

CONSTRUCTION ON PERMAFROST

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ABSTRACT

It has been estimated that 20 to 25 percent of the earth's surface is underlain by permafrost. This paper defines the term permafrost and briefly reiterates the climatic conditions necessary for its formation and existence. The various conditions in which permafrost can exist are reviewed and maps of the North American and Eurasian continents are presented showing the extent of permafrost or "eternally frozen ground" as it is often called.

The sensitivity of the established thermal regime in permafrost areas to surface disturbances produced by man is discussed. Man's desire to live in and make use of such areas made the erection of housing, roads, airfields, and various other installations inevitable. Many of the earlier buildings and related efforts resulted in discouraging failures through lack of understanding by designers of the weaknesses and limitations of the foundation materials. It is indicated how a careful examination of the conditions prevailing at a site can lead to the selection of an adequate economical foundation design. The common types of foundation materials encountered in the Arctic and Subarctic are described, and the problems accompanying them are explained. Various conditions must be satisfied to insure the continued existence of a building founded on permafrost; these are mentioned and discussed. Finally, the various types of design devised by foundation engineers to overcome the limitations of perennially frozen subgrade materials are briefly described.

PERMAFROST

Not too many years ago the meaning of the term permafrost was known to relatively few people — principally those who had a special interest in the geology of the Arctic. Today, due to the intensified activity in all parts of the northern hemisphere, the Arctic and permafrost have become more common, if not familiar, terms to many and have aroused the interest and curiosity of large numbers of people. Permafrost is defined as perennially frozen ground — ground that is frozen the year around. The mean annual air temperature required to produce permafrost is generally given as 30°F. to 24°F. There appears to be some disagreement between various authorities on the subject as to the actual mean air temperature required to produce permafrost. Theoretically, frozen ground should occur in areas where the average yearly mean air temperature is 32°F. or less. The actual temperature would depend, of course, on the physical configuration of the surface, presence or absence of vegetation, exposure to sunshine, type of soil, and many other factors. The thickness of the permafrost layer generally varies with the latitude, being greater in the Arctic than in the Subarctic regions.

It has been estimated that 1/5 to 1/4 of the land surface of the earth is underlain by permafrost. Figure 1 shows the distribution of perennially frozen ground. The darker shaded section indicates the areas where permafrost is firmly established. In the lightly shaded areas, permafrost may be sporadic, varying from a considerable thickness to complete absence in places. The southern boundary is estimated since information is available from only relatively few borings in these regions.

Permafrost to a depth of 2000 feet has been reported in

Siberia and as much as 1300 feet in Alaska, with a minimum temperature of about 8°F. and 14°F., respectively.

Figure 2 illustrates the various conditions in which permafrost may exist:



FIGURE 3 — Drilled core of frozen ground showing 19-inch thick ice layer beginning at depth of 4 feet.

- (1) As a continuous layer with its upper surface at the bottom of the annual frost zone. This is a condition common in the Arctic.
- (2) As a continuous layer with its upper surface at some depth below the annual frost zone. This condition is referred to as a degrading permafrost.
- (3) As islands within unfrozen materials.
- (4) As layers separated by layers of unfrozen material.

The frozen soil may or may not contain large accumulations of pure ice in form of ice lenses, films, grains, fillings, veinlets, wedges and other masses. The ice structures in the soil may be quite large and sporadic or they may be small and numerous. Figure 3 is a photograph of a drilled core of frozen ground containing a thick layer of ice.

During the course of a large number of years, under the prevailing climatic conditions, an equilibrium has been established in which the permafrost zone is quite stable. This equilibrium, however, is quite sensitive to even slight changes which are gone into in more detail later. As long as the surface ground conditions are not disturbed, the thermal regime will be maintained and the permafrost will change only very slowly in response to long-term climatic conditions. Thawing of the frozen ground occurs at the surface during the summer months when the monthly mean surface temperatures are above 32°F. On turf and vegetation covered surfaces, thawing will occur to shallow depths. Upper limits of permafrost may vary from few inches to several feet from the surface. In poorly drained fine grained soil in shaded areas, insulated with moss and other vegetation, it may be only four inches from surface.

If trees are present, less thawing will occur due to the shading effect. As the surface melts and the accumulated ice and snow turn to water, unable to drain into or through the frozen soil below, the ground soon becomes soft and unstable, presenting great difficulties to transportation and construction operations.

CONSTRUCTION PROBLEMS

The design of every structure has two aspects: the design of the working habitable part of the structure, assuming certain loads and forces working on it, and the provision of a reliable foundation. Under normal conditions in the continental temperate climate of the United States, the first consideration in the design of a building is the stability of the building, and secondly, the comfort of its inhabitants. Thus, for the former, we have structural engineers, and for the latter, heating, lighting, air conditioning and sanitary engineers. However, in the United States, in general, design of a foundation involves principally engineers concerned with soil mechanics, sometimes soil dynamics, but only rarely is soil thermodynamics involved.

In the Arctic and Subarctic in permafrost areas, the stability of soils and their bearing capacity are intimately related to temperatures and heat flows in the ground, so that soil engineers are forced to assume responsibilities of design usually divided among different branches of the science of engineering in more temperate climates. Early designs of buildings in northern Canada and Alaska neglected the more involved considerations of the thermal interaction of building and ground, and paid the price of the consequences in cracked walls, sagging floors, broken and patched utilities.

Over the years, and particularly with the concentration of strategic attention in the north, an application of experience and experiment to building problems has resulted in a growing number of successful methods of overcoming foundation problems in different areas under widely varying soil conditions. Some of these methods, and their influence on the thermal regime in the underlying ground will be described.

In order to clarify the discussion, it is necessary to point out that only permanent types of structure are being considered, those which are heated or contain machinery or connections to adjacent buildings to which damage would result by substantial movements in the structure itself, relative to other structures. Small, temporary, wooden storage buildings do not come into this category; they can generally be built on small wooden mat foundations on top of the ground surface, of the type known as "mudsills". Uneven settling in such buildings can easily be corrected by jacking and shimming up. Highways and airfields must, of course, be considered structures to which differential settlements are detrimental and not easily correctable.

As in all other areas where foundation problems are present, subsurface investigations are the first step to be taken. These may consist of driving of a rod probe into the ground, augering to bring samples of the soil, excavating a test pit or using more advanced techniques of soil sampling over the site area. One added complication, mentioned earlier, presents itself in Arctic permafrost areas: It is necessary to know something about the natural thermal regime in the ground before foundation designs can be carried to an advanced stage. To this end, in many inhabited areas where a meteorological station is maintained, soil temperatures are measured at regular intervals, to a depth of twenty or thirty feet by means of thermocouples imbedded in the ground. The soil temperature

data thus accumulated are an extremely important part of all foundation investigations in permafrost, and in recent years much attention has been given to the task of correlating soil temperatures, in particular the annual depth of summer thaw in permafrost (corresponding to the depth of annual freezing of the ground in the temperate zone, which presents a similar problem) to the relevant meteorological parameters and soil properties. The ultimate aim of such studies is, of course, the prediction of soil temperatures and depths of anticipated thaw in any given area where meteorological data are available or can be closely estimated. From such studies, it will be possible to calculate the thermal effect in the ground of various disturbances made at the ground surface. Examples of disturbances include the clearing of forest or vegetative cover and its replacement with gravel or sand pads, buildings or airfields. Records of weather observations made in the past years and correlated with ground temperatures have already been of great use in studying the general thermal behaviour in frozen ground. Data from existing and additional new stations being developed will, in due course, permit prediction of ground temperature changes and eliminate time consuming soil temperature observations.

Figures 4 and 5 show the results of studies made of the effect on permafrost of altering the surface cover of an area. Figure 4 illustrates the effects on permafrost by simply removing the trees and brush and by further stripping the area of all surface vegetation. Figure 5 shows the effects of construction of a highway on the cleared ground. The reasons for the degradation of the permafrost may be gone into briefly. In Figure 4, the presence of the natural vegetative cover and trees inhibits the maximum daily and annual temperatures which reach the ground surface — the warming of the sun's rays is absorbed by leaves, or reflected and its effect does not reach the ground. The removal of trees allows more of the solar radiation to reach and be absorbed by the ground surface, which gets warmer in consequence. Then the seasonal thaw progresses further into the permafrost. In Figure 5, the layer of moss and peat, a good insulator and heat absorber with its high water content, had been removed and replaced with a black bituminous road surface. The road surface not only absorbs more of the sun's rays, but the moist gravel base has a greater heat diffusivity than the peat, and the result is further degradation of permafrost.

Where roads are unavailable movement of supplies and equipment can be accomplished only with the greatest difficulty in the summer. The early Eskimo did most of his travelling while the ground was frozen. Today, of course, the travel situation has changed since the Eskimo is generally employed by the Canadian or American Governments, with the associated conveniences of such employment.

As may be visualized, permanently frozen ground constitutes a material of high bearing capacity. Its bearing capacity, when thawed, depends on the nature of the soil which is determined by the very necessary preliminary soil investigations. If the frozen ground is a clean sand or gravel (the adjective "clean" means containing a very small proportion of fine-grained material of silt size) then it is unlikely that *thawing* of the ground will give cause for concern. Construction on top of such clean sands and gravels, containing no ice masses, presents few problems and will not be considered further here. However, if the material is predominantly a silt or clay, or contains a considerable proportion of silt or clay, it is very likely that it has a low density, and a high water content in the form of ice. That is to say, it has been found that silts and clays, during freezing, exhibit the ability of drawing water (either

from a water table below, or from the free water in the soil below the freezing level) into the freezing zone. This water freezes and forms segregated ice lenses and veins in the soil, whose structure must expand to accommodate the increased volume. Consequently, the soil surface "heaves". Such a soil is known as "frost-susceptible" and is a familiar problem to road engineers in New England and other parts of the United States.

Now two situations present themselves. Such a frost susceptible soil, existing frozen in the permafrost, usually has a loose soil structure and/or contains large quantities of ice in the form of veins and lenses (see Figure 3). Therefore, upon thawing, large reductions in volume take place; first, due to the melting of the ice lenses, and second, due to the consolidation (or packing together) of the silt grains. This will give large settlements in a structure situated above such a material and creates the first problem situation. The second one arises should such a material refreeze under the structure, in which case the heaving phenomena could take place and result in an upward movement of the structure, creating problems no less severe than those produced by thawing.

One solution has been proposed and a great deal of work has been done on its investigation by the Arctic Construction and Frost Effects Laboratory. Assuming a frost susceptible soil has thawed, is it possible to restrict the heaving consequent upon refreezing by adding chemicals to the soil? Research has shown considerable promise but so far the method has not adapted itself for use on a large scale in the Arctic. Other solutions involve construction techniques which will be described further below.

Buildings in the Arctic and Subarctic regions, when constructed on frost susceptible soils, are likely to experience considerable heaving and settlement, due to freezing and thawing in the underlying soil. Differential movements cause sloping floors, jammed doors and windows, cracks in walls and ceilings and may produce serious stresses in structural members leading to failure. Therefore the design of stable foundations on permafrost becomes a special problem if we are to prevent damaging settlements and dislocations. In the city of Fairbanks, today, there are a number of small private dwellings originally built above ground which have settled a foot or more below the ground surface.

As mentioned previously, there exists a delicate balance between the heat inflow and outflow and the dependence of the existence of permafrost on that balance which is called the thermal regime. The various construction activities of man generally upset the natural thermal equilibrium and create unusual and difficult foundation design problems. A great portion of man's effort in seeking to minimize these problems has been directed toward methods and means of preserving the original thermal equilibrium as nearly as possible. In the case of buildings occupying limited space several schemes have been devised. These, however, are not adaptable to large extensive areas disturbed by grading as in the construction of roads and runways.

For the most part then the design and construction problems in the Arctic and Subarctic regions are related to the development of methods to prevent progressive thawing of the permafrost below heated structures or to design so that limited thawing will have little detrimental effect on the structure.

Three courses of action present themselves in cases where the site investigations show the area to be underlain

by frost susceptible soils containing ice lenses and masses and where no possibility exists of utilizing a better site.

1. If the depth of poor foundation materials is not great and clean sands and gravels exist below it, then it may be possible to remove the frost susceptible soil entirely. The area is filled with a good quality coarse material and the building is constructed with little likelihood of trouble developing.

2. The deposits of unsatisfactory material may be too deep to permit economical excavation, and in certain cases of this type, it may prove economical to thaw out the silty soil by means of ponding water in the area or by using steam jetting. After the soil is thawed out to a depth considered sufficient for construction purposes (usually about 3 times the depth of the active layer from the surface, i.e., if the annual thaw penetrates 5 feet from the surface, the subgrade is thawed out to 15 feet depth altogether from the surface) it is compacted by vibration (driving piles, explosives, etc.) to place it in a condition of greater density, so that future settlements will be minimized. Generally this process of consolidation, which can be hastened by placing a thick gravel loading pad on the surface, is a lengthy one, requiring a delay of several months in construction. As a rule, however, sites prepared in this manner are not generally desirable because of possible seasonal refreezing of the frost-susceptible material beneath the building foundation and the consequent heaving and resettlement upon thawing. This method of site preparation is usually modified further by one of the schemes described in the paragraph below.

3. The undesirable foundation material is accepted as it exists, and a design of a foundation is adopted which will prevent thawing temperatures from reaching the loose frost susceptible soil below. Various methods have been used and a brief résumé of them is given below, with illustrations:

- (a) The oldest and most common solution is to place a gravel mat directly on top of the surface vegetation and peat layer, during the thaw season, making an attempt to minimize disturbance of the upper layers, since they contribute greatly to the insulation of the subgrade. These materials compress under the mat in a relatively short time. The mat also assists in the operation of construction equipment over the building area. The thickness of the gravel mat is designed to prevent thawing of the undesirable material upon which it rests. Originally the thickness of such mats was designed empirically, but now methods are available for predicting depths of thaw below such mats with workable accuracy. On top of the mat the concrete floor of the building is sometimes placed directly, usually incorporating a two to four-inch thick layer of insulation to prevent excessive loss of building heat, partly from reasons of heating economy and partly to prevent foundation thawing. Figure 6 illustrates the use of a relatively thin (4 feet thick) sand and gravel mat under an experimental building on permafrost. In this case progressive thawing occurred in the soil under the building as shown by the 32° F. isotherms for the period of observations. The dots represent location of thermocouples while the crosses indicate probings made with a rod.

- (b) Nowadays, however, a more common procedure is to support the building some distances (usually 2-3 feet) above the gravel pad so that cold air can circulate beneath the building. This air, moving below the building floor, effectively carries off any heat lost through the floor, and prevents detrimental thawing of the foundation. Objections to such a design procedure arise almost solely from the

occupants point of view; it produces cold floors. However, proper design of the building heating system and floor insulation minimizes this trouble. The building can be supported on concrete or wood beams placed on a gravel pad as described in (a) above, or may be entirely supported by piles extending down into the permafrost zone as illustrated in Figure 7.

(c) The piles usually extend into permafrost at least twice the depth of the active zone. The placing of the pile is a problem of some interest in itself. Steel H-piles or pipe piles can be driven into permanently frozen silty soil, but the more common wooden or concrete piles are usually placed in augered holes. Wood piles are placed butt down to resist the uplift forces exerted on the pile during the annual freezing of the active zone. When the pile is placed in the hole in the latter method, the annular space between pile and hole is backfilled with a sand or silt and water slurry which is tamped or vibrated to ensure that the space is entirely filled. Depending on the temperatures prevailing in the permafrost at the site, the backfilling



FIGURE 8 — Photograph of excavation in frozen silt showing refrozen soil and ice around a steel pipe pile without use of artificial refrigeration.

may freeze itself if sufficient time is allowed (see Figure 8), or it may require artificial refrigeration to freeze it in a reasonably short space of time. In the latter case, the refrigeration pipes are, of course, left in place.

(d) One further design method has been used in the construction of large buildings such as hangars, whose support on beams or piles would present structural problems. In such cases, it has been found satisfactory to place rows of ducts in the foundation, generally on top of a non-frost susceptible gravel fill (see Figure 9). The concrete base for the floor is poured on top of the ducts, and layers of insulating materials are added before the final floor slab is completed. Here, the ducts are connected at one end to plenum chambers (usually 6-7 ducts per chamber) which are designed to take maximum advantage of the direction of the prevailing wind to assist the passage of winter air through the ducts. It has not been found necessary to date to construct forced draft systems. This design enables the foundation mat to be refrozen each winter. The thickness of the gravel mat is designed so that seasonal thawing does not penetrate the subgrade material below. During the warmer summer months the plenums are closed and circulation of air is halted. In such designs the heavier columns of the building supporting roof loads are generally founded on pile groups extending a safe distance into the permafrost. Experiments are being carried out on different types of duct and different designs of intake and exhaust stacks.

All the above methods, when carefully carried out and supervised, have resulted in satisfactory structures, even in the extreme conditions encountered in the land of eternally frozen ground.

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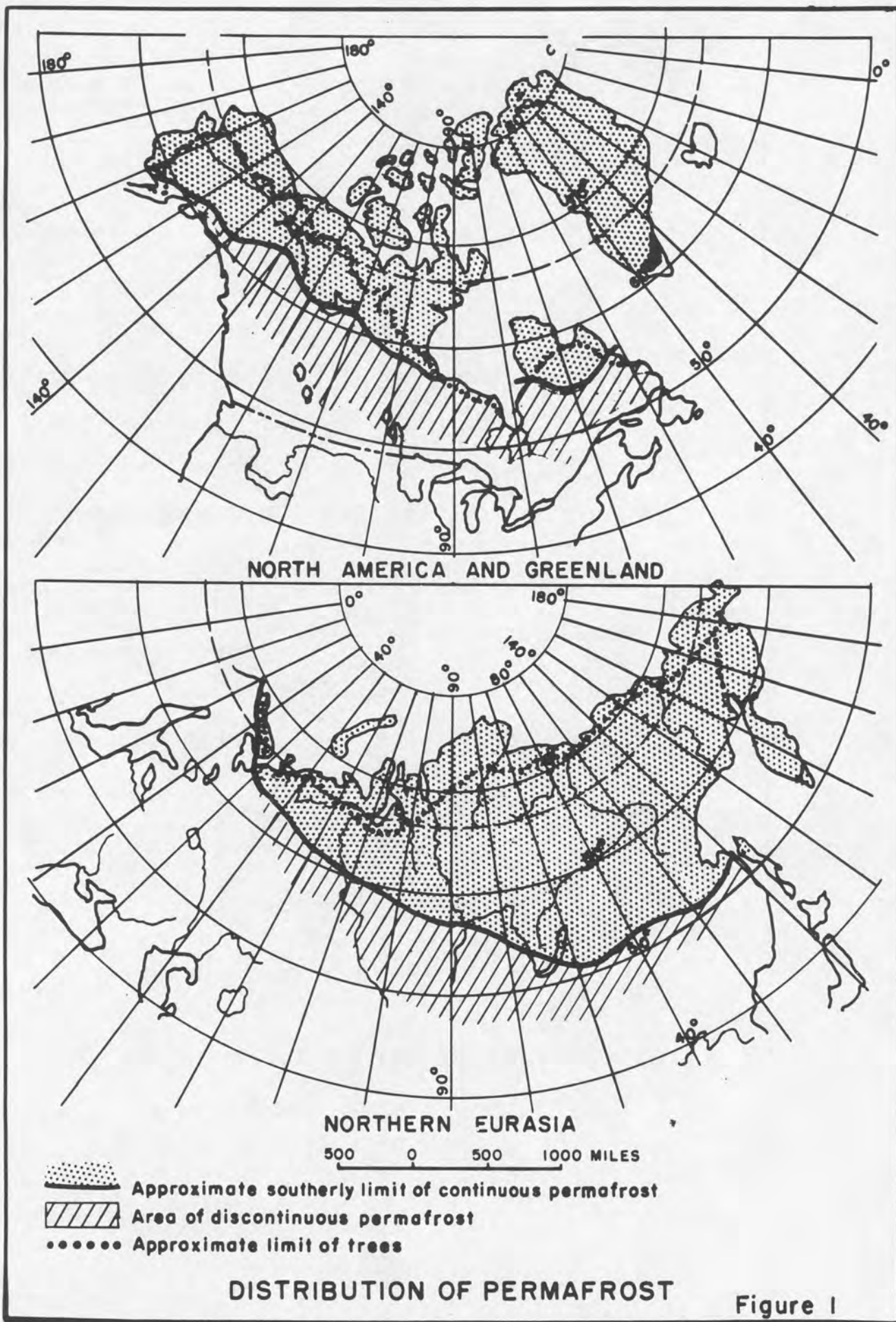
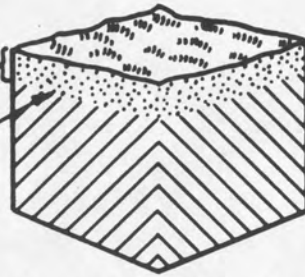


Figure 1

ANNUAL FROST ZONE AND SUPRAPERMAFROST ZONE IDENTICAL

UPPER SURFACE OF PERMAFROST

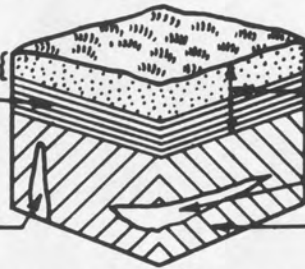


GROUND ALTERNATELY FREEZES AND THAWS

PERMAFROST (MAY OR MAY NOT CONTAIN GROUND ICE)

① ANNUAL FROST ZONE EXTENDS TO PERMAFROST

ANNUAL FROST ZONE
RESIDUAL THAW ZONE



GROUND ALTERNATELY FREEZES AND THAWS

SUPRAPERMAFROST

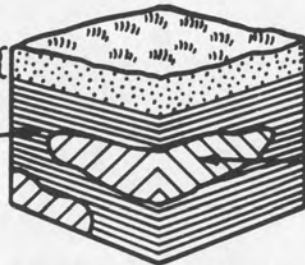
ICE LAYER

PERMAFROST

ICE WEDGE

② CONTINUOUS PERMAFROST CONTAINING GROUND ICE

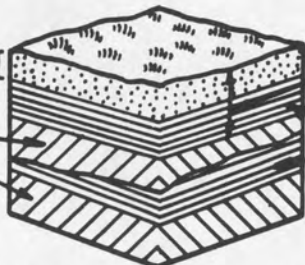
ANNUAL FROST ZONE
UNFROZEN GROUND



PERMAFROST ISLAND

③ ISLANDS OF PERMAFROST IN UNFROZEN GROUND

ANNUAL FROST ZONE
PERMAFROST

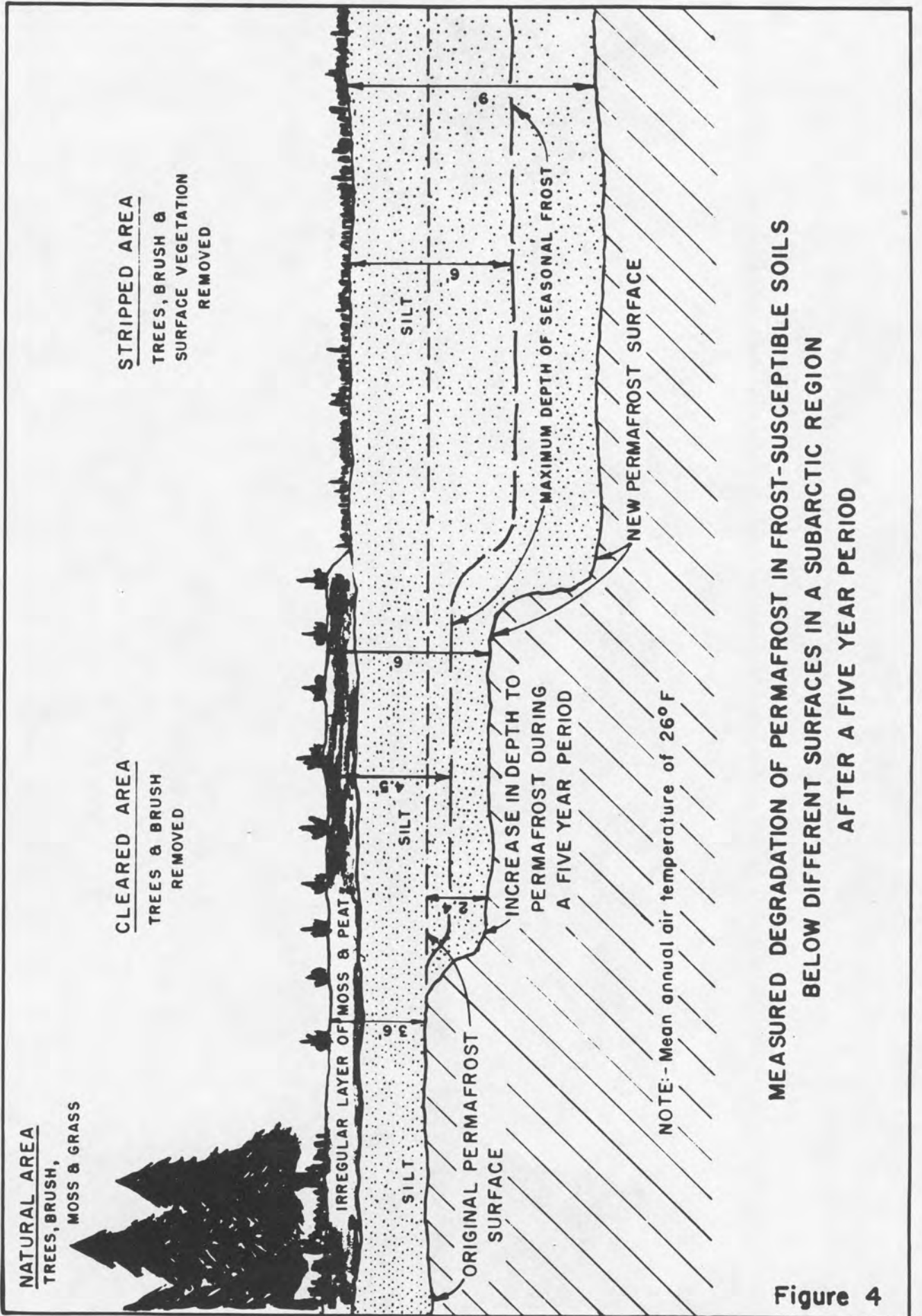


SUPRAPERMAFROST

UNFROZEN GROUND MAY CONTAIN GROUND WATER

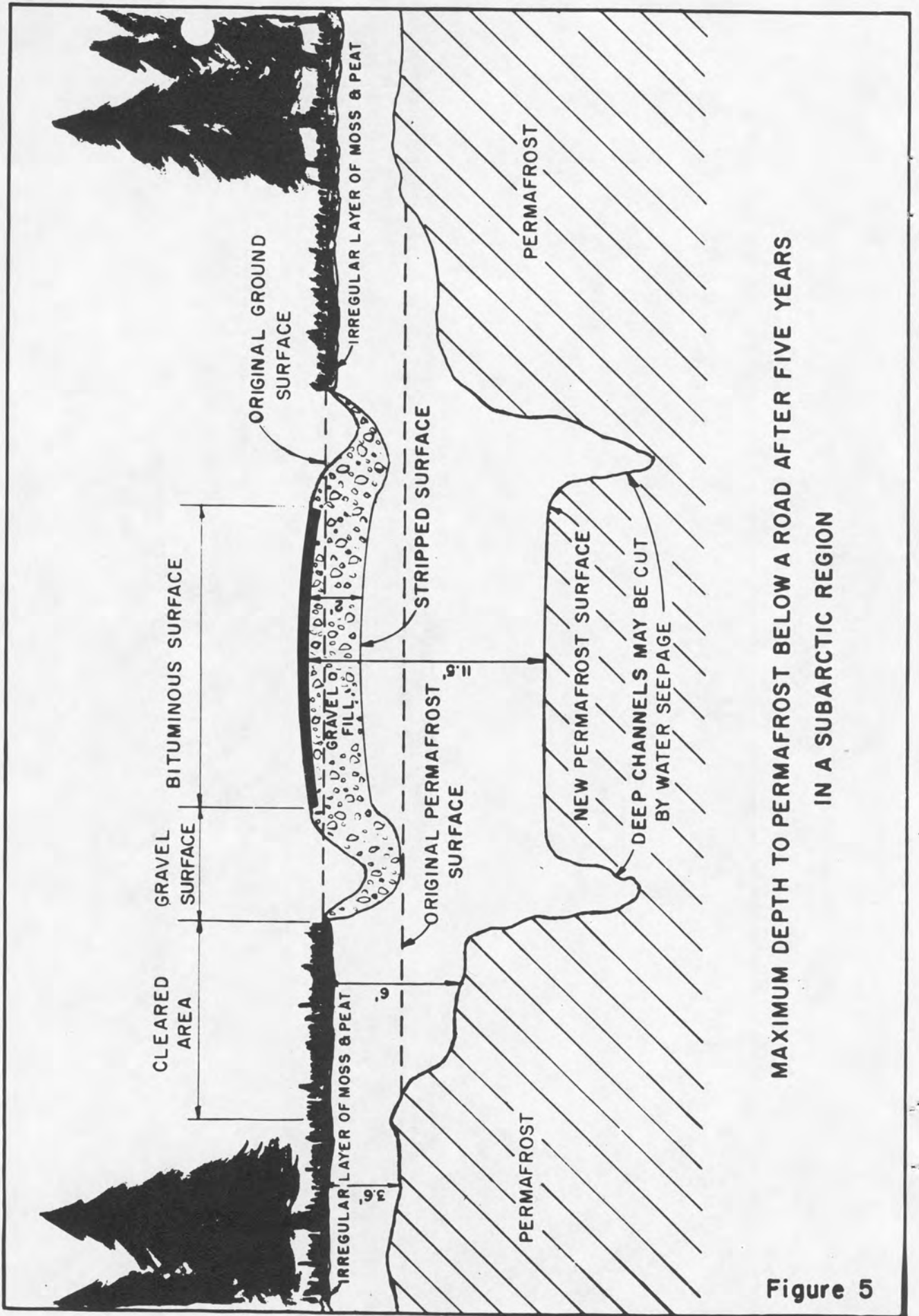
④ LAYERED PERMAFROST

TYPICAL SECTIONS THROUGH GROUND
CONTAINING PERMAFROST



MEASURED DEGRADATION OF PERMAFROST IN FROST-SUSCEPTIBLE SOILS
BELOW DIFFERENT SURFACES IN A SUBARCTIC REGION
AFTER A FIVE YEAR PERIOD

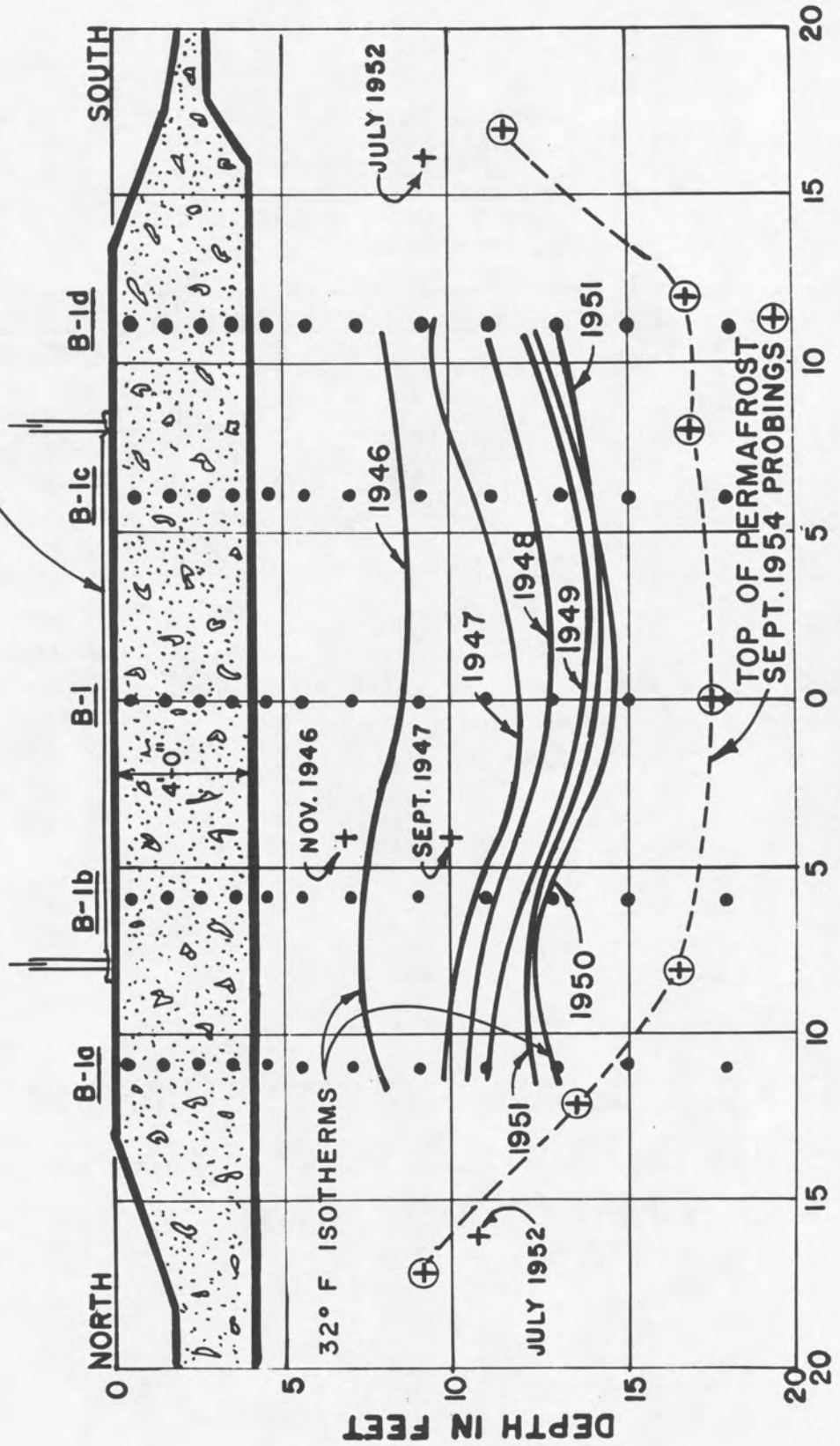
Figure 4



MAXIMUM DEPTH TO PERMAFROST BELOW A ROAD AFTER FIVE YEARS
IN A SUBARCTIC REGION

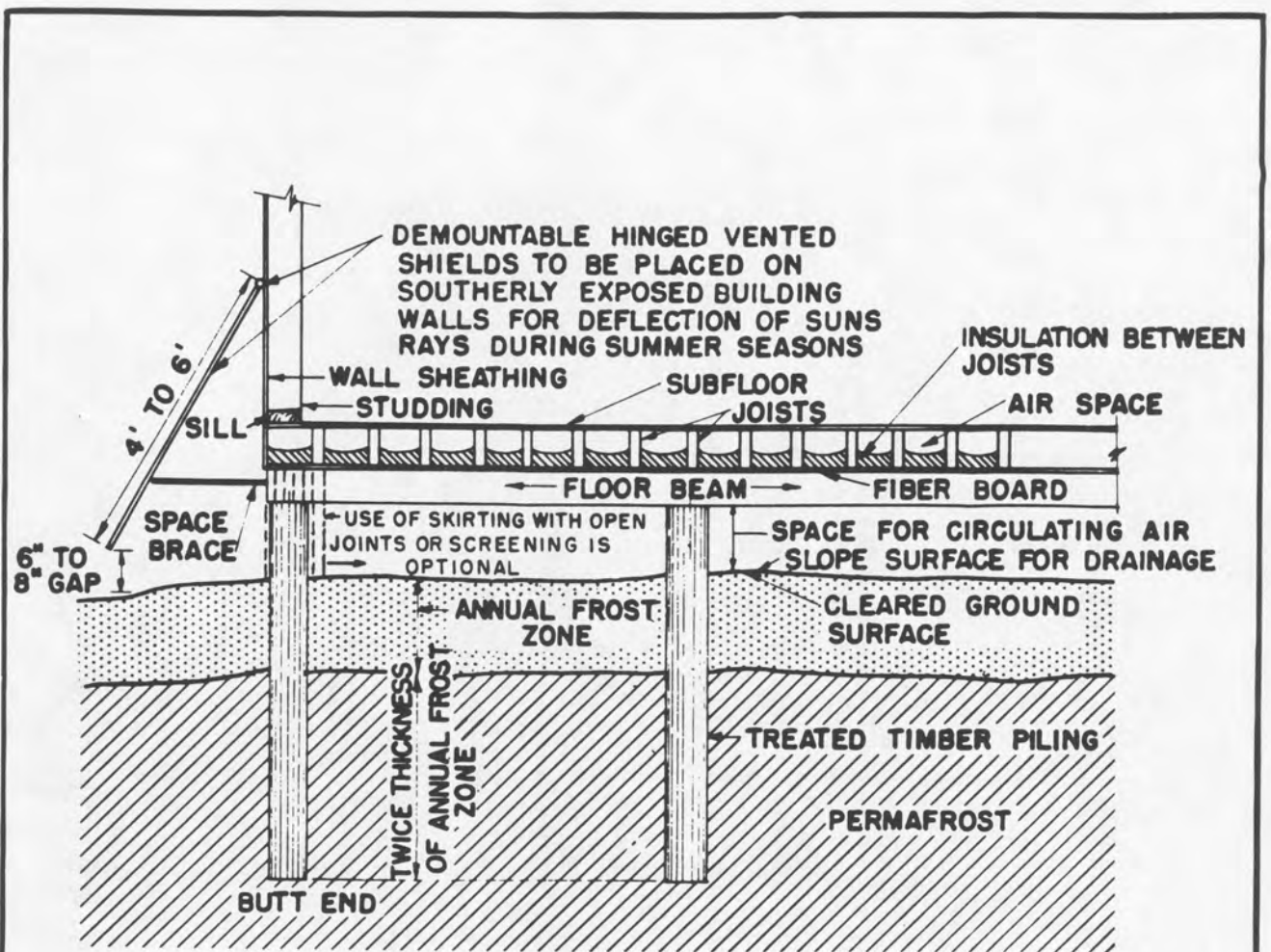
Figure 5

4" CONCRETE FLOOR EL. 484.12



BUILDING NO. 1
(Dismantled Sept. 1954)

Figure 6



TYPICAL DESIGN FOR STRUCTURES SUPPORTED ON PILES WHERE PERMAFROST IS TO BE MAINTAINED BY INSULATION AND VENTILATION

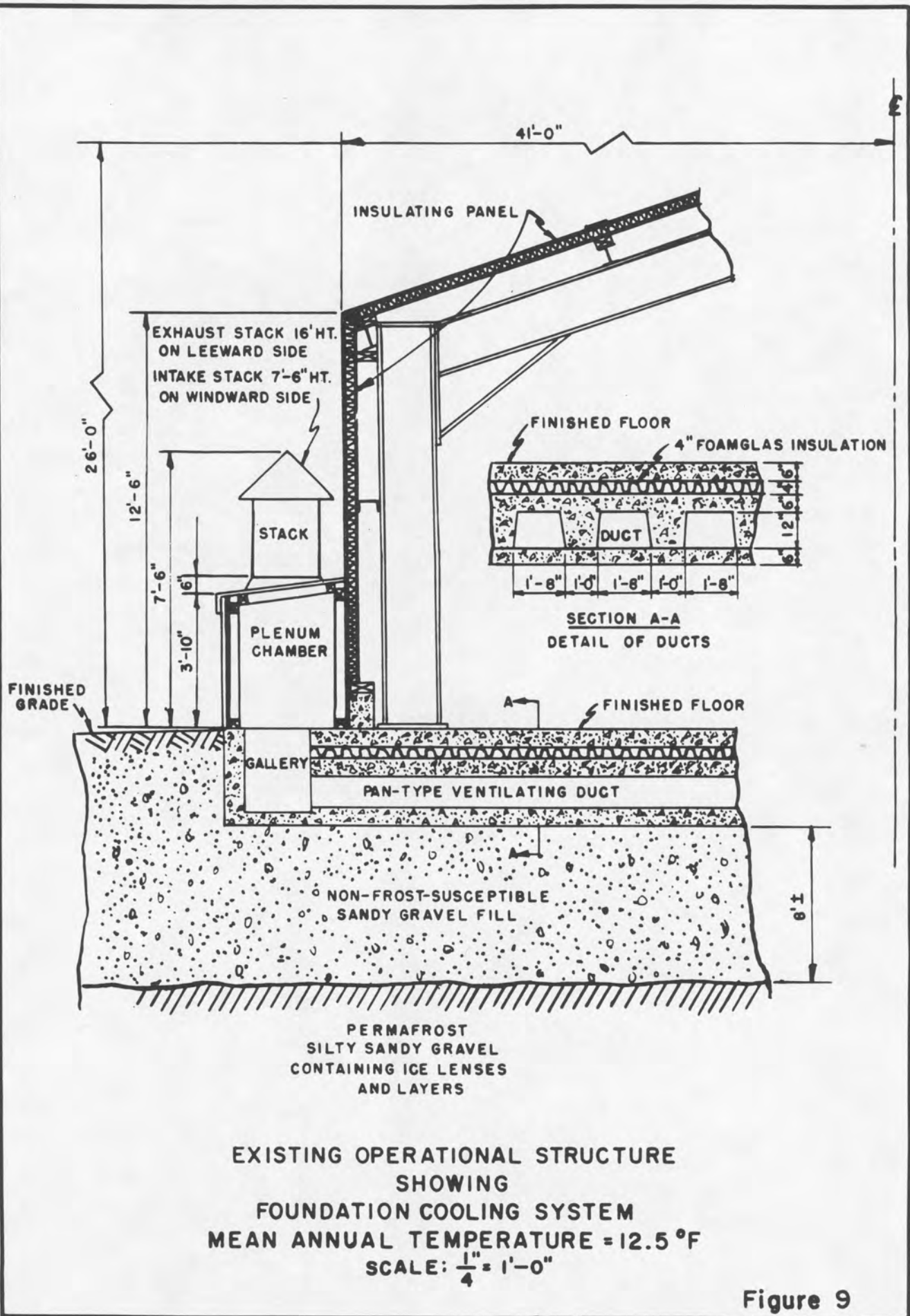


Figure 9