Introduction to Foundations in Areas of Significant Frost Penetration

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An Introduction to Foundations in Areas of Significant Frost Penetration

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(The figures, tables and formulas in this publication may at times be a little difficult to read, but they are the best available. **DO NOT PURCHASE THIS PUBLICATION IF THIS LIMITATION IS NOT ACCEPTABLE TO YOU**.)

#

1. INTRODUCTION.

1.1 TYPES OF AREAS. For purposes of this manual, areas of significant frost penetration may be defined as those in which freezing temperatures occur in the ground to sufficient depth to be a significant factor in foundation design. Areas of significant frost penetration may be subdivided as follows:

1.1.1 SEASONAL FROST AREAS.

1.1.1.1 SIGNIFICANT GROUND FREEZING OCCURS in these areas during the winter season, but without development of permafrost. In northern Texas, significant seasonal frost occurs about 1 year in 10. A little farther north it is experienced every year. Depth of seasonal freezing increases northward with decreasing mean annual and winter air temperatures until permafrost is encountered. With still further decrease of air temperatures, the depth of annual freezing and thawing becomes progressively thinner.

1.1.1.2 THE LAYER EXTENDING THROUGH both seasonal frost and permafrost areas in which annual freeze-thaw cycles occur is called the annual frost zone. In permafrost areas, it is also called the active layer. It is usually not more than 10 feet thick, but it may exceed 20 feet. Under conditions of natural cover in very cold permafrost areas, it may be as little as 1 foot thick. Its thickness may vary over a wide range even within a small area. Seasonal changes in soil properties in this layer are caused principally by the freezing and thawing of water contained in the soil. The water may be permanently in the annual frost zone or may be drawn into it during the freezing process and released during thawing. Seasonal changes are also produced by shrinkage and expansion caused by temperature changes.

1.1.2 PERMAFROST AREAS.

1.1.2.1 IN THESE AREAS, perennially frozen ground is found below the annual frost zone. In North America, permafrost is found principally north of latitudes 55 to 65 degrees, although patches of permafrost are found much farther south on mountains where the temperature conditions are sufficiently low, including some mountains in the contiguous 48 States. In areas of continuous permafrost, perennially frozen ground is absent only at a few widely scattered locations, as at the bottoms of rivers and lakes. In areas of discontinuous permafrost, permafrost is found intermittently in various degrees. There may be discontinuities in both horizontal and vertical extent. Sporadic permafrost is permafrost occurring in the form of scattered permafrost islands. In the coldest parts of the Arctic, the ground may be frozen as deep as 2000 feet.

1.1.2.2 THE GEOGRAPHICAL BOUNDARIES between zones of continuous permafrost, discontinuous permafrost, and seasonal frost without permafrost are poorly defined but are represented approximately in Figure 1.

1.2 GENERAL NATURE OF DESIGN PROBLEMS. Generally, the design of foundations in areas of only seasonal frost follows the same procedure as where frost is insignificant or absent, except that precautions are taken to avoid winter damage from frost heave or thrust. In the spring, thaw and settlement of frost heaved material in the annual frost zone may occur differentially, and a very wet, poorly drained ground condition with temporary but substantial loss of shear strength is typical.

1.2.1 IN PERMAFROST AREAS, the same annual frost zone phenomena occur, but the presence of the underlying permafrost introduces additional potentially complex problems. In permafrost areas, heat flow from buildings is a fundamental consideration, complicating the design of all but the simplest buildings. Any change from natural conditions that results in a warming of the ground beneath a structure can result in progressive lowering of the permafrost table over a period of years that is known as degradation. If the permafrost contains ice in excess of the natural void or fissure space of the material when unfrozen, progressive downward thaw may result in extreme settlements of overlying soil and structures. This condition can be very serious because such subsidence is almost invariably differential and hence very damaging to a structure. Degradation may occur not only from building heat but also from solar heating, as under pavements, from surface water and groundwater flow, and from underground utility lines. Proper insulation will prevent degradation in some situations, but where a continuous source of heat is available, thaw will in most cases eventually occur.

1.2.2.2 THE MORE INTENSE THE WINTER COOLING of the frozen layer in the annual frost zone and the more rapid the rate of frost heave, the greater the intensity of uplift forces in piles and foundation walls. The lower the temperature of permafrost, the higher the bearing capacity and adfreeze strength that can be developed, the lower the creep deformation rate under footings and in tunnels and shafts, and the faster the freeze-back of slurried piles. Dynamic response characteristics of foundations are also a function of temperature. Both natural and manufactured construction materials experience significant linear and volumetric changes and may fracture with changes in temperature. Shrinkage cracking of flexible pavements is experienced in all cold regions. In arctic areas, patterned ground is widespread, with vertical ice wedges formed in the polygon boundaries. When underground pipes, power cables, or foundation elements cross shrinkage cracks, rupture may occur during winter contraction. During summer and fall, expansion of the warming ground may cause substantial horizontal forces if the cracks have become filled with soil or ice.

1.2.2.3 ENGINEERING PROBLEMS may also arise from such factors as the difficulty of excavating and handling ground when it is frozen; soft and wet ground conditions during thaw periods; surface and subsurface drainage problems; special behavior and handling requirements for natural and manufactured materials at low temperatures and under freeze-thaw action; possible ice uplift and thrust action on foundations; condensation on cold floors; adverse conditions of weather, cost, and sometimes accessibility; in the more remote locations, limited local availability of materials, support facilities, and labor; and reduced labor efficiency at low temperatures.

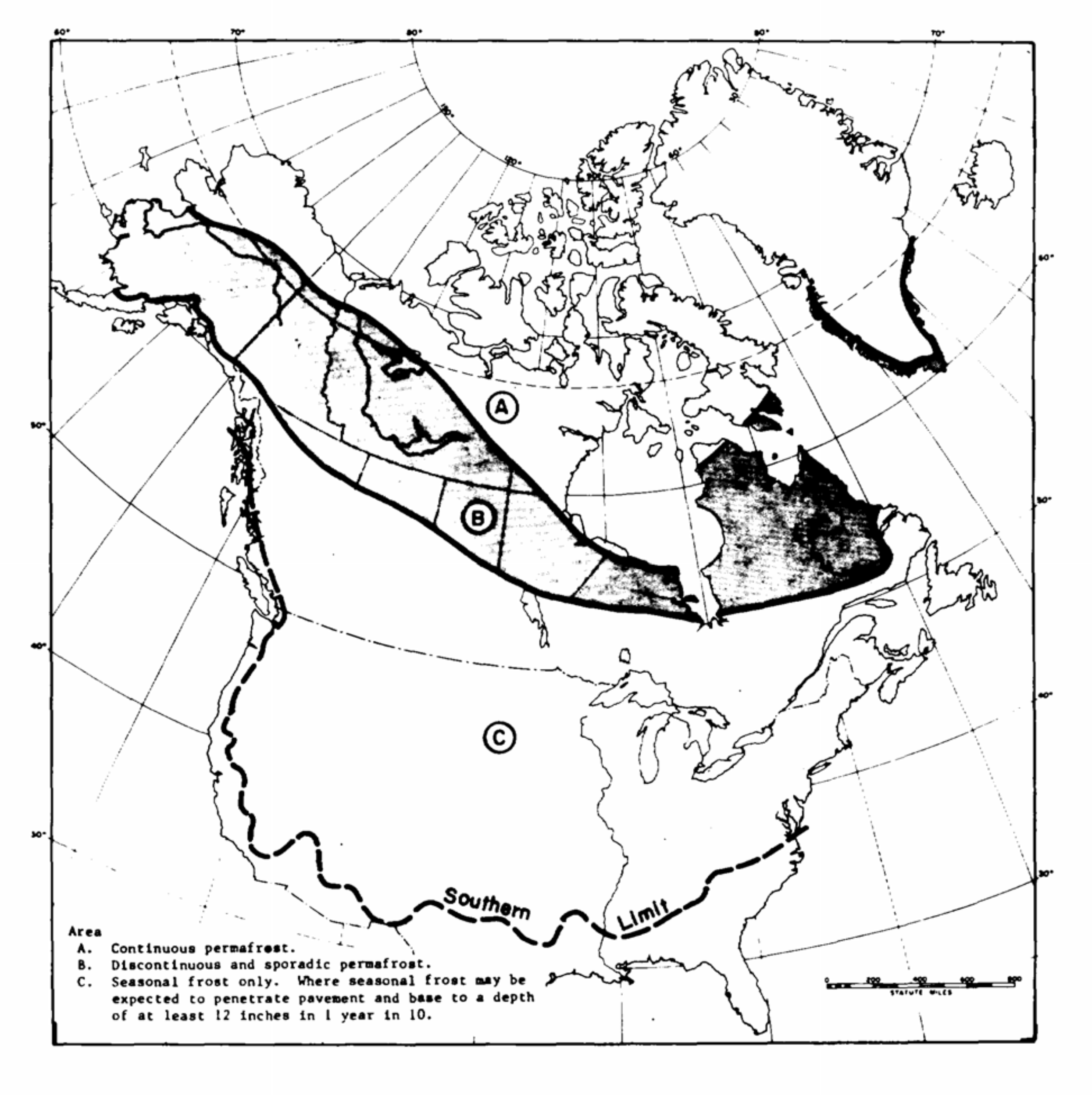


Figure 1

Frost and permafrost in North America

1.2.2.4 PROGRESSIVE FREEZING AND FROST HEAVE of foundations may also develop under refrigerated warehouses and other facilities where sustained interior below-freezing temperatures are maintained. The design procedures and technical guidance outlined in this publication may be adapted to the solution of these design problems.

2.. FACTORS AFFECTING DESIGN OF FOUNDATIONS.

2.1 PHYSIOGRAPHY AND GEOLOGY. Physiographic and geologic details in the area of the proposed construction are a major factor determining the degree of difficulty that may be encountered in achieving a stable foundation. For example, pervious layers in fine-grained alluvial deposits in combination with copious groundwater supplies from adjacent higher terrain may produce very high frost-heave potential, but clean, freedraining sand and gravel terrace formations of great depth, free of excess ice, can provide virtually troublefree foundation conditions.

2.2 TEMPERATURE. The most important factors contributing to the existence of adverse foundation conditions in seasonal frost and permafrost regions are cold air temperatures and the continual changes of temperature between summer and winter. Mean annual air temperatures usually have to be 2º to 8ºF below freezing for permafrost to be present, although exceptions may be encountered both above and below this range. Ground temperatures, depths of freeze and thaw, and thickness of permafrost are the product of many variables including weather, radiation, surface conditions, exposure, snow and vegetative cover, and insulating or other special courses. The properties of earth materials that determine the depths to which freezing-and-thawing temperatures will penetrate below the ground surface under given temperature differentials over a given time are the thermal conductivity, the volumetric specific heat capacity, and the volumetric latent heat of fusion. These factors in turn vary with the type of material, density, and moisture content. Figure 2 shows how ground temperatures vary during the freezing season in an area of substantial seasonal freezing having a mean annual temperature of 37ºF (Limestone, Maine), and Figure 3 shows similar data for a permafrost area having a mean annual temperature of 26ºF (Fairbanks, Alaska).

2.2.1 FOR THE COMPUTATION OF SEASONAL FREEZE OR THAW PENETRATION, freezing-and-thawing indexes are used based upon degree-days relative to 32ºF. For the average permanent structure, the design indexes should be those for the coldest winter and the warmest summer in 30 years of record. This criterion is more conservative than that used for pavements because buildings and other structures are less tolerant of movement than pavements. It is important to note that indexes found from weather records are for air about 4.5 feet above the ground. The values at ground surface, which determine freeze-and-thaw effects, are usually different; being generally smaller for freezer conditions and larger for thawing where surfaces are exposed to the sun. The surface index, which is the index determined for the temperature immediately below the surface, is n times the air index, where n is the correction factor. Turf, moss, other vegetative cover, and snow will reduce the n value for temperatures at the soil surface in relation to air temperatures and hence give less freeze or thaw penetration for the same air freezing or thawing index. Values of n for a variety of conditions are given in the technical literature.

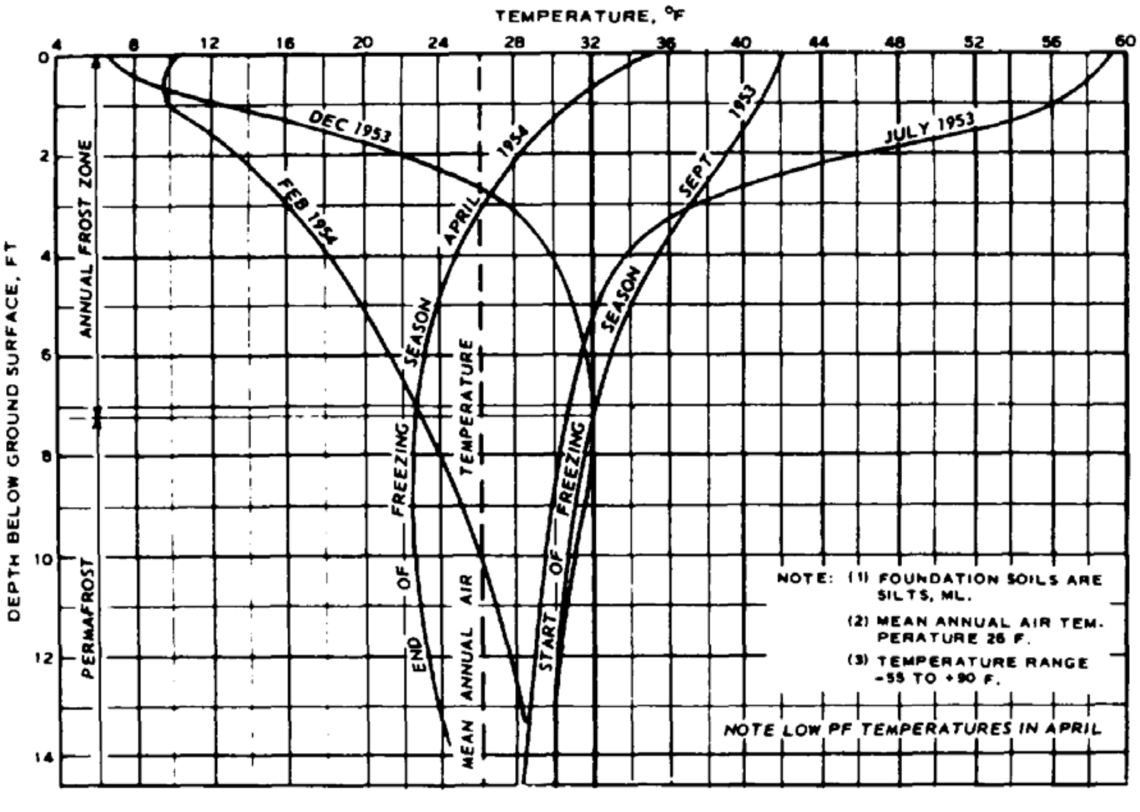
2.2.2 MORE DETAILED INFORMATION ON INDEXES and their computation is presented elsewhere in the technical literature, including maps showing distribution of index values.

2.3 FOUNDATION MATERIALS. The foundation design decisions may be critically affected by the foundation soil, ice and rock conditions.

2.3.1 SOILS.

2.3.1.1 THE MOST IMPORTANT PROPERTIES of soils affecting the performance of engineering structures under seasonal freeze-thaw action are their frost-heaving characteristics and their shear strengths on thawing. Criteria for frost susceptibility based on percentage by weight finer than 0.02 millimeter are presented in the technical literature. These criteria have also been developed for pavements. Heave potential at the lower limits of frost susceptibility determined by these criteria is not zero, although it is generally low to negligible from the point of view of pavement applications. Applicability of these criteria to foundation design will vary, depending upon the nature and requirements of the particular construction. Relative frost-heaving qualities of various soils are shown in the technical literature.

2.3.1.2 PERMAFROST SOILS cover the entire range of types from very coarse, bouldery glacial drift to clays and organic soils. Strength properties of frozen soils are dependent on such variables as gradation, density, degree of saturation, ice content, unfrozen moisture content, temperature, dissolved soils, and rate of loading. Frozen soils characteristically exhibit creep at stresses as low as 5 to 10 percent of the rupture strength in rapid loading. Typical strength and creep relationships are described in the technical literature



NOTE: (1) FOUNDATION SOILS ARE SILTS, ML.
(2) MEAN ANNUAL AIR TEMPERATURE 26 F.
(3) TEMPERATURE RANGE -55 TO +90 F.

NOTE LOW PF TEMPERATURES IN APRIL

Figure 2

Ground temperature during freezing season in Limestone, Maine

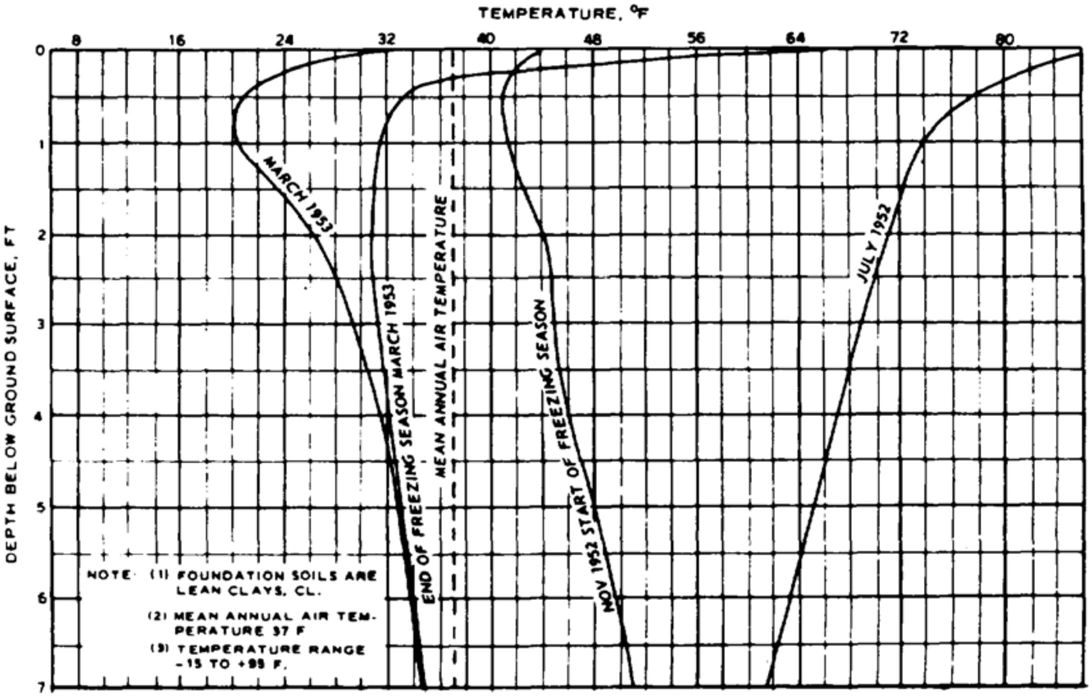


Figure 3

Ground temperatures during freezing season In Fairbanks, Alaska

2.3.2 ICE. Ice that is present in the ground in excess of the normal void space is most obvious as clear lenses, veins or masses easily visible in cores, test pits or excavations; but it may also be so uniformly distributed that it is not readily apparent to the unaided eye. In the annual frost zone, excess ice is formed by the common ice segregation process, although small amounts of ice may also originate from filling of shrinkage cracks. Ice formations in this zone disappear each summer. Below the annual frost zone, excess ice in permafrost may form by the same type of the ice segregation process as above; may occur as vertical ice wedges formed by a horizontal contraction-expansion process; or may be "fossil ice" buried by landslides or other events. Although most common in fine-grained soils, substantial bodies of excess ice are not uncommon in permanently frozen clean, granular deposits. The possible adverse effects of excess ice are discussed elsewhere.

2.3.3 ROCK. Bedrock subject to freezing temperatures should never be assumed problem-free in the absence of positive subsurface information. In seasonal frost areas, mud seams in bedrock or concentrations of fines at or near the rock surface, in combination with the ability of fissures in the rock to supply large quantities of water for ice segregation, frequently cause severe frost heave. In permafrost areas, very substantial quantities of ice are often found in bedrock, occurring in fissures and cracks and along bedding planes.

2.4 WATER CONDITIONS.

2.4.1 IF FREE WATER drawn to developing ice segregation can be easily replenished from an aquifer layer or from a water table within a few feet of the plane freezing, heave can be large. However, if a freezing soil has no access to free water beyond that contained in voids of the soil immediately at or below the plane of freezing, frost heave will necessarily be limited.

2.4.2 IN PERMAFROST AREAS, the supply of water available to feed growing ice lenses tends to be limited because of the presence of the underlying impermeable permafrost layer, usually at relatively shallow depths, and maximum heave may thus be less than under otherwise similar conditions in seasonal frost areas. However, uplift forces on structures may be higher because of lower soil temperatures and consequent higher effective tangential adfreeze strength values.

2.4.3 THE WATER CONTENT OF SOIL exerts a substantial effect upon the depth of freeze or thaw penetration that will occur with a given surface freezing or thawing index. Higher moisture contents tend to reduce penetration by increasing the volumetric latent heat of fusion as well as the volumetric specific heat capacity. While an increase in moisture also increases thermal conductivity, the effect of latent heat of fusion tends to be predominant.

2.5 FROST-HEAVE FORCES AND EFFECT OF SURCHARGE. Frost-heave forces on structures may be quite large. For some engineering construction, complete prevention of frost heave is unnecessary and uneconomical, but for most permanent structures, complete prevention is essential. Under favorable soil and foundation loading conditions, it may be possible to take advantage of the effect of surcharge to control heave. It has been demonstrated in laboratory and field experiments that the rate of frost heaving is decreased by an increase of loading on the freezing plane and that frost heaving can be completely restrained if sufficient pressure is applied. However, heave forces normal to the freezing plane may reach more than 10 tons per square foot. Detailed information on frost-heaving pressures and on the effect of surcharge is presented in the technical literature.

2.6 TYPE OF STRUCTURE. The type and uses of a structure affect the foundation design in frost areas as in other places. Applicable considerations are discussed in the technical literature.

3. SITE INVESTIGATIONS.

3.1 GENERAL. In addition to the needed site investigations and data described in the manuals for nonfrost conditions, design of foundations in areas of significant frost penetration requires special studies and data because of factors introduced by the special frost-related site conditions. Detailed site investigation procedures applicable for arctic and subarctic areas are described in the technical literature, and may be adapted or reduced in scope, as appropriate, in areas of less severe winter freezing. Methods of terrain evaluation in arctic and subarctic regions are given in the technical literature.

3.2 REMOTE SENSING AND GEOPHYSICAL INVESTIGATIONS. These techniques are particularly valuable in the selection of the specific site location, when a choice is possible. They can give clues to subsurface frozen ground conditions because of effects of ground freezing upon such factors as vegetation, land wastage, and soil and rock electrical and acoustical properties.

3.3 DIRECT SITE INVESTIGATIONS. The number and extent of direct site explorations should be sufficient to reveal in detail the occurrence and extent of frozen strata, permafrost and excess ice including ice wedges, moisture contents and groundwater, temperature conditions in the ground, and the characteristics and properties of frozen materials and unfrozen soil and rock.

3.3.1. THE NEED FOR INVESTIGATION OF BEDROCK requires special emphasis because of the possibilities of frost heave or ice inclusions. Bedrock in permafrost areas should be drilled to obtain undisturbed frozen cores whenever ice inclusions could affect the foundation design or performance.

3.3.2 IN AREAS OF DISCONTINUOUS PERMAFROST, sites require especially careful exploration and many problems can be avoided by proper site selection. As an example, the moving of a site 50 to 100 feet from its planned position may place a structure entirely on or entirely off permafrost; in either case simplifying foundation design. A location partly on and partly off permafrost might involve an exceptionally difficult or costly design.

3.3.3. BECAUSE FROZEN SOILS MAY HAVE COMPRESSIVE STRENGTHS as great as that of a lean concrete and because ice in the ground may be melted by conventional drilling methods, special techniques are frequently required for subsurface exploration in frozen materials. Core drilling using refrigerated drilling fluid or air to prevent melting of ice in the cores provides specimens that are nearly completely undisturbed and can be subjected to the widest range of laboratory tests. By this procedure, soils containing particles up to boulder size and bedrock can be sampled, and ice formations can be inspected and measured. Drive sampling is feasible in frozen fine-grained soils above about 250 feet and is often considerably simpler, cheaper, and faster. Samples obtained by this procedure are somewhat disturbed, but they still permit ice and moisture content determinations. Test pits are very useful in many situations. For frozen soils that do not contain very many cobbles and boulders, truck-mounted power augers using tungsten carbide cutting teeth will provide excellent service where classification, gradation, and rough ice content information will be sufficient. In both seasonal frost and permafrost areas, a saturated soil condition is common in the upper layers of soil during the thaw season, as long as there is frozen, impervious soil still underlying. Explorations attempted during the thaw season are handicapped and normally require cased boring through the thawed layer. In permafrost areas, it is frequently desirable to carry out explorations during the colder part of the year (when the annual frost zone is frozen) than during the summer.

3.3.4 IN SUBSURFACE EXPLORATIONS THAT ENCOUNTER FROZEN SOIL, it is important that the boundaries of frozen and thawed zones and the amount and mode of ice occurrence be recorded. Materials encountered should be identified in accordance with the Unified Soil Classification System, including the frozen soil classification system.

3.3.5 IN SEASONAL FROST AREAS, the most essential site date beyond those needed for nonfrost foundation design are the design freezing index and the soil frost-susceptibility characteristics. In permafrost areas, the date requirements are considerably more complex. Determination of the susceptibility of the foundation materials to settlement on thaw and of the subsurface temperatures and thermal regime will usually be the most critical special requirements. Ground temperatures are measured most commonly with copper-constantan thermocouples or with thermistors.

3.3.6 SPECIAL SITE INVESTIGATIONS, such as installation and testing of test piles, or thaw-settlement tests may be required. Assessment of the excavation characteristics of frozen materials may also be a key factor in planning and design.

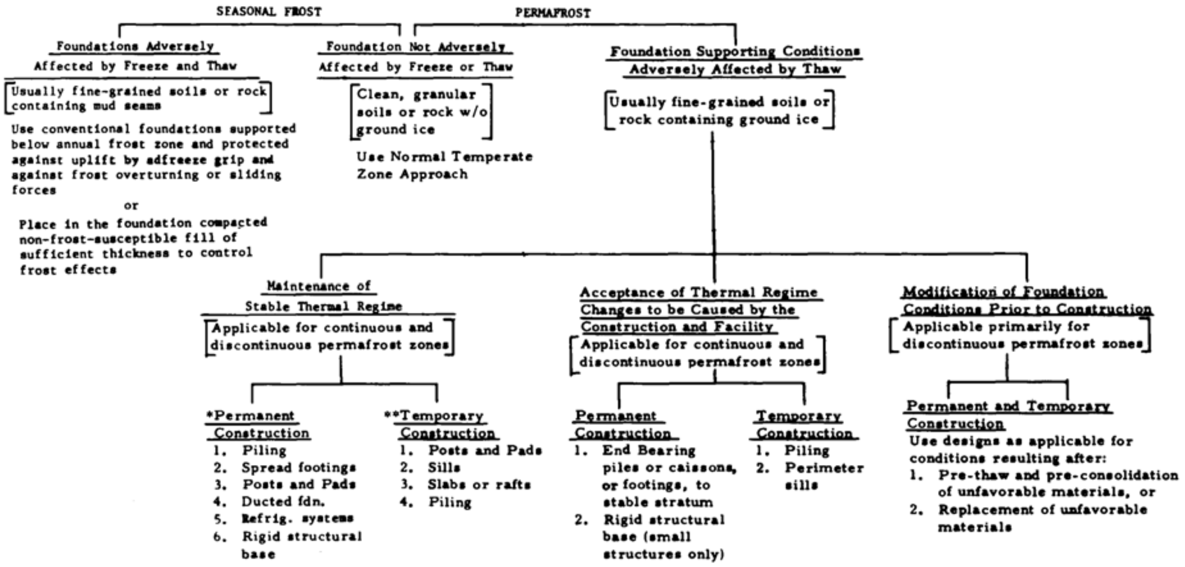
4. FOUNDATION DESIGN.

4.1 SELECTION OF FOUNDATION TYPE. Only sufficient discussion of the relationships between foundation conditions and design decisions is given below to indicate the general nature of the problems and solutions.

4.1.1 FOUNDATIONS IN SEASONAL FROST AREAS.

4.1.1.1 WHEN FOUNDATION MATERIALS WITHIN THE MAXIMUM DEPTH of seasonal frost penetration consist of clean sands and gravels or other non-frost-susceptible materials that do not develop frost heave or thrust, or thaw weakening, design in seasonal frost areas may be the same as for nonfrost regions, using conventional foundations, as indicated in Figure 4. Effect of the frost penetration on related engineering aspects, such as surface and subsurface drainage systems or underground utilities, may need special consideration. Thorough investigation should be made to confirm the nonfrost susceptibility of subgrade soils prior to design for this condition.

4.1.1.2 WHEN FOUNDATION MATERIALS WITHIN THE ANNUAL FROST ZONE are frost-susceptible, seasonal frost heave and settlement of these materials may occur. In order for ice segregation and frost heave to develop, freezing temperatures must penetrate into the ground, soil must be frost-susceptible, and adequate moisture must be available. The magnitude of seasonal heaving is dependent on such factors as rate and duration of frost penetration, soil type and effective pore size, surcharge, and degree of moisture availability. Frost heave in a freezing season may reach a foot or more in silts and some clays, if there is an unlimited supply of moisture available. The frost heave may lift or tilt foundations and structures, commonly differentially, with a variety of possible consequences.



*Permanent Construction - Construction incorporating the type and quality of materials and equipment, and details and methods of construction, which results in a building or facility suitable to serve a specific purpose over a minimum life expectancy of 25 years with normal maintenance.

**Temporary Construction - Construction incorporating the type and quality of materials and equipment, and details and methods of construction, which results in a building or facility suitable to provide minimum accommodations at low first cost to serve a specific purpose for a short period of time, 5 years or less, in which the degree of maintenance is not a primary design consideration.

Figure 4

Design alternatives

4.1.1.3 WHEN THAW OCCURS, the ice within the frost-heaved soil is changed to water and escapes to the ground surface or into surrounding soil, allowing overlying materials and structures to settle. If the water is released by thaw more rapidly than it can be drained away or redistributed, substantial loss in soil strength occurs. In seasonal frost areas, a heaved foundation may or may not return to its before-heave elevation. Friction on lateral surface or intrusion of softened soil into the void space below the heaved foundation members may prevent full return. Successive winter seasons may produce progressive upward movement.

4.1.1.4 THEREFORE, when the soils within the maximum depth of seasonal frost penetration are frost-susceptible, foundations in seasonal frost areas should be supported below the annual frost zone, using conventional foundation elements protected against uplift caused by adfreeze grip and against frost overturning or sliding forces, or the structure should be placed on compacted non-frost-susceptible fill designed to control frost effects (Fig. 4).

4.1.2 FOUNDATIONS IN PERMAFROST AREAS. Design on permafrost areas must cope with both the annual frost zone phenomena and those peculiar to permafrost.

4.1.2.1 PERMAFROST FOUNDATIONS NOT ADVERSELY AFFECTED BY THAW. Whenever possible, structures in permafrost areas should be located on clean, non-frost-susceptible sand or gravel deposits or rock that are free of ground ice or of excess interstitial ice, which would make the foundation susceptible to settlement on thaw. Such sites are ideal and should be sought whenever possible. Foundation design under these conditions can be basically identical with temperate zone practices, even though the materials are frozen below the foundation support level, as has' been demonstrated by construction in interior Alaska. When conventional foundation designs are used for such materials, heat from the structure will gradually thaw the foundation to progressively greater depths over an indefinite period of years. In five years, for example, thaw may reach a depth of 40 feet. However, if the foundation materials are not susceptible to settlement on thaw, there will be no effects on the structure from such thaw. The possible effect of earthquakes or other dynamic forces after thawing should be considered.

4.1.2.2 PERMAFROST FOUNDATIONS ADVERSELY AFFECTED BY THAW. When permafrost foundation materials containing excess ice are thawed, the consequences may include differential settlement, slope instability, development of water-filled surface depressions that serve to intensity thaw, loss of strength of frost-loosened foundation materials under excess moisture conditions, development of underground uncontrolled drainage channels in permafrost materials susceptible to bridging or piping, and other detrimental effects. Often, the results may be catastrophic. For permafrost soils and rock containing excess ice, design should consider three alternatives, as indicated in

Figure 4: maintenance of stable thermal regime, acceptance of thermal regime changes, and modification of foundation conditions prior to construction. Choice of the specific foundation type from among those indicated in Figure 4 can be made on the basis of cost and performance requirements after the development of details to the degree needed for resolution.

4.2 FOUNDATION FREEZE AND THAW AND TECHNIQUES FOR CONTROL. Detailed guidance for foundation thermal computations and for methods of controlling freeze-and thaw penetration are presented in the technical literature.

4.2.1 DESIGN DEPTH OF ORDINARY FROST PENETRATION.

4.2.1.1. FOR AVERAGE PERMANENT STRUCTURES, the depth of frost penetration assumed for design, for situations not affected by heat from a structure, should be that which will occur in the coldest year in 30 years. For a structure of a temporary nature or otherwise tolerant of some foundation movement, the depth of frost penetration in the coldest year in 10 or even that in the mean winter may be used, as may be most applicable. The design depth should preferably be based on actual measurements or on computations if measurements are not available. When measurements are available, they will almost always need to be adjusted by computations to the equivalent of the freezing index selected as the basis for design, as measurements will seldom be available for a winter having a severity equivalent to that value.

4.2.1.2 THE FROST PENETRATION CAN BE COMPUTED using the design freezing index and the detailed guidance given in the technical literature. For paved areas kept free of snow, approximate depths of frost penetration may be estimated from the appropriate chart with the air freezing index directly. A chart is also presented in the technical literature from which approximate depths of frost penetration may be obtained for a variety of surface conditions, using the air freezing index in combination with the appropriate surface index/air correction factor (n-factor).

4.2.1.3 IN THE MORE DEVELOPED PARTS OF THE COLD REGIONS, the building codes of most cities specify minimum footing depths, based on many years of local experience; these depths are invariably less than the maximum observed frost penetrations. The code values should not be assumed to represent actual frost penetration depths. Such local code values have been selected to give generally suitable results for the types of construction, soil moisture, density, and surface cover conditions, severity of freezing conditions, and building heating conditions that are common in the area. Unfortunately, the code values may be inadequate or inapplicable under conditions that differ from those assumed in formulating the code, especially for unheated facilities, insulated foundations, or especially cold winters. Building codes in the Middle and North Atlantic States and Canada frequently specify minimum footing depths that range from 3 to 5 feet. If frost penetrations of this order of magnitude occur with fine silt and claytype soils, 30 to 100 percent greater frost penetration may occur in well-drained gravels under the same conditions. With good soil data and a knowledge of local conditions, computed values for ordinary frost penetration, unaffected by building heat, may be expected to be adequately reliable, even though the freezing index may have to be estimated from weather data from nearby stations. In remote areas, measured frost depths may be entirely unavailable.

4.2.2 DESIGN DEPTH OF ORDINARY THAW PENETRATION. Estimates of seasonal thaw penetration in permafrost areas should be established on the same statistical measurement bases as outlined above for seasonal frost penetration. The air thawing index can be converted to a surface thawing index by multiplying it by the appropriate thawing-conditions n-factor. The thaw penetration can then be computed using the detailed guidance given in the technical literature. Approximate values of may also be estimated from a chart of the air thawing index versus the depth of thaw. Degradation of permafrost will result if the average annual depth of thaw penetration exceeds the average depth of frost penetration.

4.2.3 THAW OR FREEZE BENEATH STRUCTURES.

4.2.3.1 Any change from natural conditions, which results in a warming of the ground beneath a structure, can result in progressive lowering of the permafrost table over a period of years. Heat flow from a structure into underlying ground containing permafrost can only be ignored as a factor in the longterm structural stability when the nature of the permafrost is such that no settlement or other adverse effects will result. The source of heat may be not only the building heat but also the solar radiation, underground utilities, surface water, and groundwater flow. The technical literature provides guidance on procedures for estimating the depth of thaw under a heated building with time.

4.2.3.2 THE MOST WIDELY EMPLOYED, EFFECTIVE AND ECONOMICAL MEANS of maintaining a stable thermal regime under a heated structure, without degradation of permafrost, is by use of a ventilated foundation. Under this scheme, provision is made for the circulation of cold water air between the insulated floor and the underlying ground. The same scheme can be used for the converse situation of a refrigerated facility supported on unfrozen ground. The simplest way of providing foundation ventilation is by providing an open space under the entire building, with the structure supported on footings or piling. For heavier floor loadings, ventilation ducts below the insulated floor may be used. Experience has shown that ventilated foundations should be so elevated, sloped, oriented, and configured as to minimize possibilities for accumulation of water, snow, ice, or soil in the ducts. Guidance in the thermal analysis of ventilated foundations, including the estimation of depths of summer thaw in supporting materials and design to assure winter refreezing, is available in the technical literature.

4.2.3.3. NATURAL OR FORCED CIRCULATION THERMAL PILES OR REFRIGERATION POINTS may also be used for overall foundation cooling and control of permafrost degradation.

4.2.3.4 FOUNDATION INSULATION. Thermal insulation may be used in foundation construction in both seasonal frost and permafrost areas to control frost penetration, frost heave, and condensation, to conserve energy, to provide comfort, and to enhance the effectiveness of foundation ventilation. Unanticipated loss of effectiveness by moisture absorption must be avoided. Cellular glass should not be used where it will be subject to cyclic freezing and thawing in the presence of moisture. Insulation thicknesses and placement may be determined by the guidance available in the technical literature

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4.2.3.5 GRANULAR MATS. In areas of significant seasonal frost and permafrost, a mat of non-frostsusceptible granular material may be used to moderate and control seasonal freeze-and-thaw effects in the foundation, to provide drainage under floor slabs, to provide stable foundation support, and to provide a dry, stable working platform for construction equipment and personnel. Seasonal freezing-and-thawing effects may be totally or partially contained within the mat. When seasonal effects are only partially contained, the magnitude of seasonal frost heave is reduced through both the surcharge effect of the mat and the reduction of frost penetration into underlying frost-susceptible soils. The technical literature provides guidance in the design of mats.

4.2.3.6 SOLAR RADIATION THERMAL EFFECTS. The control of summer heat input from solar radiation is very important in foundation design in permafrost areas. Corrective measures that may be employed include shading, reflective paint or other surface material, and sometimes live vegetative covering. In seasonal frost areas, it may sometimes be advantageous to color critical surfaces black to gain maximum effect of solar heat in reducing winter frost problems. The technical literature provides guidance on the control of solar radiation thermal effects.

4.3 CONTROL OF MOVEMENT AND DISTORTION. The amount of movement and distortion that may be tolerated in the support structure must be established and the foundation must be designed to meet these criteria. Movement and distortion of the foundation may arise from seasonal upward, downward, and lateral displacements, from progressive settlement arising from degradation of permafrost or creep deflections under load, from horizontal seasonal shrinkage and expansion caused by temperature changes, and from creep, flow, or slide of material on slopes. Heave may also occur on a nonseasonal basis if there is progressive freezing in the foundation, as under a refrigerated building or storage tank. If the subsurface conditions, moisture availability, frost penetration, imposed loading, or other factors vary in the foundation area, the movements will be nonuniform. Effects on the foundation and structure may include various kinds of structural damage, jamming of doors and windows, shearing of utilities, and problems with installed equipment.

4.3.1 FROST-HEAVE AND THAW-SETTLEMENT DEFORMATIONS.

4.3.1.1 FROST HEAVE acts in the same direction as the heat flow, or perpendicular to the freezing plane. Thus, a slab on a horizontal surface will be lifted directly upward, but a vertical retaining wall may experience horizontal thrust. Foundation members, such as footings, walls, piles, and anchors, may also be gripped on their lateral surfaces and heaved by frost forces acting in tangential shear. Figure 5 shows an example of frost-heave forces developed in tangential shear on timber and steel pipe piles restrained against upward movement.

4.3.1.2 IN RIVERS, LAKES, OR COASTAL WATER BODIES, foundation members to which floating ice may adhere may also be subject to important vertical forces as water levels fluctuate.

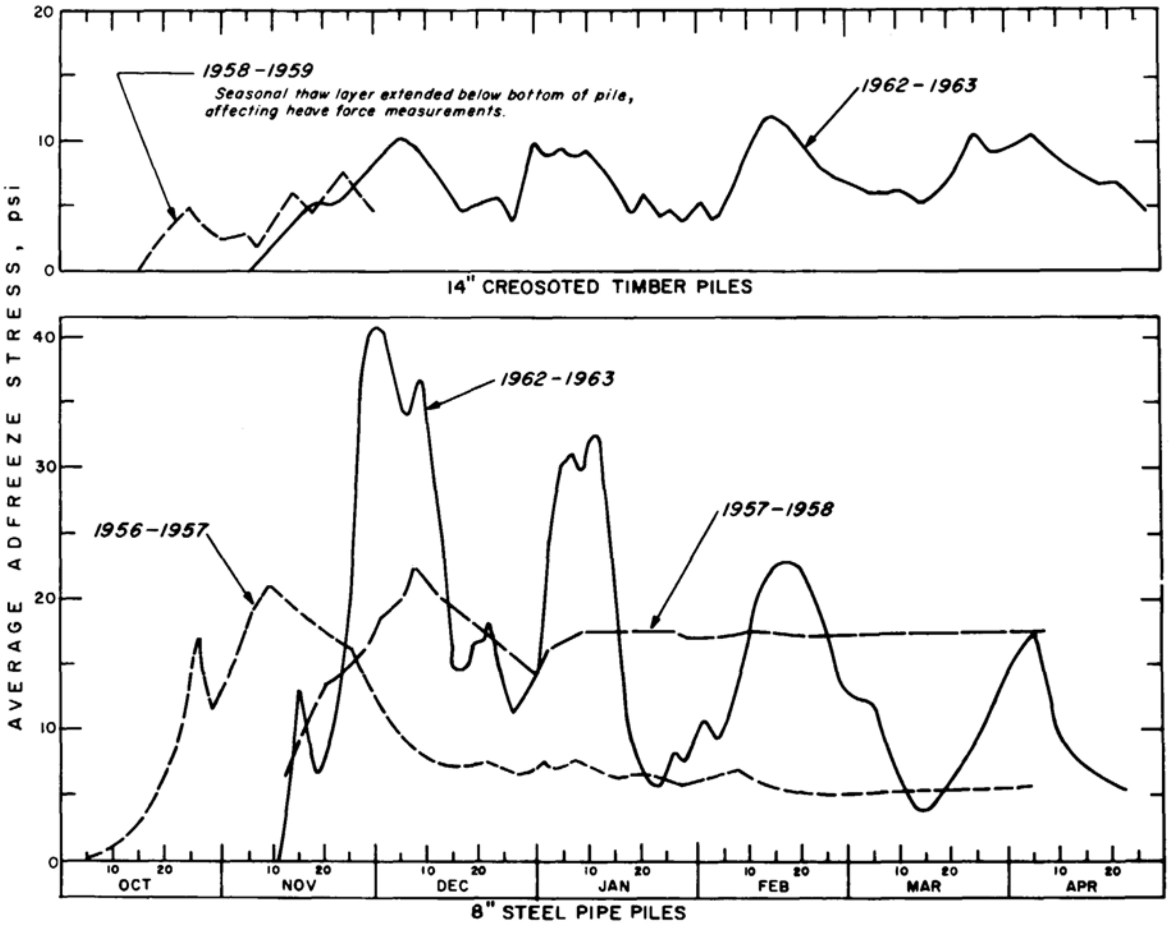
4.3.1.3 AMONG METHODS THAT CAN BE USED to control detrimental frost action effects are placing non-frostsusceptible soils in the depth subject to freezing to avoid frost heave or thrust; providing sufficient embedment or other anchorage to resist movement under the lifting forces; providing sufficient loading on the foundation to counterbalance upward forces; isolating foundation members from heave forces; battering or tapering members within the annual frost zone to reduce effectiveness of heave grip; modifying soil frost susceptibility; in seasonal frost areas only, taking advantage of natural heat losses from the facility to minimize adfreeze and frost heave; or cantilevering building attachments, e.g., porches and stairs, to its main foundation.

4.3.1.4 IN PERMAFROST AREAS, movement and distortion caused by thaw of permafrost can be extreme and should be avoided by designing for full and positive thermal stability whenever the foundation would be adversely affected by thaw. If damaging thaw settlement should start, a mechanical refrigeration system may have to be installed in the foundation or a program of continual jacking may have to be adopted for leveling of the structure. Discontinuance or reduction of building heat can also be effective.

4.3.2 CREEP DEFORMATION. Only very small loads can be carried on the unconfined surface of ice-saturated frozen soil without progressive deformation. The allowable long-term loading increases greatly with depth but may be limited by unacceptable creep deformation well short of the allowable stress level determined from conventional short-term test. Present practice is to use large footings with low unit loadings; support footings on mats of well-drained non-frostsusceptible granular materials, which reduce stresses on underlying frozen materials to conservatively low values; or place foundations at sufficient depth in the ground so that creep is effectively minimized. Pile foundations are designed to not exceed sustainable adfreeze bond strengths. In all cases, analysis is based on permafrost temperature at the warmest time of the year. For cases which require estimation of foundation creep behavior, refer to the technical literature.

4.4 VIBRATION PROBLEMS AND SEISMIC EFFECTS.

4.4.1 FOUNDATIONS SUPPORTED ON FROZEN GROUND may be affected by high stress-type dynamic loadings, such as shock loadings from high-yield explosions, by lower stress pulse-type loadings as from earthquakes or impacts, or by relatively low-stress, relatively low-frequency, steady-state vibrations. In general, the same procedures used for non-frozen soil conditions are applicable to frozen soils. Design criteria are given in the technical literature. The technical literature also contains references to sources of data on the general behavior and properties of non-frozen soils under dynamic load, and discusses types of laboratory and field tests available. However, design criteria, test techniques, and methods of analysis are not yet firmly established for engineering problems of dynamic loading of foundations.



AVERAGE ADFREEZE STRESS vs TIME

Figure 5

Heave force tests, average tangential adfreeze bond stress versus time, and timber and steel pipe piles placed with silt-water slurry in dry excavated holes. Piles were installed within annual frost zone only, over permafrost, to depths from ground surface of 3.6 to 6.5 feet.

4.4.2 ALL DESIGN APPROACHES require knowledge of the response characteristics of the foundation materials, frozen or nonfrozen, under the particular load involved. As dynamic loadings occur in a range of stresses, frequencies, and types (shock, pulse, steady-state vibrations, etc.), and the response of the soil varies depending upon the load characteristics, the required data must be obtained from tests that produce the same responses as the actual load. Different design criteria are used for the different types of dynamic loading, and different parameters are required. Such properties as moduli, damping ability, and velocity of propagation vary significantly with such factors as dynamic stress, strain, frequency, temperature, and soil type and condition. The technical literature discusses these properties for frozen ground.

4.5 DESIGN CRITERIA FOR VARIOUS SPECIFIC ENGINEERING FEATURES. In addition to the basic considerations outlined in the preceding paragraphs of this publication, the design of foundations for frost and permafrost conditions requires application of detailed criteria for specific engineering situations. Guidance for the design of various specific features, construction consideration, and monitoring of performance of foundation is presented in the technical literature.