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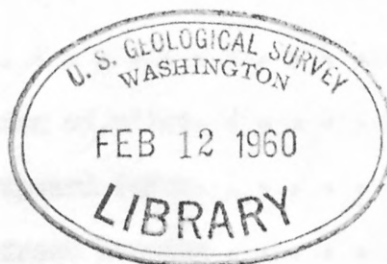
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83

FROST HEAVING OF PILES

WITH AN EXAMPLE FROM FAIRBANKS, ALASKA

by  
Troy L. Pewe<sup>8 8 1918</sup> and Russell A. Paige, 1929-



This report is preliminary and has not been edited or reviewed for conformity with U. S. Geological Survey standards and nomenclature.

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## FROST HEAVING OF PILES

with an example from Fairbanks, Alaska

by

Troy L. Péwé and Russell A. Paige

### Abstract

Seasonal freezing of the ground is common throughout most of the world's land surface. As the ground freezes the surface of the ground may rise--this rising is termed frost heaving. Upward displacement of the ground upon freezing is not due alone to the freezing of water originally contained in the soil voids, but is due mostly to the formation of clear-ice segregations in the sediments. Ice segregations form as water is drawn to points of freezing from adjacent unfrozen ground; the basic physical phenomenon which permits the growth of such segregations is that some water in the ground remains liquid although subjected to temperatures below  $0^{\circ}\text{C}$ , and can therefore move to the growing ice segregations.

As the freezing isotherm descends through the ground, water is changed from liquid to solid. The amount of ice finally concentrated in the frozen ground, the size, shape, and position of the ice segregations, and therefore, the amount and location of frost heaving, depends upon many physical factors. The three most important factors are the temperature of the air and texture and moisture content of the ground. The most favorable conditions for growth of ice segregations and for frost heaving are slow freezing of moist, non-homogeneous, organic silt or silty clay.

When ground is forced upward during seasonal freezing engineering structures are also forced upward if the forces acting upward are greater than the forces pushing downward. With piles the amount of the upward force is dependant upon: (1) the amount of clear-ice segregations formed in the seasonally frozen ground, (2) the tangential adfreezing strength, or bond, between the surface of the pile and the seasonally frozen ground, and (3) the surface area of the pile in the seasonally frozen ground. The main factor opposing the upward force is the grip of the ground on that part of the pile which lies below the seasonal frost. This grip may be either the "skin friction" of unfrozen ground or the tangential adfreezing strength between perennially frozen ground (permafrost) and the pile surface. The grip of permafrost can successfully counteract the effect of frost heaving on piling if the full tangential adfreezing strength of permafrost is attained over a large enough surface area of the pile. The tangential adfreezing strength of frozen ground varies with texture of the sediment, moisture content, temperature of the ground, and nature of the pile surface. It is strongest in ice-saturated fine sand and silt. The colder the ground the greater the adfreezing strength.

Piling of many of the wood-pile bridges of the Alaska Railroad in Goldstream Valley near Fairbanks, Alaska, are frost heaved every year. Many bridges in this poorly-drained, silt-filled valley are thrown out of line and the elevation of the track is seriously disturbed. Sharp humps that form in short bridges usually necessitate reduction of speed of the trains to avoid uncoupling of the cars or shifting of cargo. Piling of the bridges is frost heaved as much as 14 inches per year.

The engineering geology problems of frost heaving of bridge piling are of economic importance because of the maintenance necessary to: (1) maintain track elevation in winter by temporary methods, (2) correct the elevation in summer by more permanent methods, and (3) replace bridge piles periodically.

Three wood-pile bridges of the Alaska Railroad at mile posts 456.7, 458.4, and 460.4, respectively, were systematically observed for the effect of frost heaving of piling. Data were collected on moisture content and the position, thickness, and temperature of seasonal frost and permafrost at these localities. Studies of these bridges serve well to illustrate principles of the mechanics of frost heaving of piling as well as to show the position and properties of permafrost that are concerned with such principles.

Some of the piles in the first two bridges are not inserted deep enough into the permafrost to prevent the pile from pushing upward and deforming the bridge. Piling in bridge 460.4 is not subject to frost heaving because of (1) absence of frost heaving of piles in the stream bed, and (2) the low moisture content of the ground around the other piles.

## Introduction

### General statement

Seasonal freezing of the ground is a common feature throughout most of the land surface of the world. In large parts of the world this ground freezing is a problem in many fields of human endeavor, mainly in maintenance of engineering structures. As the ground freezes ice grows in sediments causing the surface to rise. This disturbance of the ground surface is termed frost heaving, and in poorly-drained areas of fine-grained sediment long cold winters provide excellent conditions for serious damage to structures built on or in the ground.

The freezing of moisture in the ground became economically important with the widespread development of highways in the 1920's (Illinois Div. Highways, 1922a, b; Older, 1922; Aaron, 1934; Beskov, 1947). With growth of highways and railroads, and with development of airfields for modern aircraft, seasonal freezing of the ground became a major factor to consider in construction and maintenance of such features. As construction activities, both military and civilian, increased in the far North, the economic importance of frost action to construction also increased. (Taber, 1943a; Corps of Engineers, 1946a, b, 1947, 1949, 1954a, b; Beskov, 1947; Skaven-Haug, 1952; Highway Research Board, 1948, 1952).

Frost action affects engineering structures in two ways: (1) by distorting the structure during frost heaving, and (2) by damage to the structure upon loss of bearing strength of the ground when the seasonal frost thaws. Differential movement is the paramount problem; such action produces extensive damage to many engineering structures whether they are built on top of the ground or on a foundation driven or sunken into the ground. If frost heaving and subsequent settling is uniform, generally little damage is done. Considerable information has been collected on the effect of frost action on engineering and a voluminous literature exists (SIPRE, 1951, 1952, 1953a, b, 1954a, b, 1955a, b, and 1956a, b, c).

In regions of cold winters many pile foundations are in ground which is subject to seasonal freezing and, therefore, may be subject to the damaging effect of frost heaving. Frost heaving tends to displace a pile upward, and thus to disturb the foundation of the structure. This displacement of piling is not limited to the far north; however, maximum disturbance probably is encountered most widely in the subarctic.

Expensive maintenance and in some instances complete destruction of bridges, school buildings, military installations, and other structures have resulted from failure to understand the principles of frost heaving of piling. The effect of heaving of piling can perhaps best be understood by visualizing the forces tending to push the pile upward and the forces tending to resist this upward push. In all instances the upward force is the result of frost heaving of ground which is adfrozen to the pile and the resistance to this force is the skin friction of the ground. However, in the subarctic and arctic powerful additional resistance to the upward shove is provided by the tangential adfreezing strength between the pile and the perennially frozen ground. An understanding of the distribution and properties of permafrost, perennially frozen ground, is important in using it to anchor piling against the effect of frost heaving.

The effects of frost heaving of piling in the subarctic are well illustrated in central Alaska, especially in the Fairbanks area (fig. 1). A study of frost heaving of wood piling of small

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Figure 1. Index map showing location of the Fairbanks area and generalized distribution of permafrost in Alaska.

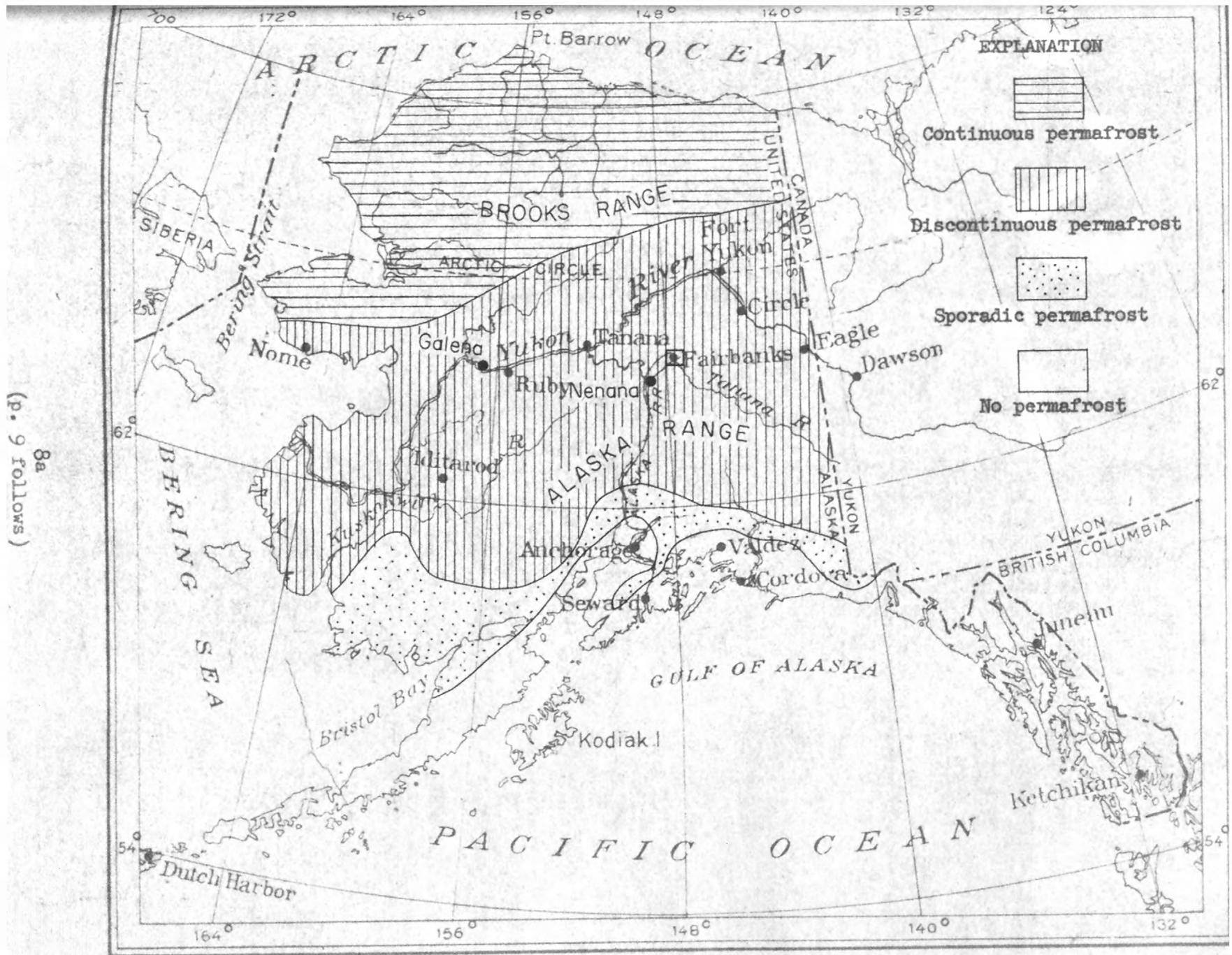
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bridges of The Alaska Railroad in Goldstream valley near Fairbanks permits an evaluation of some of the principles discussed. Many of the piles of these bridges are not sufficiently anchored in permafrost to resist the upward force.

#### Definitions

Several terms dealing with seasonal frost, permafrost, and piling may be unfamiliar to some readers, and other terms have not been clearly defined in previous papers. The writers' usage of these terms is given below.

- "Active layer"           - the layer of ground above permafrost which thaws in summer and freezes again in winter. The active layer may extend down to the permafrost table (Muller, 1945, p. 213).
- "Adfreezing strength"   - the force that is required to pull the frozen ground from the object to which it is frozen.
- "Aufeis"  
  (icing)               - a mass of surface ice formed during the winter by successive freezing of sheets of water that may seep from the ground, from a river, or from a spring (Muller, 1945, p. 218).
-



**"Degree-day"**

- each degree in any one day that the average daily air temperature varies from  $32^{\circ}\text{F}$ .

The difference between the average daily temperature and  $32^{\circ}\text{F}$  equals the degree-days for that day. The degree-days are minus when the average daily temperature is below  $32^{\circ}\text{F}$  and plus when above (Linell, 1953, p. 19).

**"Freezing index"**

- the number of degree-days between the highest and lowest points on the cumulative degree-days-time curve for one freezing season. It is used as a measure of the combined duration and magnitude of below-freezing temperatures occurring during any given freezing season. The index determined for air temperatures at 4.5 feet above the ground is commonly designated as the air freezing index, while that determined for temperatures immediately below the surface is known as the surface freezing index (Linell, 1953, p. 19).

- "Frost action"** - a general term for freezing and thawing of moisture in materials and the resultant effects on these materials and on structures of which they are a part or with which they are in contact (Hennion, 1955, p. 107).
- "Frost heaving"** - a general upward displacement of ground materials due to the freezing of water in the ground.
- "Ground-ice"** - grains or bodies of more or less clear ice in permafrost. Not applied to ice of glacial origin (Muller, 1945, p. 217).
- "Mean freezing index"** - the freezing index determined on the basis of mean temperatures. The period of record over which temperatures are averaged is usually a minimum of 10 years and preferably 30 (Corps of Engineers, 1954b, p. 1).
- "Muck"** - silt rich in organic material. Gray to black when wet or frozen and fetid upon thawing. Usually contains more ice than either perennially frozen loess or flood plain silt.
- "Permafrost table"** - an irregular surface which represents the upper surface of permafrost.
- "Permafrost"** - a thickness of soil or other surficial deposit or even of bedrock at a variable depth beneath the surface of the earth in which a temperature below freezing has existed continuously for many years (Muller, 1945, p. 219).

- "Pile"** - a long, slender timber, concrete, or steel structural element, driven, jettied, or otherwise embedded on end into the ground for the purpose of supporting a load, or of compacting the soil (Am. Soc. Civil Eng., 1946, p. 54).
- "Piling"** - pile work, a structure of piles.
- "Point bearing"** - the amount of weight supported by the area in contact with the bottom, or point, of the pile.
- "Polygonal ground"** - ground with a polygonal surface pattern caused by the subsidence of the surface over ground-ice arranged in a polygonal network.
- "Skin friction"** - the friction between a pile and the material into which it is driven (Chellis, 1951, p. 13).
- "Tangential ad-freezing strength"** - the resistance to the force that is required to shear off an object which is frozen to the ground and to overcome the friction along the plane of its contact with the ground (Muller, 1945, p. 223).

# Acknowledgments

The writers wish to extend special acknowledgment to Irvin P. Cook, chief engineer of The Alaska Railroad, who aided in the initiation of this project and generously provided records of The Alaska Railroad bridge construction near Fairbanks. Mr. Cook also arranged for personnel of The Alaska Railroad to assist the writers in the field. J. L. Alter, division roadmaster of The Alaska Railroad, was very cooperative and provided transportation to and assistance in the field. Ray Rupp aided in determining the permafrost table. Thanks are expressed to these and others of The Alaska Railroad for their cooperation.

James D. Crawford, a vice-president of the U. S. Smelting, Refining, and Mining Company generously made available the records of subsurface materials and conditions near the bridges and also reviewed the manuscript.

I. P. Cook and J. L. Alter of The Alaska Railroad, F. F. Kitz, Chief, U. S. Army Permafrost Research Area, Alaska, K. A. Linell, Chief of the Arctic Construction and Frost Effects Laboratory, Corps of Engineers, U. S. Army, and E. F. Rice, Dept. of Engineering and D. H. Rylnick, Engineer, University of Alaska, reviewed the manuscript and offered helpful suggestions. Mr. Linell's review was limited to the sections dealing specifically with frost heaving or piling.

Mechanical analyses of the silt samples were made by the Rock Island Office, Corps of Engineers, U. S. Army (No. 147), Fairbanks Permafrost Station of the Frost Effects Laboratory, U. S. Army (No. 351), Alaska District, Corps of Engineers, U. S. Army (No. 429), and J. R. Watson, U. S. Bureau of Public Roads (No. 268). The thermal data presented in figure 11 were collected by Max G. Brewer and R. N. Rivard of the U. S. Geological Survey. Mary Jean Pewé compiled figure 12.

The writers wish to thank Simon M. Soboleff, U. S. Bureau of Public Roads, and Henry Bender, U. S. Geological Survey, for their generous aid in translating some of the foreign publications used in this study.

#### Growth of clear-ice segregations in the ground

Inasmuch as frost heaving is due mostly to the formation of clear-ice segregations in the ground, for a mature understanding of frost heaving it is necessary to understand the origin of the ice segregations and the physical factors effecting their growth.

General theory of growth of clear-ice segregations  
in the ground

The present concept of frost heaving perhaps owes its origin to Taber's work (1916, 1917, 1918a, b, 1929, 1930a, b), although extensive work along the same line was done by Beskow (1947) about the same time. Much of their work is based on principles of existence, movement, and freezing of soil moisture discussed by Bouyoucos (1913, 1917, 1921, 1923; Bouyoucos and McCool 1928) and others, and the states of water as determined by Bridgman (1912). Additional basic data have been added by Kersten (1949), and freezing of soil moisture has been discussed in more detail by Winterkorn (1943), Grim (1952), Jumikis (1954, 1955, 1956), Jackson and Chalmers (1956a, b, 1958), Penner (1957), and Higashi (1958).

Ground expands upon freezing owing to the growth of ice crystals, with the resultant formation of segregations of clear-ice in the ground. The maximum force that can be developed during growth of ice crystals in a confined space is 29,100 lbs/in<sup>2</sup> (Bridgman, 1912, pl. 1). During the process of freezing of soil moisture, additional water is drawn to the points of freezing from adjacent unfrozen ground (Taber 1929, 1930a, b; Beskow, 1947). Field and laboratory investigations prove that the expansion in volume of a soil mass upon freezing cannot be due alone to the expansion of the water originally contained in the soil voids, because expansion of a soil mass would then be less than 4 or 5 percent. However, as much as 60 percent expansion in volume of the ground due to seasonal freezing has been recorded by Linell and Haley (1952, p. 299) and 140 percent by Voyslav (Liverovsky and Morozov, 1952, p. 28). The basic physical phenomenon permitting such expansion in volume of ground upon freezing is that some water in the ground remains liquid although subjected to temperatures below 0°C. As early as 1859 Sorby discovered that water in small capillary tubes will not freeze until subjected to temperatures several degrees below 0°C. In 1902 Lubimoff theorized that water was brought to the freezing ground from the wet unfrozen ground below, but Johansson in 1914 was the first to show that, during freezing of fine-grained soil, water flows to the freezing area, thus increasing the water content. Bouyoucos (1921, p. 37) also contributed much to the understanding of soil moisture below freezing temperatures. Although both Taber and Beskow realized that some soil moisture does not freeze at 0°C, and that water is drawn to the growing ice crystals, neither, according to Winterkorn (1943, p. 112), explained this mechanism thoroughly. Winterkorn shows that the physical condition of soil moisture in connection with ground freezing is conveniently explained by considering the following: (1) the phase diagram of water (Bridgman, 1912, pl. 1), and (2) the compressive forces involved in adsorption.

Bridgman demonstrated (1912) that several different allotropic forms of ice occur, each existing at different temperatures and pressures. He labeled these forms Ice I to VI. Ice I is the ordinary ice, and Ice VI exists under great pressures at temperatures both below and above  $0^{\circ}\text{C}$ . He showed that liquid water can exist, if pressures are sufficient, down to a temperature of  $-22^{\circ}\text{C}$ .

Winterkorn (1943) takes this information and using the concept that internal pressures may be assumed to produce the same type of results as external pressures, shows that soil water at the pore wall (surface of the mineral particle) is so strongly held by adsorptive pressure that it is as solid as Ice V or VI at room temperature. In some clays the soil moisture is held so tightly that moisture exists as Ice VI and the ground contracts instead of expanding when subjected to temperatures below  $0^{\circ}\text{C}$ .

In a soil capillary the water is held as Ice V or VI next to the mineral surface but in the center of the pore, farthest from the pore wall, water freezes at about  $0^{\circ}\text{C}$  and exists as Ice I. Between the pore wall and the center of the pore there exists a gradation from: (1) water as Ice V or VI (solid above  $0^{\circ}\text{C}$ ) on pore wall, (2) through water with melting points down to  $-22^{\circ}\text{C}$  to water with a higher melting point up to about  $0^{\circ}\text{C}$ , and (3) to ordinary ice, Ice I, in the center of the pore (fig. 2). It is

---

Figure 2. Diagrammatic sketch, not to scale, of condition of stable soil moisture in frozen fine silt above  $-22^{\circ}\text{C}$ . Liquid water as well as different allotropic forms of ice are shown

---

apparent, therefore, that there exists between the two types of ice a zone of liquid water possessing melting points down to  $-22^{\circ}\text{C}$  which serves as a passageway for the conduction of water to the growing ice crystal (Winterkorn, 1943, p. 113).

It would appear from the above that the solid and liquid phases of water in the soil are in equilibrium. The conversion of water to ice, or ice to water, depends upon temperature, pressure, and moisture relationships. A rise in temperature of frozen fine-grained soil from, say,  $-10^{\circ}\text{C}$  to  $-8^{\circ}\text{C}$  will cause some Ice I to melt.

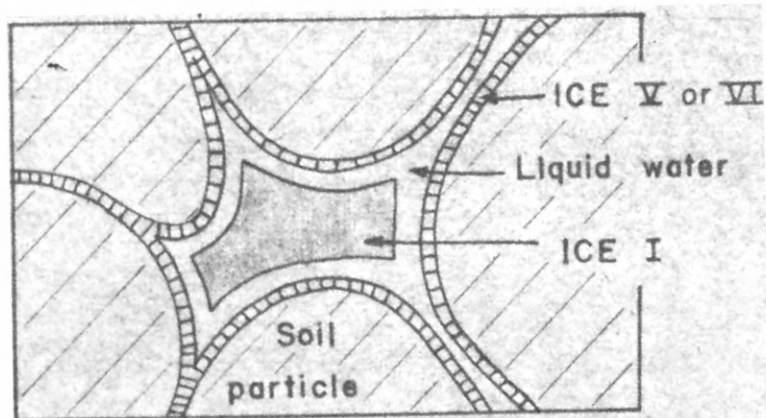


Fig. 2.--Diagrammatic sketch, not to scale,  
of condition of stable soil moisture  
in frozen fine silt above  $-22^{\circ}\text{C}$ .  
Liquid water as well as different  
allotropic forms of ice are shown.

Although Winterkorn explained the nature of the adsorbed layer and a reason for freezing point depression of water in soil, Jackson and Chalmers (1956a, 1956b, 1958), attacking the problem from the standpoint of a metallurgist, were perhaps the first to outline a theory which, in addition to explaining the freezing point depression of water, explained a source of energy for bringing in the water and causing frost heaving.

Jackson and Chalmers state the freezing point depression, or supercooling of soil moisture to a point where freezing begins, depends upon surface energy. Surface energy of a molecule is the difference between the energy of a molecule surrounded by other solid particles. The surface energy of a cluster of molecules, for example, depends on the radius of the cluster; the smaller the radius, the more surface per unit volume and the larger the surface energy of the cluster. The smaller the radius of the cluster, the smaller the soil pore. Small pores remain open to movement of liquid water until energy is removed to cause freezing. The energy to be removed is the normal energy release upon freezing--the latent heat of fusion energy--and the surface energy. Therefore soil moisture in small pores is supercooled before crystallization occurs but moisture in large soil pores undergoes little or no supercooling before ice nucleates. The amount of supercooling to a point of nucleation depends upon size of the pore.

Jackson and Chalmers state that the energy for the process of ice growth in soils depends upon the freezing of supercooled water<sup>1/</sup>.

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<sup>1/</sup>The writers are indebted to A. H. Lachenbruch, U. S. Geological Survey, for a clear explanation of work done by freezing of a supercooled liquid.

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When supercooled water freezes, undergoing the irreversible phase transformation from supercooled liquid to supercooled solid, some energy becomes available, energy that the thermodynamicist would call, "free energy". A certain amount of work can be gotten out of the ice water system by freezing supercooled water. The amount of free energy available depends on the amount of supercooling at the ice water interface, which in turn depends on the size of the pore. The greater supercooling, the more energy made available by freezing of the supercooled liquid. The work done by this phase transformation in moist soil is the pulling in of water to the ice surface and frost heaving. Jackson and Chalmers state (1956, p. 21) that at 1 degree (C) of supercooling, a 1-inch cube of water has enough free energy to lift 178 pounds up 1 inch.

## Physical factors affecting growth of ice segregations in the ground

As the freezing  $0^{\circ}\text{C}$  . isotherm is lowered through the ground, water is changed from liquid to solid. The amount of ice finally concentrated in the ground and the size, shape, and position of the ice segregations depends upon many physical factors.

Physical factors affecting the amount and location of ice segregations in the ground can be grouped into two broad classes: (1) extrinsic, and (2) intrinsic (Johnson and Lovell, 1953). The extrinsic factors are those which are imposed by the climate and surface cover and the intrinsic factors are those inherent to the ground. The most influential extrinsic factor is air temperature (Legget and Crawford, 1952, p. 933). In fact, this probably is the factor most affecting frost heaving.

Some of the intrinsic factors which influence growth of ice segregations in the ground are specific heat, heat capacity, thermal conductivity, thermal diffusivity, latent heat of water, capillarity, permeability, moisture content, availability of water, texture, discontinuities, temperature, grain shape, grain size distribution, mineral content, and organic content. All of these factors exert influence, but some factors are extremely important while the effect of others is negligible. The two most important factors are texture and moisture content of the ground.

## Texture of the ground

Texture of the ground means the size of the soil particles

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In this report the following classification is used:

clay, 0.005-0.0002 mm; silt, 0.05-0.005 mm; very fine sand,  
0.10-0.05 mm.

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and their distribution. It is the size of the particle or grain and the size distribution of the grains that control the pore size. In small pores or voids, such as those in silt or clay, some water remains liquid at temperatures considerably below  $0^{\circ}\text{C}$ . In sand and in gravel the voids are so large that most of the water freezes near or at  $0^{\circ}\text{C}$  and no channels are left open to supply a growing ice segregation. The grain size also is very important because it determines the surface area. The smaller the grains the larger the surface area and the greater the adsorptive power. The smaller the pore the greater the supercooling according to Jackson and Chalmers (1956b). The greater the supercooling the more free energy available when the supercooled liquid water is transformed to ice. The free energy is the energy available to draw water to the water-ice interface and to cause frost heaving. Lean clay and silt contain pore sizes ideal for passage of liquid water while freezing; fat or heavy clay (especially montmorillonite) may have all or most of the water so tightly held in the adsorptive layer that no free water can be added (Winterkorn, 1943; Grim, 1952, p. 169).

The grain size is also instrumental in controlling the capillarity of a soil because capillarity is inversely proportional to the radius of the pores. In general, the smaller the grain size the greater the capillarity; however, when the clay size is reached, the surface area becomes great and the adsorptive pressure becomes large and reduces the capillarity. Beskow (1947, p. 89) has shown that in laboratory tests and natural soils, the grain size for maximum rate of capillarity is silt (0.02-0.06 mm).

Theoretically the distance through which water can be pulled by capillarity has been calculated by Keen (in Baver, 1948, p. 264) to be  $31\frac{1}{2}$  feet in silt, 150 feet in fine silt (0.01-0.002 mm) and more than 150 feet in clays. Beskow (1947, p. 86) states that capillarity of fine silt (0.02-0.006 mm) in natural soils is about 20 to 39 feet and in pure silt of uniform grain size is approximately 10 to 33 feet.

Perhaps the most important factor in initiating and determining the location of an ice segregation is the presence of a discontinuity (no matter how minute) such as a crack, flaw, foreign body, rodent hole, or stratification or disconformity between sediment types (Beskow, 1947, p. 21). These are all important in fine-grained soils because in such soil the water in the small pores has a lowered freezing point because of strong adsorption by the grain surface; however, the ... "discontinuity represents a surface of weaker force of attraction on the water, that is, a higher freezing point... than water in the pores of the fine-grained sediment itself" (Beskow, 1947, p. 21). Ice crystallization begins, therefore, at discontinuities.

In summary, silt or silty clay soil in its natural state appears to be the most favorable medium for growth of ice segregations upon freezing. This concept is borne out by extensive field and laboratory investigations (Taber, 1930a, b; Beskow, 1947; and Corps of Engineers, 1946a, b). Concentration of ice is less in silty sand and silty gravel. The commonly used rule of thumb among engineers is that if the soil contains less than 3 percent silt or clay (0.02 mm or smaller) it will not frost heave to a damaging extent (Haley, 1953, p. 2). Dcker (1958, p. 11) shows, however, that the percentage of grain sizes below 0.02 mm does not entirely determine the frost behavior of a soil, but the mineralogical and chemical composition of the fines are also important.

## Moisture content of the ground

Another important intrinsic factor, perhaps the most important, is the amount, position, and distribution of moisture. In addition to being necessary for the formation of ice in the ground, water seriously modifies the thermal properties of the ground (Crawford, 1952). Also, the latent heat of water is a prime factor controlling the rate at which the  $0^{\circ}\text{C}$  isotherm penetrates the ground.

The amount of ice which forms in the ground upon freezing is dependent upon the moisture originally in the ground and the amount of water that can be drawn to the freezing centers from the unfrozen ground. Therefore, the greater the saturation of the ground before freezing, the greater the amount of ice growth and frost heaving, assuming a soil that is susceptible to frost heaving. Ice concentration will be favored if water-saturated soils underlie the freezing ground or if the local water table is close to the surface. These conditions permit available water to be drawn to the freezing ground and the end result is that more moisture is concentrated in the frozen ground than existed in the soil prior to freezing. Poorly drained areas underlain with fine-grained sediment are, therefore, ideally suited for frost heaving.

Ice growth in the ground is favored by a long duration of below freezing temperature because this permits more water to be drawn in to form ice. High moisture content of ground favors slow freezing because, (1) more latent heat must be removed, and (2) very wet soils have a lower thermal diffusivity and therefore are slower freezing (Kersten, 1949, p. 75). Crawford (1952, p. 25) states that water-holding capacity increases in a soil with increased humus. This property may be due to the greater surface area of the colloids. The sediment that has perhaps the greatest water-holding capacity is organic silt or clay.

#### Summary of physical factors

The most important physical factors determining the size, shape, and location of ice segregations in the ground are the air temperature, moisture content of the soil, and size of the mineral grains (texture of the soil). Probably the most favorable conditions for growth of ice segregations, and resultant frost heaving are slow freezing of moist, nonhomogeneous, organic silt or silty clay.

## Frost heaving of piling

### Preliminary statement

A pile foundation transmits the load of a structure through surficial material of inadequate bearing capacity to material or strata of adequate bearing capacity. The load is transferred to an underlying bearing stratum either by skin friction along the embedded length of the pile and by point bearing at the end of the pile. Piles may be classified as "friction" or "point bearing" depending upon how most of the load is supported (Chellis, 1951, p. 11-15). Piles can consist of a variety of material, but the most common materials are wood, steel pipe or beams, and pre-cast concrete.

In regions of cold climate many pile foundations are in ground part of which is subject to seasonal freezing and, therefore, may be subject to the damaging effect of frost heaving. Frost heaving has displaced wood piling upward as much as 14 inches in a single winter season on an Alaska Railroad bridge near Fairbanks, Alaska. Liverovsky and Morozov (1952, p. 48) record about 24 inches of frost heaving in a single year in Russia, and Hemstock (1953, p. 52) records 8 inches at Norman Wells, N. W. T., Canada. Because of skin friction and because unfrozen ground squeezes into the void left as the pile rises, except, perhaps, if the base of the pile is in permafrost, the pile does not return to its original position in summer. According to Liverovsky and Morozov (p. 48) the maximum recorded cumulative heaving of a pile in a Russian bridge is about 6½ feet. Piling of a bridge 8 miles southeast of Big Delta, Alaska, has been frost heaved 11 feet (fig. 3).

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Figure 3. Frost heaved piling of bridge spanning outlet of Clearwater Lake, 8 miles southeast of Big Delta, Alaska. Photograph by Mark F. Meier, August 15, 1951.

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Figure 3. Frost heaved piling of bridge spanning outlet of  
Clearwater Lake, 8 miles southeast of Big Delta, Alaska.  
Photograph by Mark F. Meier, August 15, 1951.

For many years pile foundations of buildings and bridges throughout the North have been damaged by frost heaving. Little study was given to this problem in North America until after World War II. During the war and in the post-war interval construction on piling in the far northern part of the continent was greatly expanded, and the damaging effect of frost heaving on piling was realized to be a major problem. In 1946 the Corps of Engineers, U. S. Army, began systematic studies of the effect of seasonally frozen ground and permafrost on piling near Fairbanks, Alaska, as well as many other studies of frozen ground (Barnes, 1946; Jaillite, 1947; Wilson, 1948; Corps of Engineers 1954a; Linell, 1959; Corps of Engineers, 1955, 1956). During and after the war Canada also began to investigate problems connected with the use of piling in areas of intense frost heaving (D'Appolonia, 1944; Pihlainen, 1951; Hemstock, 1949, 1952; and Trow, 1955). Such studies were started much earlier in Russia (Sumgin, 1927; Chernisheff, 1928; Muller, 1945; Datskii, 1950; Meister and Nel'nikov, 1950; Liverovsky and Morozov, 1952; and Tsytovich and Sumgin, 1957) in part because of difficulties encountered with pile railroad bridges in Siberia. When railroads were extended into Siberia during the last part of the last century and the early part of this century, severe frost heaving of the pile bridges was commonplace. Belorkrylov reports (in Tsytovich and Sumgin, 1957, p. 315) that out of 49 wood bridges on piles that were examined, 42 were deformed by frost heaving. Fink states (in Tsytovich and Sumgin, 1957, p. 315) that during the 2 years between the construction of the western part of the Amur Railroad and the first opening of the line to traffic, 30 percent of the wooden bridges had to be repaired because of a relative displacement of more than  $2\frac{1}{2}$  inches. He also states that the deformation was characterized by the center piles being pushed up during the winter, disrupting the joints of the bridge. Chernisheff (1928, p. 1) reports that the frost heaving of bridges on this railroad almost reached disaster proportions during the early years of operations.

## Mechanics of frost heaving of piles

When ground is forced upward during seasonal freezing any object on top of the ground or firmly held by the ground will also be forced upward if the forces acting upward are greater than the forces pushing downward. With piles, the upward force is the result of frost heaving of ground which is adfrozen to the pile and the downward force is the resistance to the upward force provided by the weight of the pile plus its load and the friction between the pile and the unfrozen ground beneath the seasonal frost (fig. 4), plus the tangential adfreezing strength

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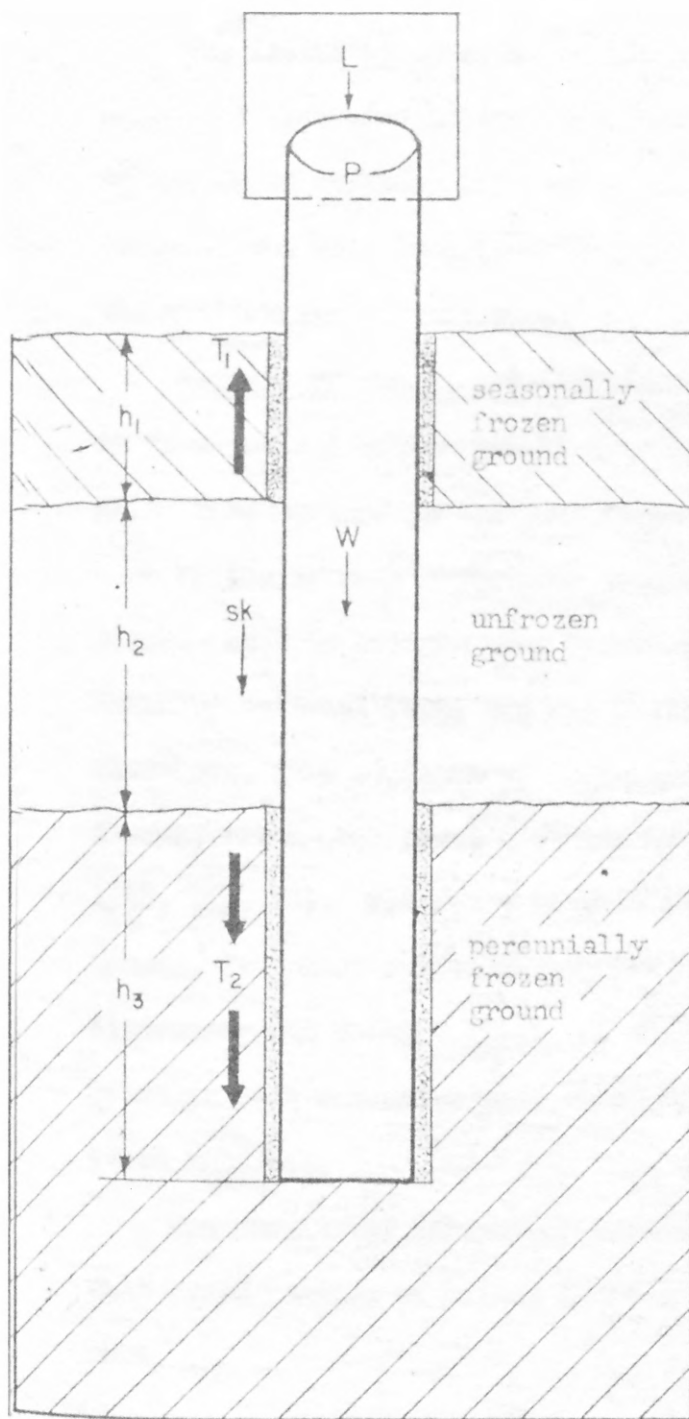
Figure 4. Forces applicable in frost action on piling.

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of permafrost if it exists.

### Factors affecting upward force

The amount of the upward force on a pile is dependent upon (1) the intensity of frost heaving, (2) the tangential adfreezing strength, or bond, between the surface of the pile and the seasonally frozen ground, and (3) surface area of the pile in the seasonally frozen ground.



$L$  - load on pile

$W$  - weight of pile

$P$  - perimeter of pile

$sk$  - skin friction between pile and unfrozen ground

$T_1$  - tangential adfreeze strength between pile and seasonally frozen ground.

$T_2$  - tangential adfreeze strength between the pile and perennially frozen ground.

$h_1$  - length of pile in seasonally frozen ground.

$h_2$  - length of pile in unfrozen ground.

$h_3$  - length of pile in perennially frozen ground.


 - zone of tangential adfreeze strength

Fig. 4.-- Forces applicable in frost action

on piling.

29a

(p. 30 follows)

## Intensity of frost heaving

The intensity of frost heaving is mostly dependent upon the amount of clear-ice segregations that forms when the ground freezes. As mentioned earlier, this amount is dependent upon many physical factors, the most important of which are texture of the ground and the availability of moisture.

Texture of the ground.--Maximum frost heaving of piles occurs in fine-grained sediments--fine sand, silt, and silty clays. Organic silt perhaps is the most favorable.

Piling of many structures placed in silt throughout central Alaska, such as bridges near Fairbanks, Manley Hot Springs, Mount McKinley National Park, and Big Delta or buildings at Northway and elsewhere, show evidence of disturbance by frost heaving. At Galena, Alaska, bench-mark posts elevated by frost heaving are in silt (Péwé, 1948, fig. 18). The frost heaving of piling at Norman Wells, N. W. T., Canada, described by Hemstock (1949, fig. 15), is in a silty soil. Liverovsky and Morozov (1952, p. 48) state that frost heaving of piles is most extensive when the active layer consists of fine-textured material.

The results of laboratory and field observations indicate that frost heaving of piling is most intense in silt or silty clay soil.

Moisture content of the ground.--The amount and position, or distribution, of moisture in the ground is perhaps the most important factor influencing the growth of ice and resultant frost heaving of piles. Therefore, if fine-grained soil is poorly drained or has readily accessible water, frost heaving of piling in such sediment will be great in a cold climate. Inasmuch as bridges generally span drainageways their pile foundations are in areas of abundant ground moisture, and if fine-grained sediments are present, two important intrinsic factors favorable for frost heaving exist.

The differential frost heaving of piles of any particular bridge often reflects differential availability of moisture to the ground near the piles. Where the foundation of a small bridge is entirely in fine-grained sediments, moisture is generally most abundant under the center of the bridge. Therefore, the piles in the center of the bridge are forced upward the most and form a hump in the center of the bridge.

This common feature is illustrated by a road bridge at Norman Wells, N. W. T., Canada, (Hemstock, 1949, fig. 49) and by railroad bridges in Russia (fig. 5) (Lubimoff, 1902, figs. 2, 4, 5; Sumgin,

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Figure 5. Hump formed in Russian bridge due to heaving of center piles. (From Liverovsky and Morozov, 1952, fig. 34).

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1927, p. 302; Liverovsky and Morozov, 1952, fig. 34). The pile bridges studied in detail along The Alaska Railroad near Fairbanks illustrate this phenomenon and will be described later. This selective frost heaving of piles, however, may be related to differential anchorage of the piles.

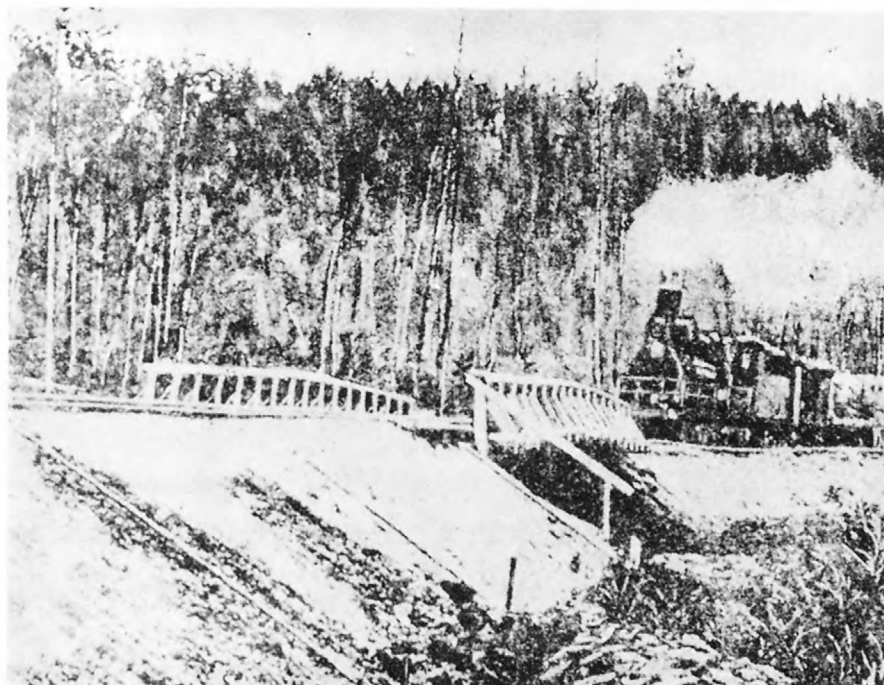


Figure 5. Hump formed in Russian bridge due to heaving of center piles. (From Liverovsky and Morozov, 1952, fig. 34).

Some pile bridges in central Alaska have the end piles forced up by frost heaving leaving the center piles unaffected. This is opposite to the bridges just described. One of the best examples of a bridge showing frost heaving of the end piles is the bridge spanning the outlet of Clearwater Lake, 8 miles southeast of Big Delta, Alaska, (figs. 3 and 6). The piles of this

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Figure 6. Geologic sketch of foundation conditions of frost-heaved bridge 8 miles southeast of Big Delta, Alaska. (See fig. 3).

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bridge have been elevated by frost action about 11 feet on one end and about 5 feet on the other. The piles are embedded in silty soil, but the center piles do not frost-heave because the deep water of the main channel prevents freezing of the ground. However, the fine-grained soil surrounding the end piles is subject to seasonal freezing because the water is shallow or even absent at low stage in the winter. The freezing ground has ready access to water which permits great ground-ice growth during freezing. Frost heaving of end piles of bridges in Alaska is not unusual under similar circumstances and has been noted at Nome, Manley Hot Springs, and elsewhere.

33a  
(p. 34 follows)

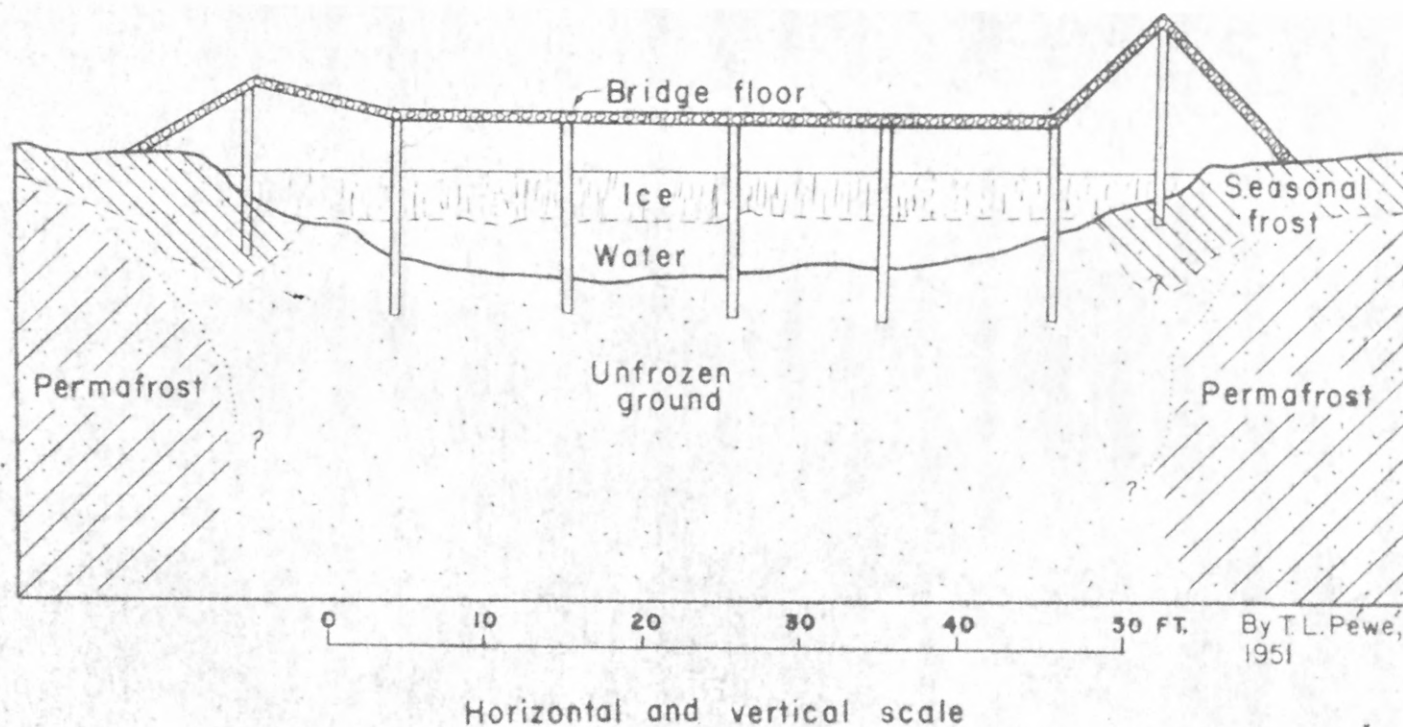


Fig. 6.--Geologic sketch of foundation conditions of frost-heaved bridge 8 miles southeast of Big Delta, Alaska (see fig. 3).

Duration of freezing.--All other factors being equal, the longer the period of seasonal frost generation the greater the frost heaving will be. A longer period of freezing permits more ground-ice to form and generally results in a thicker layer of seasonal frost. However, the depth of frost penetration or rate of freezing is not very important in ice accumulation in natural freezing of the ground (Johnson, 1952, p. 45-46; Jackson and Chalmers, 1956, p. 25). It is the duration or intensity of the cold that is closely correlated with the magnitude of heave. It is true, however, in dealing with piles that the thicker the active layer, the greater the surface area of the pile in the seasonally frozen ground. The greater the surface area, the greater the total adfreezing strength. The depth of seasonal frost in central Alaska ranges from 3 to 5 feet in silt to as much as 20 feet in gravel areas cleared of snow (Carlson and Kersten, 1953).

#### Summary of intensity of frost heaving

The upward push of frost heaving on piling is developed to the greatest extent on piles embedded in moist organic silt or silty clay in regions subjected to long periods of below freezing temperatures.

### Tangential adfreezing strength

Regardless of how intense the frost heaving may be, no frost heaving of the pile will occur if the bond between the frozen ground and the pile surface, the tangential adfreezing strength, is weak. According to Muller (1945, p. 46) the heaving force of the ground, when freezing, that is transmitted to the pile is proportional to the adfreezing strength of that ground with the piles. The tangential adfreezing strength of frozen ground varies with texture, moisture content, temperature of the ground, and nature of the pile surface.

The effect of these variables on the tangential adfreezing strength of sediments to surfaces has been reported by Russian workers. Detailed laboratory work is listed by Tystovich and Sumgin (in Muller, 1945, p. 46-52) and field work on the tangential adfreezing strength of wood and concrete to seasonally frozen ground under natural conditions is reported by Meister and Mel'nikov (1950) (table 1). It is mentioned by Meister and Mel'nikov that the tan-

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Table 1. Tangential adfreezing strength between seasonally frozen ground and different materials under natural conditions.

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gential adfreezing strength of artificially prepared laboratory soil specimens is greater than that recorded under natural circumstances. Liverovsky and Morozov (1952, p. 45) and Linell (written communication, Sept. 17, 1957) also believe laboratory tests give results that are not too applicable to field problems. Liverovsky and Morozov cite Bikov as obtaining only 8.5 to 18.5 lbs/in<sup>2</sup> tangential adfreezing strengths for piles in field tests. Laboratory work reported by Trow (1955) reveals that under rapid loading the tangential adfreezing strength of soil (types of soil and moisture content not reported) with concrete at -10° F. ranged from 304 to 495 lbs/in<sup>2</sup>. These figures are similar to those given by Muller (1945, p. 47) (table 2).

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Table 2. Effect of temperature and moisture content on the tangential adfreezing strength between different grounds and water-saturated wood and concrete.

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Table 1.--Tangential adfreezing strength between seasonally frozen ground  
and different materials under natural conditions.

(after Meister and Mel'nikov, 1950)

Type of Ground		Temperature		Moisture	Adfreezing	
Grain size (percent)		-- (degrees Centigrade)		content by	strength	
		depth 0.25 m.	depth 0.5 m.	weight	kg/cm <sup>2</sup>	lbs/in <sup>2</sup>
(0.5-0.05 mm.)						
98.00	WOOD	-2.6	-3.5	22.5	4.40	63.
99.00		-4.7	-5.1	23.5	5.00	71.
94.50		-4.8	-4.7	21.0	5.76	82.
96.25		-4.3	-3.4	32.5	6.30	90.
95.75		-8.5	-5.5	25.3	9.86	140.
98.00	CONCRETE	--	--	--	3.76	53.
100.50		-2.5	-2.8	23.2	4.08	58.
98.00		-4.8	-5.7	21.5	5.55	79.
--		-5.7	-5.4	21.5	7.71	110.
0.05 - 0.005 mm Percent	<0.005 mm Percent	WOOD				

Table 1.--Tangential adfreezing strength between seasonally frozen ground  
and different materials under natural conditions--continued  
(after Meister and Mel'nikov, 1950)

Type of Ground			Temperature		Moisture content by weight	Adfreezing strength	
Grain size			(degrees Centigrade)			kg/cm <sup>2</sup>	lbs/in <sup>2</sup>
			depth 0.25 m.	depth 0.5 m.			
63.00	4.25	WOOD	-2.3	-4.2	57.9	1.52	22.
64.50	6.50		-3.2	-3.4	112.3	3.22	46.
76.25	10.25		-2.3	-2.8	64.3	3.30	47.
70.00	6.50		-6.5	-5.1	84.6	3.58	51.
73.00	3.00		-3.5	-3.5	59.5	3.88	55.
56.50	11.50	CONCRETE	-0.2	-0.2	68.6	2.10	30.
75.00	5.50		-0.7	-0.5	70.8	2.06	29.
72.50	8.25		-1.5	-2.2	53.0	3.88	55.
69.00	8.75		-2.5	-1.5	59.8	5.73	81.
			-2.5	2.2	53.0	5.74	82.
61.00	8.25		-3.8	-2.9	64.0	7.25	103.

Table 2.--Effect of temperature and moisture content on the tangential adfreezing strength between different grounds and water-saturated wood and concrete

(From Tsytovich and Sumgin, 1937; after Muller, 1945, p. 47)

Type of ground			Temp. °C.	Water-saturated wood			Water-saturated concrete		
Grain size (millimeters)	Percent			Percent moisture	Adfreezing strength		Per- cent mois- ture	Adfreezing strength	
					kg/cm <sup>2</sup>	lbs/in <sup>2</sup>		kg/cm <sup>2</sup>	lbs/in <sup>2</sup>
Silt	0.05-0.005	63	-0.2	29.9	3.6	51.1			
Clay	0.005	36	-0.2	27.1	2.9	41.2			
Clayey sand	1 - 0.05	68	-0.2	12.1	1.3	18.5			
Silt	0.05-0.005	63	-0.2	22.4	7.0	99.5	16.4	4.4	62.6
Silt	0.05-0.005	63	-0.2	32.6	8.9	126.6	33.0	6.0	85.3
Silt	0.05-0.005	63	-0.2	43.8	7.1	101.	44.0	9.2	130.8
Silt	0.05-0.005	63	-0.2	51.2	7.6	108.1	53.2	3.1	44.1
Clay	0.005	36	-1.2	22.4	3.2	45.5	17.8	7.8	110.9
Clay	0.005	36	-1.2	26.4	5.9	83.9	26.3	4.8	68.3
Clay	0.005	36	-1.2	37.3	13.0	184.7	36.2	6.4	91.0
Clay	0.005	36	-1.2	56.5	11.8	167.8	43.9	5.8	82.5
Clayey sand	1 - 0.05	68	-1.2	6.7	2.8	39.8	5.8	2.8	39.8
"	1 - 0.05	68	-1.2	10.1	4.1	58.3	11.7	6.4	91.0
"	1 - 0.05	68	-1.2	13.3	7.2	102.4	12.1	7.0	99.5

Table 2.--Effect of temperature and moisture content on the tangential adfreezing strength between different grounds and water-saturated wood and concrete-- continued (From Tsytoovich and Samgin, 1937; after Miller, 1945, p. 47)

Type of ground		Temp. °C.	Water-saturated wood			Water-saturated concrete		
Grain size (millimeters)	Percent		Percent moisture	Adfreezing strength		Percent moisture	Adfreezing strength	
				kg/cm <sup>2</sup>	lbs/in <sup>2</sup>		kg/cm <sup>2</sup>	lbs/in <sup>2</sup>
Layered sand	1 - 0.05	68	-1.2	16.5	8.2 116.6	16.1	11.1	157.8
Clay lit	0.05-0.005	63		18.8	6.9 98.1	17.4	7.3	110.9
	0.005	14	-1.2	33.9	14.1 200.5	32.5	21.8	310.0
	organic			41.5	28.7 408.1	46.4	26.2	372.6
	matter	18		51.0	34.8 494.9	51.8	28.1	399.6
				62.2	34.7 493.4	58.3	27.7	393.9
Clay	0.005	36	-1.2	18.4	12.8 182.0	18.9	20.6	292.9
Clay	0.005	36	-10.0	21.6	15.7 223.3	25.1	21.9	311.4
Clay	0.005	36	-10.0	28.4	18.6 264.5	34.6	25.3	359.4
Clay	0.005	36	-10.0	41.4	32.2 457.9	46.1	20.1	285.8
Clay	0.005	36	-10.0	55.6	31.9 453.6	--	--	--

Table 2.--Effect of temperature and moisture content on the tangential adfreezing strength between different grounds and water-saturated wood and concrete-- continued (From Taytovich and Sumgin, 1937; after Muller, 1945, p. 47)

Type of ground		Temp. °C.	Water-saturated wood			Water-saturated concrete			
Grain size (millimeters)	Percent		Percent moisture	Adfreezing strength		Percent moisture	Adfreezing strength		
				kg/cm <sup>2</sup>	lbs/in <sup>2</sup>		kg/cm <sup>2</sup>	lbs/in <sup>2</sup>	
Clayey sand	1 - 0.05	68	-10.0	5.7	7.9	112.3	7.5	10.0	142.2
				10.1	12.6	179.2	11.9	22.8	324.2
	0.005	8		13.9	21.4	304.3	18.1	24.2	344.1
				19.9	32.3	459.3	23.8	21.0	298.6
				33.5	33.5	476.4	--	--	--

Perhaps the only extensive laboratory tests made in Alaska on the tangential adfreezing strength of sediments and water to surfaces were those made at the Soil Test Laboratory at Barrow, Alaska, during the investigations of Navy Petroleum Reserve No. 4. Some of these results are presented in table 3 (written communication,

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Table 3. Laboratory tests of tangential adfreezing strength between 1-inch diameter steel rod and various materials.

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Barrow, Alaska, Soil Test Laboratory, 1949). A figure on tangential adfreezing strength cited by Roberts and Cooke (1950, p. 38) is from this 1949 report.

A total of 15 tests were run in the laboratory by Nees (1951, p. 2-4) to determine the adfreezing strength between  $1\frac{1}{4}$ -inch standard steel pipe and a silty sand at temperatures of  $-8^{\circ}$  to  $-4^{\circ}\text{C}.$  and at varying moisture contents. These tests were conducted in the arctic in connection with the construction of large steel towers on permafrost in 1947. Although the location is not mentioned it is thought to be northern Alaska. After an evaluation of these tests, Nees decided that in this particular area a value of 20  $\text{lbs/in}^2$  could be used as a safe figure for the adfreezing strength between steel piles and most soils, except dry granular material or highly organic soils.

Table 3.--Laboratory tests of tangential adfreezing strengths between 1 inch diameter steel rod and various materials.

(Written communication, Barrow, Alaska, Soil Test Laboratory, 1949)

Description of material	Temperature and duration of freezing	Temp. after test	Tangential adfreezing strength	
			kg/cm <sup>2</sup>	lbs/in <sup>2</sup>
Fresh water ice	47 hrs. @ -25°C., 45 hrs. @ -5°C.	-6	12.	170
	48 hrs. @ -25°C., 12 hrs. @ -8°C.	-12	10.	141
	24 hrs. @ -30°C., 30 hrs. @ -5°C.	-5	10.	140
	24 hrs. @ -20°C., 24 hrs. @ -8°C.	-7	9.	125
	84 hrs. @ -6°C.	-3	6.	89
	36 hrs. @ -6°C., 12 hrs. @ -20°C.	-6	8.	115
	75 hrs. @ -6°C.	-4	14.	204
	16 hrs. @ -20°C., 4 hrs. @ -5°C.	-5	6.	92
Salt water ice	26 hrs. @ -35°C., 48 hrs. @ -8°C.	-5	2.	27
	26 hrs. @ -40°C., 31 hrs. @ -8°C.	-4	1.	17
	48 hrs. @ -20°C.	-20	2.	31
Organic silt Muck (peat and silt)	18 hrs. @ -20°C.	-4	6.	88
	56 hrs. @ -2 to -7°C.	-8	10.	141

Table 3.--Laboratory tests of tangential adfreezing strengths between 1 inch diameter steel rod and various materials--continued

(Written communication, Barrow, Alaska, Soil Test Laboratory, 1949)

Description of material		Temperature and duration of freezing	Temp. after test	Tangential adfreezing strength	
				kg/cm <sup>2</sup>	lbs/in <sup>2</sup>
Sediments from Skull Cliff, Alaska	fine sand	80 hrs. @ -2° to -7°C.	-7	6.	84
	silt and org. matter	78 hrs. @ -2° to -7°C.	-7	8.	107
	silt	26 hrs. @ -35°C., 21 hrs. @ -8°C.	-10	12	176

Moisture content of ground.--The amount of ice in the ground is one of the main factors influencing the grip of the frozen ground on the piles, in fact Tystovich and Sumgin (1957, p. 181) state that "...the ice content of frozen ground is the most important, fundamental factor determining the cohesiveness of the frozen ground and its adfreezing strength to wood and concrete." From table 2 it can be noted that with increase of moisture content (ice) there is an increase in tangential adfreezing strength. Muller states (1945, p. 46) that the maximum strength is reached in most sediments at about the maximum saturation of ground with ice. Further increase in ice, beyond maximum saturation point, tends to decrease adfreezing strength, gradually approaching that of pure ice. This is also reported by Nees (1951, p. 3).

Under laboratory conditions, wood piles in silt have the greatest tangential adfreezing strength at 50 to 60 percent (by weight) moisture content (Tystovich and Sumgin: in Muller, 1945, table 2). Under field conditions seasonally frozen silt with 60 to 80 percent moisture content by weight had the greatest bond with wood piles (Meister and Mel'nikov, 1950) (table 1).

Texture of the ground.--Fine-grained sediments (clay, silt, and fine sand) have greater tangential adfreezing strength than coarse-grained material (coarse sand, and gravel). According to Muller (p. 50-51) (table 4; fig. 7) frozen fine sand and silt are

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Table 4. Tangential adfreezing strength between different frozen ground and water-saturated wood.

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Figure 7. Tangential adfreezing strength between wood and frozen sediment of different texture. (After Tsytoich and Sumgin, 1937, from Muller, 1945, p. 50.)

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the sediments that have the greatest bond with wood. Clay has less bond than silt or fine sand. Meister and Mel'nikov (1950, p. 3) state that the tangential adfreezing strength of wood to sand is greater than that of wood to silt under approximately identical temperatures, notwithstanding the fact that the silt has a larger ice content (table 1). They also determined (p. 9) that under field conditions the adfreezing strengths are virtually the same for concrete to sand and concrete to silt when temperatures are the same, but the ice content is about 50 percent higher in the silt. If moisture content were identical sandy soil would have the greater adfreezing strength.

Table 4.--Tangential adfreezing strength between different frozen  
ground and water-saturated wood

(from Tsytovich and Sumgin, 1937, after Muller, 1945, p. 48)

Name of ground	Texture of ground		Temp. in °C.	Percent moisture	Adfreezing strength	
	Percent of grains >1 mm.	Percent of grains <0.005 mm.			kg/cm <sup>2</sup>	lbs/in <sup>2</sup>
Clay	None	45	-1.5	41	5	71.
"	13	45	-1.0	39	6	85.
"	-	41	-1.0	30	5	71.
"	6	31	-2.2	29	7	100.
"	2	30	-1.6	24	7.2	102.
Sandy clay	None	27	-0.8	35	4	57.
" "	"	25	-1.2	26	5	71.
Silty, sandy clay	"	24.8	-1.5	40	6	85.
Sandy clay with layers of ice	"	23.5	-0.8	39	4	57.
Sandy clay	"	22	-1.8	39	6	85.
" "	"	22	-1.6	34	4	57.
Sandy, silty clay with layers of ice	"	22	-1.5	43	6	85.
Sandy clay	"	20	-0.5	20	2	28.

Table 4.--Tangential adfreezing strength between different frozen

ground and water-saturated wood--continued

(from Tsytoovich and Sumgin, 1937, after Muller, 1945, p. 48)

Name of ground	Texture of ground		Temp. in °C.	Percent moisture	Adfreezing strength	
	Percent of grains >1 mm.	Percent of grains <0.005 mm.			kg/cm <sup>2</sup>	lbs/in <sup>2</sup>
Sandy clay with layers of sand	"	18	-1.0	18	5	71.
Silty, sandy clay	14	18	-2.0	25	7	100.
Sandy clay	13	17	-1.1	31	4	57.
" "	17	17	-2.2	25	10	142.
" "	None	16	-0.6	27	4	57.
" "	"	15	-1.6	28	7	100.
" "	"	15	-0.7	25	3	43.
" "	3	15	-0.5	25	2	28.
" "	3	15	-4.0	26	4.3	61.
" "	-	14	-1.2	24	6	85.
" "	None	14	-0.8	36	3	43.
" "	"	14	-2.0	33	5	71.
Sandy clay, micaceous	1	14	-1.8	32	3	43.
Sandy clay, micaceous	9	13	-0.5	25	2	28.

Table 4.--Tangential adfreezing strength between different frozen  
ground and water-saturated wood--continued

(from Tsytoovich and Samgin, 1937, after Muller, 1945, p. 48)

Name of ground	Texture of ground		Temp. in °C.	Percent moisture	Adfreezing strength	
	Percent of grains >1 mm.	Percent of grains <0.005 mm.			kg/cm <sup>2</sup>	lbs/in <sup>2</sup>
Sandy clay	25	13	-0.6	17	7	100.
" "	-	11	-0.9	27	5	71.
" "	23	10	-1.6	25	5	71.
Sandy clay, micaceous	None	10	-1.0	39	3.3	47.
Sandy clay	5	10	-1.8	23	7.2	102.
Clayey sand with silt	-	9	-1.1	28	3.1	44.
" " " "	0.5	7	-1.0	17	5.4	77.
Clayey sand	41	7	-1.5	16	1.3	19.
Silty, clayey sand						
with layers of ice	-	4	-1.6	27	3.3	47.
Granitic arkoseq	61	?	-1.7	14	2	28.
Gravel	80	3	-1.1	12	3.3	47.

Type of ground	Dominant grain-size in mm.	Temperature in C.	Coefficient of saturation in %	Adfreezing strength	
				Kg/cm <sup>2</sup>	lb/in <sup>2</sup>
ay No. 1 - - - - -	0.01	-10°	77	15.3	217.56
ni, fine No. 2 - - -	0.25	-10°	76	23.3	331.32
nd, medium No. 3 - -	1.0	-10°	78	26.8	381.09
ni, coarse to fine No. 4	3-0.25	-10°	79	21.7	308.57
nd, coarse No. 5 - -	3-2	-10°	97	19.1	271.60
avel, fine No. 6 - -	5.0	-10°	77	2.6	36.97
avel No. 7	10.0	-10°	79	0.9	12.79

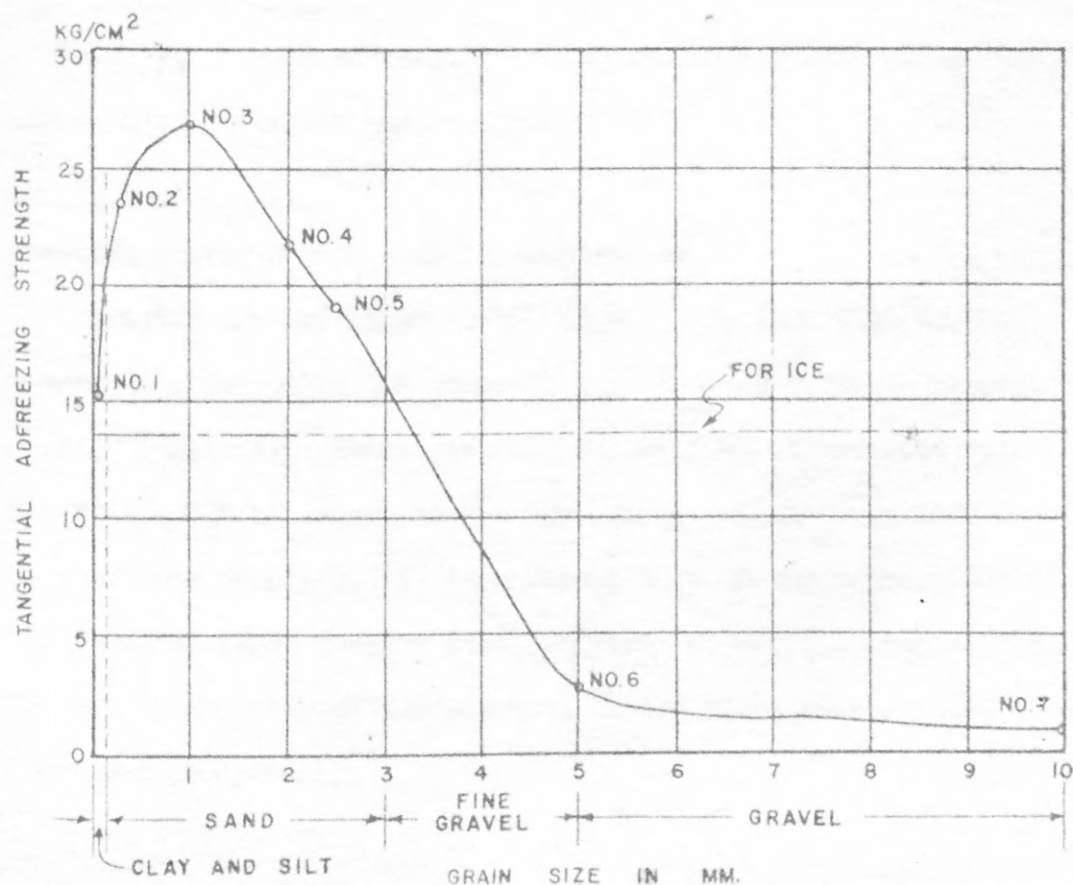


Fig. 7.--Tangential adfreezing strength between wood and frozen sediment of different texture. (After Tsytoovich and Sumgin, from Muller, 1945, p. 50)

Temperature of the ground.--Temperature of the frozen ground is a very important factor in determining the tangential adfreezing strength between frozen sediments and various surfaces. Figure 8 shows that in silt, for example, a drop in temperature

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Figure 8. Effect of temperature on the tangential adfreezing strength between wet wood and clay, silt, clayey sand, and ice. (after Tsytoich and Sumgin, 1937, from Muller, 1945, p. 51.)

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from 0° C. to -2° C. doubles the tangential adfreezing strength between wet wood and the ground. The effect is even greater with clayey sand. Table 5 demonstrates the change of tangential ad-

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Table 5. Effect of temperature on tangential adfreezing strength of different materials.

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freezing strength with drop in temperature.

Meister and Mel'nikov (1950, figs. 8-11) show that as the temperature decreases the tangential adfreezing strength increases greatly (table 1). Therefore, the temperature of the seasonal frost is quite important in the development of the grip that frozen sediment has on piles. It is apparent that as the temperature of the seasonal frost changes with variation of air temperature during the winter the grip of the sediment on the piles increases or decreases accordingly.

Table 5.--Effect of temperature on tangential adfreezing strength of  
different materials

(from Tsytovich and Sumgin, 1937, after Muller, 1945, p. 49)

	Temperature in C.	Percent Moisture by weight	Adfreezing strength	
			Kg/cm <sup>2</sup>	lbs/in <sup>2</sup>
Ice and smooth-surfaced wood (wood was placed in water in air-dry condition)	-1	-	5.0	71.
	-5	-	6.2	88.
	-7	-	11.6	165.
	-10	-	113.7	195.
	-20	-	22.0	313.
Ice and smooth concrete	From -5 to			
	-10	-	9.8	139.
Clay (Grains 0.005 mm 36%) and water-saturated wood (moisture content of grounds about $\frac{1}{2}$ of saturation)	-0.2	27.1	2.9	41.
	-1.5	26.4	5.9	84.
	-5.8	28.4	11.1	158.
	-10.8	28.4	18.6	264.
	-17.8	25.8	29.4	418.
Clayey sand (Grains: 1-0.005 mm 68%; 0.005 mm 8%) and water-saturated wood	-0.2	12.1	1.3	18.
	-1.2	13.0	7.0	100.
	-2.7	10.1	11.0	156.

44 (44a follows)

Table 5.--Effect of temperature on tangential adfreezing strength of  
different materials--continued

(from Tsytovich and Samgin, 1937, after Muller, 1945, p. 49)

	Temperature in C.	Percent Moisture by weight	Adfreezing strength	
			kg/cm <sup>2</sup>	lbs/in <sup>2</sup>
	-5.2	14.8	19.6	279.
	-5.6	12.9	20.8	296.
	-10.7	14.1	24.7	351.
	-17.4	12.8	27.4	390.
It (Grains 0.005 mm 14%; organic matter 18%) and water-saturated wood	-0.2	29.5	3.6	51.
	-0.5	33.4	6.1	87.
	-5.7	34.3	10.6	151.
	-10.3	33.1	14.3	203.
	-12.3	33.2	19.9	283.
	-22.7	34.9	25.9	368.

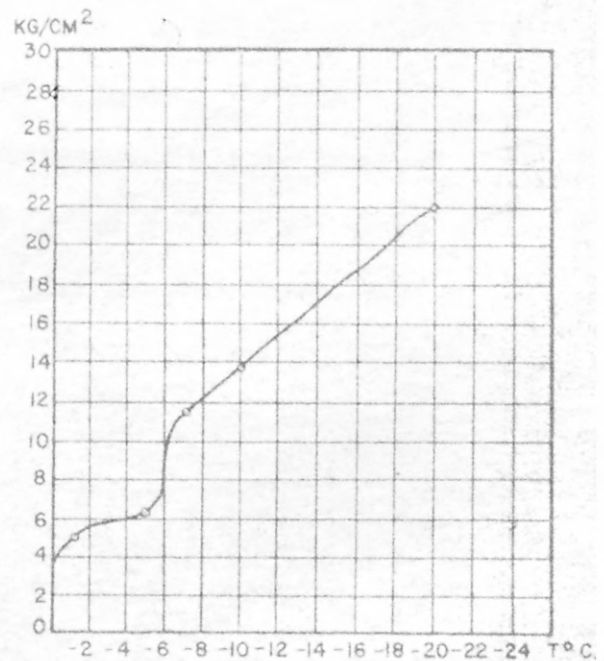
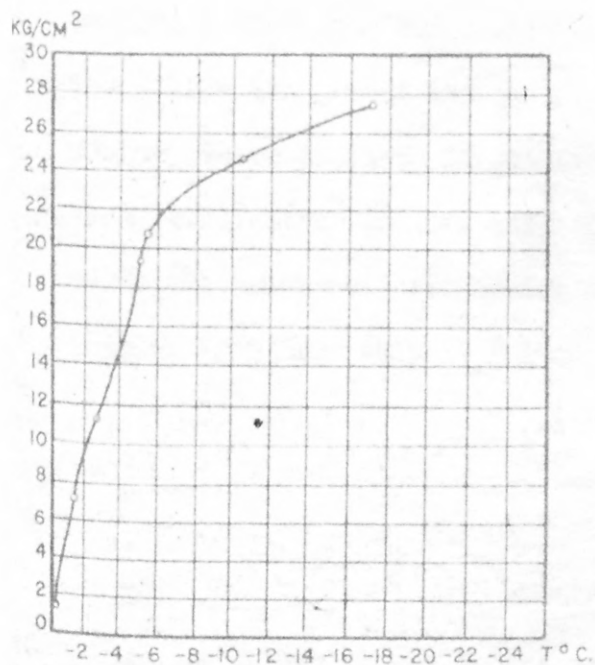
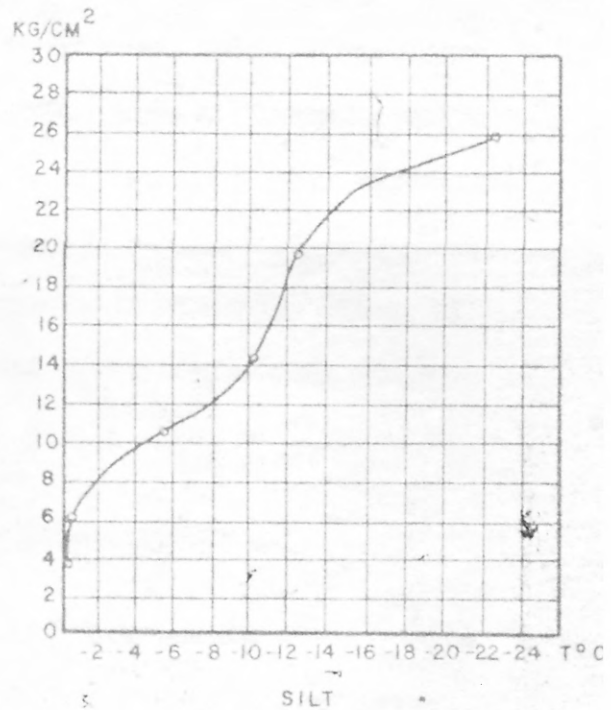
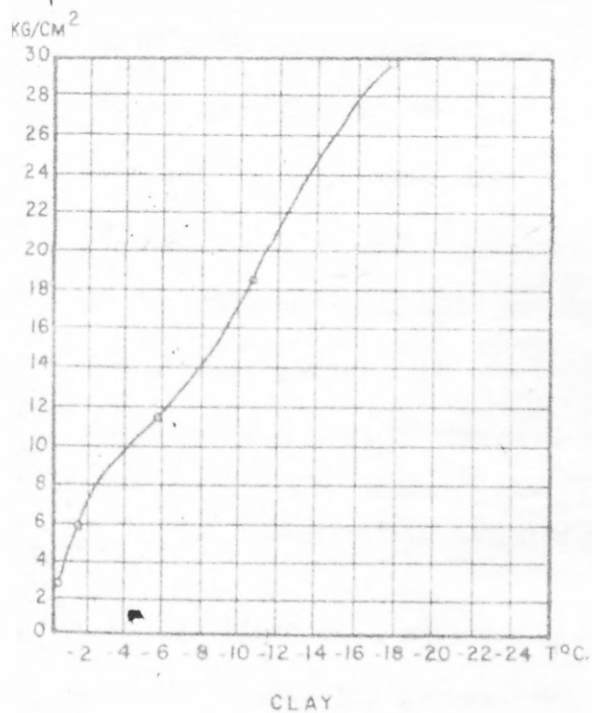


Fig. 8.--Effect of temperature on the tangential adfreeze strength between wet wood and clay, silt, clayey sand, and ice.

(after Tsytovich and Sumgin, from Muller, 1945, p. 51)

Nature of the pile surface.--The bond between the surface of the pile and the frozen ground depends in part upon the nature of this surface. The surface may be of wood, metal, stone, concrete, etc. and may be rough or smooth. Convincing quantitative data are lacking concerning the value of the tangential adfreezing strength of one over the other. However, the smoother the surface of the pile the less will be the adfreezing strength. Also, if a pile were placed with the small end up the adfreezing strength might be less than if the pile were placed with the butt end up.

#### Summary of tangential adfreezing strength

The tangential adfreezing strength between the surface of a pile and seasonally frozen ground reaches its maximum in ice-saturated fine sand and a little less than its maximum in silt. The colder the ground the greater the adfreezing strength. Laboratory tests indicate tangential adfreezing strengths of less than 14.2 lbs/in<sup>2</sup> to more than 483.4 lbs/in<sup>2</sup>. In actual field tests the tangential adfreezing strengths are less than this, ranging from less than 14.2 lbs/in<sup>2</sup> to approximately 142.2 lbs/in<sup>2</sup>.

### Other upward forces

In addition to frost heaving it has been suggested that the formation of aufeis lifts piling. The formation of overflow ice, or aufeis, around the piling of a bridge does not create any lift force in itself. However, moving water under hydrostatic pressure is generally confined between the ice and the ground or between the successively formed ice layers and creates an upward force. It is thought that if the ice has a firm grip on the pile and if the ice is pushed upwards the pile also will be pushed upwards. This lifting force is important on piles on the edges of northern lakes and seas (Lofquist, 1951).

Although there may be a slight upward force exerted on the pile by this method, the writers believe such a force is not important because: (1) piles are heaved extensively whether aufeis is present or not, (2) the tangential adfreezing strength of ice on the pile would be less than that of frozen silt with high moisture content, and (3) piles in gravel are not heaved appreciably even though considerable aufeis forms around the piles.

### Factors affecting downward force

~~Two main factors oppose the upward force of frost heaving on~~ piling; (1) the weight of the pile plus its load, and (2) the grip of the nonseasonally frozen ground on the pile. The latter may be either the "skin friction" of unfrozen ground or the tangential adfreezing strength between permafrost and the pile surface.

### Weight and load of pile

The weight of a pile alone, especially wood, is negligible when considering the upward force that is the result of frost heaving of ground that is adfrozen to the pile. A wood pile generally weighs less than 1,000 lbs. The load on a pile may be enough to resist elevation by frost heaving, especially in areas where the seasonal frost layer is thin and the moisture content low. Trow (1955) states that near Toronto, Canada, they have had some success with increasing loads to overcome frost heaving on concrete posts. However, in Alaska, average wood piles supporting small bridges or frame buildings generally have a load of less than 8 tons and frost heaving elevates these piles under circumstances of favorable ground texture and moisture. When a pile is heaved it relieves adjacent piles of some or all of their load and in turn increases the load on the heaved pile. This could slightly modify the time and amount of frost heaving in areas where the seasonal frost is thin and moisture content low.

## Grip of ground below the seasonally frozen layer

Skin friction of unfrozen ground.--In temperate latitudes and in many areas in the subarctic, the main force resisting the upward force of frost heaving on piling is the friction or grip of the unfrozen ground on that part of the pile that extends beneath the seasonally frozen ground (active layer). According to Terzaghi and Peck (1948, p. 463) the ultimate value of skin friction on piling embedded in cohesive soils is 200 to 600 lbs/ft<sup>2</sup> of contact area for soft clay and silt; 400 to 1,000 lbs/ft<sup>2</sup> for sandy silt; and 800 to 2,000 lbs/ft<sup>2</sup> for stiff clay.

Similar quantitative data are scarce in Alaska; however, a few pile extraction tests were made at Fairbanks by the Corps of Engineers, U. S. Army (Linell, 1959, p. 32-33). The unit tangential shear stress between unfrozen silt and wood and steel piles was 1.5 to 5.6 lbs/in<sup>2</sup>. These piles were embedded in unfrozen organic silt (fig. 9) of the same type and moisture content that exists in

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Figure 9. Cumulative-frequency curves of silt from near Fairbanks, Alaska.

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Goldstream Valley (fig. 10).

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Figure 10. Geologic map of part of the Fairbanks area, Alaska.

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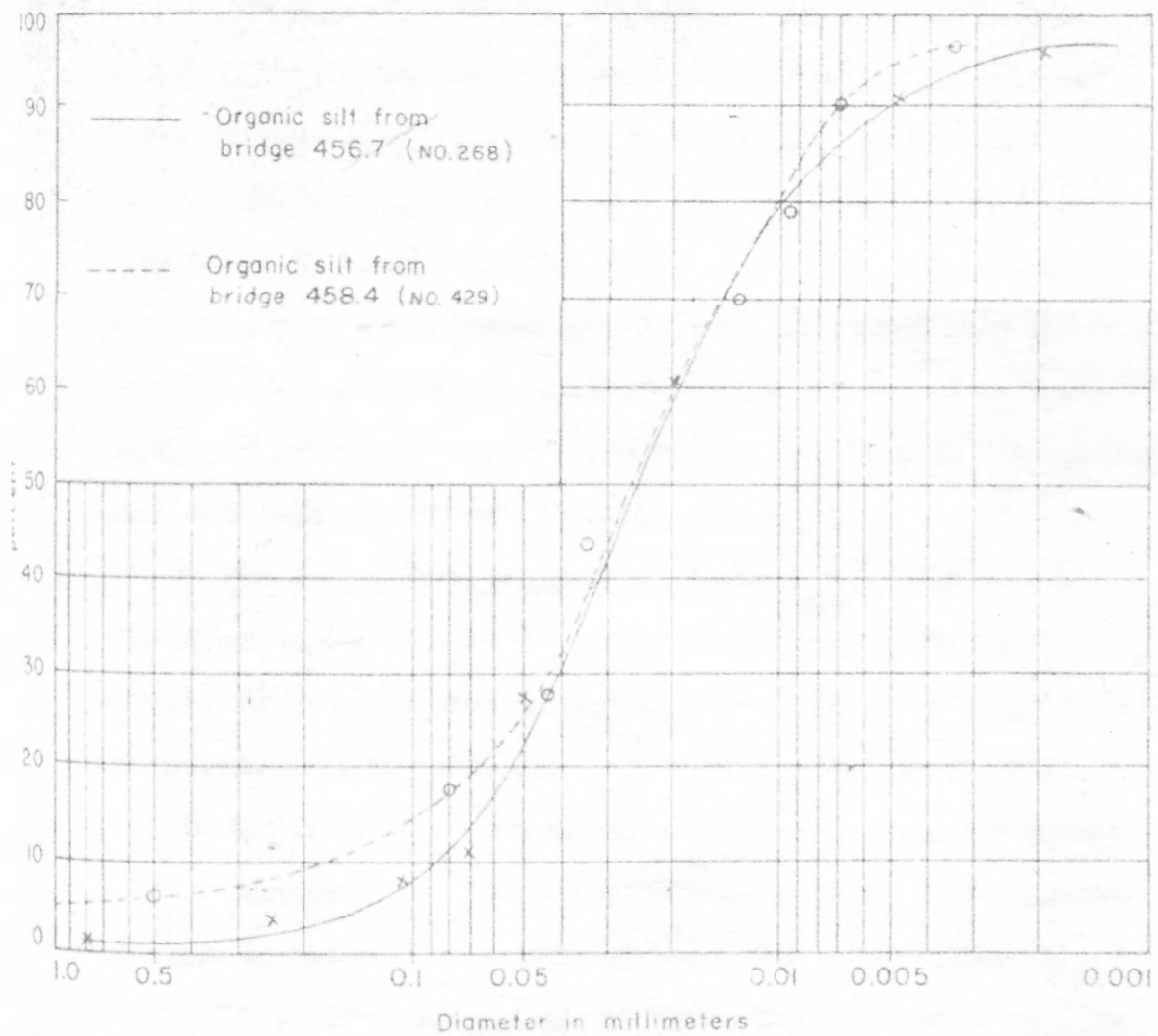


Fig. 9.--Cumulative-frequency curves of silt from near Fairbanks, Alaska.

A comparison between the tangential adfreezing strength of the active layer (tables 1-5) and the skin friction of the unfrozen ground reveals a much stronger grip of the pile by the frozen ground than by the unfrozen ground; about 1 to 10 or 1 to 50 or even more. It would be difficult to install piles with enough surface area in the unfrozen ground to resist successfully by skin friction alone the upward force that is the result of frost heaving of ground that is adfrozen to the pile in moist fine-grained sediments under severe cold climatic conditions.

Tangential adfreezing strength of permafrost.--The grip of permafrost on the pile is the tangential adfreezing strength between the pile and the perennially frozen ground. This grip of permafrost is the greatest force combating the upward force.

To the writers' knowledge the only systematic studies undertaken to determine the tangential adfreezing strength of permafrost on piles is the work being done by the Arctic Construction and Frost Effects Laboratory, Corps of Engineers, U. S. Army, at their permafrost research station (fig. 10) near Fairbanks (Corps of Engineers, 1954a; Linell, 1959; Kitze, 1957). One figure of tangential adfreezing strength between permafrost and steel piling at Norman Wells, N. W. T., Canada, is given by Hemstock (1953, p. 59).

At the U. S. Army permafrost research station, wood, concrete, steel pipe, and steel I-beam piles were installed in 1952 and 1953 in perennially frozen silt that contains a variable amount of organic matter. This silt deposit (Qsu in figure 10) is widespread in lowlands of the Fairbanks area (Péwé, 1958) and is the same formation that exists in Goldstream Valley (fig. 10). The silt is well sorted and contains little clay (fig. 9). The moisture content of the permafrost in this formation has been reported by Péwé (1958) and by the Corps of Engineers (Linell, 1959). At the permafrost research station pile test-site the moisture content by dry weight ranges from about 40 to 60 percent except for the organic layers which have a moisture content up to 180 percent (Linell, 1959, fig. 2).

The temperature of the permafrost in this formation below depths affected by seasonal variation between  $-1.0^{\circ}$  and  $0.5^{\circ}\text{C}$  (fig. 11), as determined both by the Corps of Engineers at the site

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Figure 11. Thermal profiles of permafrost near Fairbanks, Alaska.

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and by the U. S. Geological Survey elsewhere in the area (fig. 10).

The piles were installed by various methods at the research station. Some were placed in holes that were steam-thawed into permafrost and others were driven into the permafrost. Some were placed in holes drilled using water and others were drilled dry. The space between the wall of the drilled hole and the pile was filled with a silt-water slurry.

After an interval of time ranging from 15 days to more than 2 years several of the piles were extracted and the tangential adfreezing strength determined. Both the (1) ultimate tangential adfreezing strength--the point at which the pile, bond, or extracting machine failed--and (2) "plastic flow" tangential adfreezing strength were determined for various piles (Corps of Engineers, 1954a, table 1; Linell, 1959).. It is known that piles will be displaced at a lower tangential adfreezing strength between permafrost and the pile if the upward pressure is applied steadily over a long period of time. This "plastic flow" is important because the upward push of frost action and the applied structure load are forces acting over a long period of time rather than a short duration transient loading such as wind-load uplift (Linell, 1959, p. 27).

The Corps of Engineers, U. S. Army (Linell, 1959) show that, up to 1955, the ultimate tangential adfreezing strength between piles and permafrost ranged from 13.0 lbs/in<sup>2</sup> to 31.3 lbs/in<sup>2</sup>.

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✓ This particular figure differs slightly from Linell (1955) and is a modification based on later work. The studies by the Corps of Engineers of tangential adfreezing strength between piles and frozen ground are not yet completed and are subject to modification.

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for piling emplaced in drilled holes. Average stress is 22.5 lbs/in<sup>2</sup> for concrete piles, 27.1 lbs/in<sup>2</sup> for steel pipe piles, and 28.4 lbs/in<sup>2</sup> for steel I-beams. Wooden piles failed in tension (above the ground) at a stress equivalent to an adfreezing strength of more than 21 lbs/in<sup>2</sup> before the bond between the pile and the permafrost was broken (Corps of Engineers, 1954a, table 1).

The driven steel-pipe piles were embedded in permafrost only a few days prior to extraction and perhaps maximum tangential adfreezing strength was not obtained. The ultimate tangential adfreezing strength recorded averaged 23.2 lbs/in<sup>2</sup> (Linell, 1959, p. 33).

The ultimate tangential adfreezing strength between permafrost and a steel pipe that was in the ground 4 weeks was determined by Hemstock (1953, p. 59) at Norman Wells by extraction test to be 76 lbs/in<sup>2</sup>. The temperature of the permafrost at Norman Wells is -2.0°C at a depth of 10 to 20 feet.

If a comparison of the ultimate tangential adfreezing strength between perennially frozen ground and piles is made with that of the ultimate tangential adfreezing strength between seasonally frozen ground and piles, it is noted that, based on field data, the tangential adfreezing strength of seasonally frozen ground (30-55 lbs/in<sup>2</sup>) (table 1) is slightly greater than that of permafrost (13.0-31.3 lbs/in<sup>2</sup>) (Linell, 1959, p. 32) when temperatures of the two types of frozen ground are similar (between 0° and 1.5°C). These differences probably are not significant. Laboratory determinations of ultimate tangential adfreezing strengths result in figures greater than either of those of seasonally and perennially frozen ground field tests at the same temperatures. It is difficult to meaningfully compare laboratory determinations with values obtained in field tests because of different methods of freezing and other factors which must be analyzed.

From the above review one may visualize that the bond between permafrost and piles is of such a magnitude that the grip of permafrost can successfully counteract the effect of frost action on piling if the full tangential adfreezing strength of permafrost is attained over a large enough surface area.

#### Summary of mechanics of frost heaving of piling

Forces tending to displace or to prevent displacement of a pile can best be visualized by a diagram (fig. 4). The force pushing upward is transmitted to the pile through the tangential adfreezing bond. Regardless of the force that may be exerted by the upward moving of the ground, the amount that may be utilized to heave the pile is limited to that which can be transmitted to the pile through the adfreezing bond. Therefore the tangential adfreezing strength ( $T_1$ ) between the seasonally frozen ground and the pile over a distance ( $h_1$ ) of a pile with a perimeter ( $P$ ) is considered to be the maximum upward force available to heave the pile, even though the total upward force of the frozen ground as it heaves may be much more, or less. The tangential adfreezing strength varies with changes in temperature, texture, and moisture content of the ground.

The forces tending to hold the pile in place are the weight (W) of the pile, the load (L) on the pile, the force exerted through the "skin friction" bond (sk) between the pile and the unfrozen ground over a length ( $h_2$ ) of a pile with perimeter (P), and the force is exerted through the adfreezing bond. This force can have a maximum value equal to the tangential adfreezing strength ( $T_2$ ) between the pile and the permafrost over a pile length ( $h_3$ ) of a pile of perimeter (P). Here, too, the tangential adfreezing strength is dependent upon local properties of the ground.

The above parameters can be used to estimate the forces involved in frost heaving of piling. The maximum available upward force would be:  $UF = h_1 \times P \times T_1$

The maximum available downward force would be:

$$DF = W + L + (h_2 \times P \times sk) + (h_3 \times P \times T_2)$$

A pile will not be elevated if the maximum force tending to hold the pile down (DF) is greater than the maximum upward force that is the result of frost heaving of ground that is adfrozen to the pile (UF).

An analysis of the magnitude of forces acting on piles permits an understanding as to why many piles in central Alaska are not frost heaved until January or February instead of October or November. In some years the piles are pushed up in December.

If seasonal frost penetration in moist silt in central Alaska is assumed to progress as listed in a hypothetical example in table 6, then the upward push on a pile with a 40-inch perimeter

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Table 6. Hypothetical example of seasonal frost penetration into silt in central Alaska and possible upward push on 40-inch-perimeter pile (ground temperature instant).

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would increase accordingly. Tangential adfreezing strength between the moist silt and the wood pile is assumed to be  $45 \text{ lbs/in}^2$ .

Therefore, if conditions for intensive frost heaving are present (much ground-ice segregation) the pile will begin to be shoved upward at that particular part of the winter when the upward force becomes greater than the ~~downward~~ force.

Table 6.--Hypothetical example of seasonal frost penetration into silt in central Alaska and possible upward push on 40-inch-perimeter pile (ground temperature constant).

Date	Depth of frost penetration in feet	Maximum upward force in lbs.
Nov. 1	1	21,600
Dec. 1	1½	32,400
Jan. 1	2	43,200
Feb. 1	3	64,800
Mar. 1	4	86,400
Apr. 1	4½	97,200

A careful consideration of the phenomenon of increased upward push on piles as the winter progresses, however, reveals that perhaps the maximum upward force is not a straight-line relationship with the depth of frost penetration as suggested in table 6. Field observations in Russia (Liverovsky and Morozov, 1952, p. 45) show that the upper part of the seasonal frost layer does not remain frozen to the pile when the frost penetrates deeper into the ground. In fact it is suggested that only 60 to 75 percent of the active layer is frozen to the pile, for example, where the seasonal frost layer is 6 feet thick. If some of the upper part of the seasonal frost loses its grip as the lower part is extending its grip, the upward push in March and April, for example, is less than that suggested in table 6, and perhaps is not much more than the upward force active in February. It is not known why the upper part of the seasonal frost would lose its grip. Perhaps it is due to the contraction of the frozen ground as the upper layers become intensely cold and therefore could pull away from the pile. The upper part of the seasonal frost may have lost its grip on the pile early in the winter when the ground is rising but the adfreezing bond is not strong enough to raise the pile. Perhaps the upper part does not recement.

A variation from the straight-line relationship suggested in table 6 could be caused by a reduction of the grip of permafrost on the lower end of the pile. As the pile is shoved upward during the winter less and less of the pile is embedded in permafrost; thereby reducing the total resistance to the upward force.

As the ground begins to warm from above in late winter and early spring, the tangential adfreezing strength becomes considerably less and the maximum upward push decreases. The maximum push could also decrease at any time in the winter if the ground became warmer. To the writers knowledge there are no quantitative data published illustrating the continuous variation of maximum upward force on piles throughout a winter. Such data would permit a more accurate assessment of the problems of the frost heaving force acting on piles.

**Frost heaving of bridge piling of the Alaska Railroad  
near Fairbanks**

**Preliminary statement**

In 1914 the United States Congress authorized the construction of a railroad from the Pacific Coast of Alaska to the navigable waters of the interior of the Territory (Alaska Eng. Comm. 1916, p. 9). Construction started in 1915 at Anchorage and the line was extended in two directions: south toward Seward and north toward Nenana on the Tanana River (fig. 1). In 1916 construction started at Nenana and the line was extended south toward Anchorage and north toward Fairbanks (Capps, 1940, p. 13). The Alaska Railroad was completed in 1923 and is owned and operated by the United States Government.

Three lines were considered as possible routes from Nenana to Fairbanks (Alaska Eng. Comm., 1916, p. 59-60; Map VIII): (1) through the silt-filled Goldstream Valley, (2) along the north side of the Tanana River near the base of the unfrozen southward-facing bedrock slopes and (3) along the south side of the Tanana River.

The Goldstream Valley route was chosen where poor drainage and perennially frozen silt with large ground-ice masses has caused many engineering-geology problems that are concerned with both permafrost and seasonal frost. Maintenance of this section of the track is difficult, and one of the serious problems is frost heaving of bridge piling.

#### Typical piling

#### Notes

A. V. S. Peatley Forest Station was established at the U. S. Department of Agriculture experimental station near Fairbanks in 1904, and its records represent climatic conditions in the north timbered permafrost-free slopes. Since 1907, when the Peatley Forest station was moved to Fairbanks, the records represent the climate on the flat plains of the Tanana-Chena River.

Many small pile-supported bridges were built in Goldstream Valley during 1917. Permafrost necessitated different construction methods than those used in temperate latitudes. Holes for the wood piles were steam-thawed in permafrost to the total depth that the pile was to penetrate, then the pile was driven.

The rigorous climate plus poorly drained fine-grained sediment permits frost heaving of piling every year on many of the wood-pile bridges. Many bridges are thrown out of line and the elevation of the track is seriously disturbed. In short, the bridge humps that form are sometimes sharp enough to uncouple the cars of trains passing over the bridges at moderate to high speeds. Reduction of speed to avoid uncoupling of cars or shifting of cargo is necessary.

#### Physical setting

#### Climate

A U. S. Weather Bureau station was established at the U. S. Department of Agriculture experiment station near Fairbanks in 1904, and its records represent climatic conditions on the southward-facing permafrost-free slopes. Since 1929, when the Weather Bureau station was moved to Fairbanks, the records represent conditions on the flood plains of the Tanana-Chena Rivers.

The Fairbanks area has a continental climate, characterized by an extreme range between summer and winter temperatures (fig. 12).

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Figure 12. Climatic data for Fairbanks, Alaska.

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The absolute minimum recorded temperature is  $-66^{\circ}\text{F}$ ; the absolute maximum is  $99^{\circ}\text{F}$ . The mean annual number of days with freezing temperatures is 233, and freezing temperatures have been reported during every month except July (U. S. Weather Bureau, 1943).

The mean annual temperature is not the best measure of the duration and intensity of cold. Perhaps a better method to classify the intensity is by the use of the freezing index. The freezing index is the number of degree days during a freezing season. The degree days for any one day equal the difference between the average daily air temperature and  $32^{\circ}\text{F}$ .

The mean air freezing index at Fairbanks, based on a 45-year record of air temperatures, is 5,220 degree days (Carlson, 1952, p. 218). Such a measure of seasonal cold intensity for Anchorage, Alaska, is 3,000 degree days and for Barrow, Alaska, is 8,500 degree days. In contrast to Alaska, the mean freezing index at Minneapolis, Minnesota, is 1,560 degree days and at Burlington, Vermont, it is 1,260 degree days (Linell, 1953, p. 24).

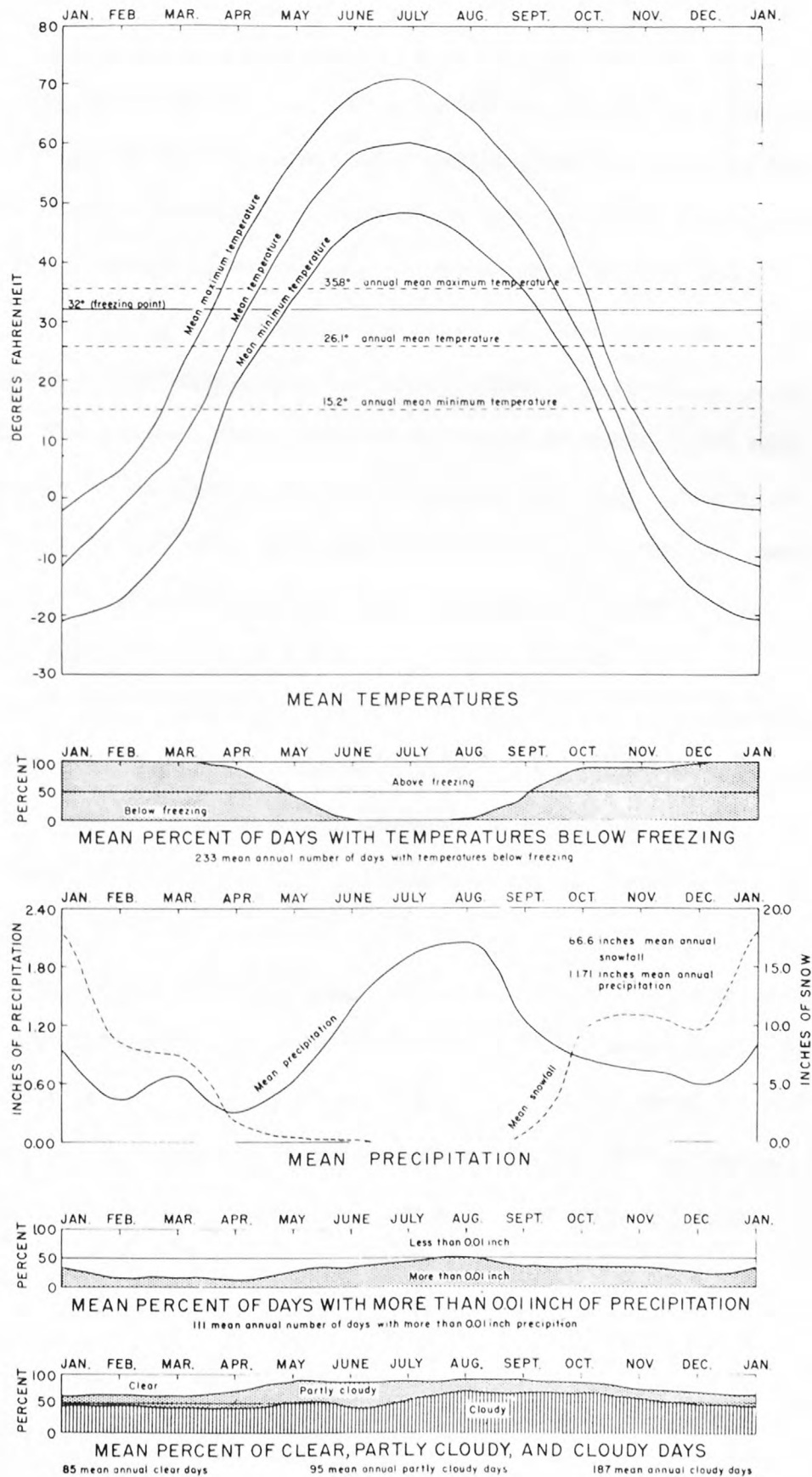


Figure 12. Climatic data for Fairbanks, Alaska.

The wind regimen in central Alaska is, in general, composed of a long, relatively calm winter period from September to May and a short, slightly windy summer period from June to August. A 10-year record at Fairbanks, (U. S. Weather Bureau, 1943) indicates that the prevailing surface-wind direction for winter is north to northeast, and the summer direction is south to southwest. The average wind velocity in winter is about 3.5-4 mph, and in summer it is about 6 mph. The annual mean wind velocity at Fairbanks is 4.9 mph. High winds occur but are uncommon; about one gale is recorded yearly. The percentage of calms for the winter period is 6.3, and for the summer period 3.3.

The mean annual precipitation is 11.7 inches. Thunderstorms occur during the summer, but most of the precipitation during the growing season falls in light showers. Sixty-three percent of the annual precipitation is concentrated in the period May through September.

Evaporation rates probably are relatively high in the Fairbanks area during summer, but no quantitative data are available. Tests at Norman Wells in northwestern Canada reveal that summer evapotranspiration rates are high (Sanderson, 1950). Norman Wells, at the same latitude as Fairbanks, has a similar summer climate.

## Physiography and geology

Fairbanks, about 100 miles south of the Arctic Circle, is on the north side of the broad Tanana River Valley at the base of the hills constituting part of the Yukon-Tanana Upland, an eastward-trending upland between the Yukon and Tanana Rivers (fig. 13). The upland is a maturely dissected area of accordant

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Figure 13. Landform map of the Yukon-Tanana Upland and surrounding area. (Modified slightly from Erwin Raisz's Landform Map of Alaska, prepared for the Quartermaster Corps, U. S. Army, 1948. Reproduced through the courtesy of Dr. Erwin Raisz, Cambridge, Mass.).

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rounded ridges 2,000-3,000 feet in altitude. Scattered discontinuous groups of higher mountains project above the upland ridges to altitudes of 5,000-6,000 feet. The upland is part of a large area of rolling country in central Alaska between the Brooks and Alaska Ranges.

The rounded ridges of the upland near Fairbanks have summits 1,250-1,800 feet above sea level. Local relief ranges from 600 to 1,300 feet. The bedrock is chiefly schist but includes local masses of basalt, quartz diorite, and granite. Loess, windblown silt (Péwé, 1951), ranging in thickness from a few feet on summits to more than 100 feet on middle slopes, blankets the ridges (fig. 4) (Péwé, 1955). The valleys are filled with 10 to 100 feet of gravel overlain by 10 to 300 feet of alluvial silt.

65a  
(p. 66 follows)

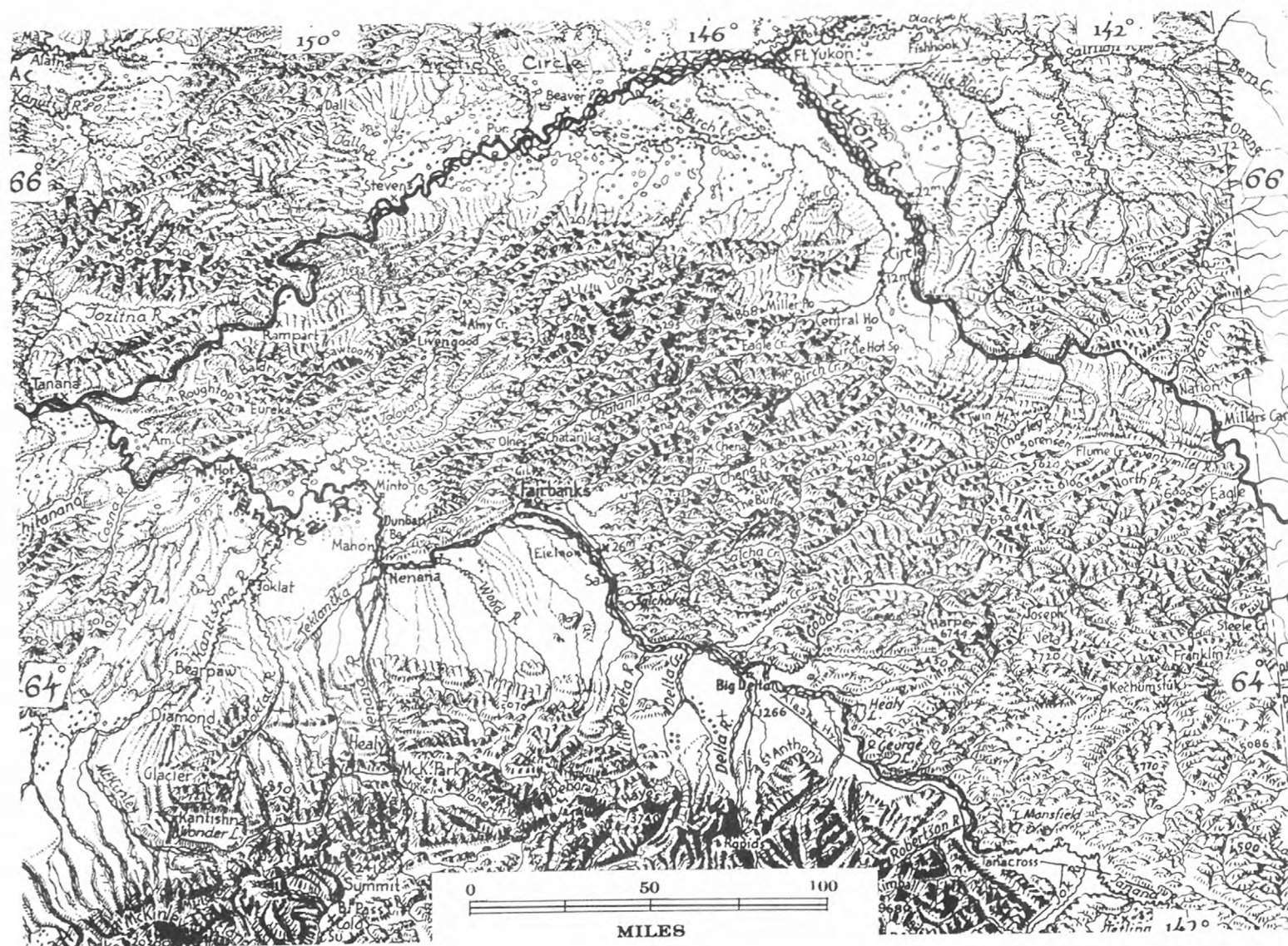


Figure 13.--Landform map of the Yukon-Tanana upland and surrounding area

South of the Yukon-Tanana Upland lies the wide Tanana lowland, a sediment-filled trough between the Upland on the north and the towering Alaska Range on the south. Huge alluvial fans extend northward from altitudes of about 1,000 feet at the foot of the mountains to altitudes of about 450 at Fairbanks.

Central Alaska has not been glaciated, except in small local mountain masses, but glaciers from the Brooks Range on the north, the Alaska Range on the south, and the Yukon Plateau (Bostock, 1948, map 922A) on the east almost surrounded the interior of Alaska during times of glacial maxima. Glaciers from the Alaska Range probably approached within 50 miles of the Fairbanks area (Capps, 1932, pl. 1; Pewé, 1952, p. 1289, Pewé and others, 1953). During the glacial advances, the heavily loaded rivers deposited several hundred feet of sand and gravel in the Tanana and Yukon valleys. Aggradation of the trunk valleys raised base level and caused tributaries from the unglaciated Yukon-Tanana Upland to aggrade their lower valleys. More than 300 feet of sediment was deposited in creek valleys of the upland in the vicinity of Fairbanks.

Despite the small rainfall, the Fairbanks area has abundant lakes, swamps, and marshes. Except on hill tops, steep slopes, and cultivated land the ground is wet almost everywhere during early and middle summer and sometimes throughout the summer. Drainage is poor because underlying perennially frozen ground often prevents downward percolation of water. A luxuriant spongy mat of low vegetation, consisting of mosses and sedges or small shrubs, restricts surface-water movement and acts as a reservoir. Summer thawing of the seasonally frozen ground releases additional water.

The sediments of the floodplain in (Qal) the Fairbanks area (fig. 10) consist of beds and lenticular layers of silt, sand, and gravel. Micaceous sandy silt covers the surface to a depth of 1 to 15 feet. Sandy gravel in proportions of about 40 percent sand and 60 percent gravel make up a layer of variable thickness immediately under the silt. Cobbles approximately 3 inches in diameter are generally the largest in the gravel (Pewe<sup>i</sup>, 1948, p. 4-5). Alternating lenses or beds of silt, sand, and gravel are found to a depth of 364 feet, the deepest well record available. Geophysical work indicates that these sediments continue to a depth of about 700 feet (Pewe<sup>i</sup>, 1958).

The gently sloping area between the hills and the flood plain is composed of alluvial fans and lowlands of well-sorted silt (Qsu) (fig. 10). The apices of the broad, gently sloping, coalescent alluvial silt fans extend well into the upland valleys, in some places almost reaching the crests of the hills. The lower part of the alluvial fans coalesce to form silt aprons around the hills. In addition to the silt fans there are small lowlands of organic silt (muck) and peat (Qso) the largest of which extends from the toe of the fans to the flood plain and lies just north of Ester Road (fig. 10).

In the creek-valley bottoms of the upland, such as Goldstream Creek (fig. 10) the alluvial fan deposits of silt (Qsu) extend from opposite hill slopes and coalesce, flooring the narrow valley bottom with a silt cover 15 to 190 feet thick (fig. 14). The silt is gray to brown, well sorted (fig. 15) and contains organic

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Figure 14. Diagrammatic sketch showing permafrost distribution in Goldstream Valley near Fairbanks, Alaska (after Péwé, 1949).

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Figure 15. Cumulative-frequency curves of organic silt from the Alaska Railroad bridge sites in Goldstream Valley near Fairbanks, Alaska.

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matter in thin beds and lenses, comminuted particles, and local peat and forest beds. The silt is underlain by a layer of angular to subangular gold-bearing gravel (Qg) 5 to 100 feet thick which lies on bedrock. Some of the silt flanking the hills extends outward in a fan, the lower part of which (Qsf) overlies flood plain alluvium.

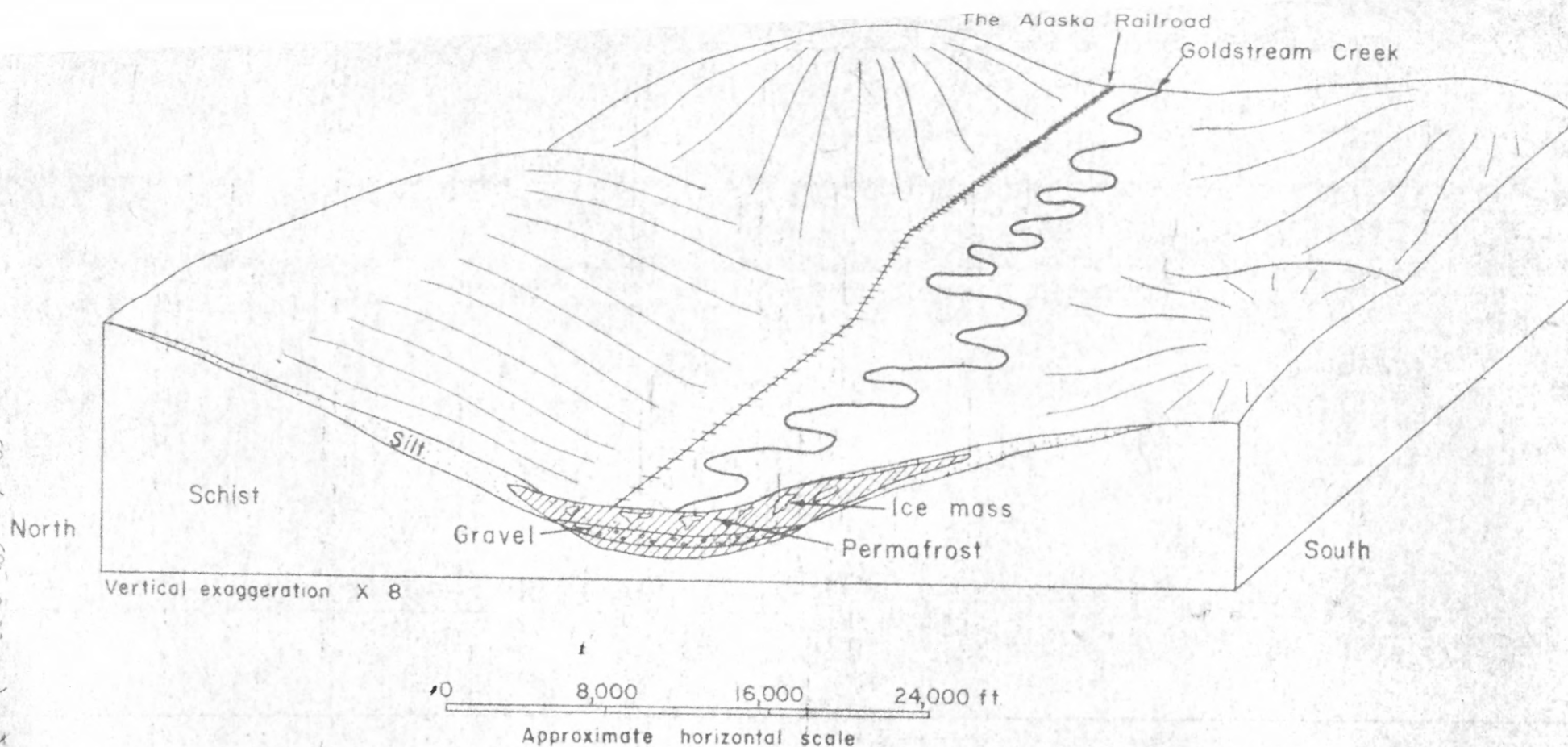


Fig. 14.--Diagrammatic sketch showing permafrost distribution in Goldstream valley near Fairbanks, Alaska (after Péwé, 1949).

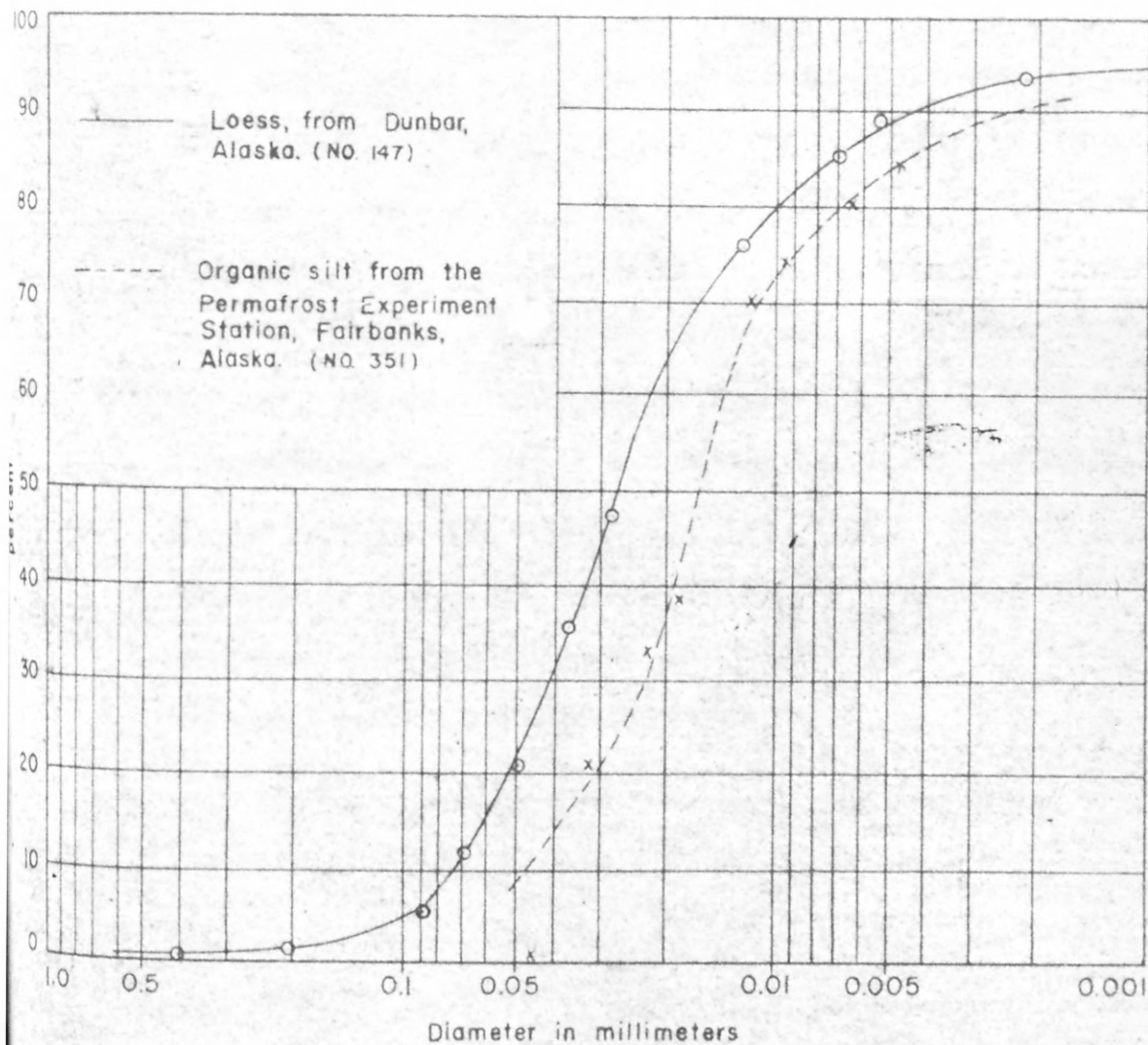


Fig. 15.--Cumulative-frequency curves of organic silt from the  
Alaska Railroad bridge sites in Goldstream valley, Alaska

## Permafrost in the Fairbanks area

Permafrost is a widespread phenomenon in the northern part of North America and Asia; it is estimated to underlie one-fifth of the land surface of the world (Muller, 1945, p. 1). The term "permafrost" was originally coined by Muller (1943) for a shorter and more convenient expression of the phrase, "permanently frozen ground". The term permafrost is now well established; however, a more accurate and commonly designated synonym is, "perennially frozen ground". The need for this more accurate term was realized by Mozley, and he suggested it in 1937; but it did not come into widespread use until after Taber (1943b) published his monograph on frozen ground in Alaska.

Permafrost is present throughout most of Alaska but is more widespread and extends to greater depths in the north than in the south. Alaska can be divided arbitrarily into three generalized permafrost zones, the continuous, discontinuous, and sporadic permafrost zones (fig. 1). In the continuous zone of the north, permafrost is nearly everywhere present and extends to about a depth of 1,000 feet or more (Brewer, 1958). In this area the temperature of permafrost at a depth of 50 to 75 feet is less than  $-5^{\circ}\text{C}$ . (50 to 75 feet is the maximum depth to which appreciable annual temperature fluctuations penetrate the ground). Southward in the discontinuous permafrost zone of central Alaska, the thickness of permafrost decreases, and nonfrozen areas are more and more abundant. Here the temperature of the permafrost at a depth of 50 to 75 feet may be between  $-0.5$  and  $-5^{\circ}\text{C}$ . Permafrost conditions at Fairbanks are probably typical of the discontinuous zone. In the sporadic permafrost zone to the south the perennially frozen ground is confined to local areas and the mean annual ground temperature is generally above  $-0.5^{\circ}\text{C}$ .

Permafrost may be encountered nearly everywhere in the Fairbanks area except beneath hilltops, moderate to steep southward-facing slopes, and under rivers and lakes (fig. 10) (Pewe, 1954, pl. 9). The Tanana River flood plain is underlain by zones of perennially frozen ground interspersed and interstratified with zones in which the sediments are unfrozen. Large ice masses are lacking. The gently sloping alluvial fans (Qsu) that extend from the upland to the flood plain, and also fill the creek valleys of the Yukon-Tanana upland, are underlain by continuous permafrost containing abundant large ground-ice masses except under lakes where permafrost may be absent. In the Fairbanks area the temperature of permafrost below the zone of seasonal fluctuation is about  $-1^{\circ}\text{C}$ .

#### Permafrost of the flood plain

Sediments of the flood plain of the Chena (fig. 10) and Tanana Rivers (2 miles south of map area) are perennially frozen to a maximum known depth of 265 feet but not everywhere is permafrost encountered in a single body. The thickness of the frozen layer varies widely and in many areas permafrost is lacking. Thawed areas occur beneath existing or recently abandoned river channels, sloughs, or lakes. Elsewhere layers of frozen sand and silt are intercalated with unfrozen layers of gravel. The gravel layers are commonly lens-like so that no single unfrozen layer of broad lateral extent exists. Unfrozen vertical zones are connected with unfrozen layers to comprise irregular unfrozen passages throughout the permafrost of the flood plain.

The depth to the top of permafrost in undisturbed areas ranges from 2 or 3 feet in the older parts of the flood plain to more than 4 feet on the inside of meander curves near the rivers. As the river meander advances, permafrost forms in the new deposits on the slipoff slope (Pewé, 1947). Fires, clearings, and construction since 1903 have increased the depth to permafrost from 3 to 4 feet to as much as 25 to 40 feet in many places.

Ice in the perennially frozen sediments of the flood plain consists of granules and cement between mineral grains. Large ice masses, common beneath the colluvial slopes, are lacking in sediments of the flood plain. This condition may be due in part to the coarseness of the flood plain sediments, which are less favorable for growth of large ice masses than the well-sorted silt of the slopes and creek-valley bottoms.

### Permafrost of the silt fans and silt lowland

Permafrost in the alluvial fans (Qsu) and silt lowlands (Qso) probably extends unbroken from the flood plain of Chena River to the hills. Perennially frozen ground in the silt fans and lowlands reaches a known maximum thickness of 176 feet near the flood plain and in creek-valley bottoms but decreases toward the hills, pinching out at the base of steep southward-facing slopes. Permafrost may extend further upslope on northward-facing slopes. The permafrost may consist of a few isolated, small bodies where it becomes very thin near the contact with permafrost-free slopes.

Permafrost lies at a depth ranging from 2 to 4 feet on the lower slopes and in creek-valley bottoms such as Goldstream Valley and at a depth ranging from 5 to 20 feet near the contact with the permafrost-free slopes. Depth to permafrost is 1 to 3 feet in the poorly drained silt and peat lowlands.

Permafrost in the fans (Qsu) and lowlands (Qso) is characterized by large masses of ice occurring as horizontal sheets, vertical or inclined sheets, and wedges a quarter of an inch to 10 feet in thickness and from 1 to 100 feet in length and width. The ice in some masses is clear but most masses contain many silt particles that give the ice a gray color. Much of the ice is arranged in a polygonal or honeycomb-like network that encloses silt polygons 10 to 40 feet in diameter. The ice masses lie at depths of 5 to 25 feet in the fans (Qsu) and  $1\frac{1}{2}$  to 5 feet in the silt lowland (Qso). Large masses of ground-ice are not unique to the Fairbanks area and have been reported from many other localities in Alaska (Kotzebue, 1821, v. 1; Leffingwell, 1915, 1919; Taber, 1943b; Frost, 1950; Black, 1951; Hopkins, Karlstrom and others, 1955).

#### Boundaries between areas with and without permafrost

The boundary between permafrost and permafrost-free areas is determined by plotting ground temperature measurements, well log data, the distribution of thermokarst features (Pewe<sup>1</sup>, 1954, p. 329) in cleared fields, and changes in plant cover. The most accurate criteria for determining this boundary are temperature measurements (fig. 11) and well data, which can reliably indicate the presence of permafrost even though it may underlie a thawed layer 20 or 25 feet thick. Less reliable indicators for determining the boundary are thermokarst features and vegetation (Pewe<sup>1</sup>, 1954, p. 329).

The boundary between the permafrost and the permafrost-free areas is at a higher altitude on northward-facing slopes that receive less solar heat than the southward-facing slopes. Permafrost locally reaches to the summit of low-angle northward-facing hillslopes. Generally, however, the contact is near a break in slope such as the contact between erosional and depositional slopes; where the steeper angle of a hillside gives way to a more gentle slope, drainage becomes sluggish and the water-saturated ground is frozen.

#### Frost action in the Fairbanks area

An extensive blanket of silt, long periods of freezing, and poor drainage form ideal conditions for intense seasonal frost action in Central Alaska. Four broad zones of frost action intensity are present in the Fairbanks area: (1) loess-covered hills, (2) lower hillslopes and creek valley-bottoms, (3) organic silt lowlands, and (4) flood plains of the Chena and Tanana Rivers (figs. 1, 10). These zones coincide with the permafrost zones in the area.

Hilltops and steep or moderate southward-facing hillslopes are not underlain by permafrost, and drainage is good except locally on flat summits and saddles; therefore, frost action is absent to mild, and damage to engineering structures is rare.

The silt deposits of the lower hillslopes and creek valley bottoms are underlain by an impermeable substratum of permafrost, especially in valley bottoms, and drainage is poor. As a result frost action is intense in these fine-grained sediments, and most of the engineering structures on these slopes and valley bottoms (except near the contact with the permafrost-like loess) have been damaged. Structures damaged are railroad tracks, pile bridges, highways, and buildings.

The areas of most intense frost action are the lowland of organic silt between the Farmers Loop Road and Ester Road and two small lowland areas in Goldstream Valley (fig. 10). These poorly drained areas of organic silt and peat are underlain by continuous permafrost and contain few engineering structures. Where the Ester Road crosses the lowland (fig. 10), the highway is damaged by frost action and thawing of permafrost.

The flood plains of the Chena (fig. 10) and Tanana (fig. 1) Rivers support most of the engineering structures in the Fairbanks area; here is built the city of Fairbanks, the International Airport, and Ladd Air Force Base (the latter two are outside the limits of fig. 10). The silt of the flood plain is poorly to fairly well drained. Drainage improves when the vegetation is removed and the permafrost table subsequently lowered. Locally, the flood plain silt is poorly drained and subject to intense frost action.

Many meander scars, swales, and intermittent drainage lines filled with organic silt trend sinuously across the flood plain. These deposits are poorly drained and highways and buildings on this material have been seriously damaged by freezing and thawing of moisture in the ground. The organic silt is 1 to 30 feet thick and in some places has been removed prior to construction.

#### Economic considerations

The engineering geology problems of frost heaving of bridge piling of The Alaska Railroad are of economic importance because of the maintenance necessary to: (1) maintain track elevation in the winter by temporary methods; (2) correct the elevation in the summer by more permanent methods; and (3) replace bridge piling periodically.

Piles are frost heaved as much as 14 inches per year. To maintain track elevation in the winter and early spring it is necessary to raise the track at either end of the bridge by inserting wedges (shims) under the rails (Tessendorf, 1956, p. 94-95). As much as 6 to 8 inches of cumulative "shimming" is necessary adjacent to some bridges every year.

In the summer the former elevation of the track is regained by removing the shims and reducing the elevation of the frost-heaved rail. The latter is accomplished by chopping a few inches from the wooden caps or beams or by removing the caps and sawing off the top of the frost-heaved piles.

Frost-heaved pile bridges must be replaced more often than would be necessary under conditions of no frost action. If 4 to 14 inches of the pile, for example, are sawed off each year, the structure is soon weakened and new piles must be driven. Since each pile is heaved a different amount, differential stresses are set up in the bridge with the resulting failure of cross-braces and other structural members.

It is estimated that it costs \$125.00 per pile to replace the wood-piles on an average bridge in Goldstream Valley (I. P. Cook, The Alaska Railroad, written communication, Nov. 28, 1956). Frost action has elevated piles consistently on some bridges, and 2 or 3 sets of old piles at a bridge site is evidence of periodic replacement.

Added to increased maintenance expense is the cost of slowing down a heavily loaded train because of track irregularity produced by a frost-heaved bridge. It is estimated that it costs \$10.00 to reduce speed of a 70-car freight train from 40 mph to 20 mph and then regain the original speed (I. P. Cook, The Alaska Railroad, written communication, Nov. 30, 1956).

### Location of bridge sites and method of study

The three wood-pile bridges of The Alaska Railroad which were systematically observed for the effect of frost heaving of piling are at mile posts 456.7, 458.4, and 460.4 (fig. 10). The mile post at Fairbanks is 470.3.

These bridges were visited winter and summer from the winter of 1953-54 until the summer of 1957. The position of the permafrost table was determined by hand augering in early fall of 1954 and 1955 and seasonal frost thickness was determined in 1956 by use of a 16-inch diameter power auger provided by The Alaska Railroad. Samples of the ground were taken from the walls of the auger holes for determination of moisture content. Moisture content was computed as a percentage of the oven-dry weight of the sample. Thicknesses of silt, gravel, and permafrost were obtained from prospect drilling records of the United States Smelting, Refining, and Mining Company.

## Bridge at mile post 456.7

### Description

The wooden bridge which is 43 feet long is supported by four bents of piles and spans a small creek that lies in a V-shaped valley 15 feet below the elevation of the track (fig. 16). The creek

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Figure 16. The Alaska Railroad bridge at mile post 456.7 in Goldstream Valley near Fairbanks, Alaska showing three generations of piles. (Photographs by T. L. Pewe)

A. Total depth of small creek valley observable in summer.

Sept. 22, 1954.

B. Same locality with 7 feet of aufeis beneath bridge. Feb. 3, 1956.

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generally has only a few inches of water and drains southward from the loess-covered slopes across gently sloping terrain into Goldstream Creek.

### Geology of the site

A gold prospect drill hole 700 feet south of the site indicates that 23 feet of organic silt overlies 8 feet of creek gravel which in turn lies on bedrock.



View A.



View B.

Figure 16. The Alaska Railroad bridge at mile post 456.7 in Goldstream Valley near Fairbanks, Alaska showing three generations of piles. (photographs by T. L. Péwé)

- A. Total depth of small creek valley observable in summer. Sept. 22, 1954
- B. Same locality with 7 feet of aufeis beneath bridge. Feb. 3, 1956.

## Permafrost

Permafrost extends from within 2 feet of the surface down to more than 37 feet, the total depth of the prospect hole. Base of permafrost was not reached.

Permafrost is close to the surface except in the drainage way; as shown in figure 17 the permafrost table on September 27, 1955,

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Figure 17. Geologic cross sections at The Alaska Railroad bridge at mile post 456.7 in Goldstream Valley near Fairbanks, Alaska.

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was about 9 to 10 feet below ground surface at the end of the bridge and 10 feet deep under the creek bed. These permafrost determinations indicated the permafrost table to be within 2 inches of that measured on September 29, 1954.

No data are available concerning the temperature and moisture content of the perennially frozen silt at this site; however, a U. S. Geological Survey temperature cable 350 feet south of the railroad tract at mile post 459.75 indicates that the temperature of the permafrost at 70 feet was  $-0.88^{\circ}\text{C}$  on May 31, 1957 (fig. 11). Moisture content for similar perennially frozen material near Fairbanks (fig. 10) ranges from 40 to 180 percent by dry weight (Corps of Engineers, 1955, fig. 2).

## Aufeis

Aufeis, or overflow ice, is a common feature on many streams in Alaska. Because of the long duration of intense cold, streams freeze to the bottom forcing water to overflow and form ice on top of the original ice. This process continues throughout the winter with the development of several layers of ice, some of which are separated one from another by moving water. Little or late snowfall favors the formation of aufeis. It is not unusual for great thicknesses of aufeis to form on streams, and such ice may cover structures or objects built or left near the river.

A considerable thickness of aufeis forms every winter in the drainageway crossed by the bridge at mile post 456.7. In February, 1954, the aufeis was  $10\frac{1}{2}$  feet thick under the bridge and covered all but the upper 2 feet of the piles (fig. 18). In March, 1955,

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Figure 18. Steam thawing of holes for pile installation at The Alaska Railroad bridge at mile post 456.7 in Goldstream Valley near Fairbanks, Alaska. New bridge is in place. Aufeis surface within 2 feet of lower bridge surface. (Photograph by T. L. Pewe, Feb. 11, 1954.)

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aufeis was only a few feet thick and on February 22, 1956, ice was about 7 feet thick in the center of the drainageway (fig. 16b).



Figure 18. Steam thawing of holes for pile installation at The Alaska Railroad bridge at mile post 456.7 in Goldstream Valley near Fairbanks, Alaska. New bridge is in place. Aufeis surface within 2 feet of lower bridge surface. (Photograph by T. L. Pewé, Feb. 11, 1954).

### Seasonal frost

The temperature, moisture content, and thickness of the seasonal frost in this drainageway under the bridge was determined on February 22, 1956 (fig. 17). In Hole A on the right bank the seasonally frozen ground, which lay under a 3-foot cover of snow, is composed of organic silt with a few twigs. The upper 6 inches contains gravel pebbles from the railroad fill. The seasonal frost was 3 feet 4 inches thick, and the temperature was determined by inserting a glass thermometer graduated by  $2^{\circ}\text{C}$  in a close-fitting hole bored in the wall of the large excavation. The thermometer was inserted all the way (buried) and left for 20 minutes.

A silt sample taken 2 feet below the surface in Hole A contained 62.1 percent moisture (fig. 19).

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Figure 19. Lithology, moisture, and temperature data from drill holes at The Alaska Railroad bridge sites at mile posts 456.7, 458.4, and 460.4 in Goldstream Valley near Fairbanks, Alaska.

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A second hole was augered in the middle of the drainageway; however, as soon as 5 feet of aufeis was penetrated, water trapped between the aufeis and the ground bubbled up with a great flow. Water was still flowing vigorously from this 16-inch diameter hole more than 2 hours later.

A third hole, Hole B, was drilled on the left bank of the stream near Bent III (fig. 17). This hole went through  $4\frac{1}{2}$  feet of aufeis and  $3\frac{1}{2}$  feet of seasonal frost. The seasonally frozen silt is slightly organic and contains 6 inches of gravel fill at the top. No temperature measurements were made, but a silt sample taken 2 feet from the surface had 75 percent moisture.

#### Unfrozen ground

About 7 feet of unfrozen silt is present between the seasonally frozen ground and the perennially frozen ground at Hole A. A sample taken 1 foot below the base of the seasonal frost had a moisture content of 43 percent. In Hole B about 10 feet of unfrozen silt occurs between the seasonal frost and the permafrost. A silt sample taken 4 inches below the base of the seasonal frost contained 65 percent moisture.

#### History of bridge

A bridge was built at this site in 1917. Little information is available concerning maintenance on this bridge in the early years except that it reportedly was affected by frost heaving annually. Piles probably were replaced during the 30-year interval from 1917 to 1947, but the earliest record of pile replacement is in 1947.

The 1947 piles were regularly elevated 2 or 3 or more inches by frost heaving every year; the tops of the piles were sawed off periodically and the caps chopped down at intervals. The cap on the 1947 piles in Bent III (fig. 18) has been partly chopped away to lower the track 2 inches. Figure 20 illustrates the

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Figure 20. Deformation of wood bridge by frost action. Mile post 456.7, The Alaska Railroad in Goldstream Valley near Fairbanks, Alaska. The cross-brace has been split by upward thrusting of the pile. The cap beam has been chopped to lower the track after upward movement by frost heaving. (Photograph by T. L. Pewe, Feb. 11, 1954)

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chopped cap as well as a cross-brace that was split by frost heaving of the pile. No record is available as to the depth that the piles penetrated the permafrost; however, inasmuch as the piles were frost heaved, they probably did not penetrate permafrost very far.



Figure 20. Deformation of wood bridge by frost action. Mile post 456.7, The Alaska Railroad in Goldstream Valley near Fairbanks, Alaska. The cross-brace has been split by upward thrusting of the pile. The cap beam has been chopped to lower the track after upward movement by frost heaving. (Photograph by T. L. Pewe, Feb. 11, 1954)

In February of 1954 new piles were placed under this bridge. Inasmuch as the method of pile emplacement is vital to the problem of frost action on piling in permafrost areas, a description of the method used is included. The piles are driven into a steam-thawed hole. Holes are thawed in frozen silt by forcing steam under pressure through a three-fourth inch diameter steel pipe 20 feet long with three small holes at the end. Steam is supplied to the pipe by a rubber hose (fig. 18). The pipe is held vertically and forced down into the ground, thawing the ground as it progresses.

The holes are crudely thawed and are larger than the diameter of the pile. The piles in the bents are about  $2\frac{1}{2}$  to 3 feet apart; however, because of excess thawing the end result is not a series of holes but a coalescence of thawed holes to form a trench of thawed ground about 2 or  $2\frac{1}{2}$  feet wide and 15 feet long.


Generally, piles are not driven into fresh holes immediately after they are thawed, but a series of holes are first thawed and then a series of piles are driven. This necessitates keeping the mud in the earlier holes warm from one day to several days. If a pile is not placed in a hole before quitting time the thawed hole is covered with snow (in wintertime) to prevent it from freezing until work is resumed the next day or next week. Workers report

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✓ Pile driver crew, Bridge 456.7; oral communication, Feb. 11, 1954.

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that during a Christmas vacation one year the holes were covered with snow to keep the mud from freezing, and that two weeks later, when the piles were driven, the mud that oozed out was still warm.

The 1954 piles were installed with the large (butt) end down in an attempt to minimize the effect of frost heaving. Records of the depth of penetration of the piles indicated that penetration into the ground ranges from 11 to 33 feet. An example of the variation in the penetration is illustrated by Bent III and by a longitudinal cross section of the bridge (fig. 17) . Several

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 In order to combat frost heaving the piles were to be driven to a depth of at least 15 feet. A penetration of 15 feet from ground surface in February would mean penetration of only 11 or 12 feet of sediment because of the 3 or 4 foot thickness of overlying ice.

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piles in the center of the drainageway do not penetrate permafrost, but some of the piles, especially on the end bents, penetrate more than  $11\frac{1}{2}$  feet of permafrost.

The bridge at mile post 456.7 was examined during the summers and winters of 1954, 1955, 1956, and no evidence of frost heaving was noticed during the two winters since the installation of the piles in 1954.

## Bridge at mile post 458.4

### Description

The bridge is 71 feet long and is supported by six bents of wooden piles. It spans a small creek which drains the hills to the north and empties into Goldstream Creek (fig. 21). This

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Figure 21. The Alaska Railroad bridge at mile post 458.4 in Goldstream Valley near Fairbanks, Alaska. Compare with figure 23. (Photographs by T. L. Pewe.)

- a. Bridge bowed up 9 inches by frost action on center piling. Feb. 11, 1954.
- b. Bridge lowered and placed on new piling. April 28, 1954.
- c. Total depth of small creek valley observable in summer. Sept. 29, 1954.
- d. Bridge bowed up 3 inches by frost action on center piling. Feb. 3, 1956. Compare aufeis level with level shown in B.

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unnamed creek lies in a flat-floored valley 11 feet below track level and flows southward between two gently sloping alluvial fans of silt.



View A.



View B.

Figure 21. The Alaska Railroad bridge at mile post 458.4 in Goldstream Valley near Fairbanks, Alaska. Compare with figure 23. (Photographs by T. L. Pêwé)

- A. Bridge bowed up 9 inches by frost action on center piling. Feb. 11, 1954.
- B. Bridge lowered and placed on new piling. Apr. 28, 1954.



View C.



View D.

Figure 21. The Alaska Railroad bridge at mile post 458.4 in Goldstream Valley near Fairbanks, Alaska. Compare with figure 23. (Photo by T. L. P. C. Total depth of small creek valley observable in summer. Sept. 29, 1955. D. Bridge bowed up 3 inches by frost action on center piling. Feb. 3, 1956. Compare aufeis level with level shown in B.

## Geology of the site

A gold prospect drill hole 600 feet west of the bridge shows that there is 28 feet of organic silt overlying 14 feet of creek gravel which in turn lies on bedrock.

## Permafrost

Permafrost extends from within 2 feet of the surface down to more than 52 feet, the total depth of the prospect hole. Base of permafrost was not reached. Permafrost is close to the surface except in the drainageway. The permafrost table on September 29, 1954, was about 11 or 12 feet below ground surface at the ends of the bridge but was 13 feet deep under the creek (fig. 22). Perma-

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Figure 22. Geologic cross sections at The Alaska Railroad bridge at mile post 458.4 in Goldstream Valley near Fairbanks, Alaska.

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frost determinations on September 27, 1955, indicated the permafrost table to be within 4 inches of that measured in 1954.

The temperature and moisture content conditions of the perennially frozen ground at this locality are similar to the conditions cited for the bridge at mile post 456.7.

## Aufeis

Aufeis was 5 feet thick in the drainageway in March 1954. During the winter of 1955 only about 3 feet formed. On February 21, 1956, the amount of aufeis encountered in auger holes A, B, and C was 2 feet 9 inches, 3 feet 3 inches, and 3 feet respectively (fig. 19).

## Seasonal frost

The moisture content and thickness of the seasonal frost in this drainageway under the bridge was determined on February 21, 1956. No temperature measurements were taken.

Hole A was drilled between Bents II and III on the west side of the little valley (fig. 22). The hole penetrated 2 feet 9 inches of aufeis and 2 feet 11 inches of seasonal frost. The seasonally frozen ground is organic silt except for the upper 6 inches which contains some gravel from the roadbed. A silt sample taken 2 feet below the surface contained 64.9 percent moisture (fig. 19).

Hole B was drilled between Bents III and IV in the center of the valley. Aufeis 3 feet 3 inches thick overlay 3 feet of seasonally frozen organic silt with a few twigs and wood fragments. The upper 6 inches of the ground contain a few pebbles. A sediment sample taken 10 inches below the surface contained 42 percent moisture.

Hole C was drilled between Bents IV and V on the east side of the valley (fig. 22). The hole penetrated 3 feet of aufeis and 3 feet 6 inches of seasonally frozen silt. As in the previous holes, the upper 6 inches of the ground contains a small amount of gravel. The moisture content of a sediment sample taken a foot beneath the surface was 51.6 percent (fig. 19).

#### Unfrozen ground

About  $10\frac{1}{2}$  feet of unfrozen ground is present between the seasonally frozen ground and the perennially frozen ground at Hole A. A sample of ground taken 6 inches below the base of the seasonal frost contained 58 percent moisture. At Hole B, 11 feet of unfrozen silt occurs between the seasonal frost and the permafrost. This hole is in the middle of the drainage way and the unfrozen ground is very wet. Five inches below the base of the seasonal frost the ground contained 61 percent moisture and a silt sample taken 20 inches below the base of the seasonal frost contained 71 percent moisture. Near Hole C there is 9 feet of unfrozen silt between the seasonally and perennially frozen ground. The moisture content of the ground at a point 8 inches below the base of the seasonal frost was 61 percent.

## History of bridge

This wooden pile bridge, which was built originally in 1917, is affected more by frost heaving than any other pile bridge of The Alaska Railroad. Serious frost heaving of the bridge has occurred for many years and has caused expensive maintenance. The earliest record of pile replacement is in 1923 when new piles were driven for all bents. These piles were emplaced to various depths and the amount of penetration ranged from about 12 to 23 feet. Greatest penetration was under the end bents. These piles were installed by the same method as those on bridge 456.7 and some of them penetrated 6 or 8 feet of permafrost, but some, especially in the middle of the bridge, did not penetrate permafrost at all. It is assumed that the permafrost level was approximately the same in 1923 as it was in 1955 because there were no drastic changes in the vegetative cover, drainage, or climate between 1923 and 1955.

The piles installed in 1923 were greatly affected by frost heaving. During the winter of 1952-53, for example, the center of the bridge was frost heaved 14 inches. Such a displacement produced a sharp bend in the track, sharp enough to uncouple cars of a train. It was necessary to saw off 14 inches from the top of the piles to restore the track to grade. This action, plus the stresses on the bridge over the preceding years must have considerably weakened the structure. During the winter of 1953-54 the piles began to be pushed up in December. This is a little unusual because in most years the elevating of piles by frost heaving is not evident until January. However, during October of 1953 the air temperature was colder than usual and the snowfall was lighter. This colder weather coupled with the reduced insulation of the ground by snow may have permitted more ground freezing and ice accumulation than in normal years. By February, 1954, the center of the bridge was pushed up 9 inches (fig. 21A; fig. 23A). In the latter part of February new piles were installed and the

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Figure 23. Views of roadbed and track of The Alaska Railroad bridge at mile post 458.4 in Goldstream Valley near Fairbanks, Alaska. (Photographs by T. L. Pewe.)

- a. Bridge with hump in center caused by bridge piling being raised 9 inches by frost action. Feb. 11, 1954.
- b. Bridge lowered and placed on new piling. Track on bridge now lower than track on each side which is still "shimmed" up to accommodate hump formerly present in bridge. April 28, 1954.
- c. Bridge not disturbed by frost action. Jan. 14, 1955.
- d. Bridge with small hump in center caused by bridge piling being

raised 3 inches by frost action. Feb. 3, 1956.

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bridge lowered. These piles were installed in the manner described for bridge 456.7, and penetrate the ground to depths ranging from 18 to 30 feet (fig. 22). None of the piles in the center of the bridge penetrate permafrost very far and some do not penetrate the permafrost at all. Most of the piles in the end bents are placed deeply in permafrost. The piles of this bridge were not frost heaved during the winter of 1954-1955 (fig. 23C).



View A.



View B.

Figure 23. Views of roadbed and track of The Alaska Railroad bridge at mile post 458.4 in Goldstream Valley near Fairbanks, Alaska. (Photographs by T. L. Pêwé)

- A. Bridge with hump in center caused by bridge piling being raised 9 inches by frost action. Feb. 11, 1954.
- B. Bridge lowered and placed on new piling. Track on bridge now lower than track on each side which is still "shimmed" up to accomodate hump formerly present in bridge. April 28, 1954.

95a (p. 95b follows)



View C.



View D.

Figure 23. Views of roadbed and track of The Alaska Railroad bridge at mile post 458.4 in Goldstream Valley near Fairbanks, Alaska. (Photographs by T. L. Péwé)

C. Bridge not disturbed by frost action. Jan. 14, 1955.

D. Bridge with small hump in center caused by bridge piling being raised 3 inches by frost action. Feb. 3, 1956.

During the second winter (1955-56) after pile installation, the effect of frost heaving on the bridge was quite evident. By February 3, 1956, the bridge had been elevated 3 inches at Bent III (fig. 21D; fig. 23D). By the end of the winter the bridge was elevated 5 inches.

#### Bridge at mile post 460.4

#### Description

The bridge is 91 feet long and is supported by 10 bents of wooden piles (fig. 24). It spans Goldstream Creek which is 20 feet

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Figure 24. Side views of The Alaska Railroad bridge at mile post 460.4 over Goldstream Creek near Fairbanks, Alaska. No frost action apparent. (Photographs by T. L. Pewe.)

a. View north (upstream) Sept. 27, 1955.

b. View north (upstream) Feb. 3, 1956.

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wide and 4 feet deep at a normal stage of the water. At such a stage the water is about 18 feet below track elevation.



View A.



View B.

Figure 24. Side views of The Alaska Railroad bridge at mile post 460.4 over Goldstream Creek near Fairbanks, Alaska. No frost action apparent. (Photographs by T. L. Péwé)

A. View north (upstream) Sept. 27, 1955.

B. View north (upstream) Feb. 3, 1956.

### Geology of the site

A gold prospect drill hole 800 feet west of the bridge (and 100 feet from Goldstream Creek) shows 13 feet of organic silt overlying 96 feet of creek gravel which in turn overlies bedrock. Hand augering during the fall of 1955 revealed creek gravel near the surface of this site. The stream bed of the creek is gravel with a veneer of silt. At the west side of the bridge, 13 to 15 feet of silt overlies the gravel (fig. 25).

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Figure 25. Geologic cross section at The Alaska Railroad bridge at mile post 460.4 over Goldstream Creek near Fairbanks, Alaska.

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### Permafrost

In the forested area near the bridge permafrost extends from within 2 feet of the surface down to more than 109 feet, the total depth of the prospect hole. Base of permafrost was not reached. No permafrost was found in either the silt or the gravel by hand augering in the vicinity of the bridge, although permafrost is within 2 feet of the surface in the forested area only 100 feet away from the bridge.

## Aufeis

A few feet of aufeis forms over Goldstream Creek during the winter but the ice is confined by steep banks to the area immediately above the creek.

## Seasonal frost

The thickness, temperature, and moisture content of the seasonal frost in the drainageway under the bridge was determined on February 21, 1956. Hole A was drilled adjacent to the roadbed fill near Bent III and penetrated 3 feet of seasonally frozen silt (fig. 19). Hole B was drilled adjacent to Bent IV on the south side of the bridge and penetrated 2 feet 9 inches of seasonally frozen slightly organic silt. In Hole B samples of ground for moisture determinations were taken at 11 inches and 1 foot 9 inches from the surface of the ground; the moisture contents were 18 percent and 62 percent respectively.

Temperature measurements were made of the seasonally frozen ground in Hole B by the method described for bridge 456.7. The temperature at a depth of 10 inches below the surface was  $-2.2^{\circ}\text{C}$ . At a depth of 1 foot 6 inches it was  $-1.7^{\circ}\text{C}$ ; and at a depth of 2 feet 3 inches it was  $-0.6^{\circ}\text{C}$ . Temperature of the air at the time ground temperatures were determined was  $-23.5^{\circ}\text{C}$ .

Hole C was drilled at Bent V near the break in slope on the west bank of Goldstream Creek. Seasonal frost was 3 feet 10 inches thick and rather "dry". The moisture content of a sample taken 1 foot 5 inches below the surface contained only 5.9 percent moisture (fig. 19).

#### Unfrozen ground

About 15 feet of unfrozen slightly organic silt occurs between the seasonally frozen silt and the underlying creek gravel near Hole A. No evidence is available from hand augering to indicate that the gravel is frozen. At Hole B about 14 feet of unfrozen silt lies under the seasonal frost and above the creek gravel. A sample of the unfrozen ground 3 inches below the base of the seasonal frost contained 30 percent moisture. The temperature of the unfrozen ground 2 inches below the base of the seasonal frost was  $-0.0^{\circ}\text{C}$ .

In Hole C about 10 feet of unfrozen silt is present between the frozen silt and the gravel (fig. 25). This silt is moist (moisture content 37.3 percent 2 inches below the base of seasonal frost) and becomes more moist downward until the water table is encountered at a depth of 8 feet below the ground surface.

### History of bridge

When this bridge was originally built in 1917 only the piles in Bents III, IV, V, and VI penetrated the gravel. New piles were installed in 1939 and again in 1954, and most of these piles penetrated considerably deeper.

No record has been found of any deformation of this bridge due to frost heaving of piling.

### Interpretation

Studies of frost heaving of piling of bridges of The Alaska Railroad serve well to illustrate principles of the mechanics of frost heaving of piling as well as to show the position and properties of permafrost that are concerned with such principles. As discussed earlier, the factors affecting frost heaving of piling deal with the upward forces (fig. 4). The amount of the upward force on piling is dependent upon: (1) intensity of frost heaving, (2) the tangential adfreezing strength between the pile and the seasonally frozen ground, and (3) surface area of the pile in the seasonally frozen ground.

### Upward forces

The piles at bridge 458.4 penetrate seasonally frozen moist organic silt (fig. 15) and will be used as an example to illustrate the upward and downward forces acting on piles. As discussed earlier such sediment is ideal for the formation of ground-ice with resultant frost heaving. The organic matter provides minute discontinuities to act as ice growth centers as well as to increase moisture. A small stream adjacent to the piles provides a high water table ideal for a source of water during freezing.

The duration and intensity of winter freezing in central Alaska is great (fig. 12). Drilling in February 1956 indicated 3 feet 6 inches of seasonally frozen ground under about 3 feet of snow. Seasonal frost generally continues to form during the month of March and even into April and, therefore, the base of the seasonal frost indicated in figures 17, 22, and 25 is not quite the maximum depth of frost penetration. Heavy snowfall during the winter of 1955-56 perhaps prevented maximum seasonal frost penetration in the Fairbanks area. Therefore, it probably is safe to assume that at least 4 feet of seasonally frozen ground is formed in an average year in the vicinity of the piling of bridge 458.4.

Considering the principles outlined earlier, it is possible to estimate the maximum available upward force applied to piles by frost heaving of ground adfrozen to the piles at this bridge. The maximum available upward force is:  $UF = h_1 \times P \times T_1$ .

The length of the pile in the seasonally frozen ground is assumed to be 48 inches and the circumference of the pile is 38 inches. It is now necessary to determine the tangential adfreezing strength between the pile and the organic silt at the bridge. The silt has a temperature of  $-2.2^{\circ}\text{C}$ . to  $-0.6^{\circ}\text{C}$  and a moisture content of about 50 to 60 percent. Based on data reported earlier (tables 1-5; figs. 7, 8) an estimate of  $45\text{ lbs/in}^2$  for the tangential adfreezing strength between the wood pile and this silt is considered probable.

$$UF = 48 \times 38 \times 45 = 82,080\text{ lbs.}$$

When there is growth of ground-ice and frost heaving in the silt under this bridge there is a maximum force available of 82,080 lbs. pushing upward on each pile near the center of the bridge.

#### Downward forces

Resistance to the upward force is given by: (1) weight of the pile, (2) load on the pile, (3) skin friction of the unfrozen ground, and (4) tangential adfreezing strength between the pile and the permafrost.

Pile No. 5 of Bent IV in the 1923 bridge did not penetrate permafrost and the maximum forces resisting upward movement would be:

$$DF = W + L + (h_2 \times P \times sk)$$

The weight of a pile is less than 1,000 lbs. and the load is less than 2,000 lbs. This pile extended 8 feet into unfrozen ground and had a perimeter of 40 inches. Skin friction is estimated at 2 lbs/in<sup>2</sup>.

$$DF = 1,000 + 2,000 + (96 \times 40 \times 2) = 10,680 \text{ lbs.}$$

From this it is evident that the maximum available upward force on this pile (82,080 lbs.) exceeded the maximum available resisting force and the pile was easily elevated by frost action for several years until it was replaced.

The 1954 piles penetrated deeper into permafrost than those of 1923. As illustrated in figure 22, the 1954 piles of Bent III of bridge 458.4 penetrate different depths into permafrost. If all but one pile are securely anchored, this one pile still can be elevated by frost heaving with such force that it can push up the bridge, even to pushing the bridge away from the anchored piles.

Pile No. 4 of Bent III (1954) can be assumed to have a maximum upward force of about 82,000 lbs. applied when frost heaving is active. The maximum resisting or downward force on this pile should be:

$$DF = W + L + (h_2 \times P \times sk) + (h_3 \times P \times T_2)$$

The pile is embedded 9 feet into permafrost and passes through 8 feet of unfrozen ground. The tangential adfreezing strength of wood pile in warm permafrost, such as is present here, can be estimated from experimental work by the Corps of Engineers (Linell, 1959) in similar sediment under similar moisture and climatic conditions. They report that for wood piles that were placed in drilled holes the pile failed structurally upon extraction and the full tangential adfreezing strength was not determined. The piles failed at  $21 \text{ lbs/in}^2$ . However, as discussed earlier the "plastic flow" limit, the limit at which the bond between the frozen ground and the pile fails under slow steady pressure, probably is the tangential adfreezing strength determination that should be used in frost action calculations. No "plastic flow" determinations were made on wood piling because of pile failure; however,  $20 \text{ lbs/in}^2$  appears to be about average for the concrete and steel piles. This figure may be too high for creosoted wood piles; however, it will be used for calculations.

$$DF = 1,000 + 2,000 + (96 \times 40 \times 2) + (108 \times 40 \times 20) = 97,080 \text{ lbs.}$$

Therefore about 98,000 lbs. of force is the maximum resistance force to counteract the upward pressure. If these figures are correct no frost heaving of the piles should occur because the maximum available downward force exceeds the maximum available upward force (82,080 lbs.). However, inasmuch as the pile is elevated by frost heaving a modification is needed somewhere in the magnitude of the factors involved.

The factors that may be incorrectly evaluated are the tangential adfreezing strength between the pile and the seasonally and perennially frozen ground. The grip of the seasonally frozen ground on the pile may be slightly stronger than  $45 \text{ lbs/in}^2$ , but this appears to be in line with known work. Laboratory work has produced much higher strengths between frozen ground and various materials (tables 2-5).

The tangential adfreezing strength between the pile and the perennially frozen ground probably has not been correctly evaluated in the light of the steam thawing methods associated with the installation of the piles and the presence of a stream of running water. Both of these factors tend to raise the temperature of the permafrost and produce a minimum tangential adfreezing strength between the frozen ground and the pile. Perhaps the ground around the pile had not completely frozen. With a lower adfreezing strength than the  $20 \text{ lbs/in}^2$  used above, the maximum upward force would be larger than the maximum resisting force, and frost heaving would occur.

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Recent work at the U. S. Army Fairbanks Permafrost Research area indicates that tangential adfreezing strength of  $5 \text{ lbs/in}^2$  may be near the correct order of magnitude for the Fairbanks area. (K. A. Linell, written communication, Sept. 17, 1957).

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Pile No. 5 Bent III (1954) in bridge 458.4 extends slightly less into permafrost than does pile No. 4 of this bent and would be frost heaved even if an adfreezing strength of  $20 \text{ lbs/in}^2$  were used.

In summary it is reasonable to assume that bridge 458.4 was frost heaved because some of the piles are not sufficiently anchored in permafrost to overcome the upward force. Even those piles that penetrate 8 to 9 feet in permafrost are elevated because of the low tangential adfreezing strength between the permafrost and piles, due in part to steam thawing the holes, and failure, perhaps, of permafrost to reform around the pile.

#### Frost heaving of middle of bridge

Using the principles of frost heaving of piling outlined earlier and the geologic cross section of bridge 458.4 (fig. 22), it is possible to gain an idea why the middle bents are elevated and the end bents are not (fig. 23). The two prime factors involved are the intensity of frost heaving and the depth of anchorage in the perennially frozen ground.

If none of the piles extend into permafrost, and this was quite possible of the 1917 piles (not shown), only one factor, intensity of frost heaving, is involved; therefore, the duration of freezing, moisture content, and texture of the ground must be evaluated for the middle versus the end bents. The moisture content of the ground around the piles in the center of the bridge would be considerably greater than that around the end piles; however, the duration of ground temperature below  $0^{\circ}\text{C}$  should be the same on all piles. The sediment which becomes seasonally frozen around the piles of the end bents is not entirely organic silt; the upper part of the piles of the end bents are surrounded by gravel of the railroad fill and the intensity of frost heaving would be lower because of the coarse sediments. Also, the tangential adfreezing strength between this dry gravel and silt and the piles would be low. Therefore, because of more moisture and entirely fine-grained sediment the center piles are subject to great frost heaving and tend to be pushed up, but the piles of the end bents have drier and coarser sediment and are subject to less frost action.

Piles of the end bents of bridges 456.7 and 458.4 extend considerably deeper into permafrost than do piles of the middle bents (figs. 17 and 22). This is especially true of the 1954 piles in each bridge. Thus deeper penetration of the piles (10 to 15 feet) in permafrost is sufficient to eliminate frost heaving of piles of the end bents.

#### Absence of frost heaving of new piles

Railroad workers report (John Alter, The Alaska Railroad, oral communication, 1954) that there is little frost heaving of bridge piling during the first or second year after the piling is installed. This is corroborated by observations at bridge 456.7 and bridge 458.4. New piling was installed in both of these bridges in February 1954; no disturbance by frost action was noted on bridge 456.7 during the next two winters and no disturbance on bridge 458.4 during the first winter (1954-55). Frost heaving did occur on this latter bridge during the winter of 1955-56. Both the winters of 1954-55 and 1955-56 were average in duration and intensity of cold. Some of the piles of bridge 456.7 do not penetrate permafrost.

Although conclusive evidence is lacking the authors believe the affect of frost heaving on wood piles may be weak the first year or two after installation because of the liberal coating of creosote applied to the piling prior to installation. This may result in a low tangential adfreezing strength between the piles and the seasonally frozen ground. The coating may also retard water saturation of pile and thus reduce the adfreezing bond.

#### Absence of frost heaving of piles of bridge 460.4

The piles of bridge 460.4 have not been affected by frost heaving as far as is known. The explanation for this apparent anomaly is found in the geologic and topographic conditions of the site (fig. 25). Although permafrost is present in the forested areas nearby, no permafrost is known at this bridge over Goldstream Creek. The piles, therefore, are not anchored in permafrost.

The skin friction between the piles and the creek gravel is insufficient to hold down piles subjected to intense seasonal frost heaving. Most of the 1917 piles did not extend into the gravel and if the skin friction provided by the gravel were important the short piles would still have been subject to frost heaving.

The answer to the absence of a powerful upward push on piles by frost heaving of ground that is adfrozen to the piles at this bridge must then be sought in an analysis of the seasonally frozen ground.

The geology of the site (fig. 25) reveals that the stream is entrenched in a relatively steep-walled little valley and flows on gravel overlain by a 2-foot veneer of silt. This silt veneer is probably swept away during periods of high water. The silt banks on either side of the stream slope steeply to the water and are well drained.

The piles are in two locations: (1) those which are in the stream bed and penetrate only gravel (plus an ephemeral veneer of silt) and (2) those which do not lie in the stream bed and penetrate several feet of silt. The piles in the stream bed are not subject to frost heaving because the flow of Goldstream Creek is great enough during winter to prevent freezing of the stream bed. The remaining piles penetrate 3 to 4 feet of seasonally frozen silt (fig. 25). This silt is the same as that of bridge 456.7 and 458.4 (fig. 15) except that the moisture content and nearness to the water table is greatly different. The moisture content of all but one of the samples of seasonally frozen and unfrozen ground examined at bridge 460.4 is far below that of the silt from the other bridges (fig. 19). The seasonally frozen ground of Hole C (bridge 460.4), near the break of slope contained, for example, only 6 percent moisture.

Because of low moisture content the amount of ice segregated in the ground during seasonal freezing is very low and therefore frost heaving probably is mild. The tangential adfreezing strength between the pile and the seasonal frost is also weak because of the low moisture content of the ground. Therefore, small growth of ice segregations coupled with weak seasonal frost grip, allows the piles to remain undisturbed.

The source of moisture, Goldstream Creek, lies many feet from the seasonally frozen ground around piles and is not adjacent to the freezing ground around piles as in bridges 456.7 and 458.4. This distance is evidently too great to permit sufficient moisture migration to cause great ground ice growth and therefore destructive frost heaving.

#### Resume of techniques to combat frost heaving of piling

It is not the purpose of this report to discuss in detail the engineering techniques developed to combat frost heaving of piling; however, it might be well to review the subject briefly to permit a more complete evaluation of frost heaving of bridge piling of The Alaska Railroad.

Techniques to combat frost heaving of piling can be evaluated in the light of the forces acting on piles (fig. 4): (1) methods devised to decrease the upward force and, (2) methods devised to increase the resisting forces in the (A) unfrozen zone, and (B) permafrost.

### Methods to decrease upward force

This may be attacked along two major lines: (1) reduce the intensity of frost heaving or (2) reduce the effect of frost heaving of the pile by (A) reducing the tangential adfreezing strength between the pile and the seasonally frozen ground, and (B) reducing the surface area of that part of the pile in the seasonally frozen ground.

### Reduce intensity of frost heaving

Intensity of frost heaving may be reduced by changing any of the three basic requirements: moisture, texture of the ground, or the duration and intensity of cold. The moisture can be reduced by lowering the water table (Lubimoff, 1902, p. 111), an action that is locally accomplished by improving surface drainage. It has been reported that chemical treatment of the soil increases the viscosity of the moisture and is effective in reducing ice segregations and therefore frost heaving (Hardy, 1953a, b). Chemical treatment, however, is not a permanent solution to the problem of reducing frost heaving (see also Lambe, 1956).

Ground that is susceptible to frost heaving may be removed and replaced by coarse-grained material. This may be feasible on short piles (Trow, 1955) but would appear impractical for multiple long piling.

It is possible to change the seasonal freezing of the ground by modifying the flow of heat. By covering the ground with moss (Hemstock, 1953, fig. 26), straw (Lubimoff, 1902, p. 111), snow, or other insulating materials it is possible to decrease the depth of frost penetration. Also chemical treatment of the ground will temporarily lower the freezing point of the soil moisture and reduce the amount of ground-ice formation (Jumikis, 1955, p. 133).

#### Reduction of the tangential adfreezing strength between the seasonally frozen ground and the pile

The bond, or tangential adfreezing strength, between the seasonally frozen ground and the pile may be reduced by placing a substance between the frozen ground and the pile. The material is gripped and elevated by the frozen ground but slides over the pile permitting the latter to remain in place. A steel sleeve may surround that part of the pile or post which is in the active layer. The sleeve slides up with swelling of the ground and the pile is not affected (Gray, 1955). Eventually the sleeve would be forced out of the ground if not anchored. Soil or water must not be allowed to collect between the sleeve and the pile.

The tangential adfreezing strength may be reduced by greasing that part of the pile which will be in the seasonally frozen ground and then wrapping the greased part with tar paper (Muller, 1945, p. 96; Lewin, 1948, p. 29; Pihlainen, 1951, p. 15; Hemstock, 1949, p. 51; Rathjens, 1956, p. 14). The ground grips the paper which in turn slides over the smoothed, greased pile surface. This method is not permanent as the paper deteriorates in a few years. A variant of this method is to wrap the greased part in a waterproof polyethylene bag (Trow, 1955).

The tangential adfreezing strength probably will be reduced by using tapered piles with the small end up. A wood pile embedded "butt" end down, for example, would be tapered upward. Although this would seem to be a logical way to reduce the tangential adfreezing strength the writers do not know of any quantitative tests successfully evaluating this factor.

#### Reduction of surface area of pile

It is possible, in some instances, to reduce the surface area of that part of the pile which is in the seasonally frozen ground without materially reducing the strength of the pile or post (Trow, 1955). This, therefore, reduces the area over which the seasonal frost can grip the pile and in turn weakens the upward force.

### Methods to increase downward forces

It is possible to increase the weight of the pile to aid the downward force; however, a more practical method is to increase the pile load. In areas of small or moderate frost heaving an increase in the load may be enough to combat successfully frost heaving of the pile.

Most techniques developed to increase the downward force are concerned with that part of the pile that lies beneath the active layer, both in (A) unfrozen ground, and in (B) perennially frozen ground.

#### In unfrozen ground

Methods to increase downward force in unfrozen ground fall into two groups: (1) increasing the area of skin friction and (2) use of anchor attachments.

The area of skin friction may be increased by increasing the length of the pile or modifying the surface of the pile. Various modifications have been devised to anchor the pile (Pihlainen, 1951, fig. 33; Hemstock, 1953, p. 53; and Trow, 1955).

## In permafrost

Methods to improve the anchoring of piles in permafrost depends upon two basic factors: (1) the tangential adfreezing strength between the pile and permafrost and (2) the surface area of the pile in permafrost.

Methods depending upon tangential adfreezing strength between permafrost and the pile.--The basic objective is to obtain maximum tangential adfreezing strength; this is achieved by preserving, or re-establishing after pile emplacement, the natural thermal regime of the ground. Any action of pile emplacement which heats or locally destroys permafrost will weaken or destroy the tangential adfreezing strength between the pile and permafrost. The strength, however, will increase as permafrost cools, or the bond may be re-established when permafrost forms again (freezes back). The sooner maximum tangential adfreezing strength is reached, the sooner the perennially frozen ground can be used as a medium to combat frost heaving.

The freezeback or re-establishment of the thermal regime of the ground and formation of maximum tangential adfreezing strength depends upon: (1) temperature of the permafrost, (2) amount of heat introduced, and (3) time of the year when piles are emplaced. The colder the permafrost the greater the tangential adfreezing strength; also, the re-establishment of maximum tangential adfreezing strength after thawing is quicker in cold permafrost than in warm. Much of the permafrost in central Alaska is about  $-1.0^{\circ}\text{C}$  and freezeback would be slower here than in regions of colder permafrost such as near Barrow, Alaska, (Brewer, 1955), Resolute Bay, N. W. T., Canada, (Misenar, 1955, p. 1059), and Norman Wells, N. W. T., Canada (Hemstock, 1953, p. 18).

Heat is generated by the action of pile emplacement. As far as the thermal regime of the ground is concerned the method which would generate the least amount of heat is the most desirable when emplacing piles in permafrost. The driving of piles into the ground generates less heat than placing the piles in augered holes. Holes augered without water are less destructive to permafrost than holes drilled with water. Steam thawing of holes for pile emplacement introduces the most heat.

At a school being constructed (1956) at Fort Yukon, Alaska, the steel structure is supported by many 10- to 12-inch-diameter wood piles placed 16 feet into the ground. The piles were placed in dry augered holes, and in order to preserve the thermal regime, it was required of the contractor that he leave the hole open for not more than 2 hours. Piles installed for a building at Bethel, Alaska, were "frozen-in" the permafrost by using artificial refrigeration (Anonymous, 1956). A variant of this method has been used in northern Alaska (Jensen, 1952, p. 157).

Piles that necessitate re-establishment of the thermal regime (freezeback) for formation of maximum tangential adfreezing strength should be placed in the ground between March and June so that there will be maximum opportunity for natural freezeback to occur before the next period of seasonal frost action.

Methods depending upon surface area of the pile in permafrost.--

The exact area of the pile to be anchored in permafrost would depend upon the magnitude of all the forces acting on the pile (fig. 4); however, Tsytovich calculated that the pile should be embedded in permafrost twice the depth of the active layer, and this also was established independently by field work conducted at the Skovorodino Frozen Ground Station (Tsytovich and Sumgin, 1957, p. 313). This rule appears to be correct if maximum tangential adfreezing strength is developed between the pile and the permafrost (F. F. Kitze, U. S. Army Fairbanks Permafrost Research area, oral communication, 1955).

Two factors which affect the surface area of the pile in permafrost are: (1) method of emplacement of slurry around a pile and (2) the variation of the position of the permafrost table.

Piles placed in auger-drilled holes and then back-filled with a silt-water slurry may not have maximum surface area in contact with the frozen ground because voids may remain due to unsuccessful back-filling. Placement of the slurry should be by a tremi-type method to insure maximum surface area contact (Corps of Engineers, 1955, p. 10; Scott, 1956, 1959).

If the permafrost table is lowered the pile has less surface area in permafrost and the total resistance to upward forces is reduced. It is important, therefore, to maintain the original position of the permafrost table by keeping heat from penetrating the ground. Various methods to keep heat from the ground have been devised, such as having an air space between the ground and a heated building (Muller, 1945, p. 98; Hardy and D'Appolonia, 1946, fig. 10) or insulating the ground in the pile area (Roberts and Cooke, 1950, p. 38; Nees, 1951, p. 6). Piling supporting oil derricks in northern Alaska were kept firm by circulating a refrigerant to keep the ground frozen (Robinson, 1956, p. 46).

#### Summary and evaluation of frost heaving of piling of bridges of The Alaska Railroad

Bridges in Goldstream Valley are underlain by permafrost; therefore, it is perhaps best to combat frost heaving of piling by using methods to increase the downward forces. The basic factors to consider are: (1) the tangential adfreezing strength between the pile and permafrost, and (2) the surface area of the pile in permafrost.

Tangential adfreezing strength between permafrost  
and the pile

The basic objective is to obtain maximum tangential adfreezing strength and this is achieved by preserving, or re-establishing a after pile emplacement, the natural thermal regime of the ground. Inasmuch as the temperature of permafrost in Goldstream Valley is about  $0^{\circ}\text{C}$  . it is not wise to emplace piles by any method that would introduce heat into the ground, such as steam thawing. The thermal regime of the ground would be disturbed the least if piles were installed by driving them into the permafrost. Piling should be driven between March and June and steel piles can be driven without much difficulty. The amount of heat introduced in the ground by conduction along the steel pile is not known but may be important especially where the permafrost is warm, such as near Fairbanks. If steel piles were installed in steam-thawed holes it is felt that freezing back would be seriously delayed although no quantitative data are available.

Wood piles installed in dry auger-drilled holes and then back-filled with a silt-water slurry that is emplaced by a tremi-type method would be satisfactory for this area.

### Surface area of the pile in permafrost

The depth to which a pile should be anchored in permafrost depends upon the magnitude of all the forces acting on the pile (fig. 4). As mentioned earlier the Russians state that piles should be emplaced in permafrost twice the depth of the active layer. As shown by observations at bridge 456.7 and 458.4 some piles emplaced this deep in permafrost were frost heaved. This was perhaps due to the warm temperature of the permafrost and the disturbance of the natural thermal regime by steam thawing.

Because of the relatively warm temperature of the permafrost in Goldstream Valley and the nearness of a stream of running water, steel piles or wood piles should be installed into permafrost 3 or 4 times the thickness of the active layer. The active layer is about 4 feet thick; therefore the piles should be extended at least 16 feet into permafrost. This would mean a total ground penetration of about 22 to 30 feet depending upon the depth to the permafrost table.

Literature cited

- Aaron, H., 1934, Frost heave in highways and its prevention:  
Public Roads, v. 15, p. 10-25.
- Alaskan Engineering Comm., 1916, Reports for the period from  
March 12, 1914, to December 31, 1915: House Document 610,  
p. 2, 64th Congress, 1st sess., Wash., D. C., p. 1-210.
- Anonymous, 1956, Alaska's frost and food problems: Western  
Construction, v. 31, p. 24-26.
- Am. Soc. C. E., 1946, Pile foundations and pile structures:  
Manuals of engineering practice, Am. Soc. E. E., no. 27, 72 p.
- Barnes, L. C., 1946, Permafrost: A challenge to engineers: The  
Military Engineer, v. 38, p. 9-11.
- Baver, L. D., 1948, Soil physics: John Wiley & Sons, Inc., New  
York, N. Y., 398 p.
- Beakow, Gunnar, 1947, Soil freezing and frost heaving with special  
application to roads and railroads: Swedish Geological Society,  
(1935), Series C, no. 375, 145 p. English translation plus  
supplement by Osterberg. Pub. by Northwestern Univ.
- Black, R. F., 1951, Structures in ice wedges of northern Alaska:  
Geol. Soc. America Bull., v. 62, p. 1423-1424.
- Bestock, H. S., 1948, Physiography of the Canadian Cordillera, with  
special reference to the area north of the fifty-fifth para-  
llel: Geol. Survey Canada Mem. 247, 106 p.

Literature cited--continued

- Bouyoucos, G. J., 1913, An investigation of soil temperature and some of the factors influencing it: Tech. Bull. no. 17, Mich. Agricultural College, Exp. Station, 196 p.
- \_\_\_\_\_, 1917, Classification and measurement of the different forms of water in soil by means of the dilatometer method: Tech. Bull. no. 36, 48 p.
- \_\_\_\_\_, 1921, A new classification of soil moisture: Soil Science, v. 11, p. 33-48.
- \_\_\_\_\_, 1923, Movement of soil moisture from small capillaries to the large capillaries of the soil upon freezing: Jour. of Agricultural Research, v. 24, p. 427-431.
- Bouyoucos, G. J., and McCool, M. M., 1928, The correct explanation for the heaving of soils, plants, and pavements: Jour. of the American Society of Agronomy, v. 20, p. 480-491.
- Bridgman, P. W., 1912, Water, in the liquid and five solid forms, under pressure: Proc. Am. Acad. Arts and Sci., v. 7, p. 441-558.
- Brewer, M. C., 1955, Geothermal investigations of permafrost in Northern Alaska: Am. Geophys. Union Trans., v. 36, p. 503.
- Brewer, M. C., 1958, Some results of geothermal investigations of permafrost in northern Alaska: Trans. Amer. Geophysical Union, v. 39, p. 19-26.

Literature cited--continued

- Capps, S. R., 1932, Glaciation in Alaska: U. S. Geol. Survey, Prof. Paper 170, p. 1-8.
- \_\_\_\_\_, 1940, Geology of the Alaska Railroad Region: U. S. Geol. Survey Bull. 907, 201 p.
- Carlson, Harry, 1952, Calculation of depth of thaw in frozen ground: Highway Research Board Spec. Rept. no. 2, p. 192-223.
- Carlson, Harry, and Kersten, M. S., 1953, Calculation of depth of freezing and thawing under pavements: Highway Research Board, Bull. 71, p. 81-95.
- Chellis, R. D., 1951, Pile foundations: McGraw-Hill Book Co, Inc., New York, N. Y. 665 p.
- Chernisheff, M. IA., 1928, Deformation to wooden bridges due to frozen ground. Railroad Work, v. 5, p. 1-3 (In Russian).
- Corps of Engineers, 1946a, Airfield pavement design: frost conditions: Ad Interim Engineering manual for War Department construction, pt. 12, ch. 4, Corps of Engineers, U. S. Army, 10 p.
- \_\_\_\_\_, 1946b, Airfield pavement design: construction of airfields on permanently frozen ground: Engineering manual for War Department construction, pt. 12, ch. 7, Corps of Engineers, U. S. Army, 20 p.
- \_\_\_\_\_, 1947, Report on frost investigation, 1944-1945; Corps of Engineers, U. S. Army, Boston, Mass., 66 p., 15 appendices.

Literature cited--continued

- \_\_\_\_\_, 1949, Addendum no. 1, 1945-1947, report on frost investigation 1944-1945: Corps of Engineers, U. S. Army, Boston, Mass., 47 p., 2 appendices.
- \_\_\_\_\_, 1954a, Arctic and subarctic construction: building foundations: Engineering manual for military construction, pt. 15, ch. 1, Corps of Engineers, U. S. Army, 14 p.
- \_\_\_\_\_, 1954b, Airfield pavement design: frost conditions: Engineering Manual for military construction, pt. 15, ch. 4, Corps of Engineers, U. S. Army, 21 p.
- \_\_\_\_\_, 1956, Engineering problems and construction in permafrost regions: in The Dynamic North, Book II, no. 3, U. S. Navy, 53 p.
- Crawford, C. B., 1952, Soil temperatures, a review of published records: Highway Research Board Spec. Rept. no. 2, p. 17-41.
- Datskii, N. G., 1950, Ground swelling under railway beds under permafrost conditions: Acad. Sci. Moscow, U. S. S. R., Trudy v. 4, p. 170-187 (1935) English trans. by E. A. Golomshtok for Office Chief Eng., Mil. Const. Div., St. Paul Dist. U. S. Army, 18 p.
- D'Appolonia, Elio, 1944, Foundations in permafrost regions, pt. 1, Construction in permafrost regions: pt. 2, Wood pile foundations in permafrost regions: unpublished report in files of Northwest Service Command, Canada, p. 1-39.

Literature cited--continued

- Dücker, Alfred, 1958, Is there a dividing line between non-frost susceptible and frost-susceptible soils?: Strasse and Autobahn, v. 3, p. 78-82 (1956). Translated by D. A. Sinclair, reprinted as Tech. Translation 722, Nat. Research Council, Canada, 18 p.
- Frost, R. E., 1950, Evaluation of soils and permafrost conditions in the Territory of Alaska by means of aerial photographs: U. S. Army, Corps of Engineers, v. 1, 50 p., v. 2, 112 p.
- Gray, Hamilton, 1955, Discussion: in Trow, W. A., 1955, Frost action on small footings: Highway Research Board, Bull. 100, p. 28-33.
- Grim, R. E., 1952, Relation of frost action to the clay-mineral composition of soil materials: in Frost action in soils, a symposium, Special Rept. no. 2, Highway Research Board, p. 167-171.
- Haley, J. F., 1953, Cold-room studies of frost action in soils, a progress report: Highway Research Board Bull. 71, p. 1-18.
- Hardy, R. M., 1953a, Chemical highways: Manix, v. 1, p. 8-12.
- \_\_\_\_\_, 1953b, Prevention of frost heaving by injection of spent sulphite liquor: Proc. 3rd International conf. of Soil Mechanics and Foundation Eng. v. 2, p. 103-106.
- Hardy, R. M., and D'Appolonia, Elio, 1946, Permanently frozen ground and foundation design: Eng. Jour. Canada, v. 29, p. 4-12.

Literature cited--continued

- Hemstock, R. A., 1949, Permafrost at Norman Wells, N. W. T.:  
Dap. Oil Ltd., Calgary, Canada, 100 p. (pub. in 1953).
- \_\_\_\_\_, 1952, Engineering in permafrost in Canada's  
Mackenzie Valley: Proc. 2nd International Conf. of Soil  
Mech. and Found. Eng.
- Hennion, Frank, 1955, Frost and permafrost definitions: Highway  
Research Board, Bull. 111, p. 107-110.
- Higashi, Akira, 1958, Experimental study of frost heaving: SIPRE  
Research Rept. 45, 20 p.
- Highway Research Board, 1948, Bibliography of frost action in  
soils: Highway Research Board, Wash., D. C., 57 p.
- \_\_\_\_\_, 1952, Frost action in soils, a symposium:  
Highway Research Board, Wash., D. C., Pub. no. 213, 383 p.
- Hopkins, D. M., Karlstrom, T. N. V., et al., 1955, Permafrost  
and ground water in Alaska: U. S. Geol. Survey Prof. Paper  
264-F, p. 133-145.
- Illinois Div. of Highways, 1922a, Frost action and uniformity of  
subgrade support: unpub. rept. files Illinois Div. of High-  
ways, Springfield, Illinois, 10 p.

Literature cited--continued

- \_\_\_\_\_, 1922b, Slab and subgrade movements due to frost action: unpub. rept. files Illinois Div. of Highways, Springfield, Illinois, 5 p.
- Jackson, K. A., and Chalmers, Bruce, 1956a, Kinetics of solidification: Canadian Jour. Physics, v. 34, p. 473-490.
- \_\_\_\_\_, 1956b, Study of ice formation in soils: Tech. rept. no. 65, Arctic construction and Frost Effects Laboratory, Corps of Engineers, U. S. Army, Boston, Mass., 28 p.
- \_\_\_\_\_, 1958, Freezing of liquids in porous media with special reference to frost heave in soil: Jour. of Applied Physics, v. 29, p. 1178-1181.
- Jaillite, W. M., 1947, Permafrost research area: The Military Engineer, v. 39, p. 375-379.
- Jensen, R. C., 1952, How wells are drilled in permafrost: World Oil, v. 135, p. 152, 154, 157-158.
- Johansson, Simon, 1914, Die Festigkeit der bodenarten bei, verschiedenem Wassergehalt: S.G.U., Ser. C, no. 256 (in Beskow, 1947).
- Johnson, A. W., 1952, Frost action in roads and airfields: Highway Research Board Spec. Rept. no. 1, 287 p.
- Johnson, A. W., and Lovell, C. W., Jr., 1953, Frost action research needs: Highway Research Board Bull. 71, p. 99-124.

Literature cited--continued

- Jumikis, A. R., 1954, Suction force in soils upon freezing: Am. Soc. Civil Engineers Proc. v. 80, Separate no. 445, p. 1-14.
- \_\_\_\_\_, 1955, The frost penetration problem in highway engineering: Rutgers University press, New Brunswick, N. J. 162 p.
- \_\_\_\_\_, 1956, The soil freezing experiment: Highway Res. Board Bull. 135, p. 150-165.
- Kersten, M. S., 1949, Thermal properties of soil: Bull. no. 28, Univ. of Minn., Inst. of Tech. Eng. Exper. Sta., v. 52, 225 p.
- \_\_\_\_\_, 1952, Thermal properties of soils: Highway Research Board Spec. Rept. no. 2, p. 161-166.
- Kitze, F. F., 1957, Installation of piles in permafrost: Paper presented at Eighth Alaskan Sci. Conf., September 13, 1957, Anchorage, Alaska, 20 p.
- Kotzebue, Otto von, 1821, A voyage of discovery into the South Sea and Behring's Straits for the purpose of exploring a northeast passage: English translation in 3 v., London.
- Lambe, T. W., 1956, Modification of frost-heaving of soils with additives: Highway Res. Board Bull. 135, p. 1-23.
- Leffingwell, E. de K., 1915, Ground-ice wedges: the dominant form of ground-ice on the north coast of Alaska: Jour. Geol., v. 23, p. 635-654.

Literature cited--continued

- \_\_\_\_\_, 1919, The Canning River Region, Northern Alaska: U. S. Geol. Survey Prof. Paper 109, 251 p.
- Legget, R. F., and Crawford, C. B., 1952, Soil temperatures in waterworks practice: Jour. American Water Works Assoc., v. 44, p. 923-939.
- Lewin, J. D., 1948, Essentials of foundation design in permafrost: Public Works, v. 79, no. 2, p. 28-30; no. 3, p. 27-30.
- Linell, K. A., and Haley, J. F., 1952, Investigation of the effect of frost action on pavement-supporting capacity: Highway Research Board Spec. Rept. no. 2, p. 295-326.
- Linell, K. A., 1953, Frost design criteria for pavements: Highway Research Board Bull. 71, p. 18-32.
- \_\_\_\_\_, 1959, Interim report on load tests of piles in permafrost: Science in Alaska, Proc. 6th Alaska Sci. Conf., Alaska Div., AAAS, College, Alaska, p. 24-400.
- Liverovsky, A. V., and Morozov, K. D., 1952, Construction on permafrost: Moscow, (1941). English trans. by Meir Pilch for Office Chief Engr., Mil. Const. Div., St. Paul Dist., U. S. Army, 306 p.
- Lofquist, Bertil, 1951, Lifting force and bearing capacity of an ice sheet (Lyftkraft och Barformaga hos ett Istacke) Teknisk Tidskrift, v. 25, Stockholm, 27 p., 1944 Technical Translation TT-164, Nat. Res. Council of Canada, Ottawa, trans. by H. A. G. Nathan.

Literature cited--continued

- Lubimoff, Von.L. von, 1902, Verdrückung von Brücken durch Frost auf der sibirischen Eisenbahn: Organ for the progress of the railroad industry, v. 39, p. 110-113.
- Meister, L. A., and Mel'nikov, P. I., 1950, Determination of adfreezing strength of wood and concrete to ground and shear strength of frozen ground under field conditions: Acad. Sci. Moscow, U.S.S.R., Trudy v. 10, p. 85-107, (1940). English trans. by William Mandel for Office, Chief of Engineers Mil. Constr. Div., St. Paul Dist. U. S. Army, 19 p.
- Misener, A. D., 1955, Heat flow and depth of permafrost at Resolute Bay, Cornwallis Island, N.W.T., Canada: Am. Geophys. Union Trans., v. 36, p. 1055-1060.
- Mozley, Alan, 1937, Frozen ground in the sub-arctic region and its biological significance: Scottish Geog. Mag., v. 53, p. 266-270.
- Muller, S. W., 1943, Permafrost or permanently frozen ground and related engineering problems: U. S. Geol. Survey Spec. Rept. Strategic Engineering Study 62., 2d ed. 1945, Military Intelligence Division, Office, Chief of Engineers, U. S. Army. Also lithoprinted by Edwards Bros., Ann Arbor, Mich., 1947, 231 p.
- Nees, L. A., 1951, Pile foundations for large towers on permafrost: Proc. Am. Soc. Civil Eng., v. 77, separate 103, 10 p.

Literature cited--continued

- Older, Clifford, 1922, Bates experimental road: Ill. Div. Highways  
Bull. no. 18, 24 p.
- Penner, E., 1958, The nature of frost action: Proc. 38th Conv.  
Canadian Good Roads Assoc., p. 234-243 (1957). Reprinted as  
Tech. Paper no. 53, Div. Building Research, Nat. Res. Council,  
Canada, 10 p.
- Péwé, T. L., 1947, Permafrost and geomorphology in the lower Yukon  
Valley, Alaska: Geol. Soc. America Bull., v. 58, p. 1257.
- \_\_\_\_\_, 1948, Terrain and permafrost, Galena area, Alaska:  
Permafrost Program Report no. 7, Engineer Intelligence Div.,  
OCE, U. S. Army, 52 p.
- \_\_\_\_\_, 1949, Preliminary report of permafrost investigations  
in the Dunbar area, Alaska: U. S. Geol. Survey Circ. 42,  
3 p.
- \_\_\_\_\_, 1951, An observation on windblown silt: Jour.  
Geology, v. 59, p. 399-401.
- \_\_\_\_\_, 1952, Preliminary report on the late Quaternary history  
of the Fairbanks area, Alaska: Geol. Soc. America Bull.,  
v. 63, p. 1289-1290.
- \_\_\_\_\_, 1954, Effect of permafrost on cultivated fields,  
Fairbanks area, Alaska: U. S. Geol. Survey Bull. 289-f, p. 315-

Literature cited--continued

- \_\_\_\_\_, 1955, Origin of the upland silt near Fairbanks, Alaska:  
Geol. Soc. America Bull., v. 67, p. 699-724.
- \_\_\_\_\_, 1958, Geologic map of the Fairbanks D-2 quadrangle,  
Alaska: U. S. Geol. Survey Quad. Map no. GQ 110.
- Péwé, T. L., and others, 1953, Multiple glaciation in Alaska: a  
progress report: U. S. Geol. Survey Circ. 289, 13 p.
- Pihlainen, J. A., 1951, Building foundations on permafrost, Mackenzie  
Valley N.W.T.: Division of Building Research, Tech. rept. no.  
8, Ottawa, Canada, 37 p., 3 appendices.
- Rathjens, G. W., 1956, Construction techniques developed in mining,  
power plant construction and electrical distribution in Alaska:  
in The Dynamic North, Book II, no. 2, U. S. Navy, 17 p.
- Roberts, P. W., and Cooke, F. A. F., 1950, Arctic tower foundations  
frozen into permafrost: Eng. News-Rec., v. 144, no. 6, p. 38-39.
- Robinson, F. M., 1956, Core tests and test wells Oumalik area,  
Alaska: U. S. Geol. Survey Prof. Paper 305-A, 69 p.
- Sanderson, Marie, 1950, Measuring potential evapotranspiration at  
Norman Wells: Geog. Rev., v. 40, p. 636-645.
- Scott, R. F., 1956, Freezing of slurry around wood and concrete piles:  
Arctic Construction and Frost Effect Laboratory, Corps of  
Engineers, U. S. Army, Boston, Mass., 6 p.
- \_\_\_\_\_, 1959, Freezing of slurry around piles in permafrost:  
Jour. Soil Mech. and Found. Div., Proc. Am. Soc. of Civil  
Engineers, v. 85, no. SM4, pt. 1, p. 1-10.

Literature cited--continued

- SIPRE, (Snow, Ice, and Permafrost Research Establishment), 1951,  
Annotated Bibliography on Snow, Ice, and Permafrost:  
Rept. 12, v. 1, Corps of Engineers, U. S. Army, 226 p.; 1952,  
v. 2, 356 p.; 1953a, v. 3, 315 p.; 1953b, v. 4, 360 p.;  
1954a, v. 5, 293 p.; 1954b, v. 6, 366 p.; 1955a, v. 7, 270 p.;  
1955b, v. 8, 284 p.; 1956a, v. 9, 273 p.; 1956b, vv. 10,  
190 p.; 1956c, Index, 182 p.
- Skaven-Haug, Sv., 1952, The Norwegian State railway's measures  
against frost heaving: Highway Research Board Spec. Rept.  
no. 2, p. 341-345.
- Sorby, H. C., 1859, On the freezing-point of water in capillary  
tubes: Philosophical magazine, v. 18, p. 105-108.
- Sumgin, M. J., 1927, Perennially frozen soil in the limits of  
U.S.S.R.: Far Eastern Geophys. Obs., Vladivostok, U.S.S.R.,  
372 p. (in Russian).
- Taber, Stephen, 1916, The growth of crystals under external  
pressure: Am. Jour. Sci., v. 41, p. 532-56.
- \_\_\_\_\_, 1917, Pressure phenomena accompanying the growth of  
crystals: Proc. Nat. Acad. Sci., v. 3, p. 297-302.
- \_\_\_\_\_, 1918a, Ice forming in clay soils will lift surface  
weights: Eng. News-Record, v. 80, p. 262-263.
- \_\_\_\_\_, 1918b, Surface heaving caused by segregation of  
water forming ice crystals: Eng. News-Record, v. 81, p. 683-  
684.

Literature cited--continued

- \_\_\_\_\_, 1929, Frost heaving: Jour. Geology, v. 37, p. 428-461.
- \_\_\_\_\_, 1930a, The mechanics of frost heaving: Jour. Geology, v. 38, p. 303-317.
- \_\_\_\_\_, 1930b, Freezing and thawing of soils as factors in the destruction of road pavements: Public Roads, v. 11, p. 113-132.
- \_\_\_\_\_, 1943a, Some problems of road construction and maintenance in Alaska: Public Roads, v. 23, p. 247-251.
- \_\_\_\_\_, 1943b, Perennially frozen ground in Alaska its origin and history: Geol. Soc. Am. Bull., v. 54, p. 1433-1548.
- Terzaghi, Karl, and Peck, R. B., 1948, Soil mechanics in engineering practice: John Wiley and Sons, Inc., New York, N. Y., 543 p.
- Tessendorf, Z. H., 1956, Rules and regulations for maintenance of way and structures: The Alaska Railroad, Anchorage, Alaska, 102 p.
- Trow, W. A., 1955, Frost action on small footings: Highway Research Board, Bull. 100, p. 22-28.
- Tsyrovich, N. A., and Sumgin, M. I., 1957, Principles of mechanics of frozen ground: Acad. Sci. U.S.S.R., Moscow, 432 p. (1937). English trans. by E. A. Golomshtok, Steffansson Library. Published by SIPRE, Wilmette, Ill.

Literature cited--continued

- \_\_\_\_\_, 1929, Frost heaving: Jour. Geology, v. 37, p. 428-461.
- \_\_\_\_\_, 1930a, The mechanics of frost heaving: Jour. Geology, v. 38, p. 303-317.
- \_\_\_\_\_, 1930b, Freezing and thawing of soils as factors in the destruction of road pavements: Public Roads, v. 11, p. 113-132.
- \_\_\_\_\_, 1943a, Some problems of road construction and maintenance in Alaska: Public Roads, v. 23, p. 247-251.
- \_\_\_\_\_, 1943b, Perennially frozen ground in Alaska its origin and history: Geol. Soc. Am. Bull., v. 54, p. 1433-1548.
- Terzaghi, Karl, and Peck, R. B., 1948, Soil mechanics in engineering practice: John Wiley and Sons, Inc., New York, N. Y., 543 p.
- Tessendorf, Z. H., 1956, Rules and regulations for maintenance of way and structures: The Alaska Railroad, Anchorage, Alaska, 102 p.
- Trow, W. A., 1955, Frost action on small footings: Highway Research Board, Bull. 100, p. 22-28.
- Tsyтовich, N. A., and Sumgin, M. I., 1957, Principles of mechanics of frozen ground: Acad. Sci. U.S.S.R., Moscow, 432 p. (1937). English trans. by E. A. Golomshtok, Steffansson Library. Published by SIPRE, Wilmette, Ill.

Literature cited--continued

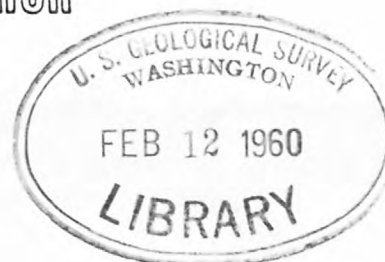
- U. S. Weather Bureau, 1943, Climatic atlas for Alaska: Rept. 444 (229 p.) and supplement (72 p.) of the Weather Information Branch, Headquarters, Army Air Forces.
- Wilson, W. K., Jr., 1948, The problem of permafrost: Mil. Eng., v. 40, p. 162-164.
- Winterkorn, H. F., 1943, The condition of water in porous systems: Soil Science, v. 56, p. 109-115.

Print - Int. 3717



## DEPARTMENT OF THE INTERIOR

### INFORMATION SERVICE



GEOLOGICAL SURVEY

For Release To PM's, FEBRUARY 11, 1960

#### FROST HEAVING AND ITS EFFECTS ON STRUCTURAL PILES DESCRIBED

A report discussing frost heaving and its effect on structural piles, with examples near Fairbanks, Alaska, has been placed on open file by the Geological Survey, the Department of the Interior announced today.

Seasonal freezing of the ground is common throughout much of the world. During the process of seasonal freezing, not only is the original water of the soil frozen, but additional water is drawn to points of freezing from adjacent unfrozen ground. By this means <sup>that</sup> clear-ice segregations grow in the soil, and as these masses grow, the surface of the ground rises, or "heaves". The most favorable conditions for growth of ice segregations and for frost heaving are slow freezing of moist nonhomogeneous organic silt or silty clay. *good, clear nontechnical terms for lay readers!*

When ground is forced upward during seasonal freezing, engineering structures may also be forced upward. Piles may be moved upward if the upward force of the frost heaving of ground which is frozen to the piles is greater than the downward forces of the weight of the pile, its load, and friction between the pile and the ground below the seasonal frost. If piles penetrate perennially frozen ground (permafrost) one of the main factors opposing the upward force is the tangential adfreezing strength between permafrost and the pile surface.

Piling of many of the wood-pile bridges of the Alaska Railroad in Goldstream Valley near Fairbanks, Alaska, are frost heaved every year, necessitating expensive maintenance of the bridges. Many of the bridges in the poorly drained, silt-filled valley are thrown out of line, and the elevation of the track is disturbed. Studies of these bridges illustrate principles of the mechanics of frost heaving of piling, and show the properties of permafrost that are concerned in these principles.

Entitled "Frost heaving of piles with examples from Fairbanks, Alaska" by  
L. Péwé and Russell A. Paige, the report has been placed on open file at the  
following Geological Survey offices: Library, 1033 General Services Administration  
Bldg., Washington, D. C.; Brooks Memorial Mines Bldg., College, Alaska; 117 Federal  
Bldg., Juneau, Alaska; 204 Denali Bldg., Anchorage, Alaska; Library, 345 Middle-  
field Road, Menlo Park, Calif.; 468 New Customhouse, and Library, Denver Federal  
Center, Denver, Colo.; 1031 Bartlett Bldg., Los Angeles, Calif.; 232 Appraisers  
Bldg., San Francisco, Calif.; 602 Thomas Bldg., Dallas, Texas; South 157 Howard  
St., Spokane, Wash.; State Division of Mines and Minerals, Territorial Bldg.,  
Juneau, Alaska. Copies from which reproductions of text and illustrations can be  
made at private expense are available at 345 Middlefield Road, Menlo Park, Calif.

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