature measurements in the Thompson area. G. H. Johnston added that temperatures to depths of 25 feet measured by thermocouples have ranged from 31°F to 31.5°F.

J. R. Lotz wished to know what extent the settlement and movement of buildings caused by the thawing of permafrost have caused people occupying houses to complain, to leave the town, or to avoid buying and building their own houses. In other words, how much social disruption has been caused by this physical disruption? C. A. Nesbitt replied that before 1958 there was a problem because drilling was not undertaken on each house lot to determine whether or not permafrost was present. Since 1958, this has been a requirement and lots having permafrost were not used for houses.

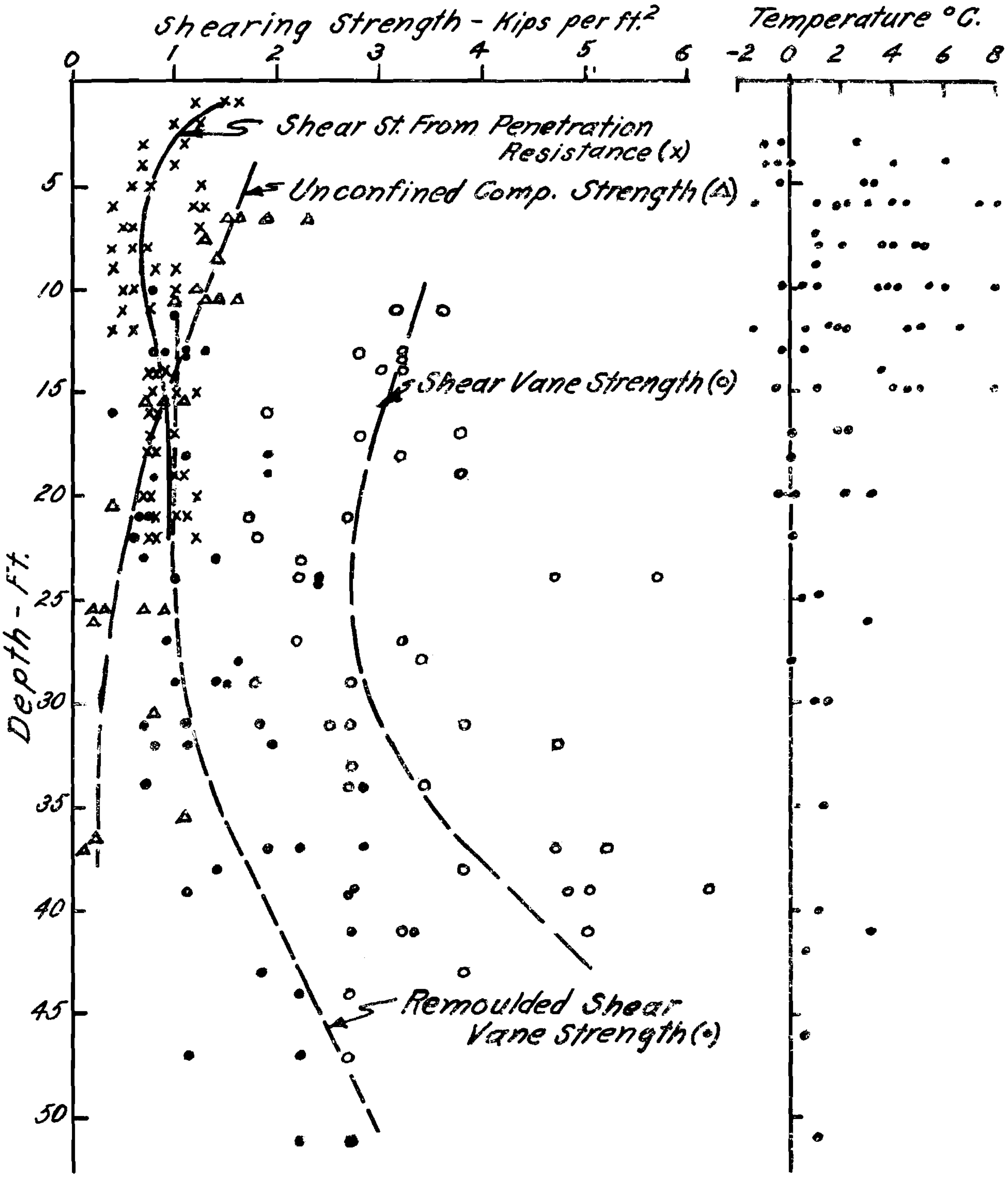

Shearing Strength - Kips per ft.^{2}
0
1
2
3
4
5
6
Temperature °C.
-2
0
2
4
6
8
Shear St. From Penetration Resistance (x)
Unconfined Comp. Strength (△)
Shear Vane Strength (○)
Remoulded Shear Vane Strength (•)
Depth - Ft.
5
10
15
20
25
30
35
40
45
50

FIGURE 1

III. 2. REVIEW OF A RECENT ARCTIC SOIL INVESTIGATION *

A. Thorley

(Summary)

Several isolated locations were investigated in the northern areas of Canada stretching from Cape Dyer, on Baffin Island, in the east to the Alaska coast in the west between latitudes 60°N and 70°N.

Mobilization in the arctic was done by staging out of Montreal and Edmonton and demobilization via Winnipeg in DC-4 aircraft. DC-3 aircraft were used for lateral flights in the east-west direction. As a result of this, medium-weight Longyear Junior drills with hydraulic heads were chosen for the investigation.

The investigations for each of these locations were carried out for various types of structures which include, warehouse, office quarters, and, in one instance, a water tower. In most cases, the foundation for each structure was investigated by at least three holes across the diagonal of the proposed area, two of which were carried to a depth of 25 feet and the middle hole to 50 feet provided no bedrock was encountered within these limits.

DRILLING TECHNIQUES

Throughout the investigation NXL series of drill equipment was used. Both carbaloid and diamond bits were supplied to the crews. Generally speaking, these bits were mostly of the bottom discharge type although ordinary standard bits were used with some success when the supply of bottom discharge bits ended. Both water and diesel oil were used throughout the investigation as bit coolants. Generally speaking, in the eastern portion of the investigated area diesel fuel was used continuously while in the west, where soil conditions differed, water was found to be quite adequate.

The coolant was circulated in a closed system. The returns from the hole collected in a settlement basin with a run-off to an additional basin from which the coolant was re-pumped down the hole. At no time during the investigation was refrigeration used.

PERFORMANCE OF DRILLING EQUIPMENT

The most successful diamond bit used in the performance of

---

* Additional information on this investigation can be obtained from the author.

this work was the broad-faced bottom discharge type. Other types of bits which have come to be known as permafrost bits were used. These bits, having a very sharp leading edge set with diamonds, are slanted down approximately 45° to the inside gauge. This particular type of bit was found to be inadequate in the regions of very dense bouldery soils in the eastern arctic because the cutting edge failed. The cut-out value on this type of bit, however, is relatively high. Carbaloid bits were also tried during this period of the investigation, but the standard type of carbaloid bit which has a simple vertical insert was found to be inadequate because the inserts dropped out in the bouldery material causing a complete burn-out of the bit after only a few feet of penetration. These bits were used quite successfully, however, in the easier drilling conditions encountered in the eastern end of the area investigated. Core recovery during the period of this investigation was usually about 100%. It was noticed, however, that a loss of 15% to 20% of core diameter occurred during coring. This loss is dependent upon the time taken for coring. In the dense bouldery soils, coring time is rather long and therefore the loss of diameter is greater than in the perennially frozen silts and clays where coring time is of the order of 5 to 10 minutes for a five foot run.

Another difficulty which was encountered during the drilling was the jamming of the casing when drilling with diesel fuel. The soil cuttings had no natural inclination to mix with the diesel fuel but tended to come up suspended in the diesel fuel filters through this artificially formed filter. This condition is not hard to detect because the engine begins to labour and eventually stalls. This difficulty is overcome by a simple operation of retracting the casing about 12 inches before further advance.

TYPES OF PERMAFROST ENCOUNTERED

The character of the permafrost was somewhat different at each location, but for the sake of clarity three typical types were described.

1. Large isolated lenses of frozen silt in the till were observed in the Cape Dyer region.
2. Overburden, 7 to 8 feet thick, perennially frozen overburden or overburden frozen throughout or containing patches of permafrost, was observed in the central part of the investigated region.
3. In the western part of the investigated region, particularly in Alaska, permafrost was found throughout the full 50 foot depth of each hole.

TYPES OF FOUNDATIONS UTILIZED FOR THE PERMAFROST CONDITIONS

1. In the areas of isolated lenses of permafrost in till, spread foundations enclosed in gravel pads were utilized to preserve the frozen state of the existing overburden.
2. In the areas of thin perennially frozen overburden and overburden containing patches of permafrost, spread foundations and gravel pads were utilized.
3. In the area where the permafrost existed just below the surface or at depths of 8 to 15 feet below the surface, piles drilled down to the permafrost were utilized for the foundations of structures. In one area, where the permafrost was about 12 inches below the existing ground surface, a gravel pad was considered as an alternative with a structural raft foundation for heavier foundations associated with the water tower.

CONCLUSION

This paper was submitted in order that the experiences gained with drilling equipment could be presented. It is hoped that the difficulties experienced and comments may be of assistance to investigators and that this paper has indicated the necessity for the pooling of all information gained in this type of investigation in order that the techniques of drilling may be improved.

******

Discussion

T. A. Harwood stated that the DEW Line sites were chosen under difficult conditions in late winter when the ground was snow covered. He asked whether the author noticed any foundation deflection in the three types of foundations used, i.e. piles, pads, foundations anchored to bedrock. The author replied that no movements were noticed. Gravel pads were used widely in the eastern arctic, for example in the Foxe Basin area where coarse-grained tills exist. Pile foundations were used in the western arctic where fine-grained soils are widespread.

A. Taylor reported on a visit to some of the DEW Line sites in the Committee Bay, N.W.T. area in 1958. The buildings were placed on thick fills on sharp bedrock ridges. The gravel pads were placed quickly with no subsequent compaction. Settlements of 18 inches developed in some of the buildings and shims were required to level the buildings. T. A. Harwood commented that in some cases the contractor changed the specifications.

G. Jacobsen asked what procedure was used when a boulder was encountered in the drilling. The author's answer was that the hole was drilled through the boulder.

J. C. Osler wished to know the cost of the diamond bits. The author replied that about $1800 worth of diamonds were used.

J. C. Osler submitted the following discussion:
The purpose of this discussion is to present some parallel data to that presented by the author, based on several investigations performed in permafrost areas by Geocon Ltd. during the past two years.

During 1960, soils investigations were carried out at 11 sites, bounded by longitude 60°W to 150°W and latitude 65°N to 70°N. Another major investigation was carried out in the Fort Churchill area in November and December of 1961.

Equipment

The drilling was carried out using Longyear Junior Straitline drill rigs with "A" heads. Both hydraulic and screw feed heads were used. In general, the hydraulic head machine proved more satisfactory for permafrost drilling because of the greater variation in the rate of feed, but it is emphasized that the experience and technique of the operator is perhaps just as important as the type of equipment used.

All of the drilling was carried out in NX size. For the work in 1960, standard NX double tube core barrels were employed, both rigid and swivel types. In general, the swivel-type barrels, believed to be NXM series, were employed for drilling frozen soil while the rigid barrels were sometimes used for rock coring. In 1961, "L" series core barrels were employed. The NXL barrels produced superior core recoveries, particularly in unsaturated and poorly bonded granular soils.

Much of the work in 1960 was carried out between July and September, under summer conditions. During this period, the drilling fluid was cooled by a refrigerator. The other work reviewed in this discussion was carried out at different times between November and March and the drilling fluid was cooled by the atmosphere. The refrigerator used was custom-built to Geocon specifications by a Montreal firm. It was basically a three-ton commercial refrigeration unit powered by a 5 horse power air cooled gasoline motor. The unit measured about 4'-6" by 3'-3" by 4' high and weighed about 900 pounds. Freon was used as a refrigerant and the heat exchanger was an open system, which is believed to be superior for this type of work, since there is less chance of plugging of the heat exchanger by dirt in the circulating fluid. The specification given for the refrigerator was that it should cool 125 gallons of kerosene per hour from 40°F to 20°F; the unit provided had a capacity of 36,000 btu's per hour. The cost of the refrigerator was $1,550, not including the motor. The unit proved sufficiently rugged for this type of work, although one breakdown was experienced due to rough handling.

Diamond bits were employed for all the drilling in permafrost. Standard, bevel wall, surface set bits were generally used and the wear experienced ran usually between $1.00 and $2.00 per foot drilled. This type of bit did not prove satisfactory for drilling in strata of poorly bonded sand and gravel with a low degree of ice saturation. Much better results were obtained by using impregnated diamond bits when drilling in these strata. Whereas surface set bits were worn out in a few feet, a similar experience to that described by the author, the impregnated bits lasted from 20 to 40 feet.

Drilling Time

The time required to investigate 10 sites during the period July to September 1960 has been analyzed. The work was executed in 42 working days, comprising a total of 430 hours. In this period, 30 boreholes were drilled with a total footage of 700 feet. This time includes all time spent setting-up and moving at the individual sites but does not include time spent moving between sites. The time required to move between sites amounted to 59 days. Air transportation was used for all but one move where water transportation was employed.

Considering that the work was carried out during the period when weather conditions are at their best in this region, the delays encountered on this job are considered significant. Of the 59 days spent moving, 15 were incurred by one crew waiting to move to a final scheduled eleventh site. Work at this site was ultimately cancelled. Even if this 15-day period is disregarded, some 44 days were required for moving between sites compared to 42 working days at the sites.

Core Recovery in Frozen Soil

Two typical borehole logs are presented which show core recoveries obtained in a wide variety of types of frozen soil and rock. Both holes were drilled with standard core barrels and so the recoveries are lower than would have been obtained using the "L" series core barrel. For example, at Fort Churchill, over 300 feet of core was drilled in poorly bonded frozen sand and gravel or siltstone bedrock using the "L" series barrel and the average core recovery was about 70 per cent.

The logs show the extent that crystalline ice can occur in permafrost. A knowledge of the existence of such unfavourable subsoil conditions is of major importance in foundation design in the Arctic and indicates the value of reliable soils information.

GEOCON

OFFICE REPORT ON SOIL EXPLORATION

CONTRACT S-2497 BORING # DATUM LOCAL CASING NX
BORING DATE AUG. 18, 1960 REPORT DATE SEPT. 12, 1960 COMPILED BY J. W. A. CHECKED BY R. C.
SAMPLER HAMMER WT. 140 LBS. DROP 30 INCHES CASING HAMMER WT. ____ LBS. DROP ____ INCHES

SAMPLE CONDITION

- ▭ DISTURBED
- ▥ FAIR
- ▨ GOOD
- ■ LOST

SAMPLE TYPES

- A.S. - AUGER SAMPLE
- S.T. - SLOTTED TUBE
- W.S. - WASHED SAMPLE
- D.O. - DRIVE-OPEN
- D.F. - DRIVE-FOOT VALVE
- C.S. - CHUNK SAMPLE
- F.S. - FOIL SAMPLE
- S.O. - SLEEVE-OPEN
- S.F. - SLEEVE-FOOT VALVE
- T.O. - THIN WALLED OPEN
- R.C. - ROCK CORE

ABBREVIATIONS

- V - IN-SITU VANE TEST
- M - MECHANICAL ANALYSIS
- U - UNCONFINED COMPRESSION
- Qc - TRIAXIAL CONSOLIDATED QUICK
- Q - TRIAXIAL QUICK
- S - DEGREE OF ICE SATURATION
- γ_f - FROZEN UNIT WEIGHT
- K - PERMEABILITY
- C - CONSOLIDATION
- γ_w WET UNIT WEIGHT
- WL - WATER LEVEL IN CASING
- WT - WATER TABLE IN SOIL

SOIL PROFILE

ELEVN. / DEPTH	WATER CONDITIONS	SOIL DESCRIPTION	SYMBOL	ICE DESCRIPTION
12.7 / 0.0		GROUND		LEVEL
9.2 / 3.5		LOOSE GREY-BROWN SAND & GRAVEL FILL	GP	UNFROZEN
8.7 / 4.0		DARK BROWN SILTY PEAT HIGH DEGREE OF ICE SATURATION	PT ML	PROBABLY UNFROZEN
7.5 / 5.2				FROZEN, WHITE CLOUDY IRREGULAR ICE LENSES
1.7 / 11.0		10% TO 20% ± - MOSTLY DARK BROWN PEAT INCLUSIONS INCLINED @ 45° TO 60°, SOME WOOD, OCCASIONAL GRAVEL	PT ICE	ICE, HARD, CLOUDY, ABOUT 80% TO 90% OF TOTAL VOLUME
-5.3 / 18.0		GREY SLIGHTLY SILTY FINE & MEDIUM SAND, OCCASIONAL GRAVEL, HIGH DEGREE OF ICE SATURATION	SM IC IX	FROZEN, SAND WELL-BONDED, GRAVEL PARTICLES POORLY BONDED, ICE CRYSTALS
-6.0 / 18.7		PROBABLY GREY BROWN GRAVELLY SAND	SW	FROZEN, POORLY BONDED
		END	OF	HOLE

WATER CONTENT W% ○ NAT. □ Lw △ Pw 20 40 60
CASING PENETRATION BLOWS PER FOOT

ELEVATION SCALE	WATER CONTENT / PLOT	OTHER TESTS — % CORE REC.	CONDITION	TYPE	NUMBER	PENETRATION RESISTANCE BLOWS FT.
9		28%	☒	NX RC	1	—
8	WC 51.5%	S=99.5% γ=64pcf	☒	2" DO	2	35/6"
6.5		58%	▥	NX RC	3	—
4.5		91%	▨	NX RC	4	—
2		32%	☒	NX RC	5	—
-1	S=96.0%	M γ105pcf 30%	☒	NX RC	6	—
-4		0%	■	NX RC	7	
-5.3			☒	2" DO	8	50/5"
-6	WC=18.5%	S=100% γ=81pcf	☒	2" DO	9	—

Elevation scale: 14, 12, 10, 8, 6, 4, 2, 0, -2, -4, -6

GEOCON

OFFICE REPORT ON SOIL EXPLORATION

CONTRACT S-2497 BORING # ________ DATUM LOCAL CASING NX
BORING DATE SEPT. 2, 1960 REPORT DATE SEPT. 27, 1960 COMPILED BY J. W. A. CHECKED BY R. A. S.
SAMPLER HAMMER WT. 140 LBS. DROP 29 INCHES CASING HAMMER WT. ________ LBS. DROP ________ INCHES -

SAMPLE CONDITION

- ☐ DISTURBED
- ▥ FAIR
- ▨ GOOD
- ■ LOST

SAMPLE TYPES

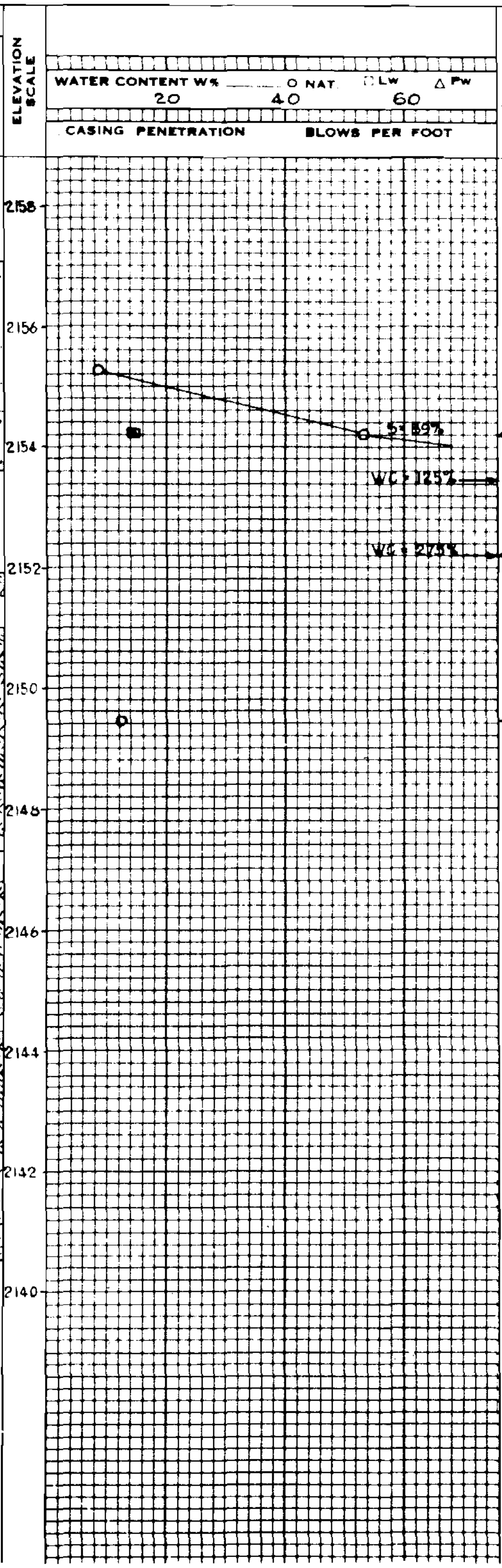
A.S. - AUGER SAMPLE
S.T. - SLOTTED TUBE
W.S. - WASHED SAMPLE
D.O. - DRIVE-OPEN
D.F. - DRIVE-FOOT VALVE
C.S. - CHUNK SAMPLE
F.S. - FOIL SAMPLE
S.O. - SLEEVE-OPEN
S.F. - SLEEVE-FOOT VALVE
T.O. - THIN WALLED OPEN
R.C. - ROCK CORE

ABBREVIATIONS

V - IN-SITU VANE TEST
M - MECHANICAL ANALYSIS
U - UNCONFINED COMPRESSION
QC - TRIAXIAL CONSOLIDATED QUICK
Q - TRIAXIAL QUICK
S - DEGREE OF ICE SATURATION
γ - FROZEN UNIT WEIGHT
K - PERMEABILITY
C - CONSOLIDATION
γ - WET UNIT WEIGHT
WL - WATER LEVEL IN CASING
WT - WATER TABLE IN SOIL

SOIL PROFILE

ELEVN. DEPTH	WATER CONDITIONS	SOIL DESCRIPTION	SYMBOL	ICE DESCRIPTION	STRAT. PLOT
2157.1 0.0		GROUND		LEVEL	
		COMPACT BROWN POORLY GRADED SANDY GRAVEL	GP GM	UNFROZEN	
2154.6 2.5		BROWN SILTY SAND	SM II	FROZEN, IRREGULARLY ORIENTED LENSES & MASSES ⅛" TO ½" THICK, ⅛" TO ½" SPACING. ICE 25%± BY VOL.	
2153.6 3.5		BROWN SILTY SAND INCLUSIONS	SM ICE	MASSIVE ICE 70%± BY VOL. ICE HARD, CLEAR COLOURLESS	
2151.9 5.2		WEATHERED BEDROCK		FROZEN	
2151.5 5.6		INCLUSION: SILTY SAND	SM ICE	MASSIVE ICE : 70%± BY VOL.	
2151.0 6.1		WEATHERED GREY BASIC VESICULAR LAVA BEDROCK	IS	FROZEN, 1 ICE LENS ½" THICK 1 ICE LENS 2" THICK	
2147.3 9.8			ICE	MASSIVE ICE : 40%± BY VOL.	
2146.8 10.3			IS	FROZEN, 5 ICE LENSES ¼" THICK 1 ICE LENS ⅛" THICK	
2144.3 12.8		SOUND GREY BASIC VESICULAR LAVA BEDROCK		FROZEN	
2140.5 16.6		END OF		HOLE	



OTHER TESTS —	% CORE REC	CONDITION	TYPE	NUMBER	PENETRATION RESISTANCE BLOWS FT.
		☒	2" DC	1	20
M γ=92pcf	91%	▨	NX RC	2	—
γ=67pcf S=99%	95%	▨	NX RC	3	—
γ=121pcf	81%	▨	NX RC	4	—
	100%	▨	NX RC	5	—
	94%	▨	NX RC	6	—

III.3. FIELD DESCRIPTION OF PERMAFROST*

J. A. Pihlainen and G. H. Johnston

(Summary)

The need for adequate investigations of permafrost conditions for an engineering appraisal at northern sites is generally recognized. To the present time, however, no uniform procedure has been used for collecting and reporting such information. A suggested method for describing permafrost conditions in the field is presented, primarily for use by engineers but also for others through adaptation.

Permafrost is defined as the thermal condition under which earth materials exist at a temperature below 32°F continuously for a number of years. Although a number of factors affect the occurrence and existence of permafrost, many are quite complex and not easily measured or described in the field. The descriptive system is, therefore, based on a recognition of terrain features which can be more readily assessed in a qualitative manner. Pertinent information should be collected on terrain features which exist on the ground surface -- vegetation and snow cover, relief and drainage; and below the ground surface -- soil type and ice phase.

The vegetative mantle of trees, shrubs, moss, lichen and other plants that covers much of the north acts as an insulator to protect and maintain permafrost. The vegetation should be described using the system outlined in the "Guide to a Field Description of Muskeg" (Technical Memorandum 44) published by the Associate Committee on Soil and Snow Mechanics of the National Research Council of Canada. Although snow is basically a part of the climate, snow cover is generally considered as a terrain factor. The type of snow, the depth of snow cover and their variability over a site throughout the winter season should therefore be observed. Terrain relief influences permafrost occurrence and since it is also a significant factor in drainage, it is an important engineering consideration. Notes on relief features should not be restricted only to the specific location under investigation but should include all of the region in the vicinity of the observation locations and, in addition, small scale or micro features.

The subsurface observations include those of the depth of thaw which is affected by and closely related to terrain features. Records

---

* The complete field description will be published in booklet form in the Technical Memorandum series of the Associate Committee on Soil and Snow Mechanics of the National Research Council.

of the depth of thaw should include notes on the date of observation, vegetative cover, relief, drainage and a description of the subsurface materials in the various areas investigated. For engineering purposes, it is convenient to describe the soil and ice phases independently. Mineral soils may be described according to the "Guide to a Field Description of Soils" (Technical Memorandum 37) published by the Associate Committee on Soil and Snow Mechanics; organic soils according to the system outlined in the "Guide to a Field Description of Muskeg" (Technical Memorandum 44).

The descriptive system for the ice phase is based on the form of ice found in frozen materials. It is not intended that this system be an assessment of frozen materials according to properties or performance. For descriptive purposes, frozen materials are divided into three major groups in which the ice is --

1. Not visible by eye
2. Visible by eye with individual ice layers less than 1 inch in thickness, and
3. Visible by eye with individual ice layers greater than 1 inch in thickness.

It is hoped that this suggested field description of permafrost will be utilized by scientists and engineers both in Canada and the United States. It is conceded to be only a first approach to the fundamental descriptive requirements of permafrost and, accordingly, all comments and criticisms will be welcomed.

****

Discussion

T. A. Harwood asked how Dr. Radforth's "climafrost" can be included in the original definition of permafrost. J. A. Pihlainen stated that there are many terms associated with permafrost which have been introduced into both the English and Russian literature. It is possible to use any of these terms including "climafrost" in this proposed field descriptive system if the terms are defined and translated into the system.

A. Thorley wanted to know how the presence of permafrost canbe detectedin a sand with a low moisture content. Pihlainen replied that sands with low moisture content are friable. The bonding characteristics should be noted.

G. Jacobsen remarked that, according to S. W. Müller's definition, permafrost includes material which remains frozen for two years or more. The definition of permafrost in the field descriptive system should be the same. Pihlainen answered that the phrase "number of years" can include two years. The possibility of the presence of seasonal frost which persists for a few years and then dissipates is acknowledged.

N. W. Radforth commented that it appears that many of the terms that we are dealing with have the suffix "frost". The authors acknowledge the presence of climafrost which demonstrates the flexibility of the field descriptive system. In the definition of permafrost, the number of years should be pinpointed. In depth of thaw observations, the year should be noted in addition to the month and day. The use of the "Guide to a Field Description of Muskeg" applies only to organic terrain. Pihlainen emphasized that this proposed field descriptive system is only meant as a first approximation. It must be tried in the field to see how applicable it is and to improve it. T. Lloyd added that the suggested field descriptive system has the important advantage of being universally applicable, independent of any particular language or local situation.

R. J. E. Brown reported that the problem of permafrost nomenclature is receiving attention in both Canada and the United States. Recently there has been a proposal to form a task committee on Frost and Permafrost nomenclature of the American Society of Civil Engineers. This task committee will consist of six members - three Canadian and three American. The proposed Canadian members are: T. A. Harwood, Defence Research Board, Ottawa; J. R. Mackay, Department of Geography, University of British Columbia; R. J. E. Brown, Division of Building Research, National Research Council. The proposed American members are: F. Hennion, U. S. Corps of Engineers, Washington; A. W. Johnson, Highway Research Board, Washington; A. L. Washburn, Department of Geology, Yale University. It is hoped that this task committee can achieve some uniformity in the definition and use of permafrost terms.

III. 4. FOUNDATION PROBLEMS AT FORT McPHERSON, N.W.T.

R. Harding

During the period from July 1956 to December 1958, the Department of Public Works was responsible for the construction of several buildings at Fort McPherson, N.W.T. The construction of these buildings was complicated by the presence of permafrost throughout the entire area covered by the project. This paper deals with the problems encountered in placing the foundations for these structures.

The settlement of Fort McPherson is located on the Peel River at latitude 67° 30' N and longitude 135°W. Fort McPherson is approximately 1,200 miles northwest of Edmonton, 60 miles south of Aklavik and 60 miles north of the Arctic Circle.

Although Fort McPherson is not actually in the Mackenzie River delta, the general conditions of temperature and precipitation are similar. The settlement is located on the right or east bank of the Peel River, and the river flows almost due north at this point. Actually, the settlement is located on a rise of land which is an island at high water level in the Peel River. This island is roughly triangular in shape. It is approximately 7,000 feet long in the north-south axis and approximately 3,000 feet wide at the base to the south. The settlement is generally 50 to 60 feet above the average river level and the whole area is approximately 80 to 100 feet above sea level.

Fort McPherson is in a permafrost area and the estimated thickness of permafrost is 1,000 feet. On the project site, at depths varying from 9 to 16 feet, a hard grey to black shale was encountered. Test pits dug on the site gave completely inaccurate information of the depth to this shale. This grey black shale, when taken from the bottom of an excavation, is very hard and appears to be quite durable. It does not weather well and, when allowed to dry, breaks into literally thousands of small pieces. These pieces in turn, if subjected to traffic, will quickly disintegrate to rock flour.

The overburden on the project site was rotten shale, badly fragmented, due to frost action. Between the depths of 6 inches and 3 1/2 feet, large ice lenses were encountered. In places, these were nearly pure ice with only hair-line traces of silt running through them.

The surface cover in the area is moss which has an amazing insulation value. In many areas, permafrost occurred directly beneath a moss cover only 6 inches thick. In areas not cleared, there were generally small birch. In the low-lying areas around the lakes and creeks, there was a very dense growth of alders and spruce. The spruce grows in fairly dense stands and 30 foot piles with 12 inch butts and 8 inch tips were cut for the garage and wharf foundations within 1 1/2 miles of the settlement.

The Fort McPherson project consisted of the following group of structures:

100-Pupil Hostel, approximate floor area - 30,000 square feet
3-Classroom Addition to the existing school
4-Apartment Teacherage
A Generator House
A Warehouse
A Walk-in Freezer
An Ice House
4-Bay Garage
A Bulk Oil Storage Tank - 10,000 barrel capacity.

These buildings were placed on four types of foundations.

(i) The hostel and generator house were constructed on concrete piers with reinforced concrete beams poured monolithically.

(ii) The 3-classroom addition to the school, 4-apartment teacherage, walk-in freezer, and warehouse were constructed on concrete piers using laminated timber beams.

(iii) The garage was placed on timber piles, the only structure at Fort McPherson with the exception of the wharf to be placed on piles.

(iv) The ice house was placed on mud sills on a shale pad placed directly over the moss. The bulk oil storage tank was also placed on a shale pad approximately 6 feet in depth.

As stated previously, test pits were dug on the site which proved to be completely inaccurate. For example, in the area of the walk-in freezer, a test pit was dug which indicated hard shale at approximately 9 feet 8 inches. Shale was not encountered until a depth of 16 feet when the actual excavations were made for the foundations. In the area of the boiler house, the test pit indicated that shale would be encountered at 9 feet, and again, shale was not reached until a depth of 16 feet at the time of construction. These two examples will give some indication of the inaccuracy of the test pits.

During preliminary planning, it was proposed that the hostel would be constructed on piles similar to the hostel erected at Inuvik, N.W.T. As a result of the test pits, however, the design was changed to concrete piers as it was felt that there was not sufficient overburden on the shale to place piles.

The first construction crew members arrived on the site in mid-July 1956, approximately one week before the scheduled arrival of the first barges loaded with materials.

With a very short construction season ahead, the aim was to get as many buildings closed in as possible before winter began. Aggregate for concrete was to be hauled by one of the transportation companies on the Mackenzie River system, from a gravel beach at the mouth of the Peel River about 40 miles downstream from Fort McPherson. This gravel was to be loaded and hauled as soon as shipping started.

As a result, the excavations for the piers had to be started immediately to be ready to place concrete when the gravel arrived. The gravel did not arrive as scheduled and the problem arose of preventing thawing of about 100 excavations approximately 4 feet by 4 feet by 11 feet deep. This proved impossible and the large ice lenses, referred to previously, melted and literally poured into the holes. This was probably a fortunate occurrence because these lenses would have thawed perhaps under any circumstances and would have created even greater problems after the structure was erected. It did create, however, a new problem at the time of construction.

It became obvious, with the excavation of the first holes, that large quantities of backfill were going to be required. Material excavated from the holes contained less than 50% solids and did not even provide enough material to backfill the holes to one-third of their depth. This, coupled with the thawing of the large ice lenses, put demands on the limited equipment available. It became almost impossible to provide the quantity of fill required in the time available. This lack of equipment to handle adequate amounts of backfill complicated the backfilling of the holes at a later date, because it became necessary to drag the fill material under the concrete beams which had already been poured. In other words, the concrete work proceeded much faster than the holes could be backfilled.

Three methods of excavation were used for placing concrete piers. The first was with pick and shovel. The second was with air compressor and jack hammers, and the third was with open pit excavation using jack hammers to break out the material and dragline to remove the excavated material.

The pick and shovel was used at the very start of construction before the equipment arrived on the site. This was obviously a very slow process but it was considered justified because of the short construction season.

When the equipment finally arrived, the process of digging the holes was changed to the use of air compressor and jack hammers, and the native labourers became quite expert in the use of this equipment in the close confines of the 4 foot by 4 foot holes. Using this method of excavation, holes were dug to a depth of 16 feet.

The third method of excavation, the open pit method, is discussed in more detail because the problems were considerably different from the smaller holes. It was decided to use the open pit excavation for the boiler room piers because the pier spacing for this portion of the building was too close for individual hole excavation. Pier spacing was 7 feet 6 inches in the east-west direction and 6 feet 7 inches in the north-south direction. The total excavation covered an area of approximately 68 feet by 45 feet and was 16 feet in depth. This meant approximately 1,800 cubic yards of material were removed. The area was first stripped of its moss cover by the dragline down to permafrost. The jack hammers were then used to break out the frozen material and the pieces thus chipped out were gathered together and removed by the dragline. Severe thawing was experienced on the vertical surfaces exposed by the excavation, particularly on the north face which was exposed directly to the sun. The bottom of the excavation was channelled so that water flowed to one corner and was removed by continuous pumping. Solid shale was encountered at approximately 16 feet below the surface. The total excavation, forming of the piers, beams, and floor slab took exactly one month, from August 13 to September 14. As soon as the excavation was completed, 3 foot by 3 foot pier footings were placed and poured. The piers were formed in place in two 8 foot sections, the upper 8 foot section being placed approximately a week after the lower. The boiler house slab and beams were poured monolithically with the piers. Incorporated into the boiler house slab was a water tank enclosure. This structure was similar to a basement with the difference that the floor slab was supported on piers which went down to the hard shale. To date, no leaks have shown in this water tank enclosure. Figures 1 and 2 show details of the boiler house foundation and Figure 3 shows the completed hostel.

To compare the excavation of the individual holes with the open pit excavation method, the following advantages and disadvantages are listed:

The advantages of the individual holes were:

(i) Less thawing - because less surface was exposed to the sun;
(ii) Less excavation;
(iii) Less backfill is required if the permafrost can be prevented from thawing in the areas between the holes.

The disadvantages of the individual hole method over the open pit excavation were:

(i) Slow digging because of the cramped conditions of the small hole. Obviously the excavation of the hole was a one-man job;
(ii) At depths exceeding 5 feet, material had to be placed in 5-gallon pails and drawn out of the holes by hand;
(iii) Other than the jack hammers, it was impossible to use equipment for the excavation.

In conclusion, there are three points to emphasize as a result of experience at Fort McPherson in placing foundations in permafrost:

(i) Test pit or boring information must be obtained by a person qualified to assess the soil conditions as they are found;
(ii) Sufficient construction equipment of the right type to undertake the work must be available if a project schedule is to be maintained;
(iii) Material deliveries, which affect the construction schedule, must be expedited. In this regard, the critical path method of planning and scheduling appears to offer good possibilities.

******

Discussion

The question was asked by the Construction Division, Department of Public Works if water froze in the excavation during the night. The author replied that the water did not freeze and added that many of the holes were excavated during the previous year.

H. G. Dutz enquired whether the pier foundations for the hostel were satisfactory once the firm shale was reached. Furthermore, did the garage on piles have a structural floor or was it a slab on grade? The author stated that some trouble was experienced with the reinforced concrete beams but there is no record of movement of the piers which bear on the shale. The garage consisted of a laminated wood floor on wood beams on piles.

A. Thorley wondered why churn drills and caissons were not used. The author's answer was that at the time of construction it was not known how deep the holes would have to be excavated. From the test pits, it appeared that the top of the shale was at a depth of 6 feet but it was actually encountered at a depth of 16 feet. Thorley then requested information on the pile foundations. The author remarked that piles could have been installed either by steaming or drilling. He added that it was not possible to drill for the piers because they were tapered, being 12 inches square at the tops and 18 inches square at the bottoms.

G. Jacobsen wished to know if construction was undertaken during winter, to which the author replied that it was undertaken during the summer and early Spring. In September, difficulties were caused by rapidly melting ground ice which caused flooding in the excavations. Conditions were much better in April because the ice remained frozen.

R. D. Lawrence asked what material was encountered at the 9 foot depth. The author replied that it was the same as above. More than half of the ground material was ice.

N. D. Radforth commented that the use of moss and peat as insulating materials in construction is questionable. It deteriorates rapidly and has different properties from those in the undisturbed state. This applied whether it is used in buildings or roads.

In reply to M. Bruno's request for information on the performance of roads, the author stated that they performed poorly at the beginning. Eventually clay was added to the shale which was an improvement although the roads were greasy when wet. Near the end of the job, the roads were surfaced with gravel which improved them considerably.

Fig. 1 View towards the northwest corner of the excavation for the boiler room piers. Note the depth of excavation - approximately 16 ft. below grade. August 29, 1957.

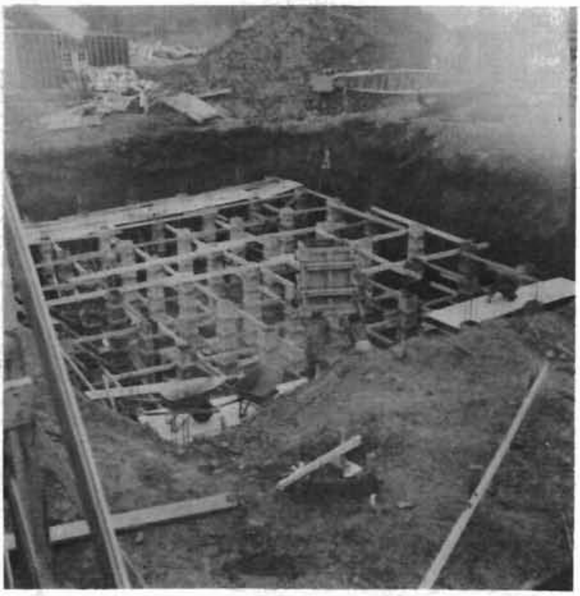


Fig. 2 Pouring first lift of boiler room piers. Note crane holding concrete hopper. August 30, 1957.

Fig. 3 View southeast showing front elevation of completed hostel. Note teacherage in background (center-right). June 1958.

III. 5. DEPARTMENT OF TRANSPORT PROCEDURES FOR THE DESIGN OF PAVEMENT FACILITIES AND FOUNDATION STRUCTURES IN PERMAFROST SUBGRADE SOIL AREAS

G. Y. Sebastyan

GENERAL

The first stage in opening northern areas for development is the establishment of transportation and communication facilities. For this reason the Canadian Department of Transport has major responsibilities in design and construction work for northern projects.

The Construction Branch of the Department of Transport carries out the design work and supervises the subsequent construction programme.

Major Construction Branch responsibilities are:

(a) The design and supervision of construction for air transportation pavement facilities.
(b) The design and supervision of construction of engineering structures related to air transportation, telecommunication, navigational aids for air and water transportation and weather stations.

There are three major factors influencing construction in the North:

(a) The climatic environment, which restricts the construction season to a few months;
(b) Transportation of equipment, spare parts, materials and manpower;
(c) Soil conditions.

Because the climatic conditions seriously restrict engineering operations, it is imperative that construction projects be planned well in advance. To carry out even small projects, two construction seasons are needed. During the first, the preliminary field investigations are carried out; in the second, the transportation of materials and the actual construction work are accomplished.

In the past, considerable difficulty was experienced because of the limited time between the approval of projects and the required completion date.

Lack of sufficient engineering design information made preliminary estimating very difficult and inaccurate. Designs carried out on the basis of insufficient factual evidence tend to be on the conservative side.

In order to carry out the Department of Transport's responsibilities in the most economical and efficient way, it is essential to have all available factual engineering data in the hands of engineers engaged in the design and construction of these facilities.

To satisfy the minimum requirements, a general programme was formulated to obtain technical data on Department of Transport sites where permafrost subgrade soil conditions exist using available Department of Transport personnel and with a minimum expenditure of money.

COLLECTION OF TECHNICAL DATA AND BACKGROUND DESIGN INFORMATION ON DEPARTMENT OF TRANSPORT NORTHERN STATIONS

In April 1961, Construction Branch requested and received the co-operation of the Meteorological and Telecommunication Branches to conduct an engineering survey.

The following programme was formulated and is in the process of being carried out:

(a) Collection and organization of background information concerning soils, materials and existing foundations on sites with permafrost soil conditions. This information is obtained from the following sources:
  (i) Search of Department of Transport files;
  (ii) Library search of published literature;
  (iii) Collection of information available from the National Research Council and other agencies having data on the North.

(b) Determination of the depth of thaw at Department of Transport stations under various climatic, soil and ground cover conditions. In permafrost areas, the depth of thaw is a major factor in the design of pavements and structural foundations. The determination of its maximum value and its variation during the freezing and thawing periods are necessary. Depth of thaw is a function of the following variables:
  (i) Climatic conditions - for the purposes of engineering studies of this type, the influence of temperature on the soil can be represented by freezing and thawing indices. Freezing index information is now available based on a ten-year observation period and was determined by E. B. Wilkins and W. Dujay, Department of Transport, Construction Branch Engineers. The freezing index is being revised on the basis of a 15-year observation period by Dujay. This will be available shortly. Thawing index data is being compiled by the Meteorological Branch at the request of the Construction Branch.

(ii) Thickness and type of cover vegetation.

(iii) Soil condition, soil type, moisture content, ice segregation, etc.

The detailed procedure for the determination of the depth of thaw penetration is given in Appendix "A".

In 1961, the depth of thaw survey was carried out at 11 sites on an experimental basis. During 1962, the survey will be carried out at 48 sites. (See map before Figure 1). This survey will be repeated at the same sites during 1963. Figure 1 gives the results of the experimental survey performed in 1961 for a typical site.

(c) Condition Survey of existing structures - In any design work, it is of considerable help for the designer if data is available concerning the behaviour of structures constructed under similar conditions and environments. It has been decided, therefore, to collect information concerning the condition and behaviour of existing major structures in permafrost areas. This survey is being performed by regional engineers who have considerable experience in this field. Information is collected on standard forms during routine visits to the sites. On Figure 2 the result of a typical building survey has been reproduced from the survey carried out in 1961.

(d) Site search for construction materials (aggregate search). The last major step in the Department's programme is the location of possible aggregate sources for construction purposes. From aerial photographs, uncontrolled aerial mosaics are prepared. Using professional help, possible aggregate deposits are selected on the basis of airphoto interpretation and pinpointed on maps.

The ground control survey is performed by regional personnel during the course of regular visits in connection with other requirements necessitating the transportation of engineers or technicians to the site. All data and knowledge available in the regional offices and on the site are collected and recorded on the same map.

GENERAL ENGINEERING PROPERTIES OF PERMAFROST

Permafrost is defined by the Permafrost Subcommittee of the Associate Committee on Soil and Snow Mechanics, of the National Research Council as: "The condition of earth materials remaining below 0°C (32°F) continuously for a number of years."

It is a four-phase system, consisting of soil material, water, ice and air. The relative proportions of these four constituents and their physical characteristics will determine the behaviour of the frozen mass as a whole. (The physical characteristics of ice change with temperature.)

Soil in the perennially frozen state can carry loads of considerable magnitude. The ultimate strength is a function of the type of soil, the density of the soil, the amount of moisture filling the pores, and the temperature of the mass.

In order to demonstrate the order of magnitude of strength for unconfined permafrost soil samples, Figure 3 gives the relationship between strength, soil type, temperature and moisture content (2).

Typical cohesion and internal friction values of frozen soils are given in Table I from laboratory test data (6).

It should be pointed out that if, as a consequence of ice segregation, there is no grain to grain contact between the soil particles, the mass may undergo a viscous deformation due to constant and continuous loadings.

The effect of viscous deformation is demonstrated by the considerable difference in strength between dynamically and statically loaded permafrost specimens. This difference is considerably larger than would be expected for soils.

Another consequence of such viscous properties is the relaxation of adfreezing forces to foundation structures under loading.

Heat transfer through the foundation structure is another contributory factor in bringing about the relaxation of adfreezing forces.

The major problem of design and construction on permafrost is related to that part of the soil profile which undergoes seasonal freezing and thawing, the so-called "active" zone.

If the soil in the active zone is a well drained, non-frost-susceptible coarse-grained material or clay without ice segregation, generally no special problem exists. In any other case, however, the load carrying capacity of the soil falls to an insignificant fraction of its frozen value when thawing. Under load, large vertical settlements and horizontal displacements occur. Figure 4 shows the effect of thawing on the void ratio during consolidation of permafrost samples (1).

During freezing, frost heaving of considerable magnitude occurs. The intensity of frost heaving forces is such that it is uneconomical and impractical in most cases to build structures to resist such forces.

Canadian data on the physical properties of perennially frozen soil is limited. It would be of considerable help for designers if the physical characteristics of permafrost were to be thoroughly investigated by the universities and research organizations. Accumulation of data and knowledge in this field would make possible a reduction of safety factors in design.

PAVEMENT DESIGN IN PERMAFROST

It is most important to take full account and consideration of the subgrade soil conditions and natural drainage when selecting a new site for runway development purposes. A considerable reduction in construction costs can result if the selected site has the best soil and drainage condition available.

Preliminary site selection may be made on the basis of aerial photography, especially by close examination of stereoscopic air photos. On this basis, an estimate can be made of soil conditions and a working knowledge of the surface drainage conditions canbe obtained.

In general, pavement construction in cut areas should be avoided.

In the case of well-drained, non-frost-susceptible coarse-grained subgrade soil or clay without ice segregation, no special problem exists. Pavement design is based on standard Department of Transport procedures. The strength of the subgrade soil is determined in the thawed state, and this strength value is used in design studies. A typical pavement structure designed and constructed as discussed above is given in Figure 5a.

The importance of a preliminary soils investigation cannot be over-emphasized. Even when all outward appearances indicate that the soil deposit is coarse-grained to a considerable depth, ice bodies or layers may occur at various locations, which would subsequently cause pavement deformations, settlement and failure.

When the subgrade soil is frost-susceptible sand, silt, clay or any combination of these soils, the loss in subgrade bearing capacity and the deformation of the subgrade during thawing and freezing is of considerable magnitude. Under thawed conditions, such a subgrade soil might not support the design aircraft load, and pavements cannot be maintained on a continuous basis.

In this case non-frost-susceptible coarse-grained fill of sufficient depth is placed on the subgrade, if the construction of an all-weather pavement is desired. (If necessary a filter is used between the subgrade and fill to prevent subgrade material entering the fill.) The depth of this coarse-grained fill should be such that the upper limit of permafrost will enter the fill and, as a consequence, the subgrade will remain in a perennially frozen state. A pavement structure representing such a design is given in Figure 5b.

A number of theoretical methods exist and are available to determine the necessary minimum fill thickness to arrive at this condition. These methods are based on the thawing index and the properties of the fill (moisture content, etc.). One such method, established by the U.S. Corps of Engineers, is given in Figure 6. Such methods serve as a general guide only. The final design should be based on actual experience on the site.

For demonstraction purposes, the pavement designed for Inuvik, N.W.T. is cited. For this site, the temperature conditions are given by the freezing index (ten-year average 8029, maximum 8581, minimum 6811). The subgrade is a mixture of sand with fines, silt and silty clay. Ice segregation was reported as fine with some thick layers on the east side. Four locations were instrumented by the National Research Council for the determination of the temperature gradient in the pavement structure within the construction area (3 points) and for one control point outside the zone influenced by construction. On Figure 7 in bar chart form, the depth of maximum thaw is demonstrated for the observation period 1957-1961. 1957 was the year of construction.

It is well demonstrated on Figure 7 that the design was exactly correct for the conditions at the site because the frost line at the stage of maximum thaw penetrated about 1 foot into the coarse-grained fill. This is the minimum safety factor desirable. Selection between rigid and flexible pavements is based on economic considerations. (It is interesting to note that the flexural strength of Portland Cement Pavements increases considerably with decreasing temperatures below 32°F.) The maintenance of asphaltic wearing surfaces is more economical under arctic conditions.

The majority of the airstrips maintained in the North have very limited use consisting of transportation of personnel, emergency supplies and maintenance of communications with the South. The construction of such a strip does not warrant the considerable expense of constructing an all-weather surfaced airstrip. To maintain essential services is no problem during winter time. To compensate for the loss of strength in the thawed condition, gravel strips are constructed utilizing the area of best soil conditions. Such strips are generally used only for moderate plane loadings during Spring. The subgrade load carrying capacity is estimated during the Spring thaw and a minimum thickness of coarse-grained fill is provided to distribute the load to the limit of subgrade load carrying capacity. This fill is topped with a well-graded gravel layer 6 to 9 inches thick to provide a fair riding surface.

Such strips require continuous maintenance to compensate for subgrade settlement, frost heaving and loss of fill.

The availability of aggregates for construction purposes is another important problem. It is hoped that the gravel search programme will add considerable information.

FOUNDATION OF BUILDINGS IN PERMAFROST AREAS

A typical soil profile in a permafrost area consists of two distinct zones, the active zone which undergoes periodical freezing and thawing and the perennially frozen zone.

The strength and load carrying capacity of perennially frozen ground is sufficient to carry structures of ordinary size. Northern design and construction work carried out by the Department of Transport fall into this category.

For demonstration purposes, the allowable bearing capacity of perennially frozen ground under various conditions is given in Table II.

Foundations of structures on permafrost become a problem as a consequence of strength and volume changes developing in the active zone. The permafrost table or the depth of thaw may fluctuate due to solar heat, heat generated within the structure, and the disturbance of the temperature regime due to the erection of the structure itself. These fluctuations may be aggravated further by the removal of organic cover, drainage, septic tanks, etc. In fact, because the structure itself usually forms part of a much larger development area, the permafrost table may be permanently changed. The designer must thus anticipate any changes that may occur in the depth of thaw observed, due to site or area development.

If the soil is a coarse-grained non-frost-susceptible deposit, or clay without ice segregation, and it has been established by soils investigation that no ground ice is present, the foundation design is not a special problem. Conventional spread footings can be used successfully. The allowable bearing capacity of spread footings is determined by conventional procedures using the physical properties of the soil in its thawed condition.

In order to improve the drainage conditions, it is preferable to place the structure on a gravel fill 1 to 3 feet in height. The gravel fill should be compacted to at least 98% modified proctor density.

If the soil is frost-susceptible with a high moisture content and ice segregation, there are a number of available methods for the design and construction of foundation structures:

(a) Unheated or small prefabricated structures of secondary importance can be placed on gravel fill 1 to 3 feet in height. The organic ground cover should be left intact under the fill for the reduction of heat exchange. During the summer thaw, such structures may undergo settlement and, during freezing, heaving. However, if the structures are small and of prefabricated wood construction, these deformations should not cause structural damage. An example of such a foundation design is given on Figure 8.

(b) For larger or heated buildings the above method can be improved by the provision of an air space between the foundation and the superstructure. Such an air space reduces the effect of heat transferred between the structure and the permafrost. In general, footings are built 6 to 12 inches into the gravel fill. Jacks are placed in between the structure and the foundation pads. During the freezing and thawing period, the structure might undergo considerable movement. Using the jacks these deformations can be compensated for to a certain degree (Figure 9).

In a similar manner, concrete pedestals were used, except that jacks were not provided between the pedestal and the superstructure. Differential movement occurs in a similar fashion to that described previously, but any readjustment is much more difficult (Figure 10).

Neither of these methods worked well in practice. It was the experience of the Department that, under normal conditions, the continuous adjustment and maintenance of such structures was not a success. In most cases the readjustment of the jacks was not carried out. In some instances, the deformation of the gravel fill during freezing and thawing was considerably larger than the potential range of the jacks.

It is the Department of Transport's policy to design and construct foundation structures which need a minimum of readjustment and maintenance. Consequently, the use of the above-described foundations was discontinued.

(c) If the soil is frost-susceptible with a high moisture content and ice segregation, one successful foundation method is to remove the frost-susceptible material to the permafrost table. Excavated material is replaced by coarse-grained non-frost-susceptible fill to the full depth of the active zone and for a somewhat larger area than the proposed structure. It is imperative that backfilling operations be accomplished within a very limited time period. The foundation structure can then be placed on the coarse-grained non-frost-susceptible material and conventional design methods used. (In the design analysis, it should be considered that the permafrost table will be depressed slightly due to the higher heat conductivity of the coarse-grained backfill.)

(d) In some cases, sub-soil exploration showed that rock was close to the surface. In such a case, the frost-susceptible material can be excavated to rock level and backfilled with coarse-grained non-frost-susceptible material. The foundation structure may be placed either on the rock or in the coarse-grained fill. An example of such a design method is given on Figure 11.

(e) Another positive foundation design method is to place the structure on sufficient depth of gravel fill placed on original grade such that the permafrost table will rise and reach a state of rest within the body of the coarse-grained fill. There are a number of theoretical methods for determining the minimum height of fill. It was found through experience that this method requires the placing of fills of considerable height, making this type of foundation method expensive and uneconomical.

(f) Theoretically, foundations could be designed to be supported by the active zone when the soil is at its minimum strength value. Because of frost heaving, lateral displacement and generally extremely poor drainage conditions, the use of such a design is impractical.

(g) Structures of any size requiring a stable foundation on a year-round basis, must be supported by the permafrost. This method of support takes advantage of the year-round high load carrying capacity of frozen soils. To ensure that the structure will not depress the permafrost table and to improve the drainage conditions, the original grade is covered with a 2 to 3 foot gravel pad and the building is elevated 2 to 3 feet over the pad. This air space allows air to circulate below the building reducing or eliminating heat exchange between the structure and the subgrade.

It is imperative that during winter this air space be kept open to air circulation; drifting snow can reduce its effectiveness. The location and orientation of the structure is of special importance in this regard.

To carry the load from the superstructure into the permafrost through the active zone, short piles are used.

The loading condition on such a pile structure during freezing and thawing of the active zone is given on Figure 12. To ensure that the piles can withstand the upheaving forces transmitted to them by the adfreezing of the soil in the active zone, the pile should be carried and frozen into the permafrost to a depth sufficient to counteract the thrust of these frost heaving forces.

It has been found through experience that the minimum depth of embedment into the permafrost of piles should be twice the maximum depth of the active layer expected during the lifetime of the structure.

This procedure has been used extensively and with considerable success by the Department. The piles are generally placed by means of steam jetting or drilling into the permafrost. Sufficient time is allowed to elapse for freezing-in before the piles are loaded. The allowable bearing capacity of the permafrost is well in excess of that necessary to carry the load safely. Generally, the strength of the pile itself is the governing factor.

The Department of Transport has found that wood piles 8 inches in diameter or 8x8 inches in size can be used successfully in the Canadian Arctic. Such a foundation design method is represented on Figure 13.

If it is impractical to carry the foundations into the permafrost on the basis of construction or economical considerations, a similar method, as discussed under paragraph "b", is used with some success. In this case, a wooden platform pedestal is used with an air space of 3 to 4 feet, in place of the methods previously mentioned. Provisions are made for jacking points and the insertion of shims.

FOUNDATION OF ANTENNA STRUCTURES IN PERMAFROST AREAS

Foundation structures for antennae have to provide reactions for vertically downward, vertically upward and horizontal forces (Figure 14).

It is the policy of the Department to design and construct these foundation structures to carry the design loads with a minimum of maintenance.

The problem is to design and construct foundation structures either in the active zone or carried through the active zone into the permafrost depending on site soil conditions. No standard solution can be proposed. The type of foundation design and construction has to suit site conditions. General principles of design will be presented and demonstrated with typical solutions used by the Department.

If the subgrade soil is non-frost-susceptible, well-drained coarse-grained material or clay without ice segregation, the freezing and thawing of the active zone does not appreciably influence the stability of the foundation structure placed on it. Spread foundation structures can be used to transmit the vertical downward forces to the subgrade, based on the strength of the thawed subgrade material. This can be either concrete prefabricated wood or steel sections of sufficient size and rigidity to take into account the load carrying capacity of the coarse-grained subgrade. Figures 15 A and 15 B give examples of this design type.

If the soil is frost-susceptible, the vertically downward forces must be carried through the active zone into the permafrost zone. For this purpose, short piles can be used. In general, the depth of "freezing-in" of these short piles in the permafrost should be twice the maximum expected thickness of the active layer during the lifetime of the structure. The piles can either be of wood or steel material and should be prefabricated. An example of this type of foundation is given on Figure 16.

To provide a reaction for the mast anchors (horizontal and vertical upward forces) two methods are presented:

(a) Prefabricated wood or steel platforms buried at a sufficient depth to provide the necessary vertical reaction by utilizing the weight of the soil material over the buried platform, and the shear strength mobilized on the perimeter of the prism. Shear strength values used for theoretical design analysis are based on the properties of the material in a thawed state. Shear strength forces of the soil in a frozen condition are disregarded. If the soil is frost-susceptible, the platform is placed a minimum of 6 inches into the permafrost.

To provide a reaction for the horizontal forces, the available passive resistance of the soil material is mobilized, assuming that the soil is in a thawed condition. Reaction due to the mobilized shearing resistance on the sides of the platform parallel with the line of forces acting can also be used, under the limiting angle of $\theta = 45° - \phi/2$ with the horizontal. An example for anchor designs illustrating these principles is given on Figure 17.

(b) When the soil is frost-susceptible fine sand and silt or clay material, the vertical upward and horizontal forces may be carried using short wood or steel pile groups.

The minimum embedment of such piles into permafrost should be twice the maximum expected thickness of the active zone plus a depth sufficient to counteract the vertical upward forces by mobilizing the adfreezing forces on the piles. Typical adfreezing forces are given on Table III. In general, two vertical piles are used to provide sufficient reaction. The type of piles, spacing, and the details are determined on the basis of structural design.

Horizontal reaction is provided by the passive resistance of the soil in a thawed condition, by the mobilized shearing resistance on the planes parallel with the direction of the forces (limited by the angle "θ") and the horizontal reaction developed by the piles in the permafrost. Figure 18 gives a typical example of anchor design utilizing pile groups.

FOUNDATION OF POLES IN PERMAFROST AREAS

If the subgrade soil is well drained non-frost-susceptible coarse-grained material, conventional methods of foundation design and construction can be used.

If the soil is frost-susceptible, the forces will have to be transmitted into the perennially frozen ground by means of piles or stub piles in accordance with the principles discussed in the previous section.

If soil conditions are such that the piles cannot be buried to a sufficient depth in accordance with the requirements already stated, an acceptable but more expensive solution is shown on Figure 19. In this case, two concentric steel piles are used with grease in the space between the two pipes. This reduces the possibility of the poles walking out of the ground by the action of freezing and thawing. The adfreezing forces in the active layer are minimized by the use of gravel backfill. Local organic cover material is placed on the finished grade in order to provide maximum insulation.

ACKNOWLEDGEMENTS

The Engineering Design Section is responsible to the Chief Engineer, Mr. G. W. Smith, for engineering pavement and foundation projects at Department of Transport sites.

The work carried out by the Section is under the general direction of the Director of the Construction Branch, Mr. H. J. Connolly.

Comments and helpful suggestions were offered by:
Mr. K. G. Ewing, Engineer-in-Charge of the Development Engineering Section; Mr. A. Douglas, previously Assistant Regional Construction Engineer, Winnipeg Region; Mr. J. K. Brown, Assistant Chief Architect of General Buildings; Mr. H. V. Wheeler, Head of Structural Design Section; Messrs. H. Dutz, J. Demellweek and F. Penner - Design Engineers of the Engineering Design Section.

REFERENCES

1. Liverovsky, A. V. and K. D. Morozov. Construction on Permafrost. Stroiizdat Narkomstroia, Leningrad-Moscow, 1941. 224 p. Translated for U. S. Corps of Engineers, May 1952.
2. Tsytovich, N. A. and M. I. Sumgin. Fundamentals of Frozen Ground Mechanics. Academy of Sciences, U.S.S.R., Moscow-Leningrad 1937. 432 p.
3. ———————— Bases and Foundations on Frozen Soil. Academy of Sciences, U.S.S.R., Moscow, 1958. 167 p. Translation - Highway Research Board Special Report No. 58.
4. U. S. Corps of Engineers. Engineering Manual, Military Construction, Part XV - Arctic and Subarctic Construction, Oct. 29, 1954, Chapter 2 - Site Selection and Development.
5. ———————————— Engineering Manual, Military Construction, Part XV - Arctic and Subarctic Construction, Oct. 29, 1954, Chapter 3 - Runway and Road Design.
6. ———————————— Engineering Manual, Military Construction, Part XV - Arctic and Subarctic Construction, Oct. 29, 1954, Chapter 4 - Building Foundations.

TABLE I

Cohesion and Angle of Internal Friction of Frozen Soils from Laboratory Tests

Material	Symbol	D_{10} mm	d	S	Cohesion, ton/sq. ft.			Angle of Internal Friction Ø
					31.5°F	30°F	20°F	
Well-graded sand	SW	0.25	112	92	3.2	12.6	24.0	30°
Uniform sand	SP	.09	95	88	6.5	14.4	26.0	44°
Inorganic silt LL=26 PI=5	ML	.004	90	90	2.6	7.0	19.8	27°
Clay LL=47 PI=27	CL	----	53	99	2.5	5.4	15.3	22°
Peat	Pt	----	15	98	5.0	10.1	16.3	29°

D_{10} - The grain diameter of which 10 percent of the soil by weight is finer. (Effective grain size, mm).
d - Unit dry weight of soil (average).
S - Degree of saturation, percent (average).

NOTES: Tests by Arctic Construction and Frost Effects Laboratory, New England Division, Corps of Engineers, Boston, Mass.

Results are from unconfined compression, tension, and direct shear tests on artificially frozen soils. A constant rate of stress increase was applied to specimens resulting in failure in approximately 2 to 5 minutes after start of load application. Plastic flow or creep of unconfined compression specimens occurred when constant loads, considerably less than maximum load in short time tests, were held on specimens for 2 to 3 days at temperatures greater than approximately 28°F.

The values of cohesion will decrease appreciably with decrease in degree of saturation.

Data From: Engineering Manual for Military Construction - Part XV - Chap. 4 - October 1954 - U.S. Corps of Engineers.

TABLE II

Allowable Design Bearing Capacities for Frozen Soils, in lbs/sq.ft.

Soils	Highest Temperature of Soil at Level of Lower Surface of Foundation During Use of Structures		
	(31.29°F)	(29.84°F)	(24.80°F)
Sands, medium and fine-grained	12,312	20,520	28,728
Clayey sands with silt, Wdr 35%	7,183	14,364	20,520
Clayey silts, Wdr 45%	6,156	10,260	16,416
Ice-saturated silty soils (clayey sands, clayey silts with sands, and clays), with a large amount of ice laminae and inclusions of more than 5-mm thickness	5,130	8,208	12,312

"It should be mentioned that Table 6[*] gives much larger resistance values for frozen soils in bases under structures than do the building codes (USSR). One should take into account that recommendations concerning the last soil listed will apply only where there is no direct contact of ice with the lower surface of the foundation. To achieve this, it is necessary to place on the excavation bottom a layer of moist sand (if only 5 to 10 cm, or 2 to 4 in, thick) and subsequently to cool it to corresponding temperatures below freezing."

<u>Data from</u>: the Permafrost Institute of the Academy of Sciences, USSR 1956.[*]

TABLE III

Allowable Shear Strength due to Adfreezing Between Ground and Wood or Concrete, lbs/sq.ft.

Adfreezing Surfaces	Temperature - 30.2°F				Temperature - 14°F			
	Ice Saturation				Ice Saturation			
	0.25	0.50	0.75	1 to 1.4	0.25	0.50	0.75	1 to 1.4
Fine-textured ground (loamy sand, sandy loam, clay loam, silt) and wood	4,100	6,150	8,200	12,300	6,150	14,350	26,650	32,800
The same ground and concrete	2,050	4,100	8,200	10,250	14,350	20,500	26,650	32,800

General Remarks:

1. The stresses at other temperatures and ice saturation are determined by interpolation.

2. In the case of gravel protected against silting and draining freely, the stress is taken as 820 lbs/sq.ft.

3. Ice saturation is determined from the Formula $I = W/W_p$, where W is the weight of ice (water) in the ground, and W_p is the water-holding capacity of the thawed ground.

Data from: "U.S.S.R. Standards and Specifications for the Design of Foundations on Permafrost. OST NO. 90032-39".

APPENDIX "A"

INSTRUCTIONS FOR DEPTH OF THAW SURVEY IN PERMAFROST AREAS

1. Purpose

The Depth of Thaw Survey is designed to determine the soil condition in the active zone and position of the permafrost table at northern Department of Transport sites, wherever possible, with emphasis on the depth of annual summertime thaw and the date at which this thaw reaches its maximum depth. Included in the conditions to be determined are organic cover, soil type, soil moisture content, exposure conditions, and climatic factors, such as precipitation and freezing and thawing indices. The freezing indices are computed at Construction Branch Headquarters from Meteorological Branch observations; thawing indices are supplied by the Meteorological Branch.

2. General

For present purposes, permafrost is considered "the condition of earth materials remaining below 0°C (32°F) continuously for a number of years".

It should be noted that frozen ground above the permafrost table is not permafrost, but is simply ground containing seasonal frost. The layer of the soil subject to seasonal freeze and thaw cycles is called the active layer.

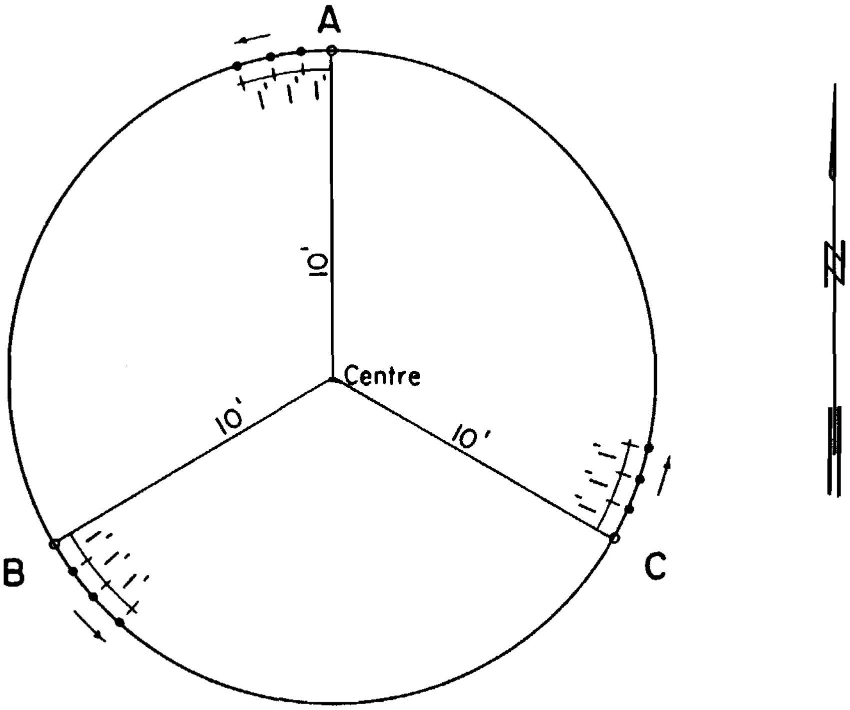
As indicated in 1961 results, maximum thaw probably occurs in Canada not earlier than late August, and may occur much later than this; in fact it occurs sometimes after surface freezing has begun owing to the supply of heat stored in the soil a few feet below the surface. Consequently for best results, depth of thaw observations should be continued as late in the season as possible. A record of the earlier part of the thawing cycle, however, is still desired.

3. Selecting and Preparing the Test Location

(a) Select two test locations in areas representative of the Department of Transport building area, and a third location representative of the airstrip where there is one; each location being selected such that any rock surface is well below the depth of the active layer.
(The locations selected do not necessarily have to be at the Department of Transport area, but should correspond to it as much as possible and must be properly described in any case.) Each test location must be at least 20 feet in diameter and should have uniform surface conditions. They should preferably be level, but any slope may be described on the Location Description forms provided. Of the two building area locations,

one must be substantially covered by vegetation, while the other must be substantially clear of organic cover. The latter location may be prepared by the clearing of the organic growth; however, a location which has already been clear for some time is much preferred. A few, sparsely scattered, small plants will not substantially affect the characteristics of an otherwise clear area, and will not constitute an organic cover. Any clearing must be done as early as possible.

(b) Mark the centre of each location with a stake to be used as reference point. Lay out A, B, C each 10 feet from the stake according to the sketch below.



(c) The test locations should be shown on a site plan or building area plan by the observer or by the Region. Also furnish a photograph of each location, if possible.

4. Determining Depth of Thaw

(a) Begin to take readings before the depth of thaw in the Spring exceeds three inches. Take sets of three readings for each test location at weekly intervals (on Tuesdays at approximately 10:00 a.m.) until measurements are no longer practical because of the thickness of the frozen active layer. As mentioned previously, maximum thaw may occur even after surface freezing of the active layer has begun. Readings will be taken according to the following outline.

(b) Take depth of thaw by sounding surface of frozen soil with a steel rod sharpened at the tip. The rod will be supplied by the Regional

Materials Engineer who will select the appropriate diameter (min. 1/2-inch) and length for each site. This rod is to be driven through the active layer to refusal. The rod should then be turned with a wrench.

If the rod turns freely, it may have been stopped by a stone, and a new sounding must be made. If back spring is felt however, it may be assumed that the sharpened tip of the rod has penetrated the permafrost for a short distance.

Note: In locations where coarse-grained soils occur with low moisture content, rod soundings may prove to be unreliable in obtaining the depth of thaw. In these cases the depth of thaw will be determined by augering with an auger to be supplied by the Regional Materials Engineer.

(c) At each test point (A, B, and C) read depth of penetration to permafrost to the nearest inch, and record on forms provided. Determine the average depth from the three readings and record.

(d) Take first set of readings at points A, B and C. Offset each further set of readings 1 foot in a counter-clockwise direction as shown. Record also the thickness of the frozen surface layer in the fall.

5. Soil Sampling

The results of the considerable work of sampling can be largely invalidated by inaccurate identification of samples. Do not overlook instructions on keeping test hole logs and on sample identification and labelling.

(a) Test hole. When the maximum depth of thaw is reached, dig a test hole to the top of the frozen ground at the centre of each test location. Clean the loose soil from a face of the test hole and examine it for changes in soil characteristics. Such changes are usually abrupt, the soil lying in well-defined strata; in the case of gradual transitions, however, the description should indicate the condition.

(b) Test hole log. Fill in all blanks at the top of the form supplied. Draw a horizontal line in the column provided at each depth where a change in soil type occurs. Be sure each individual layer of soil is described. Also note at which depth water enters the test hole and how much water has collected in the hole after 24 hours.

(c) Description of soils. Describe the soils occurring in the test hole face as follows:

COARSE-GRAINED SOILS:

Gravel - diameter of individual particles or grains ranges from 1/4 inch to 3 inches.

Sand - diameter of individual particles or grains ranges from those just visible to the naked eye to 1/4 inch.

FINE-GRAINED SOILS:

Silt - individual particles or grains are not visible to the naked eye; powders easily when dry, cannot be rolled into thin threads.

Clay - individual particles or grains are not visible to the naked eye; when moist, it sticks to fingers and does not wash off easily, can be rolled into thin threads; hard when dry.

ORGANIC SOILS (PEAT OR MUSKEG):

- brown or black fibrous or granular decomposed vegetation.

Note that there can be mixtures of any or all of the above soils in any given layers. Obviously a mixed soil will have mixed characteristics as described above.

Gravels do not tend to hold water and, when they are frozen, do not contain much ice. Fine sands and fine-grained soils hold water and, when they are frozen, often contain layers, lenses or bodies of ice. Coarse-grained soils contaminated with fine-grained soils generally behave as fine-grained.

(d) Sampling. Take one-pound (approximately) and moisture content samples from the cleaned face at 1 foot intervals numbering each one-pound sample to correspond to the number stamped into the tin box in which the moisture content sample is taken. Enter the same number in the space provided in the Log of Test Hole. Thus a single number is given at a single test location and a single depth for two samples from a single material, this number being entered in the appropriate place in the appropriate Log. Numbering, labelling and entries in the Log must be done immediately upon sampling to prevent subsequent confusion.

During sampling, avoid contamination of samples from other soil layers, and from water trickling from above or falling as precipitation. Also protect the soil of the moisture content sample against drying.

(e) Packing and labelling of sample. Place each 1-lb. sample in a fresh plastic bag to be provided, fold the top of the bag, and seal it with tape. Label the sample immediately with the number of the corresponding moisture content sample tin, the site or station where you are employed (e.g. "Frobisher"), the test location (e.g. "D.O.T. area, no organic cover"), and the sampling depth (e.g. "2 ft." or preferably, "2'-2'2 in.").

Fill each moisture content sample tin as fully as possible to expel air, and close tin tightly. Seal the lid closed with tape and with paraffin wax. These precautions are necessary because delivery of the samples to the testing laboratories may be delayed, and lost of moisture must be prevented.

Do not forget to enter sample numbers in the Log.

(f) Shipment. Pack soil samples carefully for shipment to the Regional Soils Laboratory in such a way that samples cannot be spilled or lost. Send the survey forms separately in a mailing envelope to the Regional Meteorologist, who will forward them to Meteorological Branch Headquarters.

6. Laboratory Testing

The Regional Soils Laboratory will perform all tests required for the classification of each soil sample by the USED Unified system, and for the determination of moisture content. The results will be plotted and sent to Director, Construction Branch, on form 51-0082, "Composite Soils Data Sheet", and also on form 51-0071, "Test Hole Log". Individual test sheets are not required, summarized results being sufficient.

******

Discussion

R. G. Howard enquired whether any trouble was encountered when concrete supports in the active layer were used for the support of guyed masts. The author replied that this type of foundation was used only in non-frost-susceptible soils. A more conservative design was used whenever there was any doubt.

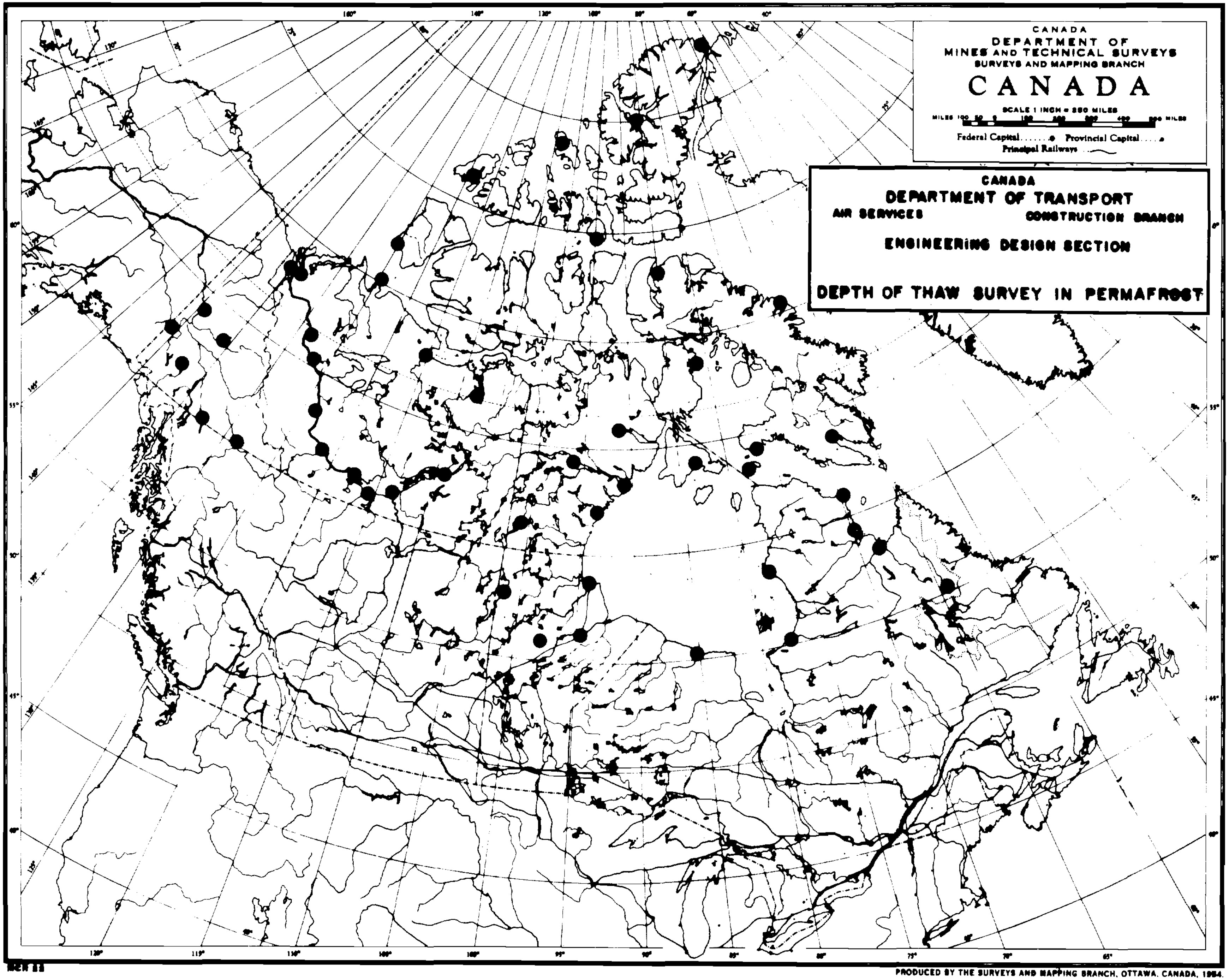
D. G. Henderson wished to know what was being done to improve construction practice, the use of materials, better insulating slabs, etc., in permafrost areas. For example, in the construction of airstrips would it not be possible to use prefabricated sections which could be laid down and insulated? The author stated that construction in permafrost areas is not simple because the structure bears on the soil which is a dynamic medium - freezing, thawing, moving, etc. It is a matter of living with the soils and permafrost conditions rather than resisting them.

R. Yong asked to what depth in the permafrost piles were embedded. He also requested information on the cohesion and shear values of the perennially frozen soils. The author's reply was that the piles were embedded in the permafrost to a depth of twice the thickness of the active layer that is anticipated during the lifetime of the structure. There has not been enough movement in piles to affect the structures placed on them. The cohesion and shear values are taken from American and Russian sources. There is a challenge here for universities and research agencies to obtain answers to these problems.
J. A. Pihlainen commented that design information from Soviet sources is scarce and this does not provide the whole answer. Economic considerations and a knowledge of conditions in Canada's north are vital. At present, our knowledge of conditions prevailing in our permafrost region is scanty. Moreover our construction methods are different

from those employed in the U.S.S.R. The author added that designs are required whether or not design data are available. Therefore structures have to be over-designed.

T. A. Harwood replied to D. G. Henderson's question about airstrip construction stating that no success was gained in the United States during fifteen years of research on airstrip design in permafrost areas. The only definite answer arising from this research was to paint the runway white to reduce heat flow from the atmosphere into the permafrost. F. E. Crory reported that, as a result of this research work, severe movements of structures have been eliminated. The effectiveness of different types of materials, such as macadam, concrete test sections with styrofoam, spruce logs, peat, etc., for insulating permafrost have been tested. Pile foundations have been studied in the perennially frozen silts of the Fairbanks, Alaska area. It has been found that a ten-foot embedment in permafrost is required to resist a heaving force exceeding 25,000 lbs. The rule of embedment down to twice the depth of the active layer is for counteracting frost heaving and is not a load requirement. The author added that 8-inch diameter piles are used and the structure depends on the strength of the piles.

T. Lloyd stressed the author's remark that one cannot and must not think in terms of "fighting permafrost conditions". Experience in many areas of the world and at various periods demonstrates that the only successful techniques in the long run are those that work with the physical environment and do not attempt to overcome it. He asked if the author, who referred favourably to Soviet arctic engineering activities, agreed with claims made by construction authorities at Norilsk, that holes drilled in winter for piles are more effective than those made with a steam jet. The author replied that the Federal Department of Transport construction is in relatively remote areas and equipment must be comparatively light. The steam jet has this advantage over a drill rig. Norilsk is a large town with some massive buildings.


CANADA
DEPARTMENT OF
MINES AND TECHNICAL SURVEYS
SURVEYS AND MAPPING BRANCH
CANADA
SCALE 1 INCH = 250 MILES
MILES
Federal Capital
Provincial Capital
Principal Railways
CANADA
DEPARTMENT OF TRANSPORT
AIR SERVICES
CONSTRUCTION BRANCH
ENGINEERING DESIGN SECTION
DEPTH OF THAW SURVEY IN PERMAFROST
PRODUCED BY THE SURVEYS AND MAPPING BRANCH, OTTAWA, CANADA, 1954.

DEPARTMENT OF TRANSPORT

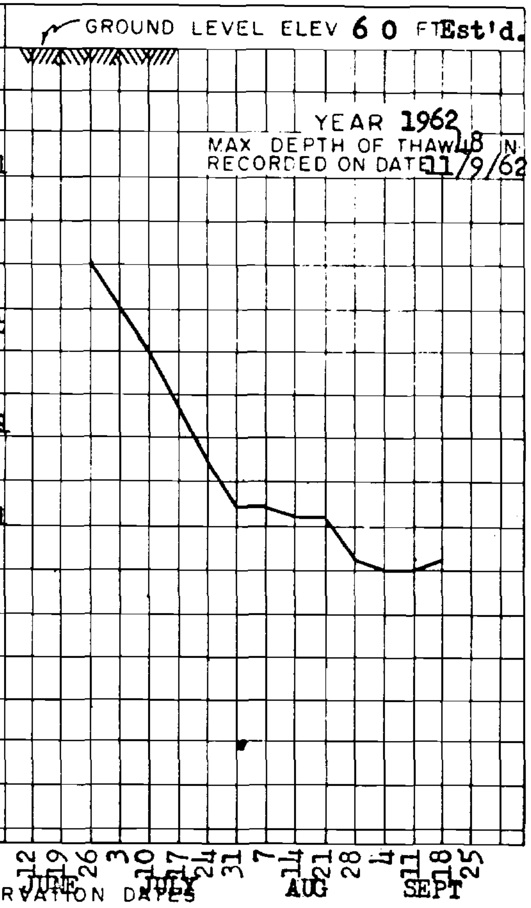
DEPTH OF THAW SURVEY IN PERMA FROST

SITE FROBISHER BAY	LOCATION See "Remarks"	OBSERVER H.G. PARDY	THAWING INDEX	FREEZING INDEX 7008(7 yr.)	

WITH ORGANIC COVER

GROUND LEVEL ELEV 6 0 FT Est'd.

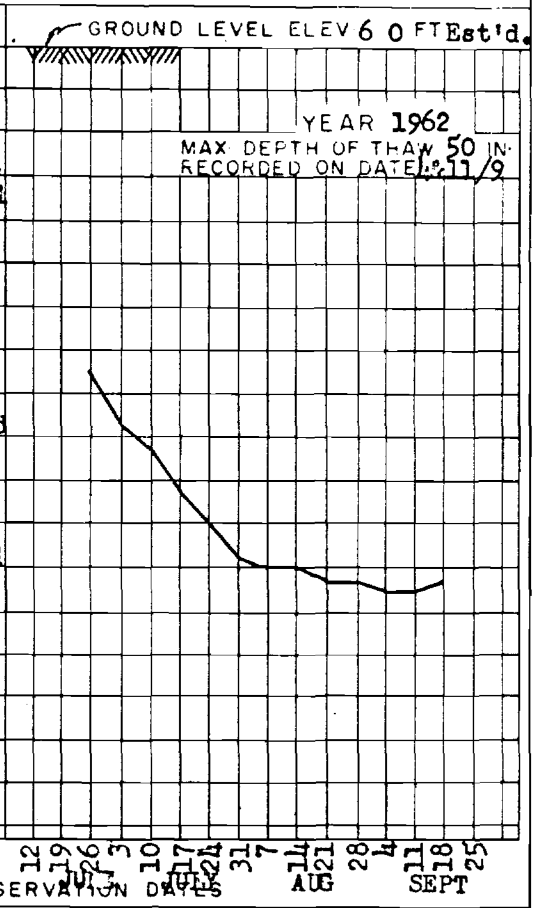
DEPTH TO FROZEN SOIL INCHES	Wn	USED CLAS.	SOIL DESCRIPTION
0			
4			Organic Material
12	4.0	SW	SAND lit gravel tr silt
24	4.3	SP	SAND some gravel tr silt
36	13.0	SP	SAND lit gravel
44	15.4	SM	SAND lit gravel lit silt



WITHOUT ORGANIC COVER

GROUND LEVEL ELEV 6 0 FT Est'd.

DEPTH TO FROZEN SOIL INCHES	Wn	USED CLAS.	SOIL DESCRIPTION
12	13.3	SM	SAND lit silt lit fine gravel
24	12.3	SM	SAND & SILT
36	15.0	ML	SILT some sand tr gravel
48	22.8	ML	SILT lit sand tr gravel



DETAILED DESCRIPTION OF ORGANIC COVER 1 - 3 inches cover of grass.

OTHER REMARKS Located in a large rolling field. Hole began to fill with water at 32".

REMARKS

Located in the vicinity of the present married quarters. The area has been without vegetation cover for two years and was graded earlier this year.

FIG- 1

DRAWN BY: PTH DATE: 14/3/62

DEPARTMENT OF TRANSPORT

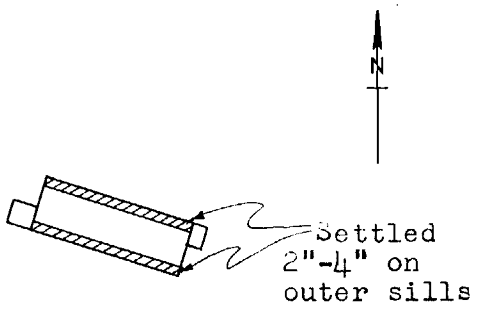
BUILDING SURVEY IN PERMAFROST

AIRPORT Alert, N.W.T. **DATE** Aug.21/61
COMPILED BY O. J. Green

STRUCTURE I.G.Y. Quarters
USED AS Quarters and Lab.
DIMENSIONS 44'x16'
TYPE OF FOUNDATION Mudsill
COMPLETION DATE 1956
STRUCTURE HEATED OR UNHEATED Heated
AVERAGE INSIDE TEMPERATURE 68°
PERFORMANCE OF STRUCTURE Has settled
FLOOR MOVEMENT, (SETTLING OR HEAVING) MAXIMUM 4" AVERAGE 2"
FOUNDATION MOVEMENT, (SETTLING OR HEAVING) MAXIMUM 4" AVERAGE 2"
FOUNDATION CRACKING, MAXIMUM N/A AVERAGE
WALLS CRACKING, MAXIMUM ½" AVERAGE ½"

on shale pad

LOCATION PLAN (Indicate Location of Worst Conditions)



Settled 2"-4" on outer sills

SCALE 1 in = 50 ft.

PERMAFROST CONDITIONS OF SITE

TYPE OF GROUND COVER None
MAXIMUM THICKNESS OF ACTIVE LAYER 20"

SOIL CONDITIONS OF SITE

	TYPE	THICKNESS
ORGANIC MANTLE	None	

AVERAGE MOISTURE N/A %

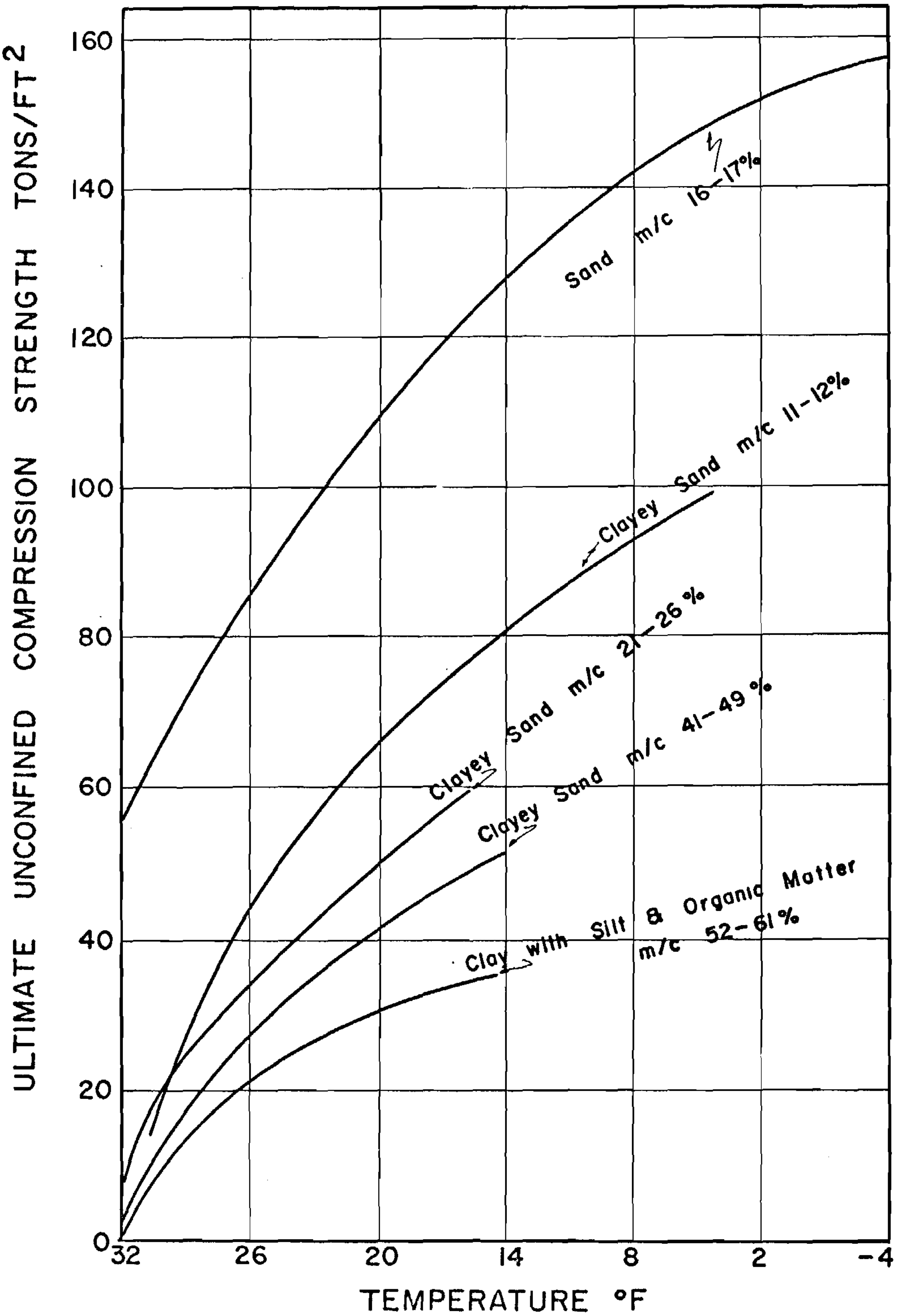
SUBSOIL	DEPTH	USED CLASS	AV. MOISTURE %	Estimated Ice Lensing % by Vol.
LAYER 1		N/A		
LAYER 2				
LAYER 3				

CLIMATOLOGICAL DATA

AVERAGE ANNUAL TEMPERATURE °F
FREEZING INDEX dd
THAWING INDEX dd
GROUND FROZEN FROM Sept. 1 **TO** June 15

FIG.-2

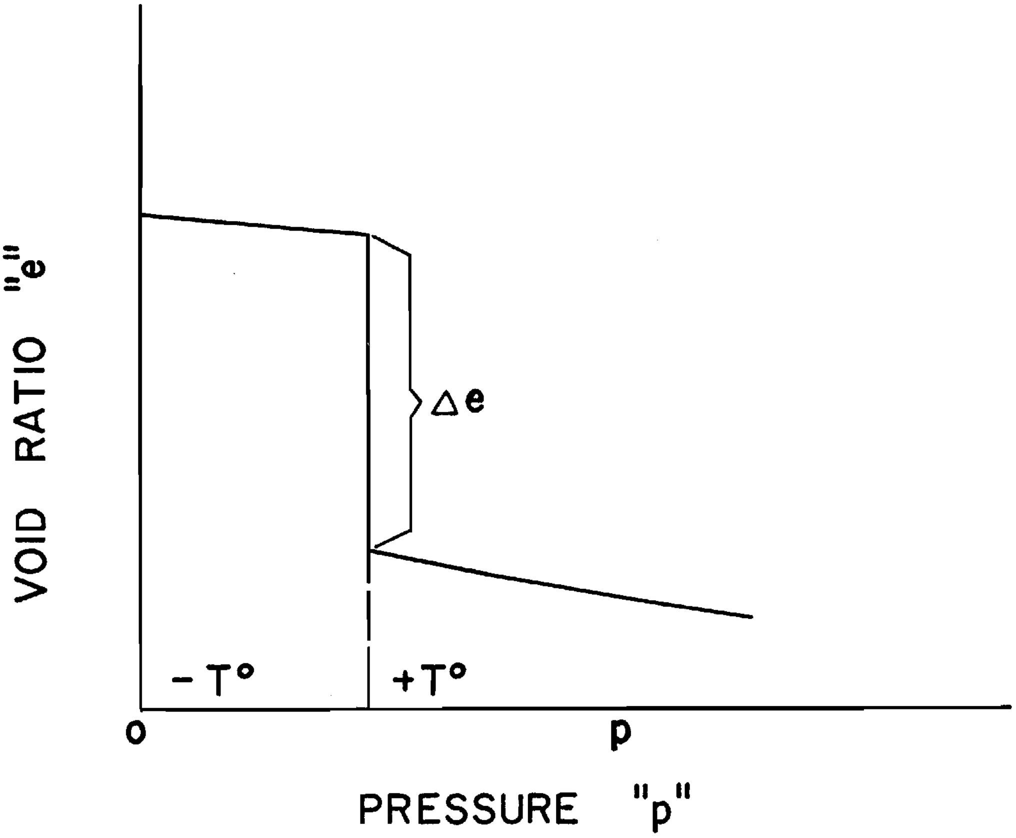
COMPRESSIVE STRENGTH OF PERMAFROST SOILS



Data from:"Fundamentals of Frozen Soil Mechanics". by TSYTOVICH & SUMGIN of MOSCOW — LENINGRAD ACADEMY of SCIENCES USSR 1937

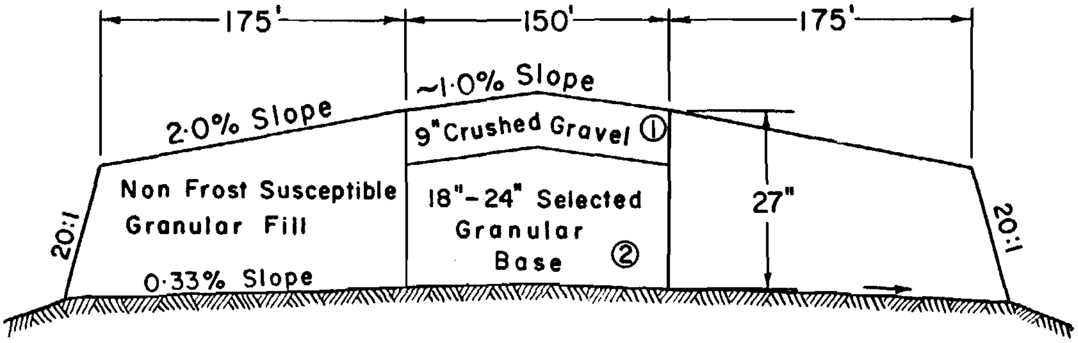
FIG-3

CONSOLIDATION CHARACTERISTICS
OF
PERMAFROST
(In the frozen and thawed state)



Data From: THE LENINGRAD ENGINEERING CONSTRUCTION INSTITUTE

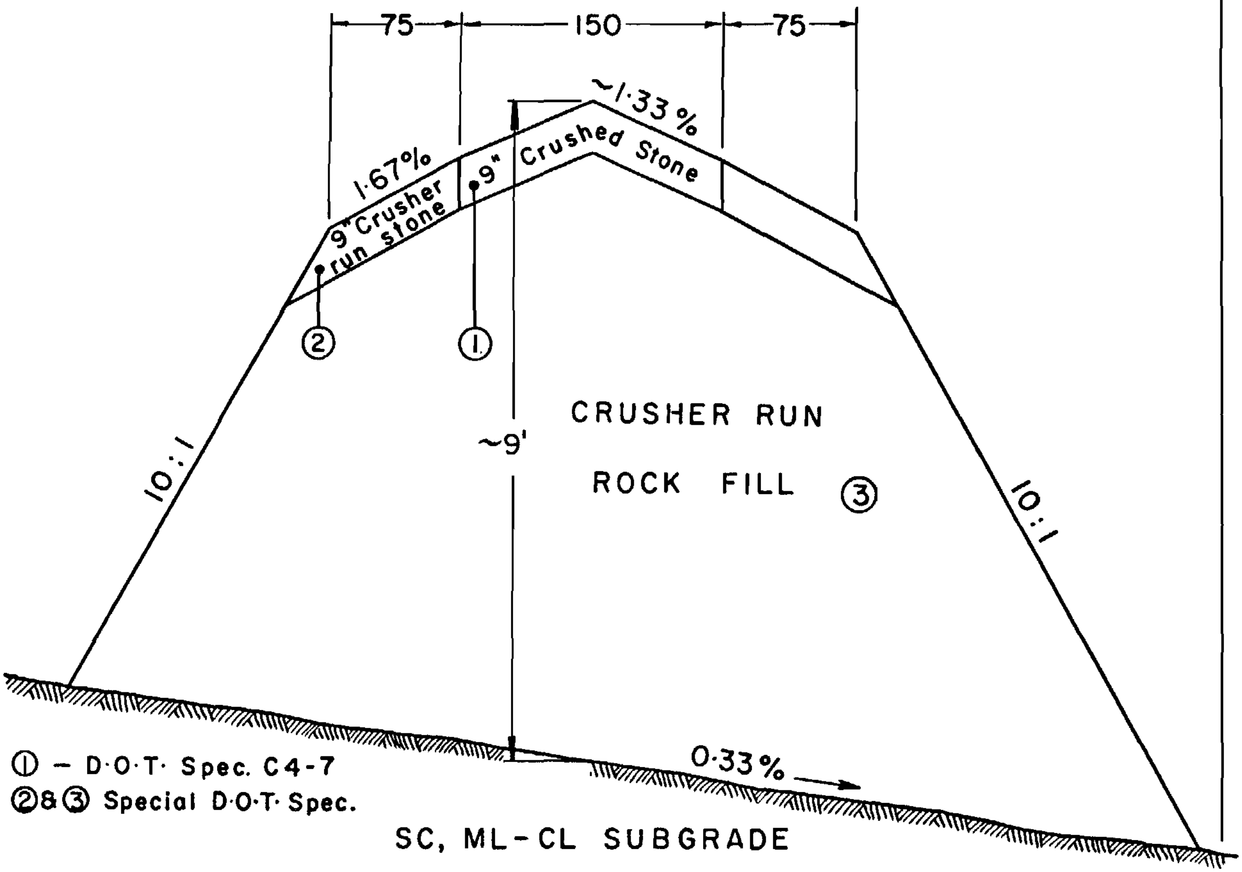
FIG - 4



GRANULAR NON FROST SUSCEPTIBLE SUBGRADE

NORMAN WELLS N·W·T·

FIG-5A

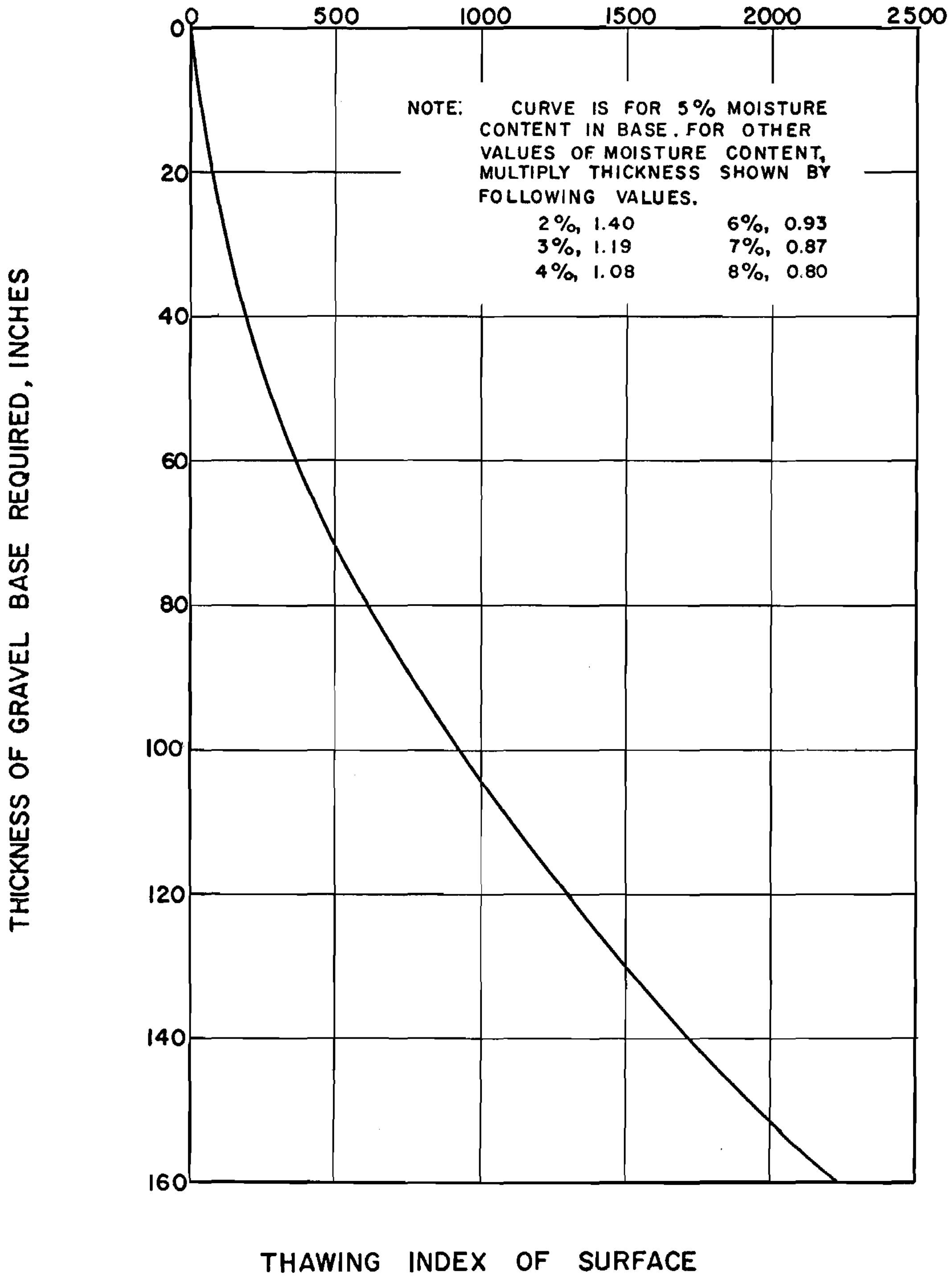


SC, ML-CL SUBGRADE

INUVIK N·W·T·

FIG-5B

THICKNESS OF BASE REQUIRED TO PREVENT THAWING OF SUBGRADE



NOTE: CURVE IS FOR 5% MOISTURE CONTENT IN BASE. FOR OTHER VALUES OF MOISTURE CONTENT, MULTIPLY THICKNESS SHOWN BY FOLLOWING VALUES.

2%, 1.40
3%, 1.19
4%, 1.08
6%, 0.93
7%, 0.87
8%, 0.80

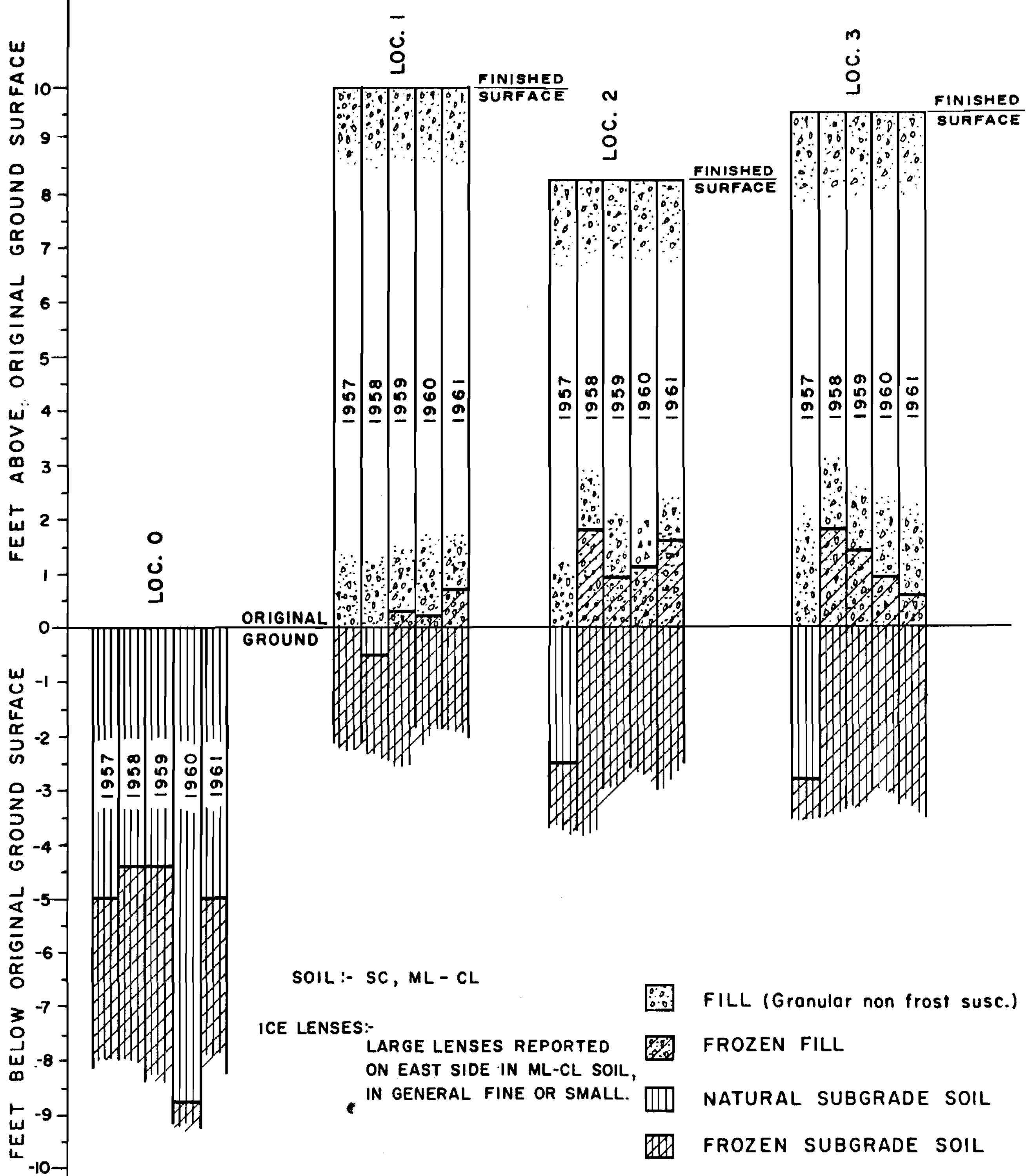
Data from: ENGINEER MANUAL MILITARY CONSTRUCTION US CORPS OF ENGINEER PART 15 CHAPTER 3

FIG- 6

RUNWAY CONSTRUCTION IN PERMAFROST

POSITION OF THE FROST LINE (MAXIMUM DEPTH OF THAW) BEFORE AND AFTER CONSTRUCTION

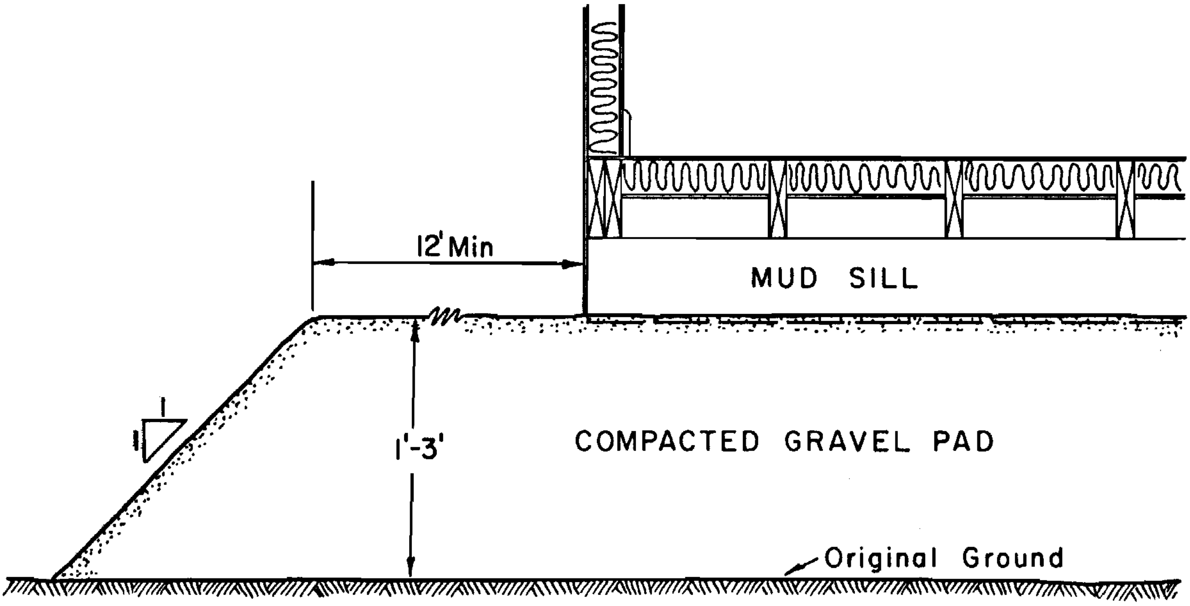
THAWING INDEX 10 YR. AVERAGE 2252 MAX. 2846 MIN. 1757
FREEZING INDEX 10 YR. AVERAGE 8029 MAX. 8581 MIN. 6811



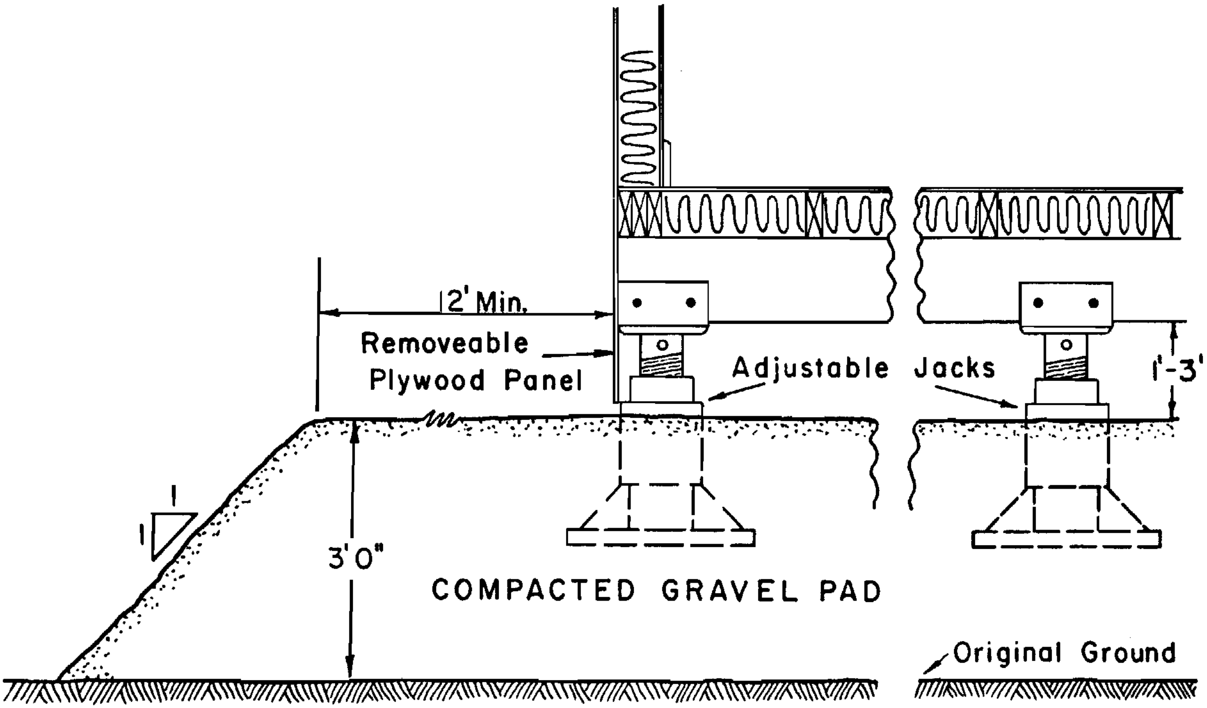
SOIL:- SC, ML-CL

ICE LENSES:-
LARGE LENSES REPORTED ON EAST SIDE IN ML-CL SOIL, IN GENERAL FINE OR SMALL.

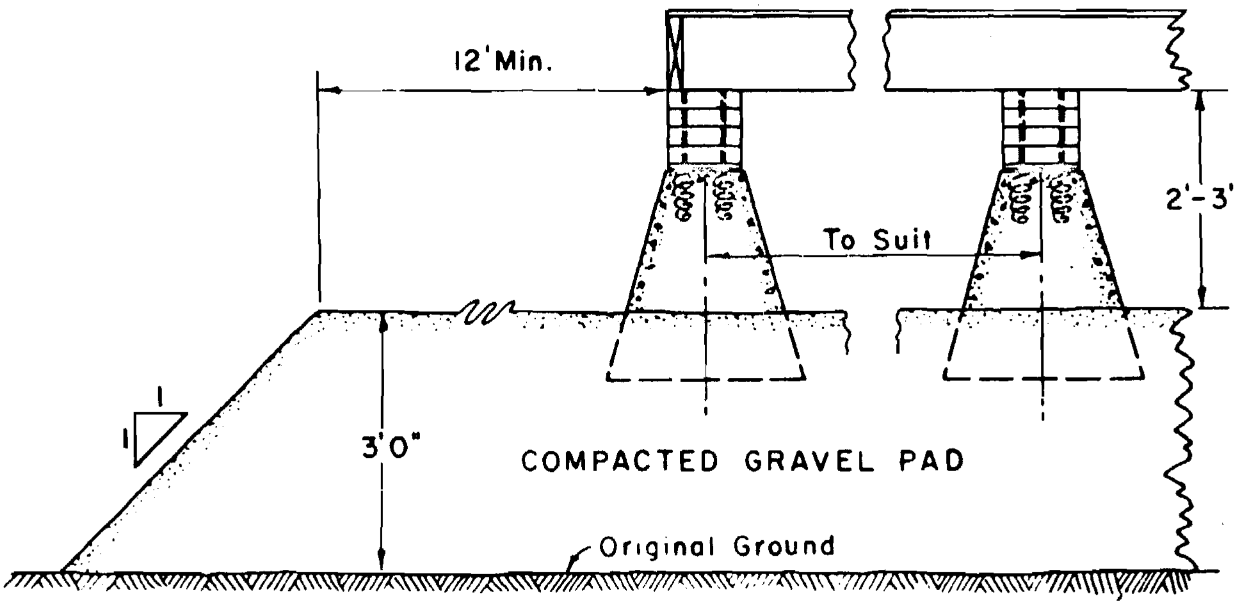
FIG.-7



GRAVEL PAD FOUNDATION
IN PERMAFROST USING MUD SILL
FIG - 8



GRAVEL PAD FOUNDATION
IN PERMAFROST USING ADJUSTABLE JACKS
FIG - 9

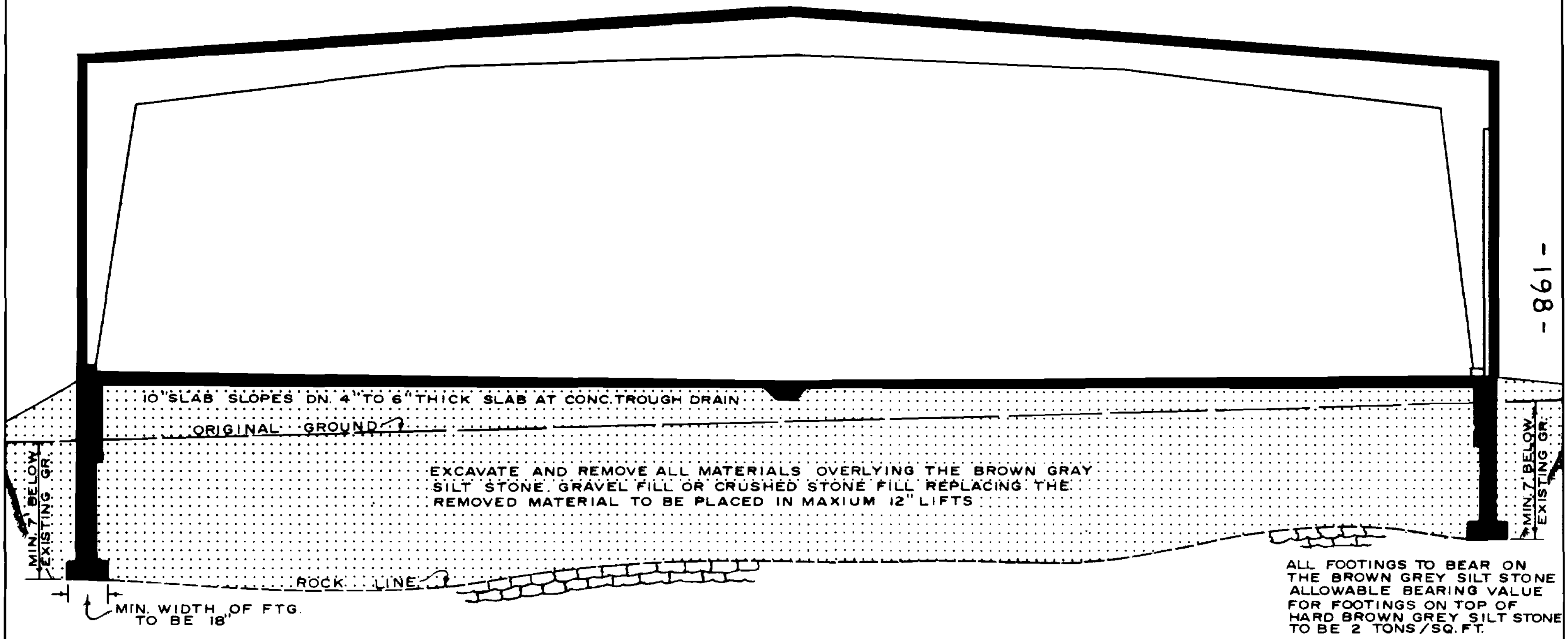


GRAVEL PAD FOUNDATION IN PERMAFROST USING CONCRETE PEDESTAL

FIG - 10

FOUNDATION ON ROCK IN PERMAFROST AREA

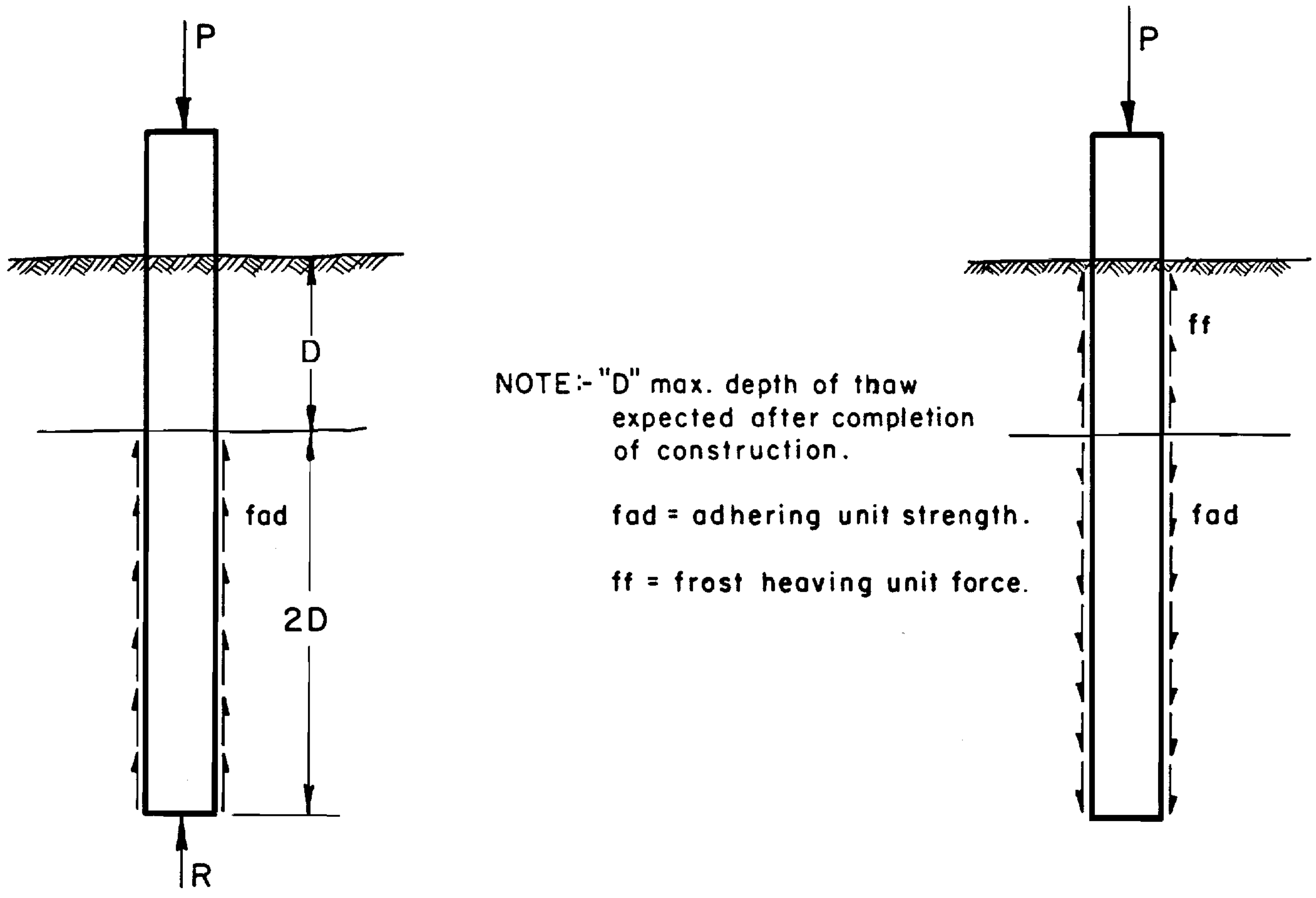
(EXCAVATION OF THE ACTIVE ZONE AND BACKFILL BY GRANULAR MATERIAL)



NORMAN WELLS MAINTENANCE GARAGE FOUNDATION

FIG.- 11

FORCES ACTING ON PILES IN PERMAFROST



NOTE:- "D" max. depth of thaw expected after completion of construction.

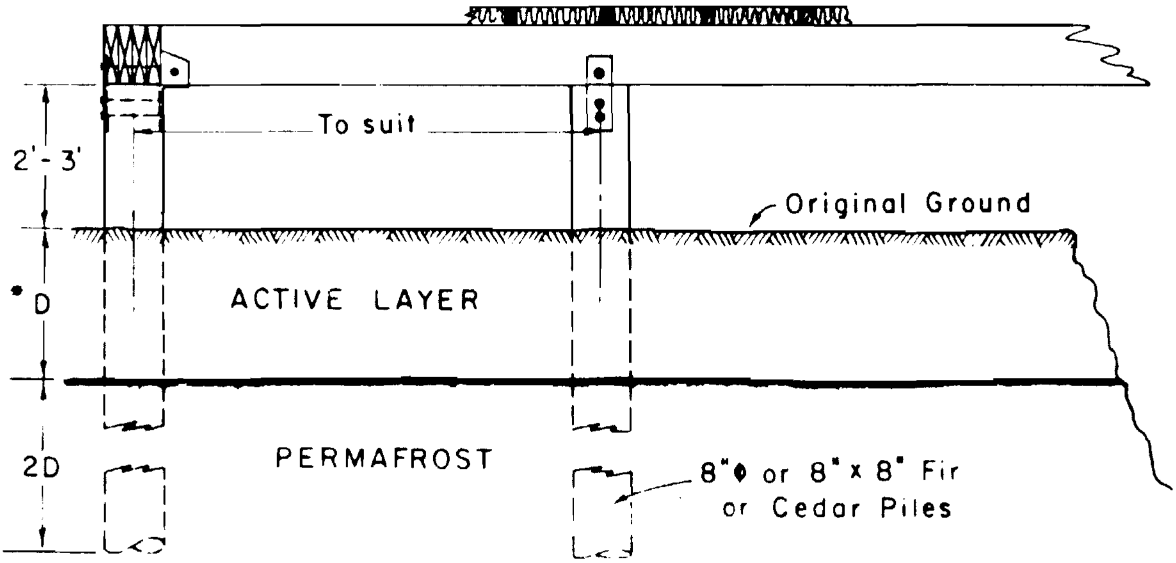
fad = adhering unit strength.

ff = frost heaving unit force.

a, UNFROZEN ACTIVE LAYER

b, FROZEN ACTIVE LAYER

FIG.-12



D = Depth of Active Layer

PILE FOUNDATION IN PERMAFROST

FIG - 13

FORCES ACTING ON MAST FOUNDATION AND ANCHORS

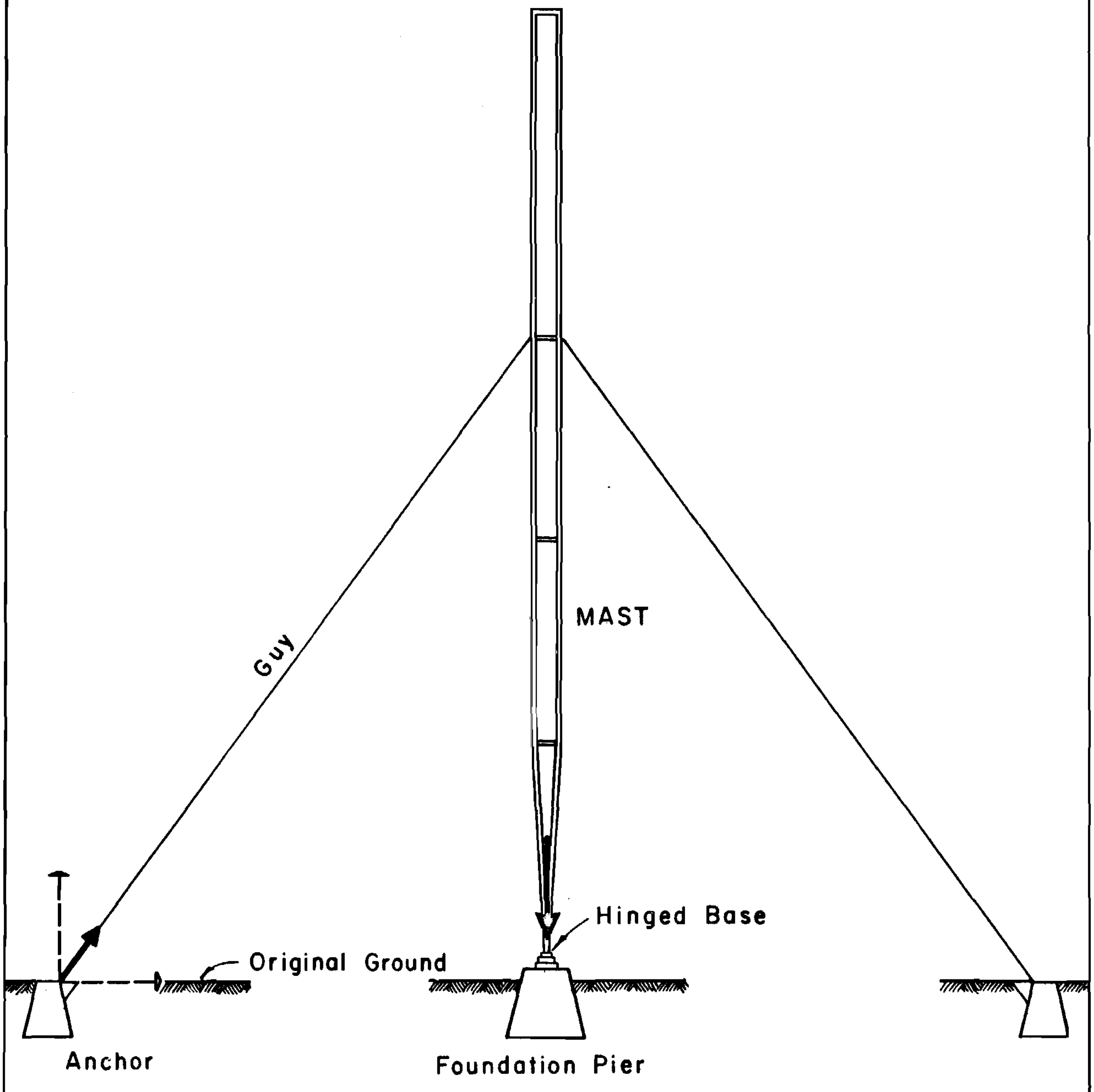


FIG - 14

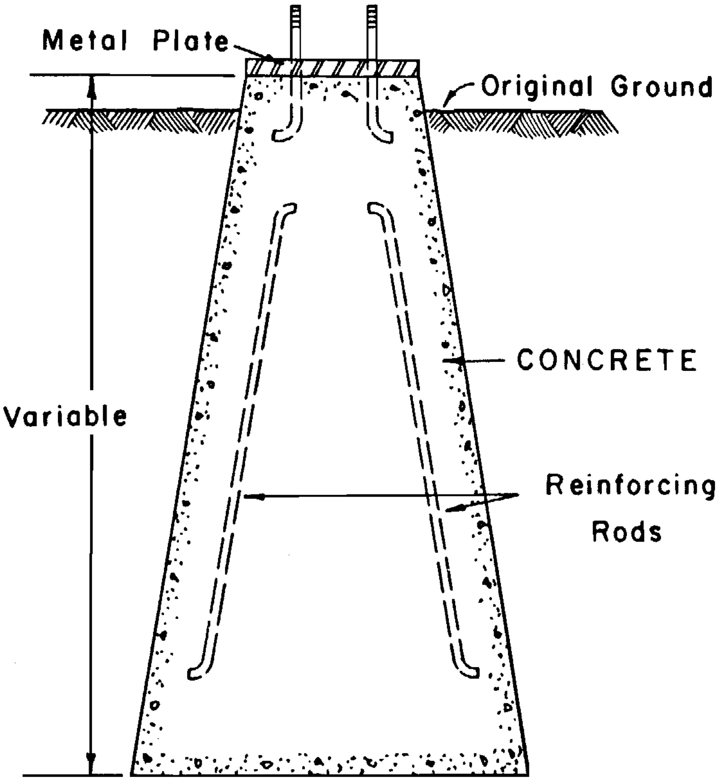


FIG-15A

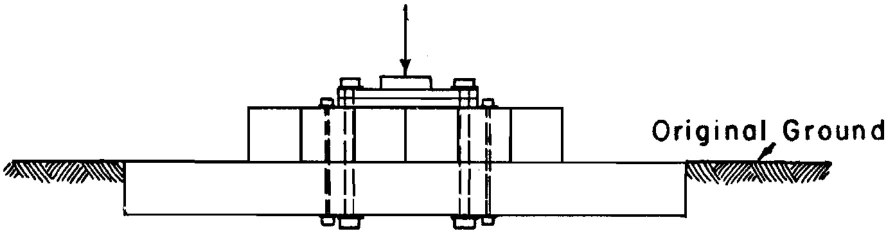


FIG-15B

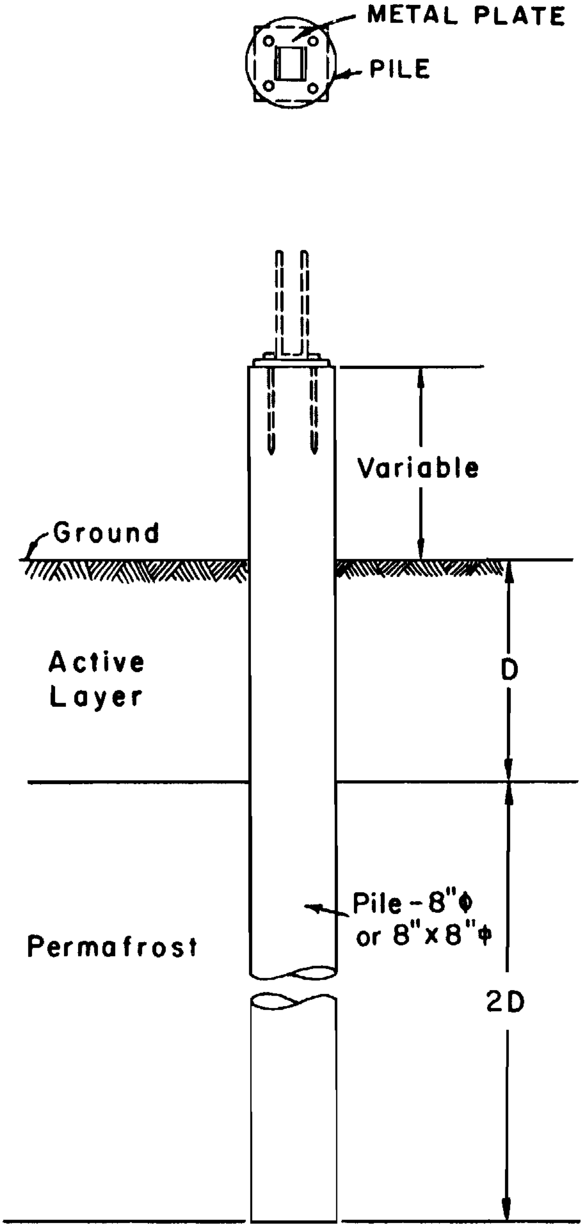

METAL PLATE
PILE
Variable
Ground
Active Layer
D
Permafrost
Pile - 8"ϕ or 8"x8"ϕ
2D

FIG - 16

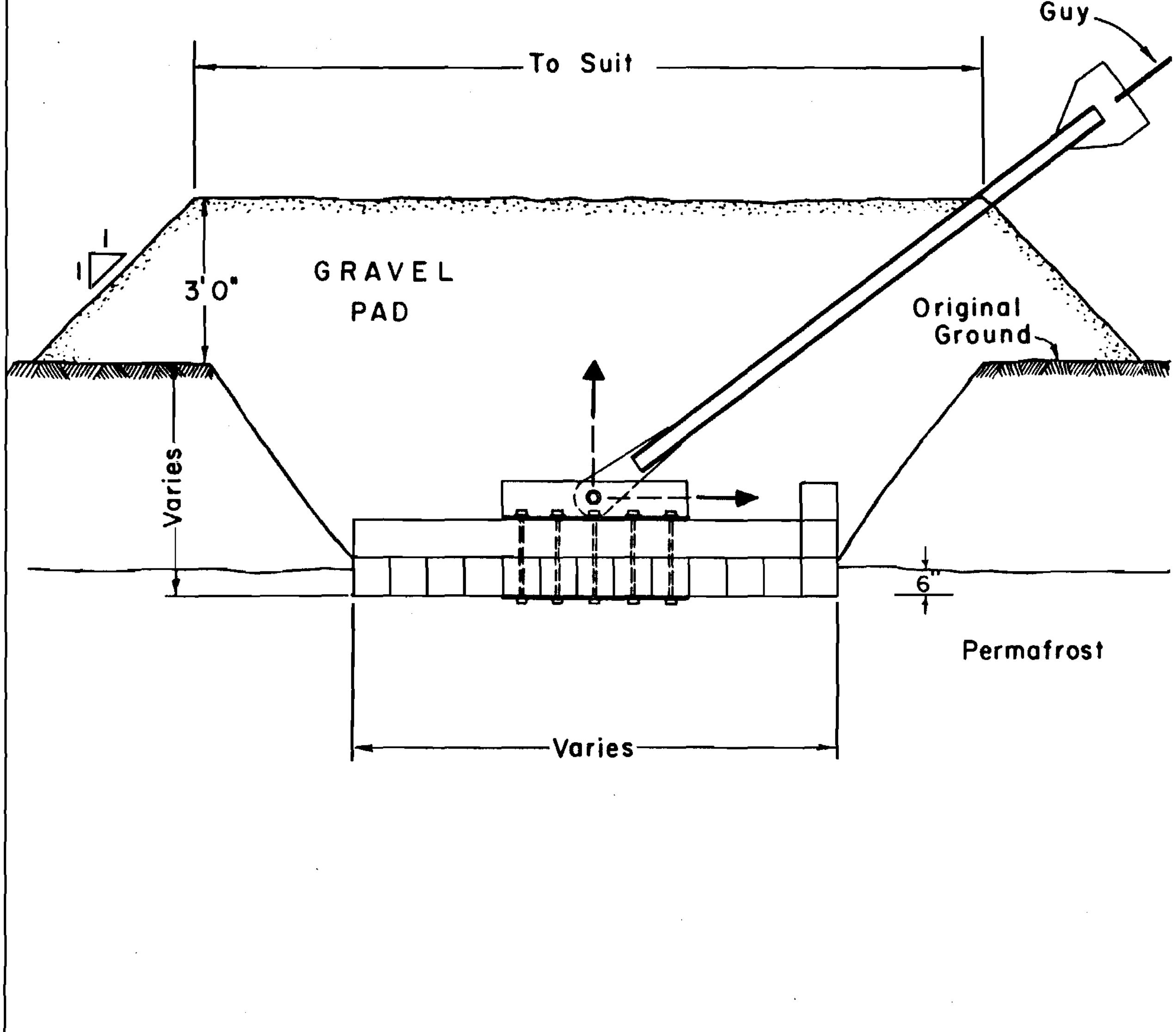
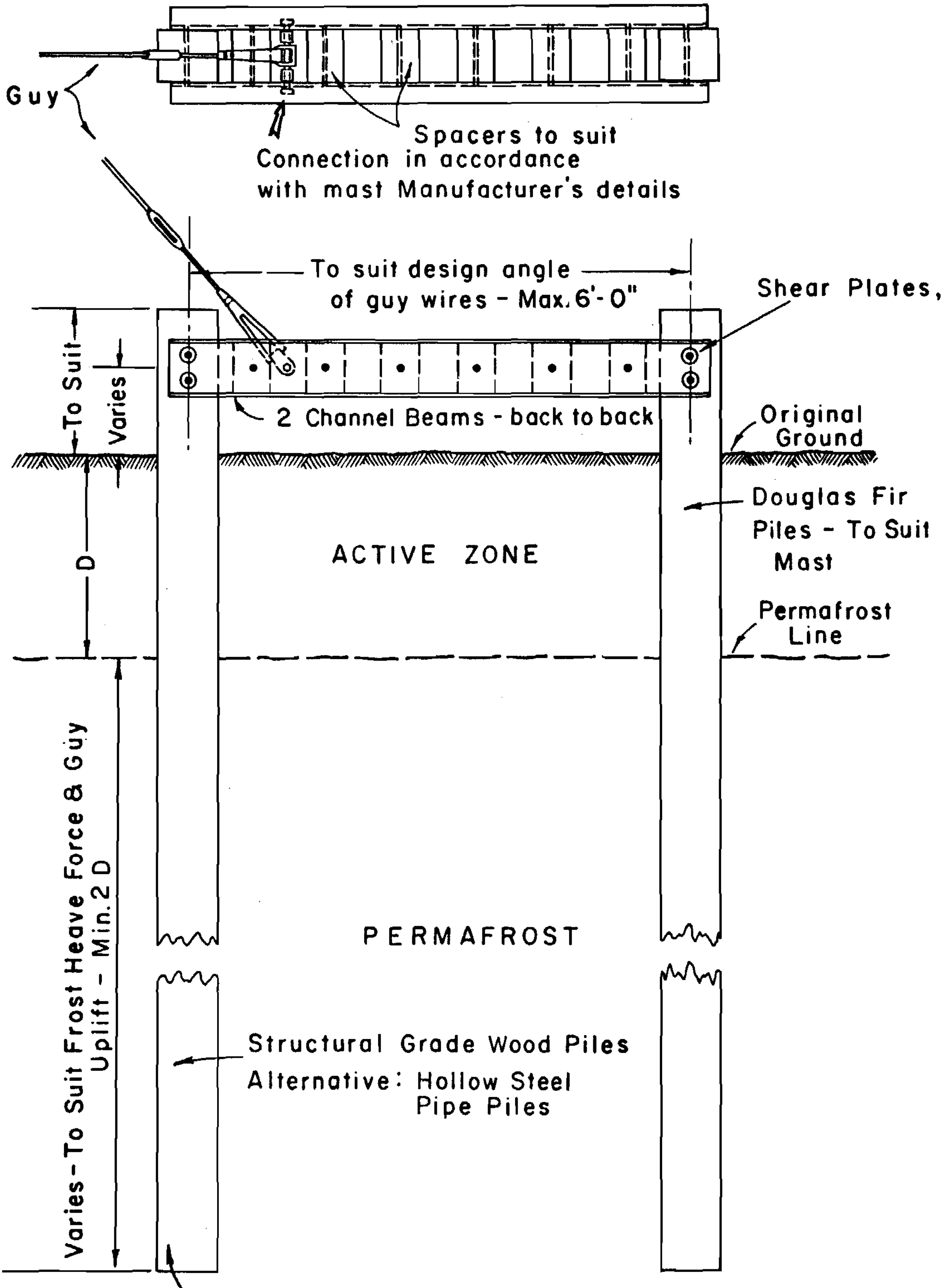

Guy
To Suit
1
1
3'0"
GRAVEL
PAD
Original
Ground
Varies
6"
Permafrost
Varies

FIG - 17



Pile should be frozen into ground, in advance of erection.

FIG - 18

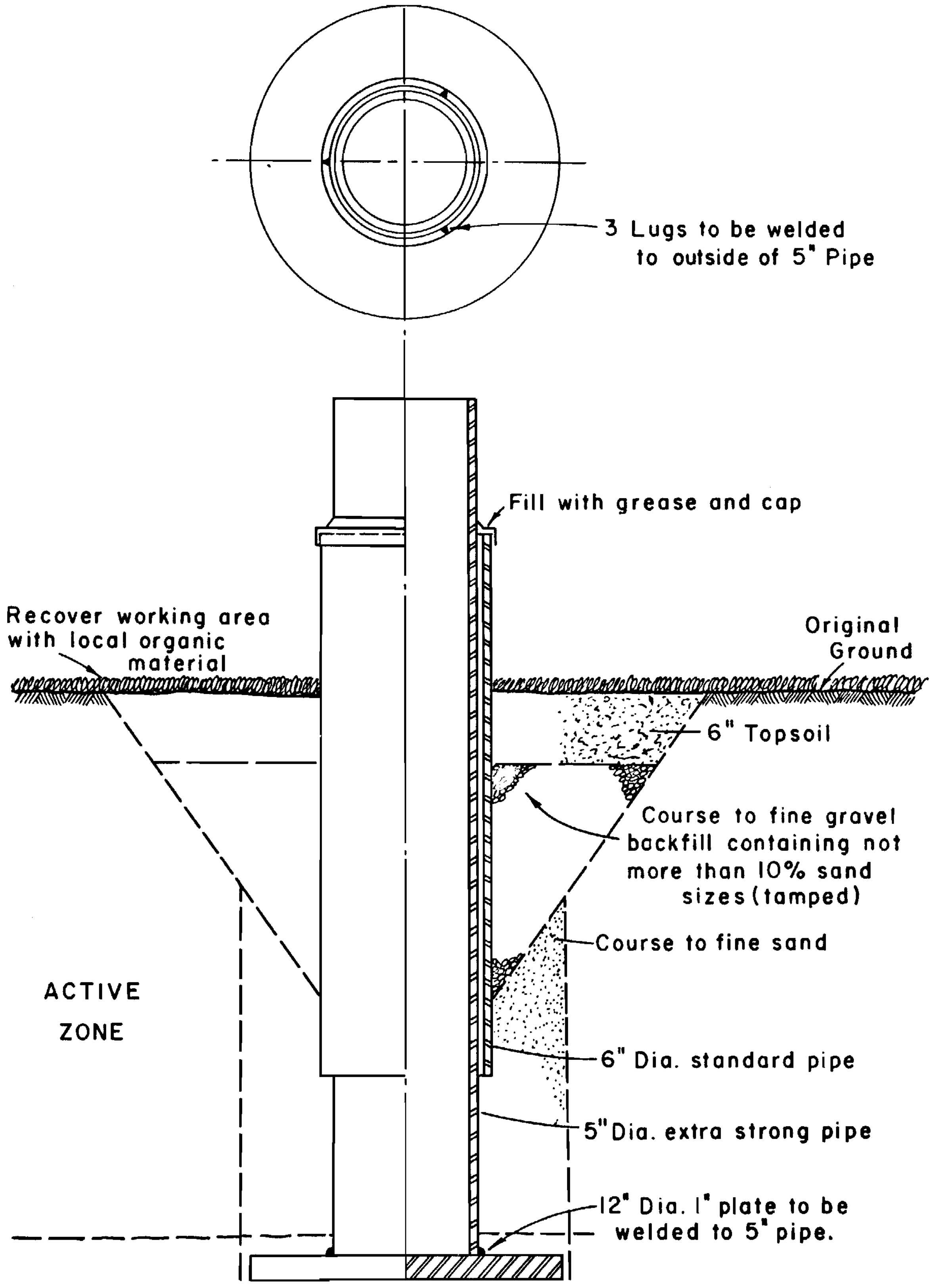

3 Lugs to be welded to outside of 5" Pipe
Fill with grease and cap
Recover working area with local organic material
Original Ground
6" Topsoil
Course to fine gravel backfill containing not more than 10% sand sizes (tamped)
Course to fine sand
ACTIVE ZONE
6" Dia. standard pipe
5" Dia. extra strong pipe
12" Dia. 1" plate to be welded to 5" pipe.
PERMAFROST

FIG - 19

IV. 1. PERMAFROST AND TERRAIN FACTORS IN A TUNDRA MINE FEASIBILITY STUDY

R. D. Lawrence and J. A. Pihlainen

Introduction

The assessment of mining and construction methods and the estimation of costs are early considerations of all mining developments. In arctic areas the principal factors that distinguish operations from more temperate regions are climate, isolation and terrain. In most cases, the climatic and isolation factors are apparent and can be compared to similar situations in other areas. The terrain factor, however, is less well-known and described.

Today it is possible to build any type of structure anywhere in the arctic. Many economies can be achieved through the use of proper design criteria and well-planned logistics. However, substantial savings can also be realized by an understanding and utilization of northern terrain.

The asbestos project of Murray Mining Corporation Limited offers an excellent example of the factors which might influence mine development and construction in the tundra region.

Location

The orebody to be developed is located at Asbestos Hill in the northern tip of the Labrador-Ungava Peninsula. It is situated 40 miles southeast of Deception Bay on Hudson Strait and is 300 miles north of the treeline. Sugluk is the nearest point of habitation and is 60 miles northwest of Asbestos Hill.

This major project includes a dock, harbour facilities, 42-mile road, mine, mill, townsite, airstrip and other ancillary facilities. As would be expected, the terrain implications are many, varied, and unusual.

Geology

The terrain of the project area is typical of the Canadian Shield in the Labrador-Ungava Peninsula. A rock upland with a shallow veneer of glacial drift and rock detritus, it is cut by winding canyons so that in places local relief exceeds 1,000 feet.

Although striking effects of glaciation are few, the results of this process are abundant and will have an important and varied influence on construction in the area. During glaciation, the submergence of the land due to the weight of thousands of feet of ice inundated large areas of the coastal region. At Deception Bay, strand lines (or old beach deposits) exist hundreds of feet above the present sea level. These deposits of sand and gravel will prove most useful during the construction of the harbour and road – both as a source of concrete aggregates and for good draining fill.

The streams from the melting glacier that eroded and deposited sands and gravels will be of wider beneficial effect to construction. Because many of the rocks in the vicinity are easily eroded, however, the resulting deposits are oversanded. These materials are the principal source of fill for the road construction.

In many of the project areas there was little direct deposition by the glacier (that is, "plastering" of glacier eroded materials or "letting down" of materials as the glacier melted). The sporadic and shallow soil remnants that were deposited had most of their fines removed by the action of water or wind. The result, with apparent implications to road construction, are extensive areas of boulder fields.

Present-day erosion is also altering the landscape. The easily eroded rocks are disintegrating rapidly and forming more fine-grained soils. Frost boils, stripes and solifluction lobes so common to the area form in these soils under the prevailing environmental conditions.

Climate

Long winters and short summers, rather than extreme temperatures, characterize the climate of the region. The mean annual temperature is approximately 17°F with summer daily maximum temperatures seldom exceeding 70°F and winter daily minimum temperatures seldom below -40°F.

The short summer construction season, compensated by the increased hours of daylight, suggests careful planning of construction so that this short interval of highly productive construction time is utilized most effectively. The short construction season also prompts the consideration of any construction that can be carried out during the winter.

The winter effects of snow and wind are of particular importance to construction in the area. The total precipitation in the area is low (14 inches) and the snowfall is about 70 inches. However, winds as high as 100 miles per hour have been reported and these high winds form drifts in the lee of any obstruction. Structures (both buildings and roads) will induce some drifting and the consequences to access, as well as drainage when the snow melts, must be individually appraised.

The first exploration camp at Asbestos Hill was placed unfortunately in the lee of a hill. As a result, the camp area had 10 feet of snow on it by Spring. The next season the camp was moved to a location where the wind kept the camp relatively free from snow.

Vegetation

The harsh environment restricts vegetative growth to the more hardy plant species such as grasses, sedges, mosses, lichens and low shrubs. Although vegetative changes (in species, growth or density) are not normally utilized in construction projects, this type of observation can be of invaluable help during the construction phase of the project. For example, very frequently the natural drainageways may have different or a more dense plant growth. Such indicators should not be overlooked, especially in the installation of culverts. In addition, low woody shrubs, willows or ground birch, may indicate a relatively deep snow cover. The absence of vegetation may suggest snow-free, windswept areas and potentially intense frost action.

Occurrence of Permafrost

Permafrost may be defined as the below 32°F temperature condition exhibited by earth materials continuously for a number of years and is basically the result of a past or present climate. Climatic data and site drilling experience suggests that the occurrence of permafrost in the Asbestos Hill locality may be described as "continuous", that is, it is found everywhere under the natural surface. A more quantitative estimate of permafrost (based on preliminary subsurface temperature measurements) would be that it can exceed 500 feet with a minimum temperature of approximately 20°F at a depth of about 100 feet.

Although permafrost conditions are described as continuous, discontinuities in its areal and vertical occurrence are experienced. The most significant permafrost discontinuities are related to the thermal characteristics of large bodies of standing or flowing water with minor deviations due to local environment, that is, a change in aspect, exposure, material, micro-drainage or surface cover. These permafrost discontinuities are of immediate concern to the docksite design where permafrost is apparently absent to the high tide level of Deception Bay; and of future concern in areas where water will be impounded to depths of more than 6 feet. This latter point is of interest for the design of a dam in a creek some 8,500 feet west of Asbestos Hill where it is proposed to impound sufficient water for one year's requirement of a production plant and townsite. The existence of a permafrost condition in this dam would be an advantage, but the impounding of water to a depth of 50 feet would affect this condition. In addition, the temperature in the walls of the canyon at the damsite will probably rise and investigation will be necessary to determine whether grouting will be necessary to prevent seepage.

These comments on the perennially frozen condition prompt some remarks on the occurrence of ice even though such generalizations may be difficult and dangerous. In the project area, extremely high ice contents normally can be expected in the fine-grained soils such as silt-clays, silts and silty fine sands. Large tabular wedge-shaped ice masses have also been observed. Relatively lower ice contents were experienced with coarse grained soils. In general, these conditions will not affect construction except for portions of the road route. Provision for adequate fill to maintain the frozen condition should minimize the problem. In frost-shattered bedrock, the ice content appears to be related to drainage and hence individual appraisals of ice must be made. Although the examination of "sound" bedrock was limited and hampered by thermally disturbed cores, the presence of ice, if any, should not affect the foundation characteristics of the bedrock.

Active Layer

The active layer is the zone immediately beneath the ground surface, where seasonal freezing and thawing occurs. The maximum depth of thaw for the Asbestos Hill project region can be assumed to be 5 feet. This five-foot active layer could be anticipated in a southern exposed coarse-grained material (gravel or rock debris) that is well-drained and has no organic cover. A depth of less than 2 feet of active layer can be expected in a poorly-drained northern exposure of fine-grained material with organic cover. Variations in exposure, material, drainage, and organic cover can result in active layer depths between these two extremes.

The active layer, or more correctly the depth of seasonal ground thaw, is especially important to future borrow pit operations. An orderly exploitation of the limited "fill" resources must be made.

The relatively slow seasonal rate of thaw (even of coarse-grained materials) dictates large areal operations on south facing or sunny exposures. Large borrow areas which will be utilized for a number of years should have planned drainage and a minimum of snow drifting. Access roads to materials should be restricted to the perimeter of the deposit as much as possible to minimize vehicle traffic over "disturbed ground".

These same considerations should also govern construction planning and programming to prevent the establishment of impossible quagmires in those limited areas in the Asbestos Hill area where poor soil conditions are found.

Soil Temperatures

Large soil temperature variations in the active layer can be expected. These variations, which depend on the micro-environment, such as snow cover, decrease with depth. During one year it is estimated that the temperature can range from -20°F to 50°F at a depth of one foot below the ground surface; and at a depth of five feet (bottom of maximum active layer) may range from 0°F to 32°F. Soil temperature variations in permafrost are not as extreme but a range of 4 Fahrenheit degrees can be experienced to a depth exceeding 25 feet.

Soil temperatures, in addition to construction and maintenance difficulties, will normally prevent the location of utilities below the ground surface. To their credit, the low soil temperatures should induce relatively quick refreezing after temporary disturbance, such as with steamed pile foundations.

A potential foundation problem concerning soil temperature fluctuations should be appreciated even though little is known quantitatively about the phenomenon. Surface soil or organic mantle contracts and expands with seasonal temperature fluctuations. Because the temperature fluctuations are most extreme near the ground surface, the largest lateral movements are experienced and reflected at the surface (as surface soil cracks, often forming a "polygonal" pattern) but can extend to depths of as much as 60 feet. Normally these seasonal lateral movements will not exceed more than 1 inch and hence are usually only of concern to structures with small movement tolerances. In such cases, good evidence of the potential problem may be inferred from surface cracks or from tabular or wedge-shaped ice inclusions in the underlying soil. Again, the work completed has indicated that this condition will not be experienced in any of the construction areas, with the exception of the road route.

Thawing of Permafrost

The serious consequences of thawing perennially frozen soils with high ice contents are now well appreciated. Much of the project area contains this potentially troublesome soil condition and it is prudent to base design considerations for the whole project on little or no disturbance of the perennially frozen condition. Naturally some modification of this overall criteria will be necessary because of economics.

Northern construction experience suggests the adaptation of the gravel pad type of foundation for the project area. At locations where little or no volume changes are expected on thawing (or if expected, can be tolerated) the function of a gravel pad would be to arch over small-scale settlements due to minor soil deviations. Where the thawing of subsurface materials will probably produce significant settlements, the function of a gravel pad is to insulate. The resulting thaw is confined generally to the pad and where some thawing proceeds to the underlying material, the arching action of the pad can accommodate the minor movements.

The design calculations for the thickness of the pad required to provide the necessary insulation involve seasonal air temperatures and the properties of the fill materials. Adequate information is not presently available but, in general, a gravel pad should be equal in thickness to the depth of the underlying active layer. Experience to date with small buildings has shown that inadequate pads can result in heaving of several inches, even on relatively well-drained soils. Pad thickness will be adjusted depending on:-

1. The settlement tolerance of the structures, for example, a local one-foot settlement in a road could be easily remedied but such a movement in a building would be disastrous;
2. Expected settlements; and
3. Differing insulating properties of the fill.

In any case, a minimum fill of 2 feet will always be specified.

In some cases of important structures (where the provision of gravel to virtually assure no movement is uneconomical or where coarse-grained fill is scarce) pile foundations offer an economical solution to the problems of thawing perennially frozen soils with high ice contents. In these cases, the minimum 2 foot gravel pad is provided as a working surface; pile locations are drilled or steamed; and the piles are driven to a depth of 15 feet. After an interval of one month to one year, depending on the disturbance by construction, the piles will be refrozen. Some thawing of permafrost will not affect the structure although some ground settlement can be expected.

Frost Action

Past studies have shown that frost action involves the interaction of three principal conditions: (1) below freezing temperatures; (2) a frost susceptible soil; and (3) a readily available source of moisture. All of these conditions exist over a large part of the project area and the frost action effect warrants elimination or control. In many cases the control of frost action can be achieved by providing adequate drainage and by the provision of non-frost-susceptible material, that is, clean gravels or coarse sands. Additives or chemicals to control water availability or to reduce frost action will be expensive and lasting beneficial effects are questionable.

Frost action in the Asbestos Hill area has resulted in the surface of the serpentinized rocks being reduced to a talus-like rubble.

The wide extent of this material, which extends to a depth of 10 to 15 feet, was the governing criterion for the location selected for the preliminary airstrip. A D-8 tractor was the only piece of equipment on hand and so the choice had to be governed by availability of fill.

The whole length of the airstrip was filled and adequate ditches were provided. To date this has proven to be a very good choice and no drainage problems were evident.

The prime criterion used in the selection of mill and townsites was adequate bedrock to support major buildings without extensive foundations. Fortunately an excellent area was located half a mile northwest of the orebody where the surface mantle over a large area is limited to several feet. Thus the majority of buildings will be built on bedrock with no serious problems of permafrost.

Drainage

The provision of adequate drainage for the many and varied aspects of the project cannot be over-emphasized. Disruption of natural drainageways can contribute to the thaw of permafrost and induce or increase frost action effects.

Maximum surface runoff can be expected early in the Spring (June) and is many times the volume of the summer flow (July-August). This short duration, high volume flow, can be expected for even smaller creeks or gullies draining snow patches. In critical areas, culverts may be stacked one on top of another to accommodate high spring flows and counteract the problem of possible freezing of the bottom culvert.

The design of artificial drainageways should supplement or correct the disruption of natural drainageways by construction. For buildings, no ponded water can be tolerated. In the case of road construction, ponding is difficult to overcome entirely, and usual construction practice is to keep major drainage ditches at least 50 feet from the roadway.

Road "icings" are not considered to be a major problem in the project area. Remedial action, by intercepting and inducing icings where no damage will be incurred, will be carried out when and if the problem is encountered.

Solifluction

Solifluction may be defined as the mass movement of earth materials due to frost action. The seasonal thawing of fine-grained soils with high ice contents on a slope form a saturated, jelly-like soil mass that can move downslope. Large-scale soil mass movements can result in lobes that resemble lava flows, while smaller soil mass movements may be in the form of 5 to 10 foot wide stripes.

Small-scale solifluction should not normally affect project construction except perhaps to indicate potentially frost-susceptible soils. Large solifluction lobes can move up to 6 inches annually. Since the factors that affect solifluction are many and dependent on the local terrain environment, individual appraisals will be made when construction is planned in the vicinity of a solifluction lobe.

IV. 2. GROUND TEMPERATURE MEASUREMENTS IN THE SCHEFFERVILLE AREA, P.Q.*

Lennart Annersten

(Summary)

The aim of this paper is to describe the permafrost investigations carried out in the Schefferville area, P.Q., and to report some preliminary results.

During the summers of 1956 and 1957, the first permafrost investigations in the area were initiated by the Iron Ore Company of Canada. Permafrost was found to vary from 12 to 60 metres (40 to 200 feet) in thickness; these variations were to some degree related to vegetation and exposure.

To evaluate such environmental factors as snow cover, vegetation, exposure, etc., 8 thermocouple cables were installed at various sites within a limited area in the summer of 1959. This research programme was made possible by the co-operation of the Iron Ore Company of Canada, the National Research Council, and the McGill Sub-arctic Research Laboratory in Schefferville. This programme, was again extended in 1961 when 6 new thermocouple cables were installed. A total of 360 metres (1185 feet) of drilling was done and thermocouple cables installed in the holes to depths varying from 15 to 60 metres (50 to 200 feet). Readings on these have been taken almost monthly.

Because of errors inherent in the measuring equipment, the readings from the thermocouples showed variations that cannot be regarded as true temperature variations. A significant test of the readings since 1959 below the 15 metre (50 feet) depth, where no seasonal temperature variations can be detected in the readings, indicate that ground temperatures over the period September 1961 - January 1962 were 0.2°C warmer than previous readings. Climatological data, however, indicate that there should have been a cooling trend in the ground temperatures, so that this warming was more likely caused by stripping of the vegetation around the installation. This has apparently changed the thermal regime of the surface, the net effect being an increase in ground temperature.

The plotting of mean annual soil temperatures, calculated for various depths and sites, produced two types of curves. The first

---

* A complete report of this study will be published by the Department of Geography, McGill University.

type indicated a general temperature increase with depth due to the influence of the geothermal gradient. The second type indicated a general temperature decrease with depth. It is suggested that this is caused by lateral heat flow in areas with different surface thermal regimes caused mainly by variations in snow cover between exposed and more protected areas.

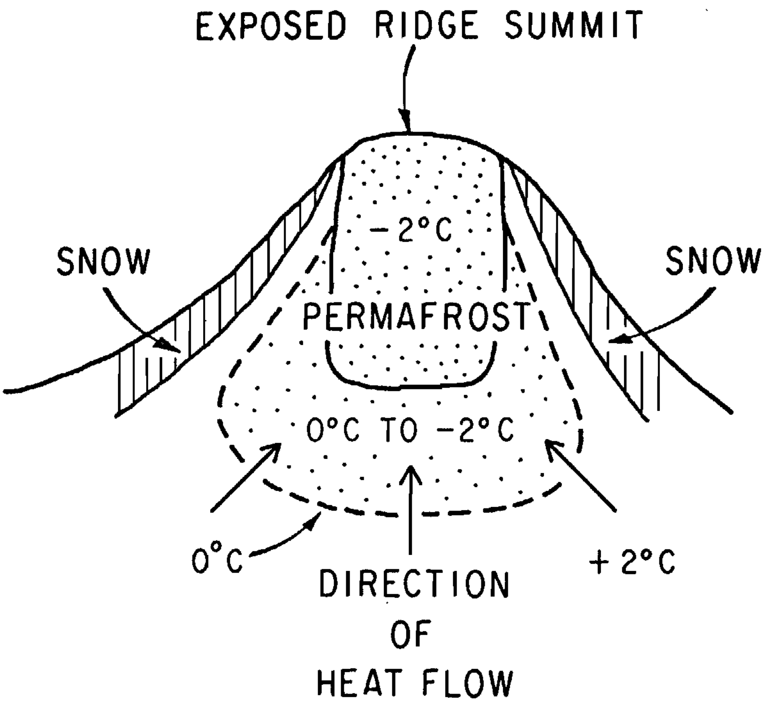
******

Discussion

J. R. Mackay asked how often readings were taken that were used in the statistical analysis of the ground temperature regime. He added that the larger the number of readings, the more significant they are statistically. The author replied that monthly readings were used in the analysis.

N. W. Radforth observed that if there is vegetation (mosses and lichens) even only a few inches thick over the area in question, then it follows that its removal would cause a subsequent increase in the mean ground temperature. In addition, if the type of vegetation changed, then the influence would change. This would afford a means of testing whether the removal of vegetation is responsible for the increase of ground temperatures during 1960-61 over 1959, whereas climatological data suggests that the reverse result in the ground temperature regime might have been expected.

R. Yong wished to know the boundary conditions assumed for heat transfer in the ground. The author replied by presenting the following illustration:-



J. D. Ives commented on the apparent increase of temperature at the 15 metre depth during the period 1959-60 and 1961-62. The stripping of the lichen mat, attendant upon drilling operations at the sites of thermocouple installations has probably had an important effect upon the ground temperature regime. At the 15 centimetre depth, a temperature difference of 11°C in 40 days accrued between an undisturbed site with a 10 centimetre thick lichen mat and a stripped site adjacent to it. This effect should result in accelerated heat flow into the ground in the summer. In winter, however, the reverse process is not necessarily operative because the variation in snow depth, rather than in vegetative cover, appears to be the dominant factor in local differences in the thermal gradient of the upper 6 metres. L. W. Gold added that if the vegetation cover is removed, then the thermal resistance to heat flow is reduced. This will result probably in an increase in amplitude of the thermal disturbance but will not necessarily change the mean ground temperature. The net effect of removing the vegetation may be a greater increase in summer ground temperatures than in winter ground temperatures because of the snow cover. C. B. Crawford remarked that the Division of Building Research has found that there is generally a good correlation between degree days and depth of frost penetration. At Schefferville, however, it was found that the depth of frost penetration was considerably deeper than the above relationship would indicate. A 50 foot thermocouple string was installed in this area near a shaft which was filled with ice. The temperatures of the thermocouples never dropped below 33°F.

IV.3. EFFECT OF A LAKE ON DISTRIBUTION OF PERMAFROST IN THE MACKENZIE RIVER DELTA

G. H. Johnston and R. J. E. Brown

(Summary)*

INTRODUCTION

The thawing effect of water in contact with permafrost is a problem of major concern to engineers engaged in northern construction. Improper drainage which allows water to pond adjacent to or under structures such as buildings, roads or airstrips, nearly always results in an increased depth of thaw of the perennially frozen ground. In many cases the performance of the structure is seriously affected even to eventual failure. The degradation of permafrost by water is of even greater concern when dykes or dams are constructed on perennially frozen ground and large areas are flooded by the water impounded behind them. The design and performance of these structures and the stability of the underlying frozen foundation material is dependent on a knowledge of the rate at which thawing will take place and the depth to which the perennially frozen ground will thaw. There is little information presently available, however, to indicate the magnitude of these factors. Mathematical analyses can and have been made, in some cases, but because of complex boundary conditions and lack of pertinent data, such as mean annual ground and water temperatures and the geothermal gradient, it is difficult to obtain an exact picture of the effects which might be expected and are of prime importance to the designer.

One method of improving knowledge of the thawing effect of water on permafrost, however, and of providing some guidance for future engineering design is by studying the present level of permafrost under natural bodies of water in the north, such as lakes and streams. Members of the Division of Building Research carried out a drilling programme in April 1961, therefore, to determine the distribution of permafrost under and adjacent to a lake in the Mackenzie River delta near the new townsite of Inuvik, N.W.T.

DESCRIPTION OF SITE

The Mackenzie River delta, which is approximately 50 miles wide and 100 miles long, is a low, flat area interlaced and dissected by numerous small meandering channels and is spotted with thousands of stagnant lakes.

---

* The full paper will be published by the Division of Building Research, National Research Council, Ottawa.

One of the lakes was selected for investigation following a preliminary study of aerial photographs and a field reconnaissance in 1960 of a portion of the delta within a 10-mile radius of Inuvik (Figure 1). This lake, located about 5 miles southwest of the town is approximately circular, having a diameter of about 900 feet. Like all delta lakes, it is shallow, being only about 4 feet deep at its centre (Figures 2 and 3).

The dense forest vegetation around the lake studied is typical of the climax developed in the lower valley and delta of the Mackenzie River. The dominant species is white spruce, the largest trees growing to a height of 50 feet. Also present are black spruce, willow and alder with scattered stands of tamarack. The largest trees growing in the surrounding area and close to the edge of the lake are as much as 220 years old. The apparently continuous moss cover is about 1 inch thick.

In making such a study it was considered important to choose a body of water that had been in existence for a sufficient period of time to have approached a condition of thermal equilibrium with the frozen ground beneath. It was realized that the selection of a delta lake is somewhat questionable because it is situated in what is essentially an old river bed and that there might be considerable effect on the occurrence of permafrost due to the large number of lakes and channels in the immediate vicinity. For such a study, however, this situation offered the advantages of accessibility from Inuvik and easier drilling and sampling because of homogeneous soils conditions.

DESCRIPTION OF INVESTIGATION

The investigation consisted primarily of a drilling and sampling operation whereby holes were bored to various depths at four locations (Figure 2). Continuous coring was carried out for the full depth of Holes Nos. 1 and 3 and good undisturbed cores of most of the materials encountered were obtained. Representative samples were taken for identification and classification testing of the soils, moisture (ice) content determinations, pollen analysis and carbon-14 age determinations.

A number of hand probings were made to determine the extent of the permafrost table beneath the edge of the lake. Surveys were carried out on a grid pattern on the lake to obtain snow depths, ice thickness, water depths and bottom contours (Figure 2). Two thermocouple cables were also installed as part of the study to measure ground temperatures - one 100 foot cable was placed in Hole No. 3 (132 feet west of the lake) with sensing junctions at the 25, 50 and 100 foot depths, and a 200 foot cable was placed in Hole No. 4 (550 feet from the lake) with points at 5 foot intervals from the ground surface to 25 feet, and at the 50, 75, 100, 150, and 200 foot depths.

DRILLING AND SAMPLING

A standard type diamond drill equipped with hydraulic feed was used to drill and sample the various materials encountered (Figure 4). The presence of permafrost, and the subnormal air temperatures which occurred during April, greatly complicated the drilling and sampling operation. Water, obtained from the lake at a temperature of 33°-35°F, was used as a circulating fluid except for one unsuccessful attempt to use arctic grade fuel oil. When using water, drilling techniques had to be modified slightly and great care taken to prevent freezing of equipment in the hole.

Double tube core barrels were used to obtain undisturbed cores of the perennially frozen ground. Two-inch diameter cores were taken from the ground surface to a depth of about 100 feet. Below this, 1-inch diameter cores were obtained. In the hole at the centre of the lake, where no frozen ground was encountered, samples were obtained using a piston-type tube sampler to about 120 feet. Below this depth a double tube core barrel was used giving 1-inch diameter cores.

DISCUSSION OF RESULTS

The drilling investigations showed that the sediments beneath the centre of the lake (Hole No. 1) were unfrozen to bedrock at a depth of 230 feet. On the other hand, permafrost did occur for the full depth of each of the three holes west of the lake (Figure 5a). These observations were substantiated by ground temperature measurements taken in May 1961 which are plotted in Figure 6.

The hand probings showed that the permafrost table extended out from shore under the edge of the lake and sloped steeply down (Figure 5b). Ten feet from the bank, the permafrost table occurred 15.5 feet below the ice surface; 12 feet from the shore - at a depth of 19.7 feet; and, at 15 feet, was greater than 22 feet below the ice.

From these observations, it is evident that the lake, although quite shallow and of small dimension, has a very marked influence on the distribution of permafrost. It is probable that the bottom of the thaw basin under the lake is located in the bedrock some tens of feet beneath the sediments. The thawing effect of the lake is confined, however, to the ground lying under the lake as evidenced by the presence of permafrost under the shoreline. The thermal effect of the lake extends into the surrounding area for some distance away from the shore as evidenced by the ground temperature observations.

Extrapolation of the two temperature profiles, assuming a straight-line gradient, produces a thickness of permafrost of about 250 feet at Hole No. 3 (132 feet west of lake) and about 300 feet at Hole No. 4 (550 feet west of lake). It is assumed that the permafrost shelves under the edge of the lake in the form of a wedge with its base curving back and downwards toward the shoreline.

The deep thaw basin under such a small and shallow lake suggests that the present environmental conditions and characteristics of the lake have prevailed for a long period of time. This assumption is supported by several features of the lake observed in the Spring of 1961. The shoreline appears to be stable as evidenced by the presence of trees as old as 220 years. It appears that flooding of the lake and surrounding area occurs at intervals of a few years but probably does not occur every year. Such flooding occurred in May 1961 when the water in the Mackenzie delta reached a record high level. Previous flooding is indicated by two features. Firstly, the moss cover is very thin and poorly developed - spring flood deposited material, killing or hindering its growth. Secondly, silt marks on tree trunks indicate an extreme high water mark about 5 feet above the present ground surface - i.e., about 20 feet above the winter ice level of a main delta channel nearby.

Observations of ice thickness and water depth in the spring of 1961 suggest that it is unlikely that the lake freezes to the bottom, even during the most severe winter. As a result, a layer of water is continuously in contact with the underlying sediment, thus maintaining a thawed condition in them. During the winter of 1960-61, air temperatures and snowfall were below normal, a situation most conducive to thick ice formation in lakes. Nevertheless, the lake, although only about 4 feet deep, was not frozen to the bottom. In April 1961, the ice cover was about 2 1/4 feet thick and the average depth of water was 1 1/2 to 2 feet.

Three main conclusions can be stated regarding the effect of the lake on the distribution of permafrost. Firstly, the existence of the lake in its present form has caused the formation and maintenance of a thaw basin several hundred feet deep. Secondly, the thawing effect of the lake is confined to the ground lying under the lake as evidenced by the presence of permafrost under the shoreline. Nevertheless, the increasing thickness of the permafrost inland from the shore indicates that the thermal effect of the lake extends for some distance beyond its perimeter. These conclusions are supported by an analysis of the thermal situation at the lake using methods reported in the following paper by W. G. Brown (Figure 5c).

In conjunction with the determination of the permafrost distribution by drilling, undisturbed core samples were obtained from

Holes Nos. 1 and 3 giving the following soil profile:

0' - 100' - Thinly stratified sandy silt with layers of decomposed organic material throughout. The content of organic material was particularly high at the bottom of this layer.
100' - 180' - Fine to medium sand with thin layers of organic material, spaced at irregular intervals throughout the full depth.
180' - 230' - Very dense clay containing scattered small pebbles from the 206 to 221 foot depth and a high concentration of pebbles in the bottom 9 feet above bedrock. No pebbles were found in the top 26 feet of the clay stratum.
Below 230' - Bedrock (dolomitic limestone).

Visible ice segregation in the form of horizontal and irregularly oriented layers was confined mostly to the top 30 feet. Below this depth, the soils were solidly frozen but only random thin ice layers, occurring in predominantly silty or clayey soil, were noted. Sandy material was well bonded by ice not visible to the eye. Moisture content determinations indicate a decrease with depth.

The soils profile revealed by drilling and sampling suggest that the subsurface materials are of glacial and post-glacial origin. It is possible that the clay occurring below the 180 foot depth is till overlain by marine clay. The change to sand containing thin layers of organic material at the 180 foot depth may indicate the beginning of deltaic deposition continuing to the present. The formation of permafrost began probably with the initiation of deltaic deposition.

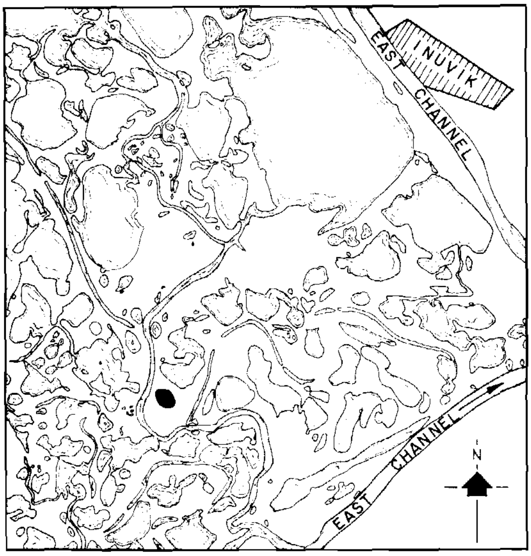
Further investigations of the distribution of permafrost under lakes are proposed for the near future.

******

Discussion

R. G. Howard reported that at Inuvik, N.W.T., probings beneath the ice in Twin Lakes revealed the existence of permafrost at a depth of 9 feet below the lake bottom. He asked how this related to the findings of the authors. G.H. Johnston stated the possibility that Twin Lakes freezes to the bottom and the proximity of a large perennially frozen land mass might be the cause of permafrost existing at such a shallow depth.

J. M. Robinson wished to know if there was any indication of decaying vegetable matter in the lake bottom sediments. Johnston replied that there was evidence of decaying vegetation at the bottom of the lake.

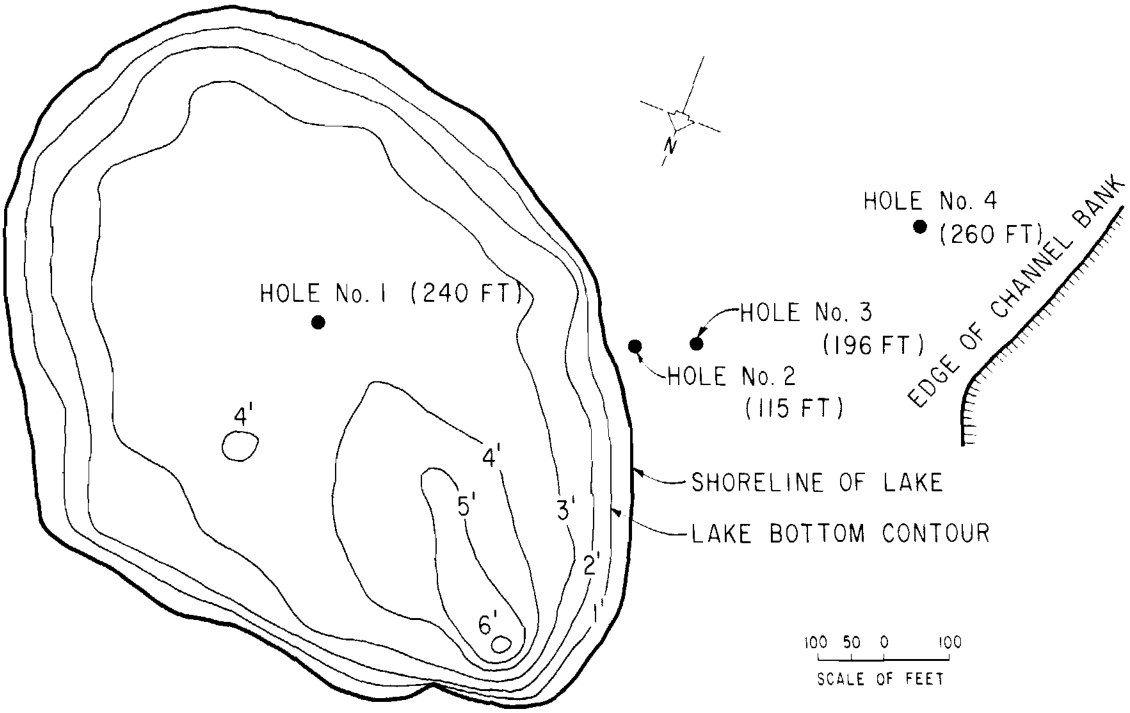


MACKENZIE DELTA LAKE INVESTIGATIONS

LOCATION OF LAKE
(shown in black)

1 1/2 0 1
SCALE OF MILES

FIGURE 1



(DEPTH OF HOLES IN BRACKETS)

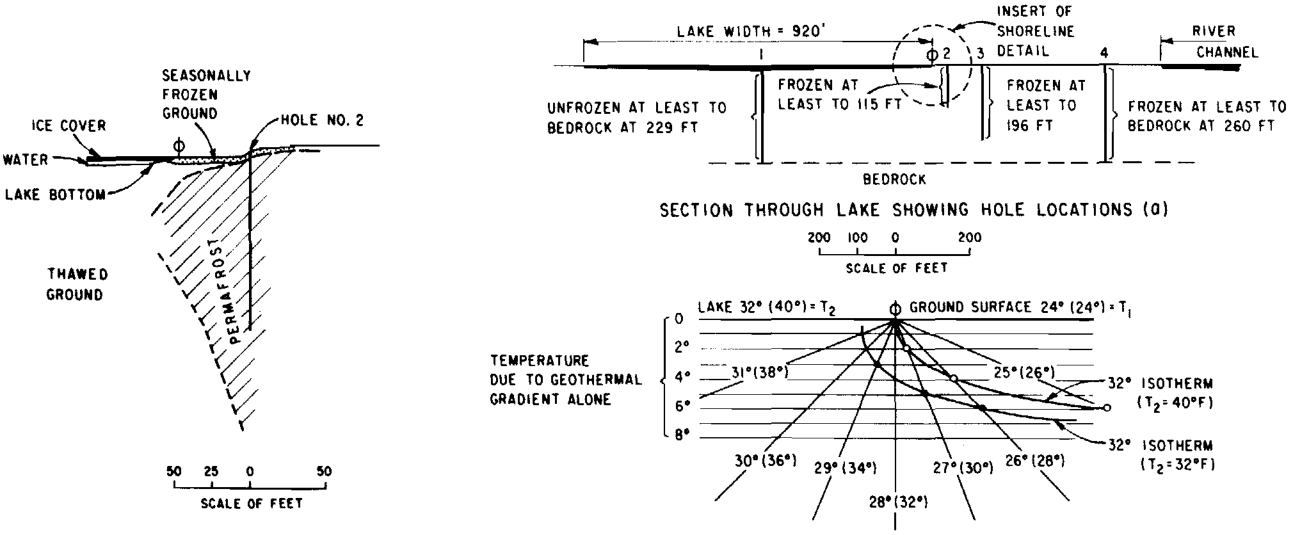
MACKENZIE DELTA LAKE INVESTIGATIONS

LAKE BOTTOM CONTOURS AND BOREHOLE LOCATIONS, APRIL 1961

FIGURE 2

Fig. 3 Aerial view of Mackenzie River delta lake investigated April 1961. View looking east from about 1000 feet altitude taken July 1960. Note dense forest vegetation around lake (right centre).

Fig. 4 Drill set-up at Hole No. 1 (centre of lake). Note core sampling table to right of drill shack and depth of snow cover.



SHORELINE DETAIL (b)

SECTION THROUGH LAKE SHOWING HOLE LOCATIONS (a)

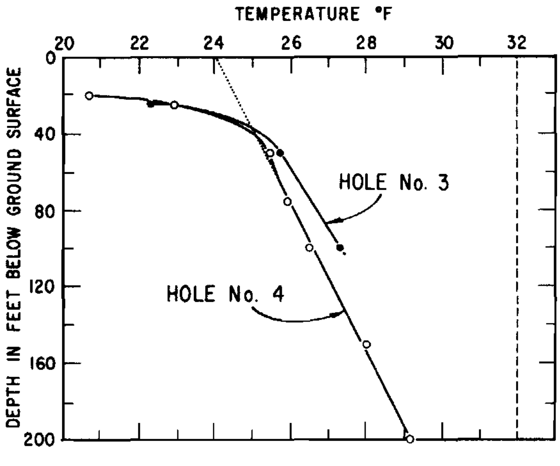
APPROXIMATE POSITIONS OF THE PERMAFROST BASE NEAR THE LAKE EDGE (c)

MACKENZIE DELTA LAKE INVESTIGATIONS

ϕ SYMBOL INDICATES POSITION OF LAKE-LAND JUNCTION

FIGURE 5

BR 2679-3



MACKENZIE DELTA LAKE INVESTIGATIONS

GROUND TEMPERATURES – MAY 1961

BR 2679-2

FIGURE 6

IV. 4. SIMPLE GRAPHICAL METHODS FOR ESTIMATING THE LOCATION OF PERMAFROST UNDER SHALLOW LAKES AND RIVERS

W. G. Brown

The investigations reported by Johnston and Brown (2) and Mackay (4) are concerned with the location of permafrost in the neighbourhood of shallow bodies of water. Because problems of this sort will probably occur with increasing frequency in the future, an introduction to some simple graphical methods for estimating the temperature regime in the ground and the resulting position of the permafrost table is presented here.

Wherever there is a body of water, whose mean annual temperature is above freezing, a thawing back of the permafrost under and about it will occur. The location of the permafrost table then depends on a number of factors, the principal ones being the mean annual water and ground surface temperatures and the geothermal gradient for the region. Other governing conditions are the size and shape of the bodies of water and the constancy of their shape and size with the passage of time. Obviously possession of detailed information on temporal variations will not probably be available, but because these would likely be quite gradual it is reasonable to assume steady-state conditions for the purpose of obtaining a general picture of the thermal regime in the ground.

The graphical method outlined in this paper relies on the fact that the resultant temperature in the ground can be considered as the sum of three separate temperature effects, these being:

(1) that resulting from a temperature difference between the water and the surrounding ground surface;
(2) the amount by which the temperature is higher than at the surface due to the geothermal gradient;
(3) the actual temperature of the ground surface.

The first of these temperature effects is depicted in Figure 1 where the temperatures near the straight edge of a large shallow body of water are shown for the case where there is no geothermal gradient. It will be readily recognized from symmetry that heat flows from the body of water to the ground in circular paths, while the isotherms, or lines of constant temperature, form radii emanating from the edge. By way of example, with the given values of lake and ground surface temperatures, the temperature directly under the edge would be equal to the average of the water and surface temperature values. If the ground surface temperature T_1 is simply subtracted at all points and

$T_2 - T_1$ set to equal ν_o, the simple schematic temperature distribution of Figure 2a is obtained. The body of water is considered to be at a temperature ν_o higher than the ground surface.

The geothermal gradient can now be added to the temperatures in Figure 2a to produce Figure 2b. Here the lines parallel to the ground surface are isotherms due to the geothermal gradient alone - i.e. in the absence of the body of water. By simply joining points of intersection of the geothermal isotherms and the radial isotherms from Figure 2a which have the same sum, it is possible to obtain the temperature profiles for the combined case. To complete the problem, the value of T_1 (the actual ground surface temperature at all points) is added. For example, if ν_o were 10°F and T_1 were 22°F then the $1.0\ \nu_o$ isotherm would outline the 32°F isotherm and the position of the permafrost.

In Figure 2c the same direct addition procedure is used to obtain the temperature regime under a river with parallel sides, in this case in the absence of a geothermal gradient. The procedure, in effect, is to superimpose a reversed copy of Figure 2a on itself separated by a distance 2d. When the temperatures due to the two sets of isotherms are added, the new isotherms are circles. Also, the temperature at the external ground surface becomes ν_o while that of the river becomes $2\nu_o$. By subtracting the value ν_o at all points, the circular isotherms in Figure 2d are obtained, to which the geothermal gradient effect can be added in the same manner as was done in Figure 2b. The curves in Figure 2d are the final resulting isotherms under a river.

A numerical example will illustrate this procedure using again a value of 10°F for ν_o and 2°F per 100 feet for the geothermal gradient. This means that the temperature regime for the $1.0\ \nu_o$ value of the geothermal gradient occurring at a depth of 500 feet, which in this case is also the width of the river has been constructed. If now the water temperature is 32°F, the ground surface is at 22°F and the position of the permafrost boundary is represented by the $1.0\ \nu_o$ curve. Were the water at 34°F, with the ground surface at 24°F, the $0.8\ \nu_o$ isotherm would represent the permafrost face, and it can be seen that in this case there is no permafrost under the central portion of the river.

From these last considerations, it is clear how critical the actual water and ground temperatures are to determine the location of the permafrost. It is necessary to know these temperatures with considerable accuracy in order to predict the permafrost position.

The examples of the edge of a large body of water and of a river are very useful in obtaining a rough idea of the distribution of permafrost in a given problem, but the majority of water bodies do not conform to such a simple geometry.*

For irregular areas the temperature is determined by a different method as depicted in Figure 3. Here the water area or areas are subdivided into circular sectors of radius R and angle θ. For these circular sectors a simple equation developed by Lachenbruch (3), is available for the temperature at any depth z under the apex. The sum of temperatures due to all sectors gives the temperature which would occur in the absence of a geothermal gradient, and to this can be added the temperature due to the geothermal gradient for that depth. For further details of this procedure the reader is referred to references (1) and (3). To reduce the labour involved in summation of this kind, the author has devised a programme for the Bendix G-15 computer which is now available to the interested reader.

In summary, it is obviously a simple matter to estimate the temperature in the ground under shallow bodies of water and thereby to estimate the permafrost location. The gross assumption of steady-state conditions will not always be warranted but will probably yield an acceptable result for many practical purposes.

---

* The graphical method for the edge of a large body of water and a river is identical with that used by Werenskiold for estimating the permafrost location in the neighbourhood of glaciers and fjords (5).

REFERENCES

1. Brown, W. G. The Temperature under Heated or Cooled Areas on the Ground Surface. Symposium on Heat Transfer of the Engineering Institute of Canada. July 1962.
2. Johnston, G. H. and R. J. E. Brown. Effect of a Lake on Distribution of Permafrost in the Mackenzie River Delta. Proceedings of First Canadian Conference on Permafrost - 1962.
3. Lachenbruch, A. H. Three Dimensional Heat Conduction in Permafrost Beneath Buildings. U. S. Geological Survey Bulletin 1052-B. Washington 1957, pp. 51-69.
4. Mackay, J. R. Origin of the Pingos of the Pleistocene Mackenzie Delta Area. Proceedings of First Canadian Conference on Permafrost - 1962.
5. Werenskiold, W. The Extent of Frozen Ground under the Sea Bottom and Glacier Beds. Jour. of Glaciology, Vol. 2, No. 13, April 1953, pp. 197-200.

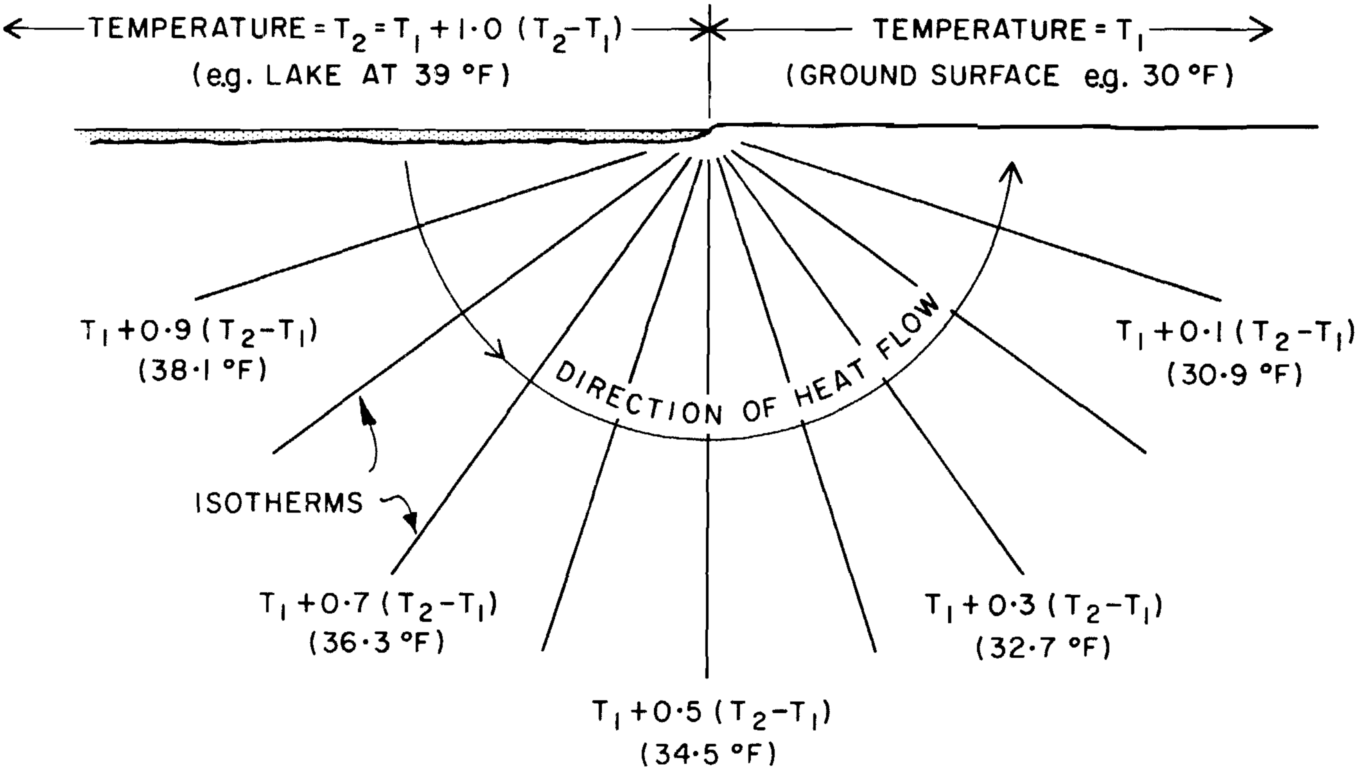


FIGURE 1
STEADY TEMPERATURE UNDER THE STRAIGHT SIDE OF A LARGE, SHALLOW BODY OF WATER ON THE GROUND SURFACE

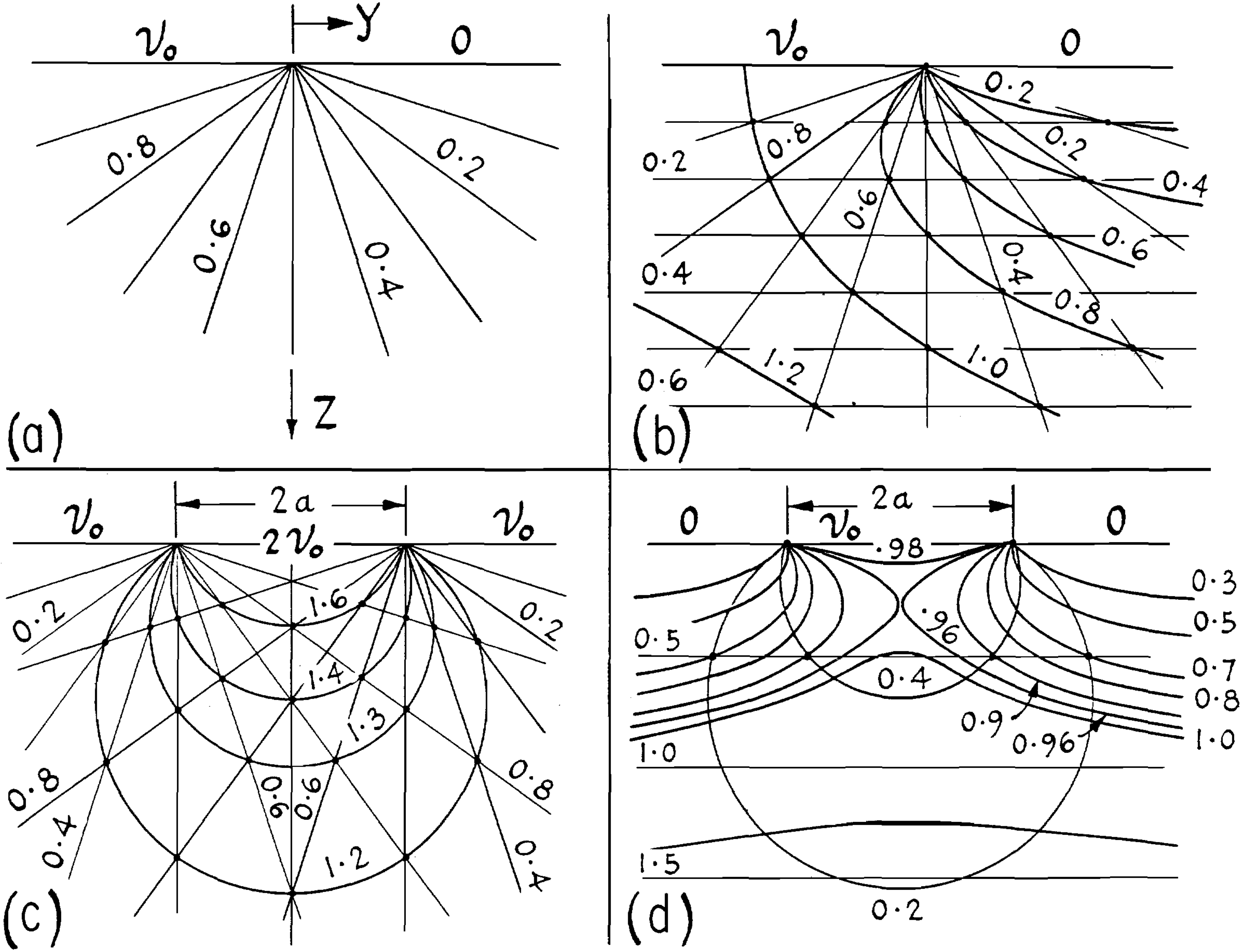


FIGURE 2
GRAPHICAL SUPERPOSITION OF TEMPERATURES

BR 2673-1

$$\nu = \sum \frac{\theta}{360} \nu_0 \left[1 - \frac{1}{\sqrt{1+(R/z)^2}} \right]$$

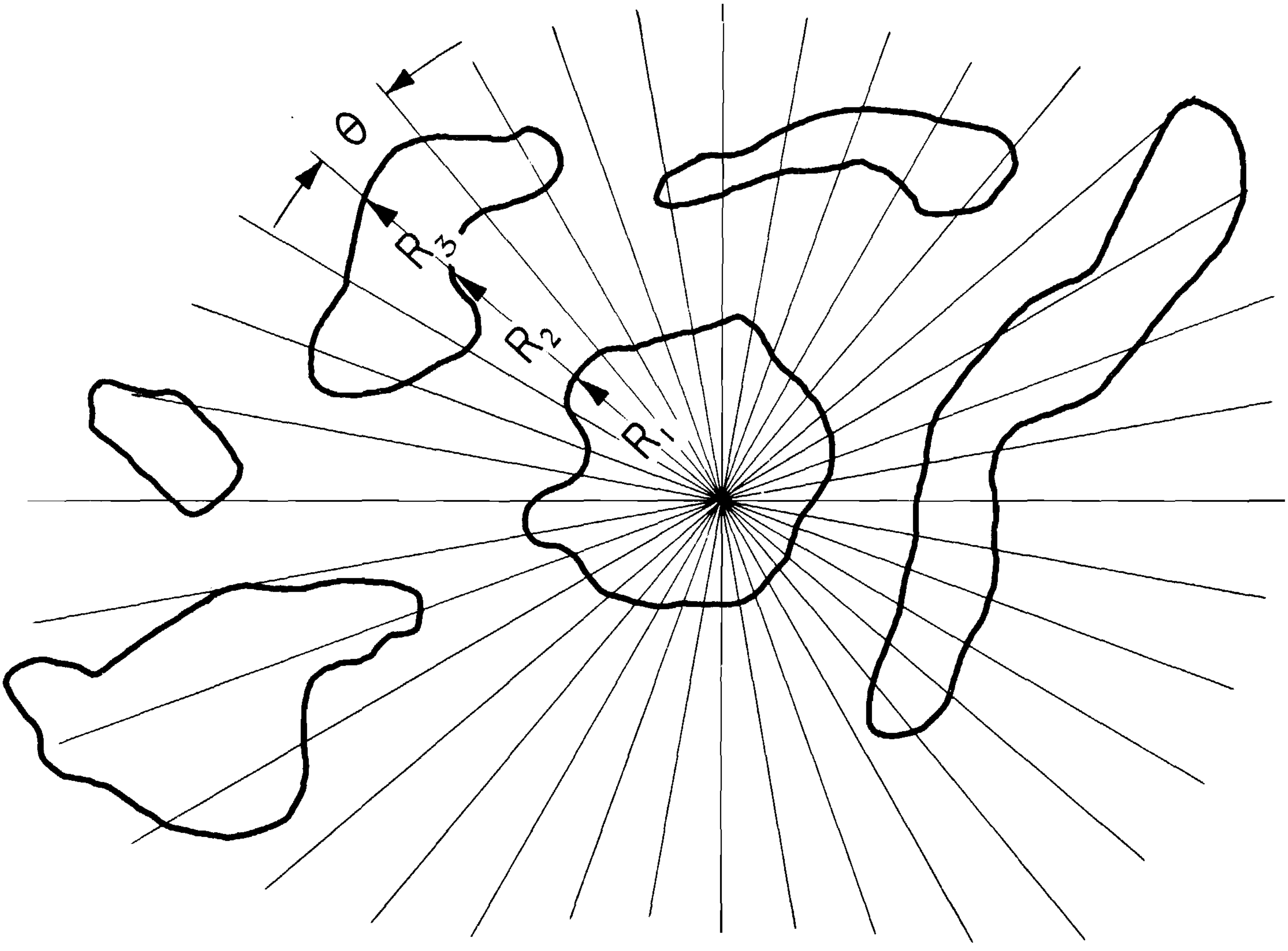


FIGURE 3

SUBDIVISION OF A LAKE-RIVER SYSTEM INTO CIRCULAR SECTORS FOR DETERMINATION OF TEMPERATURE UNDER THE COMMON APPEX

BR 2673-2

LIST OF THOSE ATTENDING FIRST CANADIAN CONFERENCE ON PERMAFROST - 1962
OTTAWA, ONTARIO
APRIL 17 and 18, 1962

N. Agensky,
Apt. 402,
6525 Cote St. Luc,
Montreal 29, P.Q.

Major R. E. Aksim,
Courses and Duties Establishment,
c/o 1 Army Administration Unit,
Canadian Army,
"C" Building,
Ottawa, Ontario.

J. T. Andrews,
Geographical Branch,
Dept. of Mines & Technical Surveys,
Ottawa, Ontario.

L. Annersten,
McGill Subarctic Research Lab.,
Schefferville, P.Q.

L. D. Baikie,
Testing Laboratories,
Department of Public Works,
Ottawa, Ontario.

Dr. P. D. Baird,
Department of Geography,
McGill University,
Montreal, P.Q.

R. E. Barrett,
Eldorado Mining & Refining Ltd.,
Box 379,
Ottawa, Ontario.

D. D. Bell,
Eldorado Mining & Refining Ltd.,
Box 379,
Ottawa, Ontario.

Dr. R. E. Beschel,
Department of Biology,
Queen's University,
Kingston, Ontario.

S. T. Bieniada,
Design Division,
Directorate of Works,
Army Headquarters,
Ottawa, Ontario.

T. H. Birt,
Shell Oil Co. of Canada Ltd.,
Edmonton, Alberta.

Dr. W. Blake, Jr.,
Geological Survey of Canada,
Dept. of Mines & Technical Surveys,
Ottawa, Ontario.

R. Boucher,
Dept. of Civil Engineering,
Ecole Polytechnique,
2500 Marie Guyard Avenue,
Montreal, P.Q.

Major F. J. Bowers, Jr.,
U.S. Army Standardization Group,
Canada,
Ottawa, Ontario.

D. W. Boyd,
Division of Building Research,
National Research Council,
Ottawa, Ontario.

M. Bozozuk,
Division of Building Research,
National Research Council,
Ottawa, Ontario.

Dr. I. C. Brown,
Geological Survey of Canada,
Dept. of Mines & Technical Surveys,
Ottawa, Ontario.

J. K. Brown,
Architectural Division,
Department of Transport,
Ottawa, Ontario.

Dr. R.J.E. Brown,
Division of Building Research,
National Research Council,
Ottawa, Ontario.

Dr. W. G. Brown,
Division of Building Research,
National Research Council,
Ottawa, Ontario.

M. Bruno,
Marshall, Macklin & Monaghan Ltd.,
1480 Don Mills Road,
Don Mills, Ontario.

A. M. Buchanan,
Rupert's Land Trading Co.,
Winnipeg, Manitoba.

R. Casperson,
Structures Division,
Department of Public Works,
Ottawa, Ontario.

J. L. Charles,
Canadian National Railways,
460 C.N.R. Station,
Winnipeg, Manitoba

R. Chevalier,
C. D. Howe Company Limited,
1421 Atwater Avenue,
Montreal, P.Q.

A. W. Chlipalski,
Structural Section,
R.C.A.F.,
Victoria Island,
Ottawa, Ontario.

W. G. Cleghorn,
Engineering Division,
Northern Administration Branch,
Dept. of Northern Affairs &
National Resources,
Ottawa, Ontario.

A. B. Connelly,
Engineering Division,
Northern Administration Branch,
Dept. of Northern Affairs &
National Resources,
Ottawa, Ontario.

A. E. Cook,
Department of Public Works,
P.O. Box 488,
Edmonton, Alberta.

D. W. Cornell,
Canadian National Telecommunications,
151 Front Street West,
Toronto, Ontario.

Dr. A. Corte,
Cold Regions Research &
Engineering Laboratory,
P.O. Box 282,
Hanover, N.H., U.S.A.

B. A. Coy,
Telecommunications and
Electronics Branch,
Department of Transport,
Ottawa, Ontario.

Dr. B. G. Craig,
Geological Survey of Canada,
Dept. of Mines & Technical Surveys,
Ottawa, Ontario.

C. B. Crawford,
Division of Building Research,
National Research Council,
Ottawa, Ontario.

F. E. Crory,
Cold Regions Research &
Engineering Laboratory,
P.O. Box 282,
Hanover, N.H., U.S.A.

T. I. Csathy,
Materials & Research Division,
Department of Highways,
Toronto, Ontario.

K. Czerwinski,
Directorate of Works,
Canadian Army,
"C" Building,
Ottawa, Ontario.

E. Daoust,
Architectural Division,
Department of Transport,
Ottawa, Ontario.

J. T. Davis,
Development Engineering Branch,
Department of Public Works,
Ottawa, Ontario.

J. H. Day,
Soil Research Institute,
Department of Agriculture,
Ottawa, Ontario.

J. H. Deacon,
Canadian Aero Service Ltd.,
Ottawa 4, Ontario.

Dr. W. G. Dean,
Department of Geography,
University of Toronto,
Toronto, Ontario.

B. Deshaye,
Chief Engineer's Office,
Department of Roads,
Quebec, P.Q.

J. Z. Dobrowolski,
Design Division,
Directorate of Works,
Army Headquarters,
Ottawa, Ontario.

A. Dubnie,
Mineral Resources Division,
Dept. of Mines & Technical Surveys,
Ottawa, Ontario.

Capt. L. Durocher,
Joint Photographic Intelligence
Centre,
R.C.A.F. Rockcliffe,
Ottawa, Ontario.

H. G. Dutz,
Construction Branch,
Department of Transport,
Ottawa, Ontario.

W. J. Eden,
Division of Building Research,
National Research Council,
Ottawa, Ontario.

W. R. Edmonds,
Public Health Engineering Division,
Dept. of National Health & Welfare,
Ottawa, Ontario.

J. E. Ellwood,
Engineering Division,
Northern Administration Branch,
Dept. of Northern Affairs &
National Resources,
Ottawa, Ontario.

P.H.L. Evans,
Northern Construction Division,
Department of Public Works,
Ottawa, Ontario.

G. Falconer,
Geographical Branch,
Dept. of Mines & Technical Surveys,
Ottawa, Ontario.

M. Fikowski,
Joint Photographic Intelligence
Centre,
R.C.A.F. Rockcliffe,
Ottawa, Ontario.

J. K. Fraser,
Geographical Branch,
Dept. of Mines & Technical Surveys,
Ottawa, Ontario.

Dr. J. G. Fyles,
Geological Survey of Canada,
Dept. of Mines & Technical Surveys,
Ottawa, Ontario.

Dr. N. R. Gadd,
Geological Survey of Canada,
Dept. of Mines & Technical Surveys,
Ottawa, Ontario.

H. C. Gardner,
Canadian Longyear Ltd.,
North Bay, Ontario.

L. W. Gold,
Division of Building Research,
National Research Council,
Ottawa, Ontario.

R. N. Gooding,
Dept. of Natural Resources,
Prince Albert, Saskatchewan.

K. S. Goodman,
Materials Testing Laboratories Ltd.,
27-6A Street N.E.,
Calgary, Alberta.

Dr. W. A. Gorman,
Department of Geology,
Queen's University,
Kingston, Ontario.

Lt-Col. T. Hagler,
U.S. Army Standardization Group,
Canada,
Ottawa, Ontario.

R. G. Harding,
Northern Construction Division,
Department of Public Works,
Ottawa, Ontario.

N. A. Harrison,
Defence Research Northern
Laboratories,
Fort Churchill, Manitoba.

T. A. Harwood,
Geophysical Research Section,
Defence Research Board,
Department of National Defence,
Ottawa, Ontario.

Dr. G. F. Hattersley-Smith,
Geophysical Research Section,
Defence Research Board,
Department of National Defence,
Ottawa, Ontario.

J. L. Haydock,
H. G. Acres & Co. Ltd.,
Niagara Falls, Ontario.

D. G. Henderson,
Provincial Planning Service,
Regional Development Branch,
Dept. of Industry and Commerce,
Winnipeg, Manitoba.

Dr. W. Henoch,
Geographical Branch,
Dept. of Mines & Technical Surveys,
Ottawa, Ontario.

H. L. Hewitt,
Structures Division,
Department of Public Works,
Ottawa, Ontario.

P. L. Hill,
Geographical Branch,
Dept. of Mines & Technical Surveys,
Ottawa, Ontario.

K. H. Ho, (McGill University)
Apt. 26,
3524 Hutchinson Street,
Montreal, P.Q.

R. Hobner,
Building Construction Branch,
Department of Public Works,
Ottawa, Ontario.

H. R. Hopper,
Manitoba Hydro Electric Board,
P.O. Box 815,
Winnipeg, Manitoba.

R. C. Hovdebo,
Dept. of Natural Resources,
Prince Albert, Saskatchewan.

R. G. Howard,
Montreal Engineering Co. Ltd.,
P.O. Box 250,
Place d'Armes,
Montreal, P.Q.

M. Huepeden,
Chief of Construction Engineering,
R.C.A.F.,
Victoria Island,
Ottawa, Ontario.

G. T. Hughes,
Dept. of Civil Engineering
Royal Military College of Canada,
Kingston, Ontario.

R. K. Irvine,
Peter Bawden Drilling Ltd.,
P.O. Box 4100,
Edmonton, Alberta.

S. A. Ismaily,
Testing Laboratories Division,
Department of Public Works,
Ottawa, Ontario.

Dr. J. D. Ives,
Geographical Branch,
Dept. of Mines & Technical Surveys,
Ottawa, Ontario.

Dr. G. Jacobsen,
Tower Construction Ltd.,
2055 MacKay Street,
Montreal, P.Q.

F. H. James,
Development Engineering Branch,
Department of Public Works,
Ottawa, Ontario.

Dr. J. L. Jenness,
Economic Division,
Dept. of Northern Affairs &
National Resources,
Ottawa, Ontario.

C. C. Johnson,
Engineering Division,
Dept. of Northern Affairs &
National Resources,
Ottawa, Ontario.

J. P. Johnson, Jr.,
Department of Geography,
Carleton University,
Ottawa, Ontario.

G. H. Johnston,
Division of Building Research,
National Research Council,
Ottawa, Ontario.

A. T. Jordan,
Resources Division,
Dept. of Northern Affairs &
National Resources,
Ottawa, Ontario.

I. Kalin,
Building Construction Branch,
Department of Public Works,
Ottawa, Ontario.

S. A. Kanik,
Resources Division,
Dept. of Northern Affairs &
National Resources,
Ottawa, Ontario.

J. A. Langford,
Deputy Minister of Public Works,
Legislative Building,
Regina, Saskatchewan.

R. D. Lawrence,
Murray Mining Corp. Ltd.,
200 Bay Street,
Toronto, Ontario.

Dr. A. Leahey,
Central Experimental Farm,
Department of Agriculture,
Ottawa, Ontario.

Dr. R. F. Legget,
Director, Division of Building
Research,
National Research Council,
Ottawa, Ontario.

A. W. H. Litzenberger,
Development Engineering Branch,
Department of Public Works,
Ottawa, Ontario.

Dr. T. Lloyd,
Department of Geography,
McGill University,
Montreal, P.Q.

Dr. O. Løken,
Department of Geography,
Queen's University,
Kingston, Ontario.

Dr. C. S. Lord,
Geological Survey of Canada,
Dept. of Mines & Technical Surveys,
Ottawa, Ontario.

J. R. Lotz,
Northern Co-ordination and
Research Centre,
Dept. of Northern Affairs &
National Resources,
Ottawa, Ontario.

A. P. Lyell, (McGill University)
3524 Durocher Street,
Apt. No. 4,
Montreal, P.Q.

I. C. MacFarlane,
Division of Building Research,
National Research Council,
Ottawa, Ontario.

S. M. MacIver,
National Harbours Board,
Ottawa, Ontario.

Dr. J. R. Mackay,
Department of Geography,
University of British Columbia,
Vancouver, B. C.

L. G. MacQuarrie,
Engineering Division,
Northern Administration Branch,
Dept. of Northern Affairs &
National Resources,
Ottawa, Ontario.

E. R. Magnusson,
Canadian Institute of Timber
Construction,
170 Donway West,
Don Mills, Ontario.

Dr. M. Marsden,
Arctic Institute of North America,
3458 Redpath Street,
Montreal, P.Q.

M.A.J. Matich,
Geocon Ltd.,
180 Vallée Street,
Montreal, P.Q.

J.J.G. McLellan,
Harbours and Rivers Engineering Branch,
Department of Public Works,
Ottawa, Ontario.

R. G. McPhie,
Ad Astra Minerals Ltd.,
526 Northern Hardware Bldg.,
Edmonton, Alberta.

C. L. Merrill,
District Administrator,
Dept. of Northern Affairs & National Resources,
P.O. Box 161,
Fort Smith, N.W.T.

J.W.L. Monaghan,
Marshall, Macklin & Monaghan Ltd.,
1480 Don Mills Road,
Don Mills, Ontario.

C. F. Morrison,
Dept. of Civil Engineering,
University of Toronto,
Toronto, Ontario.

R. J. Mott,
Geological Survey of Canada,
Dept. of Mines & Technical Surveys,
Ottawa, Ontario.

Dr. F. Muller-Battle,
Jacobsen-McGill Arctic Research Expedition,
539 Pine Avenue West,
Montreal, P.Q.

D. F. Murphy,
Foundation of Canada Engineering Corporation Limited,
1980 Sherbrooke Street West,
Montreal, P.Q.

C. A. Nesbitt,
Resident Administrator,
Local Government District of Mystery Lake,
Thompson, Manitoba.

D. R. Nichols,
Alaska Terrain and Permafrost Section,
U.S. Geological Survey,
Washington, D.C., U.S.A.

Dr. F. S. Nowosad,
Central Experimental Farm,
Department of Agriculture,
Ottawa, Ontario.

J. C. Osler,
Geocon Ltd.,
180 Vallée Street,
Montreal, P.Q.

C. R. Parke,
The Bell Telephone Co. of Canada,
1050 Beaver Hall Hill,
Montreal, P.Q.

A. Paskevicius,
Directorate of Architectural Construction,
R.C.A.F.,
Victoria Island,
Ottawa, Ontario.

J. P. Peaker,
Kemptville Agriculture School,
Kemptville, Ontario.

E. Penner,
Division of Building Research,
National Research Council,
Ottawa, Ontario.

F. Penner,
Airport Development Division,
Department of Transport,
Ottawa, Ontario.

D. N. Pickersgill,
Division of Building Research,
National Research Council,
Ottawa, Ontario.

J. A. Pihlainen,
255 Montreal Road,
Ottawa, Ontario.

Dr. N. W. Radforth,
Department of Biology,
McMaster University,
Hamilton, Ontario.

R. G. Robbie,
160 Cooper Street,
Apt. No. 5,
Ottawa, Ontario.

G. W. Robertson,
Central Experimental Farm,
Department of Agriculture,
Ottawa, Ontario.

J. M. Robinson,
Forest Research Branch,
Department of Forestry,
Ottawa, Ontario.

Dr. B. Robitaille,
Centre d'Etudes Nordiques,
Université Laval,
Quebec, P.Q.

Dr. J. S. Rowe,
Forest Research Branch,
Department of Forestry,
Ottawa, Ontario.

G. W. Rowley,
Advisory Committee on Northern
Development,
Dept. of Northern Affairs &
National Resources,
Ottawa, Ontario.

Mrs. G. W. Rowley,
245 Sylvan Road,
Ottawa, Ontario.

R. B. Sagar,
Geographical Branch,
Dept. of Mines & Technical Surveys,
Ottawa, Ontario.

M. St-Amour,
C.P. 334,
Masson, P.Q.

J. E. Savage,
Department of Public Works,
P.O. Box 488,
Edmonton, Alberta.

G. Y. Sebastyan,
Construction Branch,
Department of Transport,
Ottawa, Ontario.

S. R. Sinclair,
Department of Civil Engineering,
University of Alberta,
Edmonton, Alberta.

G. J. Sladek,
Gibb, Underwood & McLellan,
42 Charles Street East,
Toronto, Ontario.

D. H. Smith,
Engineering & Construction Division,
Department of Public Works,
Ottawa, Ontario.

H. L. Snyder,
Rio Algom Mines Ltd.,
335 Bay Street,
Toronto, Ontario.

S. Stamer,
Development Engineering Division,
Department of Public Works,
Ottawa, Ontario.

R. E. Tait,
Public Health Engineering Division,
Dept. of National Health & Welfare,
Ottawa, Ontario.

Dr. A. Taylor,
293 Island Park Drive,
Ottawa, Ontario.

Dr. J. Terasmae,
Geological Survey of Canada,
Dept. of Mines & Technical Surveys,
Ottawa, Ontario.

H. A. Thompson,
Meteorological Branch,
Department of Transport,
315 Bloor Street West,
Toronto, Ontario.

J. G. Thomson,
Imperial Oil Ltd.,
Calgary, Alberta.

A. Thorley,
Warnock Hersey Soil
Investigations Ltd.,
128 Elmslie Street,
LaSalle, P.Q.

F. E. Thurston,
Asbestos Corporation Ltd.,
Thetford Mines, P.Q.

V. F. Valentine,
Northern Co-ordination and
Research Centre,
Dept. of Northern Affairs &
National Resources,
Ottawa, Ontario.

W. A. Ward,
Building Construction Branch,
Department of Public Works,
Ottawa, Ontario.

Dr. B. P. Warkentin,
Macdonald College,
McGill University,
Montreal, P.Q.

F/L R. G. Warner,
Joint Photographic Intelligence
Centre,
R.C.A.F. Rockcliffe,
Ottawa, Ontario.

J. W. Watt,
National Harbours Board,
Ottawa, Ontario.

C. E. White,
Ungava Iron Ores Company,
550 Sherbrooke Street West,
Montreal, P.Q.

G. P. Williams,
Division of Building Research,
National Research Council,
Ottawa, Ontario.

P. J. Williams,
Division of Building Research,
National Research Council,
Ottawa, Ontario.

S. J. Windisch,
10318 Esplanade Avenue,
Montreal, P.Q.

Dr. R. Yong,
Dept. of Civil Engineering,
McGill University,
Montreal, P.Q.

J. M. Zarzycki,
Canadian Aero Service Ltd.,
348 Queen Street,
Ottawa, Ontario.

M. Zelman,
1841 Botsford Road,
Ottawa, Ontario.

A list of Technical Memoranda of the Associate Committee on Soil and Snow Mechanics may be obtained from the Secretary, Associate Committee on Soil and Snow Mechanics, c/o The Division of Building Research, National Research Council, Ottawa, Canada.