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Special Report 79

PILE FOUNDATIONS IN DISCONTINUOUS PERMAFROST AREAS

by

Frederick E. Crory

MARCH 1967

Conducted for
CORPS OF ENGINEERS, U. S. ARMY
by
U.S. ARMY MATERIEL COMMAND
COLD REGIONS RESEARCH & ENGINEERING LABORATORY
HANOVER, NEW HAMPSHIRE

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PREFACE

This study was performed in connection with Military Construction Investigations, Engineering Criteria and Investigations and Studies, Investigation of Arctic Construction: Pile Installation Methods in Permafrost.

The Military Construction Investigations program is conducted for the Engineering Division, Directorate of Military Construction, Office, Chief of Engineers and is administered by the Civil Engineering Branch (Mr. T. B. Pringle, Chief). The study of Pile Installation Methods in Permafrost was initiated by the former Arctic Construction and Frost Effects Laboratory (ACFEL)* of the U.S. Army Engineer Division, New England. Project responsibility was transferred to the U.S. Army Cold Regions Research and Engineering Laboratory (USA CRREL) in 1961.

Investigations were conducted under the general supervision of Mr. K.A. Linell, Chief, Experimental Engineering Division, USA CRREL and the direct supervision of Mr. E.F. Lobacz, Chief, Construction Engineering Branch, USA CRREL. Mr. F.E. Crory, the author of this report, was the project leader.

Lt. Col. John E. Wagner was Commanding Officer and Director of the U.S. Army Cold Regions Research and Engineering Laboratory during the publication of this report, and Mr. W.K. Boyd was Chief Engineer.

USA CRREL is an Army Materiel Command laboratory.

*ACFEL was merged with the former Snow, Ice and Permafrost Research Establishment (SIPRE) in 1961 to form the U.S. Army Cold Regions Research and Engineering Laboratory (USA CRREL), Hanover, New Hampshire.

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SUMMARY

The design and installation of piles in areas of warm permafrost present many unusual problems. Design considerations and construction methods and controls to minimize disturbance of the delicate thermal balance of warm permafrost are included in an evaluation of pile installation techniques.

The importance of adequate site investigations and proper construction inspection and control is emphasized. Preconstruction temperature information is used with climatological records and theoretical methods to predict the freezing and/or thawing that will be experienced under the structure. Natural and artificial freezeback of piles are discussed in terms of construction schedules, installation methods, and the volumetric heat capacity of the permafrost.

CONVERSION TABLE

Multiply	By	To obtain
in.	25.4	mm
ft	30.48	cm
sq ft	0.092903	sq m
cu ft	0.0283168	cu m
sq ft/hr	0.2581	sq cm/sec
lb	0.45359237	kg
Btu	1055.06	Joules
Btu/lb	2.326	Joules/g
Btu/cu ft °F	16.018	kg cal/cu m °C
Btu/ft hr °F	1.488	kg cal/m hr °C
Btu/cu ft	8.899	kg cal/cu m
°F	5/9(°F-32)	°C or °K

PILE FOUNDATIONS IN DISCONTINUOUS PERMAFROST AREAS

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INTRODUCTION

The design and construction of foundations in areas of warm, discontinuous permafrost requires a good understanding of frozen soil mechanics. Although similar foundation problems exist in continuous permafrost areas, the problems of the discontinuous permafrost areas are normally considerably more difficult. Any change, of short or long duration, in the delicate thermal balance beneath and adjacent to a foundation on frozen soil produces corresponding changes in the mechanical and physical properties of the supporting medium. In all permafrost areas, heat flow from the structure to the underlying permafrost is a fundamental consideration. Degradation of permafrost containing segregated ice will produce settlements, usually differential, of the structure. Degradation may occur not only from building heat, but from other heat sources such as disturbance of the surrounding surface cover, solar radiation, drainage, underground utilities, and ground water flow.

The design of foundations partly or completely on permafrost consisting entirely of ice-free bedrock and of clean non-frost-susceptible compact sand and gravel deposits free from segregated ice may be the same as in non-frost areas (Departments of the Army and Air Force, 1961). Sands and gravels with segregated ice which are susceptible to settlement on thawing may be made suitable by pre-thawing and consolidating (Terzaghi, 1952). However, when such ideal sites are not available, and the foundation soils are fine-grained silts or clays containing ice inclusions, the problem becomes far more complex. The advantages of pile foundations in such silts and clays for safely transferring the loads to depths unaffected by settlement or thermal regime changes are well known. This report presents some of the design and construction considerations associated with pile foundations in areas of warm, discontinuous permafrost.

SITE CONDITIONS

In areas of discontinuous permafrost, especially detailed and carefully executed site investigations should be conducted. Many foundation problems can be avoided by site selection based on aerial and ground reconnaissance. Air-photos may be advantageously used to identify soil types and their boundaries (Frost, 1952; Departments of the Army and Air Force, 1963). Air-photos can aid substantially in eliminating undesirable sites and in suggesting possible usable sites. The shifting of a site a few hundred feet may place the structure entirely on or off permafrost, thus greatly simplifying the foundation problem.

Adequate borings are essential to establish the conditions which exist at the proposed foundation site. The conditions at depth may be completely different from those at or near the surface. When a relatively shallow layer of undesirable material exists over clean sands or gravels, the design may be greatly simplified by excavation of the poor material and backfilling with acceptable non-frost-susceptible material. Conversely, an apparently acceptable layer of sand or gravel may be underlain by silts or clays with excessive ice that would lead to settlement as thawing progressed. To determine the actual extent of the foundation material, borings should be at appropriate intervals and to depths of at least the width of the structure. If presence of isolated permafrost inclusions is suspected, borings should be at close intervals. Where changes in soil types, ice distribution, ground water, and frozen and unfrozen sections are encountered, sufficient additional borings should be required to clearly delineate any factors affecting the foundation design. Whenever possible (and in some cases, it is essential), undisturbed samples, with ice layers intact, should be obtained, rather than disturbed samples from augering or other methods. Rotary core drilling will always be feasible in saturated frozen materials. Drive sampling will recover partially disturbed samples in frozen fine-grained soils down to about 25F, suitable for determining amounts of segregated ice (Kitze, 1956). The samples should be classified and described in accordance with the frozen soil classification system (Departments of the Army and Air Force, In press; Linell and Kaplar, 1966; Pihlainen and Johnston, 1963).

Selected or continuous samples should be preserved in their frozen state for laboratory testing at a temperature as near as possible to that in place. The principal laboratory data required include dry unit weight, water and organic content, grain size distribution and, in some cases, degree of frost susceptibility, consolidation characteristics, thermal conductivities (frozen and unfrozen), shear properties, and creep characteristics. From these tests and analyses, theoretical computations of the depths of freezing and thawing can be made (Departments of the Army and Air Force, 1966). Using the computed depths of thaw, the results of thaw consolidation tests can be used to predict settlements. Preliminary estimates of the amount of settlement which will occur during the thawing of permafrost can be based on estimated changes in dry unit weight, and hence the volume of the soil, from its original frozen state. If continuous frozen samples are obtained, the effect of all the included ice (whether in visible lenses or not) can be accounted for in this way.

Ideally, explorations should precede the actual foundation design by one year or more, if possible. Such a lead time is required to process soil samples and accumulate other necessary information as climatological records, design and performance information for other structures in the area or similar areas, ground temperatures, availability and costs of construction material, labor, etc. Thermocouples or other temperature-sensing equipment should be placed in bore holes to record the ground temperatures at 2 to 3-ft vertical intervals to ascertain the maximum ground temperatures prior to construction. Preferably one or more of the assemblies should be in perimeter exploration holes, just outside the construction area, to serve as control assemblies during and after construction.

Ground temperatures over a period of time are particularly important in the design of pile foundations in permafrost because the potential strength of the permafrost is temperature-dependent (Corps of Engineers, 1952; Crory, 1963). Ground temperatures in fall and early winter are the most important. Ground temperature observations, after a suitable period for dissipation of heat introduced by drilling, are recommended to establish the magnitude of annual temperature extremes at various depths. Records of precipitation, cloud cover, snow cover, and daily air temperatures when available are used to establish the influence of these factors on the ground temperatures recorded and the variation of the period from the previous means or averages recorded by the Weather Bureau (Departments of the Army and Air Force, 1966). Ground temperatures or isotherms superimposed on the soil logs give the thermal regime of the ground (Crory, 1960). A thorough appreciation of the thermal regime before, during and after construction is essential. To base the design of a pile foundation only on a measurement of the depth of the summer thaw is insufficient.

INSTALLATION OF PILES

The method of pile installation is the factor of primary concern in permafrost having mean annual temperatures greater than 28F. Each method has its merits, in terms of unit costs and resulting capacities, and with respect to disturbance of the permafrost and the mode of freezeback. Currently employed installation methods are: steam thawing, dry augering, and driving (Crory, 1960; 1963).

Most pile foundations constructed for military facilities in Alaska have been installed in dry augered holes and backfilled with soil-water slurry. Truck-mounted augers have been used efficiently in silts or clays and some sands. The efficiency of augering, unlike steam thawing, is not dependent on the amount of ice segregation or moisture-holding organic matter. Holes less than 24 in. in diameter can be augered at a rate of about 1 ft/min, approximately the same as in steaming. In sands or soils containing cobbles or boulders, augering may be difficult or impossible. In such cases, churn drilling or localized pre-thawing with steam have been used to aid in preparation of the pile hole.

Steaming is seldom used in Alaska today. Normally steam is used only in cold permafrost which can safely absorb the heat introduced. In warm permafrost, freezeback may take months or even several years. Even in cold permafrost, steaming of holes for piles should be done only by experienced operators who know the effects of using such equipment in various soil and ice conditions. Essentially all of the frictional heat developed in dry augering is removed with the auger cuttings, and soil-water slurries placed at temperatures just above freezing introduce far less heat into the permafrost than does the steaming method.

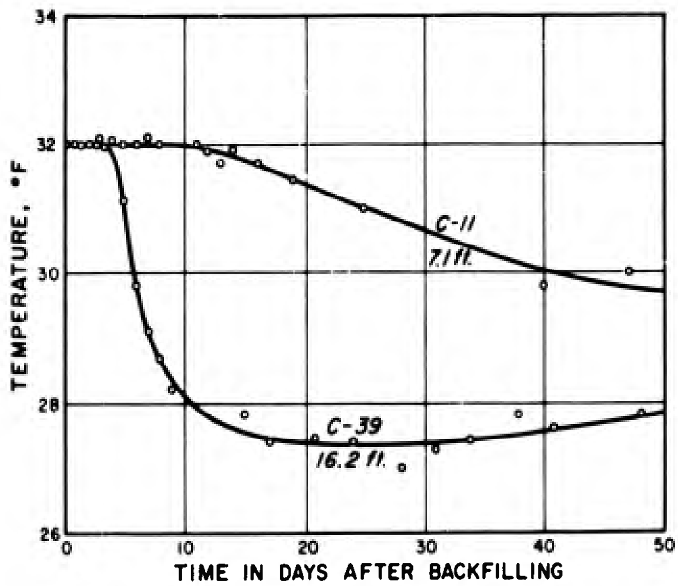
The least disturbance to the thermal regime is realized when the piles are installed by conventional or modified driving methods. Conventional driving has been advantageously employed in both the discontinuous permafrost at Bethel (Crory, in preparation) and in the permafrost at Fairbanks and Kotzebue, Alaska. In addition to the speed of installation, the distinct advantage of driving over the use of steam or slurry is that essentially no latent heat is involved, and freezeback occurs within minutes or a few hours after driving. Less perfect surface bond is attained on driven piles, but this is readily compensated for by additional pile embedment. High-energy double-acting or diesel hammers are recommended.

FREEZEBACK

The observed natural freezeback of over 100 piles of different types has been correlated with theoretical heat transfer equations and has produced a method of calculating the time required for natural freezeback. Detailed discussions of the freezeback of piles in permafrost have been previously reported (Crory, in preparation; Dias and Freedman, 1963) and only the application of the freezeback principles as applied to discontinuous permafrost will be discussed herein.

Typical natural freezeback curves for slurried H and pipe piles in augered holes, as observed by means of thermocouples, are shown in Figure 1. The heat to be absorbed by the permafrost is the heat produced by the installation method. Because the sensible heat of the backfill material is negligible in contrast to the amount of latent heat involved if the slurry placement temperature is held reasonably close to 32F, the amount of heat per foot of pile length which must be removed may be computed by the equations shown in Figure 2. Knowing the thermal properties (diffusivity, conductivity, and heat capacity) of the permafrost permits computation of the time required for freezeback by the use of the general equation shown in Figure 3. This solution to the natural freezeback problem was adapted by Leung (1958) and Lee (1962) from Carslaw and Jaeger (1959).

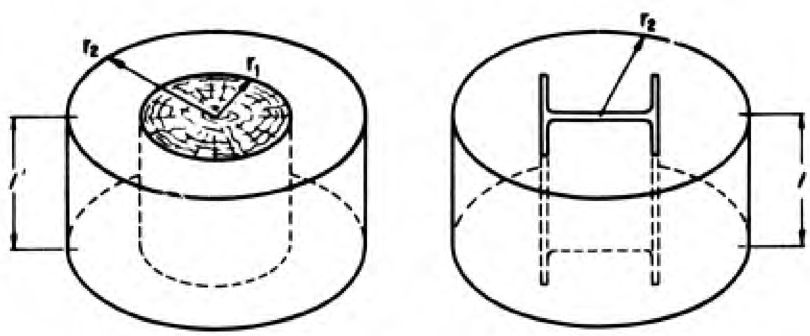
Because permafrost temperatures vary within the normal depth of pile embedment, it is often easier to prepare a specific solution for the freezeback time required, as shown by Figure 4 which illustrates the prolonged freezeback time required for installations with large Q values (relatively warm permafrost). For instance, a 12-in. timber pile in an 18 in. diam hole with a slurry backfill having a water content of 30% would require the removal by the permafrost of approximately 4000 Btu's per foot of pile. In 28F permafrost, this would require approximately 6 days to freeze back, as shown in Figure 4; at 30F it would require 16 days. Further calculations show that in 31F permafrost it would require 41 days; at 31.5F, 97 days; and at 31.8F, 302 days for freezeback to occur.



Pile No.	Size	Hole Dia.	Date Installed
C-11	10 BP 42	18-inch	25 April 1957
C-39	8" pipe	14-inch	17 April 1957

Both piles installed in dry augered holes and backfilled with silt-water slurry.

Figure 1. Typical curves of natural freezeback for silt slurry.



$Q = \pi L (r_2^2 - r_1^2) w \gamma d$ or $Q = L(\pi r_2^2 - A) w \gamma d$

where L = Latent heat of water

r_2 = Radius of hole

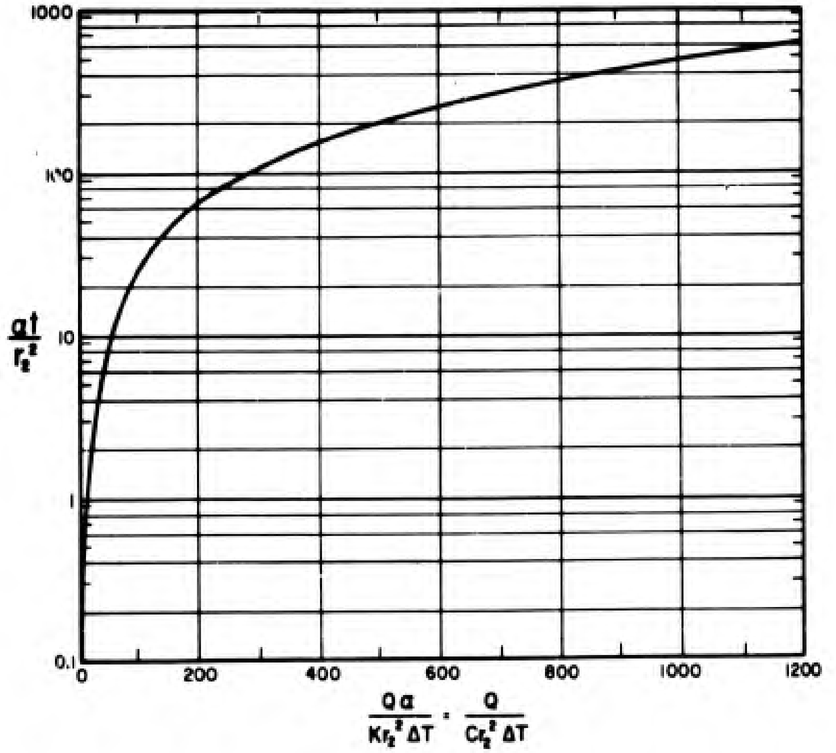
r_1 = Radius of pile

A = Cross sectional area of H-pile

w = Water content, percent dry weight

γd = Dry unit weight of slurry

Figure 2. Volumetric latent heat of slurry backfill.



where t = Freezeback time, hrs.

K = Conductivity of permafrost, BTU/hr ft °F

C = Volumetric heat capacity of permafrost, BTU/ft^3°F

α = Diffusivity of permafrost, ft^2/hr = $\frac{K}{C}$

Q = Volumetric latent heat of slurry per ft of pile length, BTU/ft

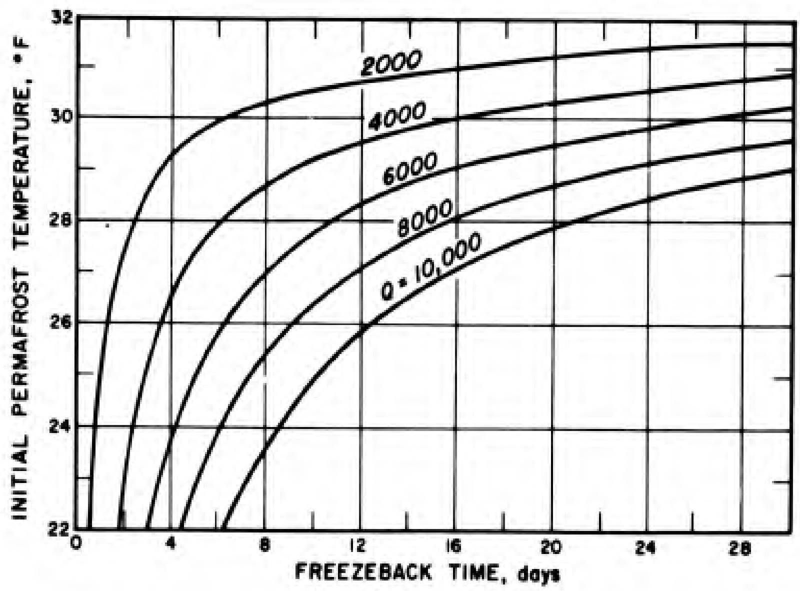
ΔT = Initial temperature of permafrost, expressed as number of °F below freezing ($32° - T_p$)

r_2 = Radius of pile hole, ft.

Figure 3. General solution of slurry freezeback.

Assuming the volume of slurry per foot of pile to be at a minimum, the temperature and water content of the slurry and temperature of the permafrost are the principal parameters that need to be considered to effect a rapid natural freezeback. For example, in some permafrost areas the time of installation should be made to coincide with the minimum ground temperatures experienced in late winter or early spring to utilize the large temperature differential existing between the slurry and the surrounding extremely cold permafrost to effect a rapid freezeback. In areas where a talik or thawed layer exists below the zone of seasonal freezing, there is no optimum installation period. Present practice, irrespective of permafrost temperature, is to mix and place the soil-water slurry at the lowest practicable water content, yet fully saturated, at temperatures between 32 and 45F.

Assuming slurry temperatures are held close enough to 32F so that only latent heat need be considered, the difference in volumetric latent heat of high water



where $C = 30\ BTU/ft^3\ °F$

$K = 1.4\ BTU/ft\ hr\ °F$

$r_2 = 0.75\ ft$

Q = Volumetric latent heat of slurry per ft of pile length, BTU/ft

Figure 4. Specific solution of slurry freezeback.

content silt and low water content sand type slurries is obtained through the use of the equation:

$$Q = Lw\gamma_d$$

where

Q = volumetric latent heat of slurry, Btu/cu ft

L = latent heat, 144 Btu/lb of water

w = water content, expressed as decimal

γ_d = dry unit weight, lb/cu ft

<u>Q(silt)</u> for w = 70%, γ_d = 58 lb/cu ft

Q = 144 (0.70)(58)

Q = 5850 Btu/cu ft

<u>Q(sand)</u> for w = 10%, γ_d = 133 lb/cu ft

Q = 144 (0.10)(133)

Q = 1915 Btu/cu ft.

In 28F permafrost a sand-water slurry would freezeback in 2 to 3 days and a silt-water slurry in 10 to 11 days; however, in 31.5F permafrost, a freezeback time of 16 days is needed for the sand-water slurry and 131 days for the silt-water slurry. Thus a careful selection of the backfill material and proper field control of the water content and temperature can substantially reduce the heat to be absorbed by the permafrost and the time required for freezeback.

The preceding general and specific solutions for the natural freezeback of piles assume the slurried pile to be a finite cylindrical heat source inside a semi-infinite medium, with a suddenly applied constant temperature source (32F) which dissipates heat only in a radial direction. The actual heat path is always toward colder permafrost than exists at the depth considered. The approximate heat paths during summer and winter are shown in Figure 5. The "effective" temperature of the permafrost at any depth can be approximated over the time and distance of the heat path to account for the vertical heat flow if initial ground temperatures

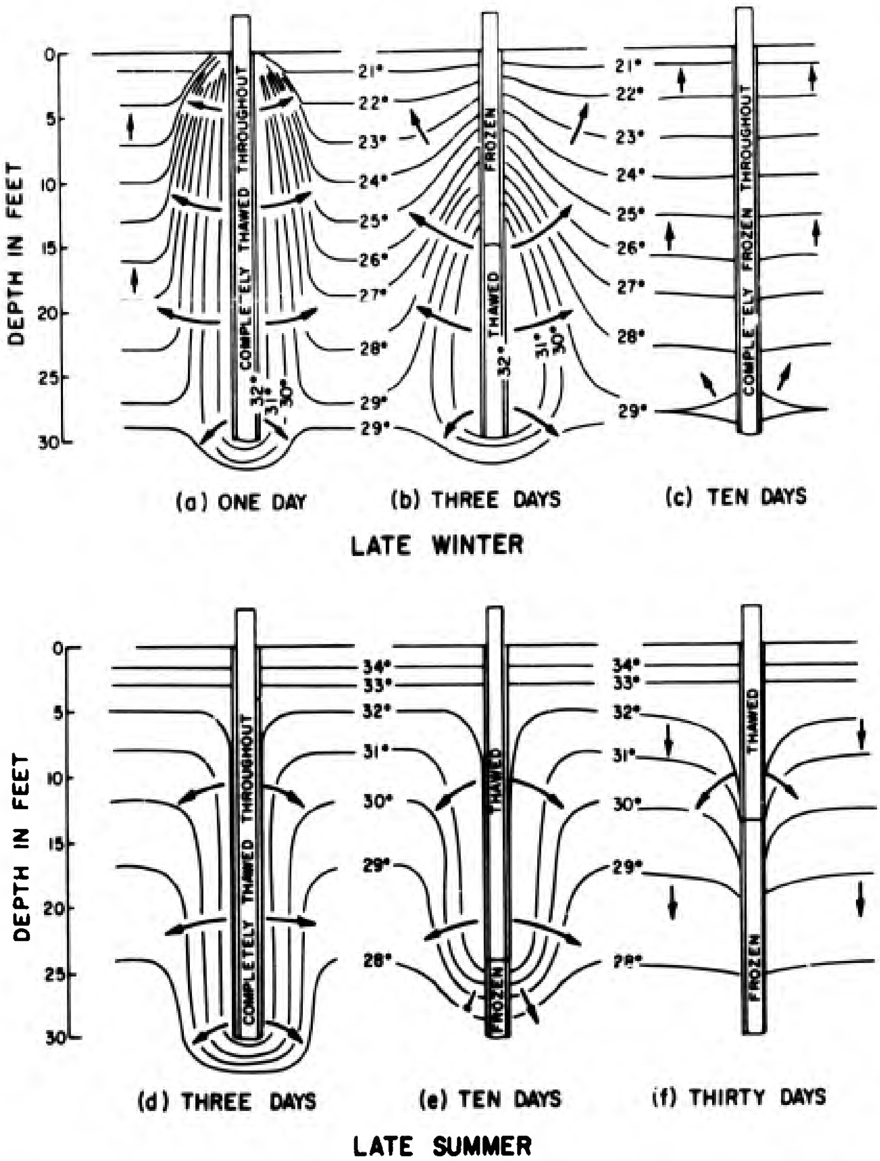
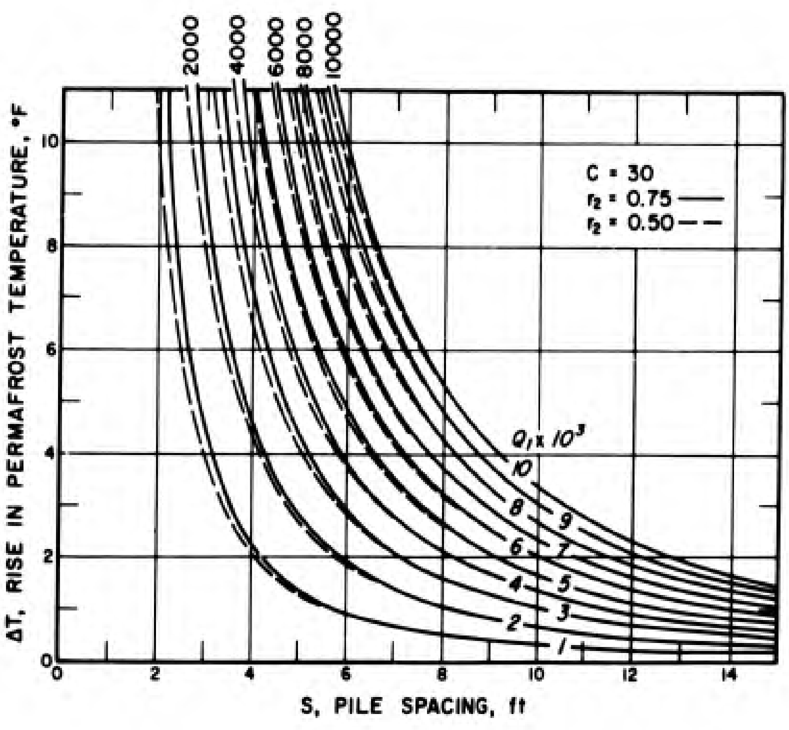


Figure 5. Natural freezeback of piles in permafrost during winter and summer.

are known. While freezeback time may be reduced by vertical heat flow, the greatest increase in freezeback time is caused by the proximity of adjacent piles.

The effect of pile spacing on the overall rise in permafrost temperatures caused by slurry heat is shown in Figure 6. The relationship between spacing and temperature rise is based on the "method of mixtures" as shown by the equations in the figure. When the rise in permafrost temperature (ΔT) indicated by Figure 6 exceeds the difference between the freezing point and the initial permafrost temperature ($32-T_p$) the permafrost will freeze only that amount of the slurry water which will raise the permafrost temperature to the freezing point. The remaining slurry will not freeze until the surrounding permafrost becomes colder. In the case of the silt- and sand-water slurries previously described, it is noted from Figure 6 that a pile spacing greater than 12 ft would be required for the 2000 Btu per lineal foot of the sand-water slurry at a permafrost temperature of 31.0F. The silt-water slurry (6000 Btu) would theoretically raise the permafrost temperature 1F even at a 15-ft spacing. If the initial permafrost temperature were 31.5F this would mean a final temperature of 0.5F above freezing. This, of course, is impossible. In reality, only about 3000 of the 6000 Btu per foot would be removed



$Q_1 = Q_2$ (Heat loss = Heat gain)

$Q_2 = C(S^2 - \pi r_2^2)\Delta T$

where Q_1 = Volumetric latent heat of slurry, BTU/ft.

C = Volumetric heat capacity of permafrost, BTU/ft^3 °F

S = Pile spacing, ft.

r_2 = Radius of pile hole, ft.

ΔT = Rise in temperature of permafrost, °F.

Figure 6. Influence of slurry on surrounding permafrost.

and the slurry immediately adjacent to the pile would remain thawed. The permafrost temperature would rise to just 32F.

When freezeback of slurried or steamed piles cannot be effected within an established construction schedule because the heat capacity of the permafrost is insufficient, or because of close pile spacing, the piles may be installed by driving, or artificial refrigeration may be employed to achieve freezeback. Pipes or tubing can be attached to the piles prior to installation and connected to a portable refrigeration system (Fig. 7, 8). Normally, positive artificial freezeback can be achieved in less than 2 days by careful control of the slurry temperature and water content, and a specific time limitation between pile placement and the start of refrigeration. The cost of such refrigeration is often offset by the savings resulting from continuous construction. The refrigeration pipes, purposely designed to remain in place, are available for use throughout the life of the structure in the event further refrigeration is required.

No factor of safety is incorporated in the freezeback equations discussed. Thermocouple assemblies, or other temperature-indicating devices, should be installed to verify the theoretical freezeback before the piles are actually loaded.

Figure 7. Refrigeration coils on timber piles for artificial freezeback.

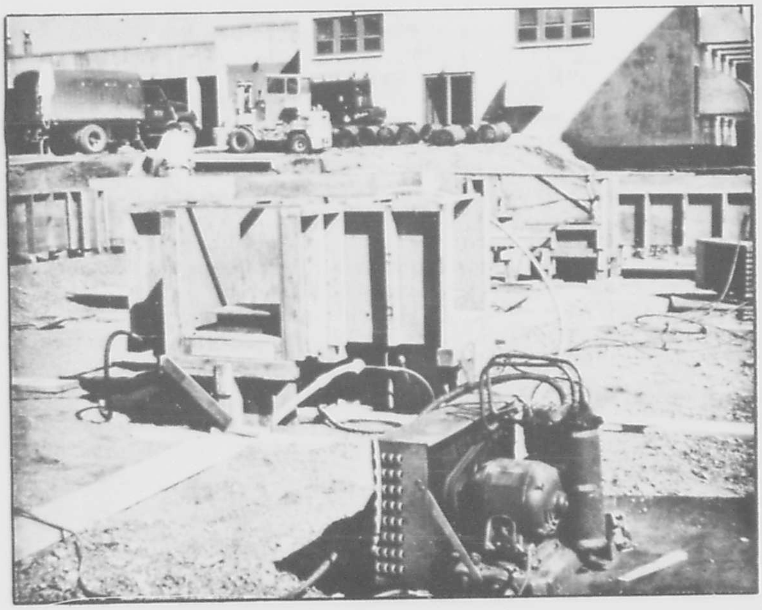


Figure 8. Compressor for artificial freezeback of piles.

BEARING CAPACITY

The bearing capacity of piles in permafrost is achieved by providing sufficient pile surface area in permafrost. In permafrost which is only slightly below the freezing point, however, the strength of the adfreeze bond is low (Crory, 1963). If a firm bearing stratum or bedrock is within economical depth, the bearing capacity can be augmented by, or solely derived from, point bearing, as in the temperate zone. The contribution of point bearing in unconsolidated soils containing ice is normally disregarded when the load is being carried by adfreeze in the permafrost.

Additional loading from negative skin friction should be considered if the soils above the permafrost are unconsolidated, or additional thawing of the permafrost will produce settlement in the soil surrounding the upper regions of the pile. Negative skin friction can be especially significant if unconsolidated soils are surcharged by gravel fills.

SUMMARY

This report has outlined only a few of the problems associated with foundations in areas of warm, discontinuous permafrost. Although a considerable amount of information has been published in ACFEL and USA CRREL reports, through the First Canadian Permafrost Conference, the First International Conference on Permafrost, and in Department of the Army foundation design manuals, many aspects are still unknown or unpublished. In addition to further research, field reports of construction and performance are needed.

The efficient design and construction of foundations on permafrost require a thorough understanding of the conditions before, during, and after construction. Instrumentation of the foundation with temperature sensing devices and vertical control points not only is good practice for obtaining design information and for monitoring effects during construction, but is also frequently essential to detect long-term changes in the thermal regime and verify the stability of the foundation.

Careful consideration of the heat introduced by the pile installation method, and of the potential heat capacity of the permafrost to absorb this heat at different ground temperatures and pile spacings, is essential in design. Theoretical freeze-back time for piles in permafrost can be advantageously employed for construction scheduling. When the heat capacity of the permafrost is insufficient for freeze-back within an established construction schedule, artificial refrigeration may be required. Artificial refrigeration may be used intermittently or continuously to establish or retain a desired thermal regime, with an adequate adfreeze or bearing strength. At the low strength of permafrost in discontinuous permafrost areas, where permafrost temperatures are only slightly below freezing, design, construction, and maintenance require a thorough understanding of the factors influencing foundation stability.

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13. ABSTRACT

The design and installation of piles in areas of warm permafrost present many unusual problems. Design considerations and construction methods and controls to minimize disturbance of the delicate thermal balance of warm permafrost are included in an evaluation of pile installation techniques. The importance of adequate site investigations and proper construction inspection and control is emphasized. Preconstruction temperature information is used with climatological records and theoretical methods to predict the freezing and/or thawing that will be experienced under the structure. Natural and artificial freezeback of piles are discussed in terms of construction schedules, installation methods, and the volumetric heat capacity of the permafrost.

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13. ABSTRACT

The design and installation of piles in areas of warm permafrost present many unusual problems. Design considerations and construction methods and controls to minimize disturbance of the delicate thermal balance of warm permafrost are included in an evaluation of pile installation techniques. The importance of adequate site investigations and proper construction inspection and control is emphasized. Preconstruction temperature information is used with climatological records and theoretical methods to predict the freezing and/or thawing that will be experienced under the structure. Natural and artificial freezeback of piles are discussed in terms of construction schedules, installation methods, and the volumetric heat capacity of the permafrost.

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