Frost Heaving of Piles With an Example From Fairbanks, Alaska

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CONTRIBUTIONS TO GENERAL GEOLOGY

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A review of the principles of ice growth in the ground with special reference to its effect on piles

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FROST HEAVING OF PILES WITH AN EXAMPLE FROM FAIRBANKS, ALASKA

By Troy 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°C, and therefore it can 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, depend upon many physical factors. The three most important factors are the temperature of the air and the texture and moisture content of the ground. The most favorable condition for growth of ice segregations and for frost heaving is slow freezing of moist nonhomogeneous 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 depends 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 the texture and moisture content, of the sediment, 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, is 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 often make it necessary for the trains to reduce speed to avoid uncoupling the cars or shifting the 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 economically important 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.

Wood-pile bridges of The Alaska Railroad at mileposts 456.7, 458.4, and 460.4 were systematically observed for the effect of frost heaving of piling. Data were collected on moisture content and on the position, thickness, and temperature of seasonal frost and permafrost at these localities. Studies of these bridges well illustrate the principles of the mechanics of frost heaving of piling and also show the position and properties of permafrost that are concerned with such principles.

Some of the piles in the first two bridges are not set 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 the absence of frost heaving of piles in the streambed and the low moisture content of the ground around the other piles.

INTRODUCTION

Seasonal freezing of the ground is a common feature throughout most of the land surface of the world. In large parts of the world, ground freezing is a serious engineering problem. As the ground freezes, ice grows in sediment and causes 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 highway development of the 1920's (Illinois Division of Highway, 1922a, b; Older, 1922; Aaron, 1934, p. 10–15; Beskow, 1935). With growth of highways and railroads and with development of airfields for modern aircraft, seasonal freezing of the ground became a major consideration in constructing and maintaining such features. As both military and civilian construction activities increased in the far North, the economic importance of the effects of frost action on construction also increased (Taber, 1943a; Corps of Engineers, 1946a, b, 1947, 1949, 1954a, b; Beskow, 1935; Skaven-Haug, 1952, p. 341–345; Highway Research Board, 1948, 1952).

Frost action affects engineering structures in two ways (1) by distorting the structures during frost heaving and (2) by damaging the structure as the ground loses bearing strength at the time of the seasonal thaw. Differential movement is the paramount problem; such action produces extensive damage to many engineering struc-

tures 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. Much information has been collected on the effect of frost action on engineering and a voluminous literature exists (Snow, Ice, and Permafrost Research Establishment, 1951–56).

In regions of cold winters many pile foundations are in ground that 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. The 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 that 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 is important in anchoring 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. 32). A study of frost-heaving effects on wood piling of small bridges of The Alaska Railroad in Goldstream Valley near Fairbanks permits an evaluation of principles discussed. Many of these bridge piles 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..... 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..... Force that is required to pull the frozen ground from the object to which it is frozen.

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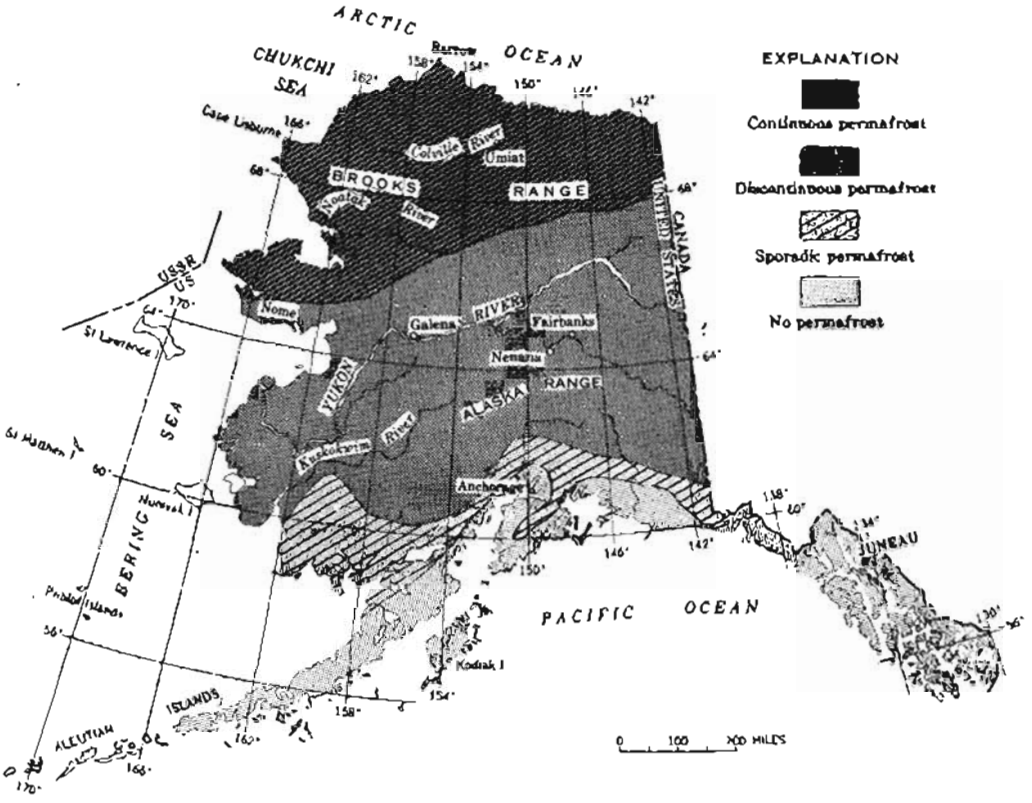

FIGURE 32.—Index map showing location of the Fairbanks area and generalized distribution of permafrost in Alaska.

Aufeis (icing)..... 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°F. The difference between the average daily temperature and 32°F. equals the degree-days for that day. The degree-days are minus when the average daily temperature is below 32°F. and plus when above (Linell, 1953, p. 19).

Freezing index..... 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 ft above the ground is commonly designated as the air freezing index, whereas that determined for temperatures immediately below the surface is known as the surface freezing index (Linell, 1953, p. 19).

Frost action..... 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 and p. 108–110).

Frost heaving..... Upward displacement of ground materials owing 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..... Freezing index determined on the basis of mean temperatures. The period of record over which temperatures are averaged is generally a minimum of 10 years but 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. Commonly contains more ice than either perennially frozen loess or flood-plain silt.

Permafrost..... A thickness of soil or other surficial deposit or even 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).

Permafrost table..... Irregular surface which represents the upper surface of permafrost.

Pile..... Long slender timber, concrete, or steel structural element that is driven, jetted, or otherwise embedded on end into the ground for the purpose of supporting a load or compacting the soil (American Society of Civil Engineers, 1946, p. 54).

Piling	Pile work; a structure of piles.
Point bearing	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	Friction between a pile and the material into which it is driven (Chellis, 1951, p. 13).
Tangential adfreezing strength.	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).

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GROWTH OF CLEAR-ICE SEGREGATIONS IN THE GROUND

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

GENERAL THEORY

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 (1935) 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 on the states of water as determined by Bridgman (1912). Additional basic data have been added by Kersten (1949, 1952), 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 (1958), Higashi (1958), and Cass and Miller (1959).

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 pounds per square inch (Bridgman, 1912, pl. 1). During the process of freezing soil-moisture additional water is drawn to the points of freezing from adjacent unfrozen ground (Taber, 1929, 1930a, b; Beskow, 1935). 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 ground volume owing to seasonal freezing has been recorded by Linell and Haley (1952, p. 299) and 140 percent by Voyslav (in Liverovsky and Morozov, 1941; translation p. 28). The basic physical phenomenon permitting such expansion in ground volume 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. Lubimoff (1902) later theorized that water was brought to the freezing ground from the wet unfrozen ground below, but Johansson (1914) was the first to show that during freezing of fine-grained soil water flows to the freezing area, and this increases 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 phase diagram of water (Bridgman, 1912, pl. 1) and 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°C. He showed that liquid water can exist, if pressures are sufficient, as low as –22°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 a 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°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°C and exists as Ice I. Between the poor wall and the center of the pore there exists a gradation from (1) water as Ice V or VI (solid above 0°C) on the pore wall, (2) through water with melting points as low as –22°C to water with a higher melting point as high as about 0°C, and (3) to ordinary ice, Ice I, in the center of the pore (fig. 33). It is apparent, therefore, that there exists between the two types of ice a zone of liquid water having melting points as low as –22°C, which serves as a passageway for the conduction of water to the growing ice crystal (Winterkorn, 1943, p. 113).

It would seem 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 on temperature, pressure, and moisture relations. A rise in temperature of frozen fine-grained soil from, say, –10°C to –8°C will cause some Ice I to melt.

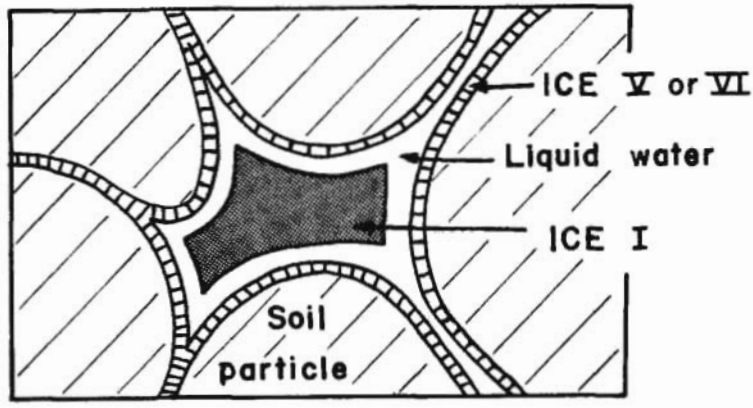

FIGURE 33.—Diagrammatic sketch, not to scale, of condition of stable soil moisture in frozen fine silt above minus 22°C. Liquid water as well as different allotropic forms of ice is shown.

Although Winterkorn explained that nature of the adsorbed layer and a reason for freezing-point depression of water in soil, Jackson and Chalmers (1956a, b, 1958), treating 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 that 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 surface molecule and 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 on the 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.

When supercooled water freezes, undergoing the irreversible phase transformation from supercooled liquid to solid, some energy becomes available—energy that in thermodynamics would be called free

energy. A certain amount of work can be obtained from 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. Greater supercooling makes more energy 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 the resulting phenomenon known as frost heaving. Jackson and Chalmers state (1956b, p. 21) that at 1°C of supercooling, a 1-inch cube of water has enough free energy to lift 178 pounds 1 inch.

Cass and Miller (1959, p. 11) do not wholly accept the explanation of Jackson and Chalmers (1956b) and state that supercooling of water is not essential to the process of frost heaving. They further state that the energy for frost heaving is not derived from a phase transition of supercooled water.

They suggest that the energy is derived during freezing by the addition of water to the unfrozen film of water that lies next to the freezing surface. The addition or recharge is necessary to maintain the film at "equilibrium thickness" when a molecule of the film is "removed" by immobilization in place, that is, freezing.

PHYSICAL FACTORS

As the freezing 0°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 on many physical factors.

Physical factors affecting the amount and location of ice segregations in the ground can be grouped into broad classes: extrinsic and 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), which is probably the factor having the most affect on 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, temperatures, grain shape, grain-size distribution, mineral content, and organic content. All these factors exert influence, but some are extremely important, whereas 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[1] 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°C. In sand and in gravel the voids are so large that most of the water freezes near or at 0°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 into ice. The free energy is the energy available to draw water to the water-ice interface and to cause frost heaving. Lean clay (low plasticity) and silt contain pore sizes that are ideal for the passage of liquid water while they are freezing; fat or heavy clay (high plasticity, 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 (1935; translation 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).

The distance through which water can be pulled by capillarity has been calculated theoretically by Keen (*in* Baver, 1948, p. 264) to be 31½ feet in silt, 150 feet in fine silt (0.01–0.002 mm), and more than 150 feet in clay. Beskow (1947, p. 86) states that capillarity of fine silt (0.02–0.006 mm) in natural soils allows water to be pulled about 20 to 39 feet and in pure silt of uniform grain size, about 10 to 33 feet.

Perhaps the most important factor controlling 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, 1935; translation p. 21). These are all important in fine-grained soils because in such soils the water in the small pores has a lowered

[1] 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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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, 1935; translation p. 21). Ice crystallization begins, therefore, at discontinuities.

In summary, silt or silty clay soil in its natural state seems 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, 1935; 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). Dücker (1956; translation p. 11) shows, however, that the percentage of grain sizes below 0.02 mm does not entirely determine the frost-heaving behavior of a soil, but that 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 greatly 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°C isotherm penetrates the ground.

The amount of ice which forms in the ground upon freezing depends on 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 the soil 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; the end result is that more moisture is concentrated in the frozen ground than existed in the soil before freezing. Poorly drained areas underlain with fine-grained sediment are, therefore, ideally suited for frost heaving.

A long duration of below-freezing temperature permits more water to be drawn into the ground to form ice. High moisture content slows freezing because more latent heat must be removed and very wet soils have a lower thermal diffusivity and therefore are slower freezing (Kersten, 1949, p. 75). Crawford (1952, p. 25) states that in a soil water-holding capacity increases 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 condition for growth of ice segregations and resultant frost heaving is the slow freezing of moist nonhomogeneous organic silt or silty clay.

FROST HEAVING OF PILING

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 or 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 precast concrete.

In regions of cold climate many pile formations are in ground which is partly 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 (1941; translation p. 48) record about 24 inches of frost heaving in a single year in Russia, and Hemstock (1949, p. 52) records 8 inches at Norman Wells, Northwest Territory, 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 (1941; translation 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. 34).

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 postwar 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,

FIGURE 34.—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.

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, p. 9–11; Jaillite, 1947, p. 375–379; Wilson, 1948; Corps of Engineers 1954a, b, 1956; Linell, 1959). 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, p. 1–39; Pihlainen, 1951; Hemstock, 1949, 1952; Trow, 1955). Such studies were started much earlier in Russia (Sumgin, 1927; Chernisheff, 1928; Muller, 1945; Datskii, 1935; Meister and Mel'nikov, 1940; Liverovsky and Morozov, 1941; Tsytovich and Sumgin, 1937) partly 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, 1937; translation p. 232) that out of 49 wood bridges on piles that were examined, 42 were deformed by frost heaving. Fink states (*in* Tsytovich and Sumgin, 1937; translation p. 232) 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 dis-

placement of more than 2½ 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 of 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. The upward force exerted on piles is the result of frost heaving of ground which is adfrozen to the pile; the downward force is the weight of the pile plus its load, and the friction between the pile and the unfrozen ground beneath the seasonal frost (fig. 35), plus the tangential adfreezing strength of permafrost if it exists.

FACTORS AFFECTING UPWARD FORCE

The amount of the upward force on a pile depends 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) the surface area of the pile in the seasonally frozen ground.

INTENSITY OF FROST HEAVING

The intensity of frost heaving mostly depends upon the amount of clear-ice segregations that forms when the ground freezes. This amount depends on 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-heaved piling at Norman Wells, Northwest Territory, Canada, described by Hemstock (1949, fig. 15), is in a silty soil. Liverovsky and Morozov (1941; translation p. 48) states 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.

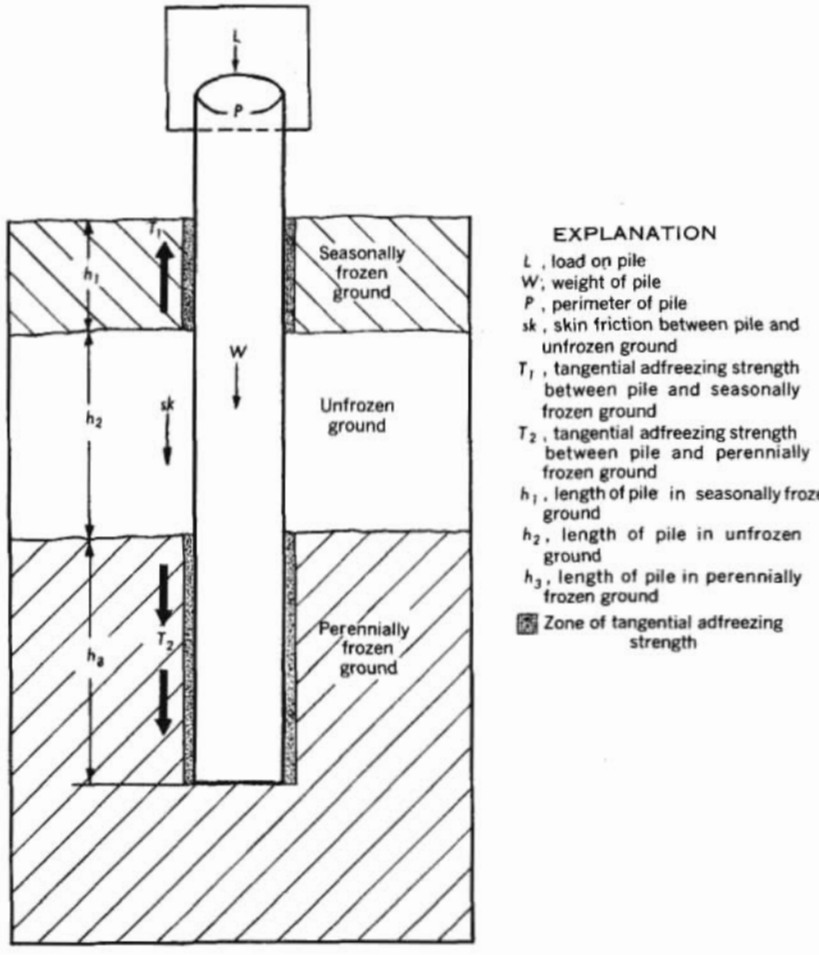

FIGURE 35.—Forces applicable in frost heaving of piling.

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 commonly 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 commonly most abundant under the

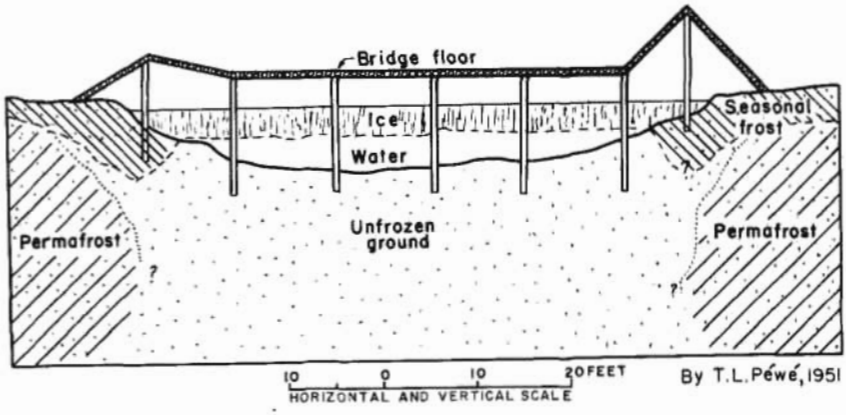

FIGURE 36.—Geologic sketch of foundation conditions of frost-heaved bridge, 8 miles southeast of Big Delta, Alaska. (See fig. 34.)

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, Northwest Territory, Canada (Hemstock, 1949, fig. 49) and by railroad bridges in Russia (Lubimoff, 1902, figs. 2, 4, 5; Sumgin, 1927, p. 302; Liverovsky and Morozov, 1941, fig. 34). The pile bridges studied in detail along The Alaska Railroad near Fairbanks illustrate this phenomenon and will be described below. This selective frost heaving of piles, however, may be related to differences in the way the piles are anchored.

Some pile bridges in central Alaska have the end piles forced up by frost heaving and 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. 34, 36). The piles of this 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.

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 commonly results in a thicker layer of seasonal frost. However, in natural freezing of the ground the depth of frost penetration or rate of freezing is not very important in ice accumulation (Johnson, 1952, p. 45–46; Jackson and Chalmers, 1956b, 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, p. 81–95).

SUMMARY OF INTENSITY OF FROST HEAVING

The upward push of frost heaving on piling is the greatest on piles embedded in moist organic silt or silty clay in regions subjected to longer 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 (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 between that ground and 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 Tsytovich and Sumgin (*in* Muller, 1945, p. 46–52) and fieldwork on the tangential adfreezing strength between wood and concrete and seasonally frozen ground under natural conditions is reported by Meister and Mel'nikov (1940). Table 1 is adapted from their report as translated by W. Mandel. Meister and Mel'nikov note that the tangential adfreezing strength of artificially prepared laboratory soil specimens is greater than that recorded under natural circumstances. Liverovsky and Morozov (1941; translation p. 45) and Linell (written communication, Sept. 17, 1957) also believe laboratory tests give results that are not reliable in field applications. Liverovsky and Morozov cite Bikov as obtaining tangential adfreezing strengths of only 8.5 to 18.5 pounds per square inch for piles in field tests. Laboratory work reported by Trow (1955) shows that under rapid loading the tangential ad-

freezing strength of soil (types of soil and moisture content not reported) with concrete at −10°F ranged from 304 to 495 pounds per square inch. These figures are similar to those given by Muller (1945, p. 47) and given in the present report as table 2.

TABLE 1.—*Tangential adfreezing strength between seasonally frozen ground and different materials under natural conditions*

[After Meister and Mel'nikov (1940), as translated by W. Mandel]

Percent of indicated grain size		Material of piling	Temperature (° C) at depth of—		Percent moisture content by weight	Tangential adfreezing strength	
			0.25 m	0.5 m		kg per cm²	lb per in²
Sand							
0.5–0.05 mm							
98.00		Wood	−2.6	−3.5	22.5	4.40	63
99.00		do	−4.7	−5.1	23.5	5.00	71
94.50		do	−4.8	−4.7	21.0	5.76	82
96.25		do	−4.3	−3.4	32.5	6.30	90
95.75		do	−8.5	−5.5	25.3	9.86	140
98.00		Concrete				3.76	53
100.50		do	−2.5	−2.8	23.2	4.08	58
98.00		do	−4.8	−5.7	21.5	5.55	79
		do	−5.7	−5.4	21.5	7.71	110
Silt and clay							
0.05–0.005 mm	<0.005 mm						
63.00	4.25	Wood	−2.3	−4.2	57.9	1.52	22
64.50	6.50	do	−3.2	−3.4	112.3	3.22	46
76.25	10.25	do	−2.3	−2.8	64.3	3.30	47
70.00	6.50	do	−6.5	−5.1	84.6	3.58	51
73.00	3.00	do	−3.5	−3.5	59.5	3.88	55
56.50	11.50	Concrete	−.2	−.2	68.6	2.10	30
75.00	5.50	do	−.7	−.5	70.8	2.06	29
72.50	8.25	do	−1.5	−2.2	53.0	3.88	55
69.00	8.75	do	−2.5	−1.5	59.8	5.73	81
		do	−2.5	2.2	53.0	5.74	82
61.00	8.25	do	−3.8	−2.9	64.0	7.25	103

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

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TABLE 2.—*Effect of temperature and moisture content on the tangential adfreezing strength between different types of ground and water-saturated wood and concrete*

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

Type of ground			Temperature (°C)	Water-saturated wood			Water-saturated concrete		
	Grain size (mm)	Percent		Moisture (percent)	Adfreezing strength		Moisture (percent)	Adfreezing strength	
					kg per cm²	lb per in²		kg per cm²	lb per in²
Silt	0.05–0.005	63	−0.2	29.9	3.6	51.1			
Clay	0.005	36	−.2	27.1	2.9	41.2			
Clayey sand	1–0.05	68	−.2	12.1	1.3	18.5			
Silt	.05–0.005	63	−.2	22.4	7.0	99.5	16.4	4.4	62.6
Do	.05–0.005	63	−.2	32.6	8.9	126.6	33.0	6.0	85.3
Do	.05–0.005	63	−.2	43.8	7.1	101.0	44.0	9.2	130.8
Do	.05–0.005	63	−.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
Do	<0.005	36	−1.2	26.4	5.9	83.9	26.3	4.8	68.3
Do	<0.005	36	−1.2	37.3	13.0	184.7	36.2	6.4	91.0
Do	<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
Do	1–0.05	68	−1.2	10.1	4.1	58.3	11.7	6.4	91.0
Do	1–0.05	68	−1.2	13.3	7.2	102.4	12.1	7.0	99.5
Do	1–0.05	68	−1.2	16.5	8.2	116.6	16.1	11.1	157.8
Silt	.05–0.005	63	−1.2	18.8	6.9	98.1	17.4	7.8	110.9
	<0.005	14		33.9	14.1	200.5	32.5	21.8	310.0
	Organic matter.	18		41.5	28.7	408.1	46.4	26.2	372.6
				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
Do	<0.005	36	−10.0	21.6	15.7	223.3	25.1	21.9	311.4
Do	<0.005	36	−10.0	28.4	18.6	264.5	34.6	25.3	359.4
Do	<0.005	36	−10.0	41.4	32.2	457.9	46.1	20.1	285.8
Do	<0.005	36	−10.0	55.6	31.9	453.6			
Clayey sand	1–0.05	68	−10.0	5.7	7.9	112.3	7.5	10.0	142.2
	<0.005	8		10.1	12.6	179.2	11.9	22.8	324.2
				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			

A total of 15 tests were made in the laboratory by Nees (1951, p. 2–4) to determine the adfreezing strength between 1¼-inch standard steel pipe and silty sand at temperatures of −8° to −4°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 probably northern Alaska. After an evaluation of these tests, Nees decided that in this particular area a value of 20 pounds per square inch 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.

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 Tsytovich and Sumgin (1937; Golomshtok's translation, p. 120) 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." Table 2 shows that with increase of moisture content (ice)

TABLE 3.—*Laboratory tests of tangential adfreezing strengths between 1-inch steel rod and different materials*

[Soil Test Laboratory, written communication, 1949]

Material	Duration and temperature of freezing	Temperature after test (°C)	Tangential adfreezing strength	
			kg per cm²	lbs per in²
Fresh-water ice	47 hours at −25°C, 45 hours at −5°C	−6	12	170
	48 hours at −25°C, 12 hours at −8°C	−12	10	141
	24 hours at −30°C, 30 hours at −5°C	−5	10	141
	24 hours at −20°C, 24 hours at −8°C	−7	9	125
	84 hours at −6°C	−3	6	89
	36 hours at −6°C, 12 hours at −20°C	−6	8	115
	75 hours at −6°C	−4	14	204
	16 hours at −20°C, 4 hours at −5°C	−5	6	92
Salt-water ice	26 hours at −35°C, 48 hours at −8°C	−5	2	27
	26 hours at −40°C, 31 hours at −8°C	−4	1	17
	48 hours at −20°C	−20	2	31
Organic silt	18 hours at −20°C	−4	6	88
Muck (peat and silt).	56 hours at −2° to −7°C	−8	10	141
Fine sand	80 hours at −2° to −7°C	−7	6	84
Silt and organic matter.[1]	78 hours at −2° to −7°C	−7	8	107
Silt[1]	26 hours at −35°C, 21 hours at −8°C	−10	12	176

[1] Sediments from Skull Cliff, Alaska.

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 (Tsytovich and Sumgin, *in* Muller, 1945, table 2). Table 1 shows that 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, 1940).

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 (1945, p. 50–51) and table 4 and figure 37 of this report, frozen fine sand and silt are the sediments that have the greatest bond with wood. Clay has less bond than silt or fine sand. Meister and Mel'nikov

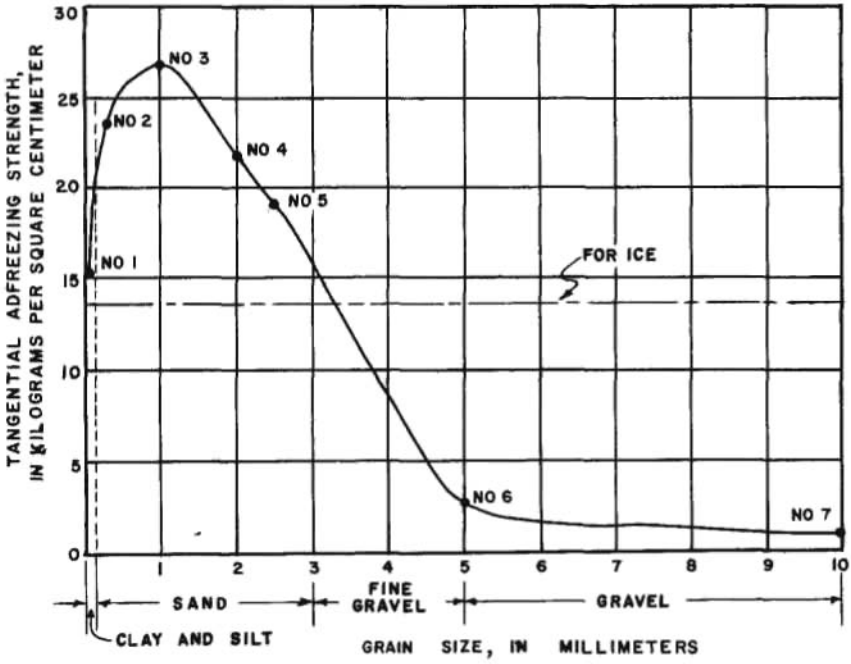

FIGURE 37.—Tangential adfreezing strength between wood and frozen sediments of different texture. Numbers refer to type of ground given in text. After Tsytovich and Sumgin, 1937, from Muller, 1945, p. 50.

(1940, translation 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 (translation p. 9) that under field conditions the tangential 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.

Tabulation of data used in constructing figure 37

[Temperature, −10° C]

Type of ground	Dominant grain-size (mm.)	Coefficient of saturation (percent)	Tangential adfreezing strength	
			kg per cm²	lb per in²
1. Clay	0.01	77	15.3	217.56
2. Sand, fine	.25	76	23.3	331.32
3. Sand, medium	1.0	78	26.8	381.09
4. Sand, coarse to fine	3–0.25	79	21.7	308.57
6. Sand, coarse	3–2	97	19.1	271.60
6. Gravel, fine	5.0	77	2.6	36.97
7. Gravel	10.0	79	.9	12.79

TABLE 4.—*Tangential adfreezing strength between different types of frozen ground and water-saturated wood*

[From Tsytovich and Sumgin (1937), after Muller (1945), p. 48]

Type of ground	Texture of ground		Temperature (°C)	Moisture (percent)	Tangential adfreezing strength	
	Grains >1 mm (percent)	Grains <0.005 mm (percent)			kg per cm²	lb per in²
Clay	0	45	−1.5	41	5	71
Do	13	45	−1.0	39	6	85
Do	--------	41	−1.0	30	5	71
Do	6	31	−2.2	29	7	100
Do	2	30	−1.6	24	7.2	102
Sandy clay	0	27	− .8	35	4	57
Do	0	25	−1.2	26	5	71
Silty, sandy clay	0	24.8	−1.5	40	6	85
Sandy clay with layers of ice	0	23.5	− .8	39	4	57
Sandy clay	0	22	−1.8	39	6	85
Do	0	22	−1.6	34	4	57
Sandy, silty clay having layers of ice	0	22	−1.5	43	6	85
Sandy clay	0	20	− .5	20	2	28
Sandy clay having layers of sand	0	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
Do	17	17	−2.2	25	10	142
Do	0	16	− .6	27	4	57
Do	0	15	−1.6	28	7	100
Do	0	15	− .7	25	3	43
Do	3	15	− .5	25	2	28
Do	3	15	−4.0	26	4.3	61
Do	--------	14	−1.2	24	6	85
Do	0	14	− .8	36	3	43
Do	0	14	−2.0	33	5	71
Sandy clay, micaceous	1	14	−1.8	32	3	43
Do	9	13	− .5	25	2	28
Sandy clay	25	13	−1.6	17	7	100
Do	--------	11	− .9	27	5	71
Do	23	10	−1.6	25	5	71
Sandy clay, micaceous	0	10	−1.0	39	3.3	47
Sandy clay	5	10	−1.8	23	7.2	102
Clayey sand and silt	--------	9	−1.1	28	3.1	44
Do	.5	7	−1.0	17	5.4	77
Clayey sand	41	7	−1.5	16	1.3	19
Silty, clayey sand having layers of ice	--------	4	−1.6	27	3.3	47
Granitic arkose	61	?	−1.7	14	2	28
Gravel	80	3	−1.1	12	3.3	47

Temperature of the ground.—Temperature of the frozen ground is a very important factor in determining the tangential adfreezing strength between frozen sediments and different surfaces. Figure 38 shows that in silt, for example, a drop in temperature from 0° 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 adfreezing strength with drop in temperature.

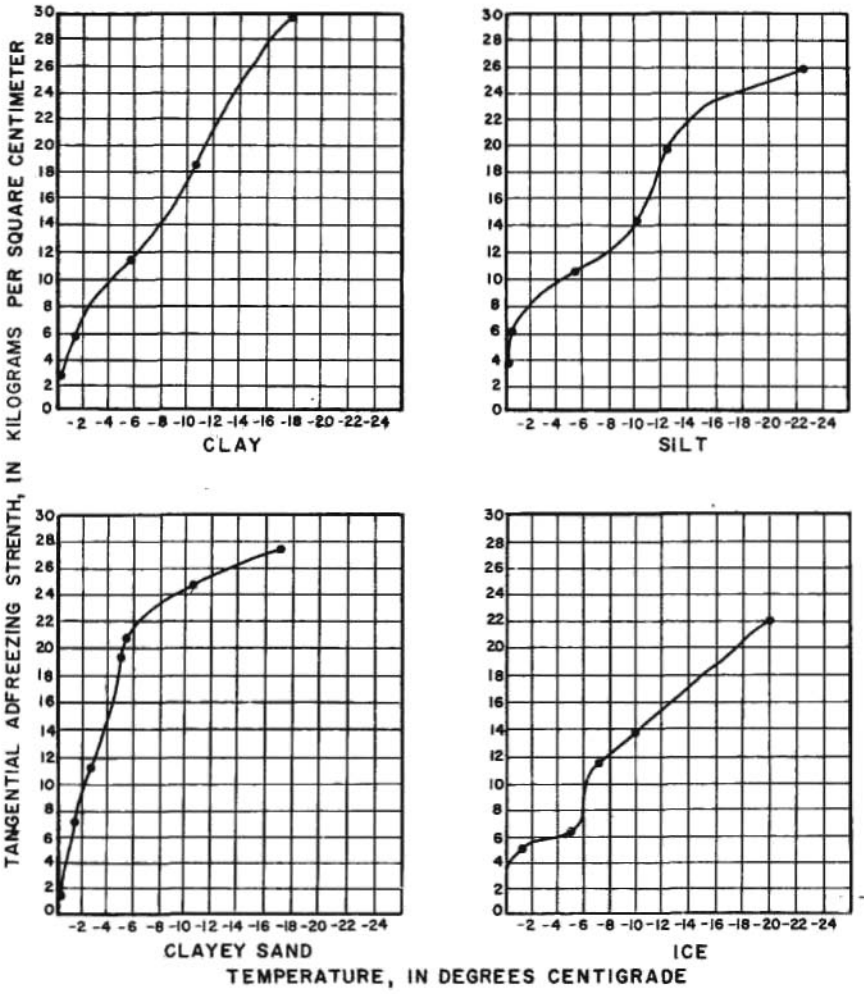

FIGURE 38.—Effect of temperature on the tangential adfreezing strength between wet wood and clay, silt, clayey sand, and ice. After Tsytovich and Sumgin, 1937, from Muller, 1945, p. 51.

Meister and Mel'nikov (1954, figs. 8–11) show that as the temperature decreases the tangential adfreezing strength increases greatly (table 1 of this report). Therefore, the temperature of the seasonal frost is very important in the development of the grip that frozen sediment has on piles. As the temperature of the seasonal frost changes with air temperature during the winter, the grip of the sediment on the piles increases or decreases accordingly.

Nature of the pile surface.—The bond between the surface of the pile and the frozen ground depends partly on the nature of this surface. The surface may be wood, metal, stone, or concrete, and may be rough or smooth. Convincing quantitative data are lacking

TABLE 5.—*Effect of temperature on tangential adfreezing strength of different materials*

[From Tsytovich and Sumgin (1937), after Muller (1945), p. 49]

Material	Temperature (°C)	Moisture (percent by weight)	Tangential adfreezing strength	
			kg per cm²	lb per in²
Ice and smooth-surface wood [1]	−1	--------	5.0	71
	−5	--------	6.2	88
	−7	--------	11.6	165
	−10	--------	13.7	195
	−20	--------	22.0	313
Ice and smooth concrete	−5 to −10	--------	9.8	139
Clay and water-saturated wood [2]	−.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 and water-saturated wood [3]	−.2	12.1	1.3	18
	−1.2	13.0	7.0	100
	−2.7	10.1	11.0	156
	−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
Silt and water-saturated wood [4]	−.2	29.5	3.6	51
	−.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

[1] Wood was placed in water in air-dry condition.
[2] Grain size: 36 percent <0.005 mm; moisture content of ground about one-half of saturation.
[3] Grain size: 68 percent 1 to 0.005 mm, 8 percent 0.005 mm.
[4] Grain size: 14 percent <0.005; includes 18 percent organic matter.

concerning the relative 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 pounds per square inch to more than 483.4 pounds per square inch. In actual field tests the tangential adfreezing strengths are less than this, ranging from less than 14.2 pounds per square inch to approximately 142.2 pounds per square inch.

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 commonly confined between the ice and the ground or between the successively formed ice layers, and creates an upward force. If the ice has a firm grip on the pile and if the ice is pushed upward the pile also will be pushed upward. This lifting force is important on piles at the edges of northern lakes and seas (Lofquist, 1944).

Although there may be a slight upward force exerted on the pile in this manner, the writers do not believe such a force is 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 that oppose the upward force of frost heaving on piling are the weight of the pile plus its load and 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 results from frost heaving of ground that is adfrozen to the pile. A wood pile commonly weighs less than 1,000 pounds. The load of 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, engineers have had some success using increased loads to overcome frost heaving on concrete posts. However, in Alaska, wood piles supporting small bridges or frame buildings commonly 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 the 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 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 fraction on piling embedded in cohesive soils is 200 to 600 pounds per square foot of contact area for soft clay and silt, 400 to 1,000 pounds per square foot for sandy silt, and 800 to 2,000 pounds per square foot 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 piles of wood and steel was 1.5 to 5.6 pounds per square inch. These piles were embedded in unfrozen organic silt (fig. 39) of the same type and moisture content that exists in Goldstream Valley (pl. 43).

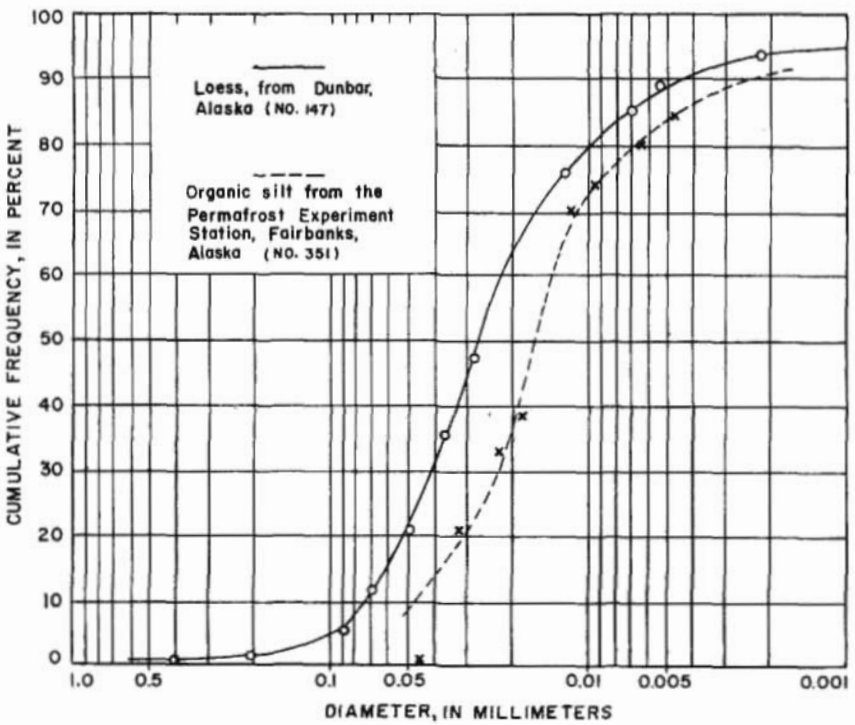

FIGURE 39.—Cumulative-frequency curves of silt from near Fairbanks, Alaska.

A comparison between the tangential adfreezing strength of the active layer (tables 1-5) and the skin friction of the unfrozen ground reveals that the grip on the pile by the frozen ground is much stronger than that of the unfrozen ground—about 10 or 50 times

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greater. It would be difficult to install piles in the unfrozen ground with enough surface area to resist successfully by skin friction alone, the upward force resulting from frost heaving of ground that is adfrozen to the pile. This would be especially difficult in moist fine-grained sediments under very cold temperatures.

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 study 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 (pl. 43) near Fairbanks (Corps of Engineers, 1954a; Linell, 1959; Kitze, 1960). One value of tangential adfreezing strength between permafrost and steel piling at Norman Wells, Northwest Territory, Canada, is given by Hemstock (1949, 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. The silt deposit (pl. 43) is widespread in lowlands of the Fairbanks area (Péwé, 1958) and is the same formation that exists in Goldstream Valley (pl. 43). The silt is well sorted and contains little clay (fig. 39). 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 pile-test site of the permafrost research station the moisture content by dry weight ranges from about 40 to 60 percent, except for the organic layers which have a moisture content of as much as 180 percent (Linell, 1959, fig. 2).

In this formation the temperature of the permafrost below depths affected by seasonal variation is between –1.0° and –0.5°C (fig. 40), as determined both by the Corps of Engineers at the site and by the U.S. Geological Survey elsewhere in the area (pl. 43).

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 piles were placed in holes drilled using water and others in holes 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 ultimate tangential adfreezing strength—the point at which the pile, bond, or extracting machine failed—and the plastic flow tangential adfreezing strength were

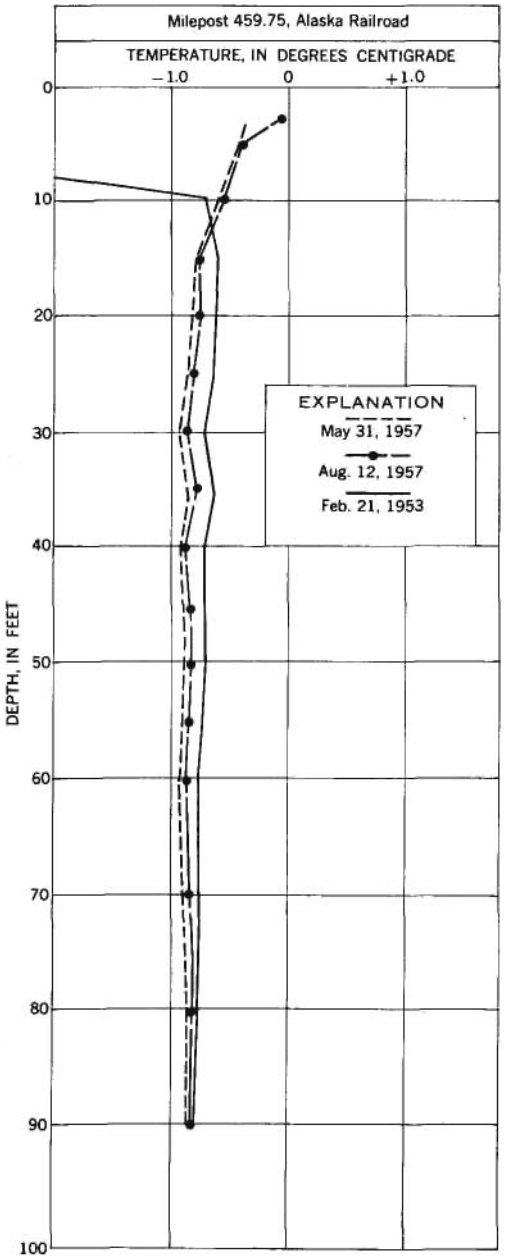

FIGURE 40.—Thermal profiles of permafrost near Fairbanks, Alaska.

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. This plastic flow is important because the upward push of frost action

and the applied structure load are forces acting over a long, rather than a short duration, such as wind-load uplift (Linell, 1959, p. 27).

The Corps of Engineers, U.S. Army (Linell, 1959) show that, until 1955, the ultimate tangential adfreezing strength between piles and permafrost ranged from 13.0 to 31.3 pounds per square inch for piling emplaced in drilled holes. Average stress is 22.5 pounds per square inch for concrete piles, 27.1 for steel-pipe piles, and 28.4 for steel I-beams. Wooden piles, failed in tension (above the ground) at a stress equivalent to an adfreezing strength of more than 21 pounds per square inch 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 before extraction, and perhaps maximum tangential adfreezing strength was not obtained. The ultimate tangential adfreezing strength recorded averaged 23.2 pounds per square inch (Linell, 1959, p. 33).

These particular values differ slightly from those given by 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.

The ultimate tangential adfreezing strength between permafrost and a steel pipe that was in the ground for 4 weeks was determined by Hemstock (1949, p. 59) at Norman Wells, by extraction test, to be 76 pounds per square inch. 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 permafrost and piles is made with that between seasonally frozen ground and piles, it is noted that, based on field data, the tangential adfreezing strength of seasonally frozen ground (30–55 pounds per square inch, from table 1) is slightly greater than that of permafrost (13.0–31.3 pounds per square inch, according to 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 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.

The above review implies 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 PILES

Forces tending to displace or to prevent displacement of a pile can best be visualized by a diagram (fig. 35). 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 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 depends on 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 would increase accordingly. The tangential adfreezing strength between the moist silt and the wood pile is assumed to be 45 pounds per square inch.

Therefore, if conditions for intensive frost heaving are present (much ground-ice segregation), the pile will begin to be shoved upward at that particular time 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 (feet)	Maximum force pushing upward (pounds)
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 relation with the depth of frost penetration, as suggested in table 6. Field observations in Russia (Liverovsky and Morozov, 1941; translation 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 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, and the total resistance to the upward force is reduced.

As the ground begins to warm from above in late winter and early spring, the tangential adfreezing strength becomes much 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

In 1914 the U.S. Congress authorized the construction of a railroad from the Pacific Coast of Alaska to the navigable waters of the interior of the Territory (Alaska Engineering Commission, 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. 32). 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 U.S. Government.

Three lines were considered as possible routes from Nenana to Fairbanks (Alaska Engineering Commission, 1916, p. 59–60; map 8): (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 have 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.

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 bridge at moderate to high speeds. Reduction of speed to avoid uncoupling of cars or shifting of cargo is necessary.

PHYSICAL SETTING

CLIMATE

A United States 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 and Chena Rivers.

The Fairbanks area has a continental climate, characterized by an extreme range between summer and winter temperature (fig. 41).

The absolute minimum recorded temperature is –66°F; the absolute maximum is 99°F. The mean annual number of days with freezing temperature 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°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). This measure of seasonal cold intensity for Anchorage, Alaska, is 3,000 degree days, and for Barrow, Alaska, 8,500 degree days. In contrast to Alaska, the mean freezing index at Minneapolis, Minn., is 1,560 degree days and at Burlington, Vt., 1,260 degree days (Linell, 1953, p. 24).

The wind regimen in central Alaska is generally 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 to 4 miles per hour, and in summer it is about 6 miles per hour. The annual mean wind velocity at Fairbanks is 4.9 miles per hour. 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

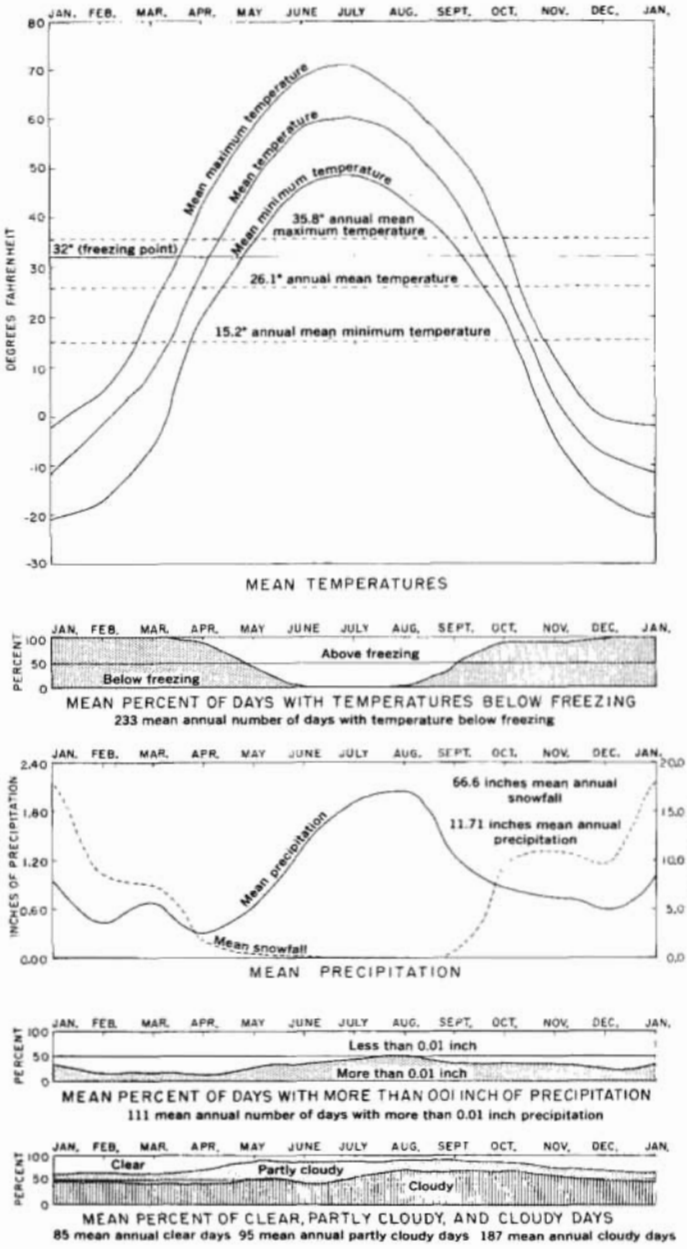

FIGURE 41.—Climatic data for Fairbanks, Alaska.

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

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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. The upland is a maturely dissected area of accordant rounded ridges 2,000 to 3,000 feet in altitude. Scattered discontinuous groups of higher mountains project above the upland ridges to altitudes of 5,000 to 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 at 1,250 to 1,800 feet above sea level. Local relief ranges from 600 to 1,300 feet. The bedrock is chiefly schist, but it 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 (Péwé, 1955). The valleys are filled with 10 to 100 feet of gravel overlain by 10 to 300 feet of alluvial silt.

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 feet 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, p. 1–8, pl. 1; Péwé, 1952, p. 1289, Péwé 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 hilltops, 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 permafrost 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 flood plain in the Fairbanks area (pl. 43) 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 comprises a layer of variable thickness immediately under the silt. Cobbles about 3 inches in diameter are commonly the largest in the gravel. 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 (Péwé, 1958).

The gently sloping area between the hills and the flood plain is composed of alluvial fans and lowlands of well-sorted eolian silt that has been retransported from the hills (Qsu on pl. 43). 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 parts 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, the largest of which extends from the toe of the fans to the flood plain and lies just north of Ester Road (pl. 43).

In the valleys of the upland creeks, such as the Goldstream Creek Valley (pl. 43), the alluvial-fan deposits of silt extend from opposite hill slopes and coalesce, flooring the narrow valley bottom with silt that is 15 to 190 feet thick (fig. 42). The silt is gray to brown, well sorted (fig. 43), and contains organic 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, 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 overlies flood-plain alluvium.

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 (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

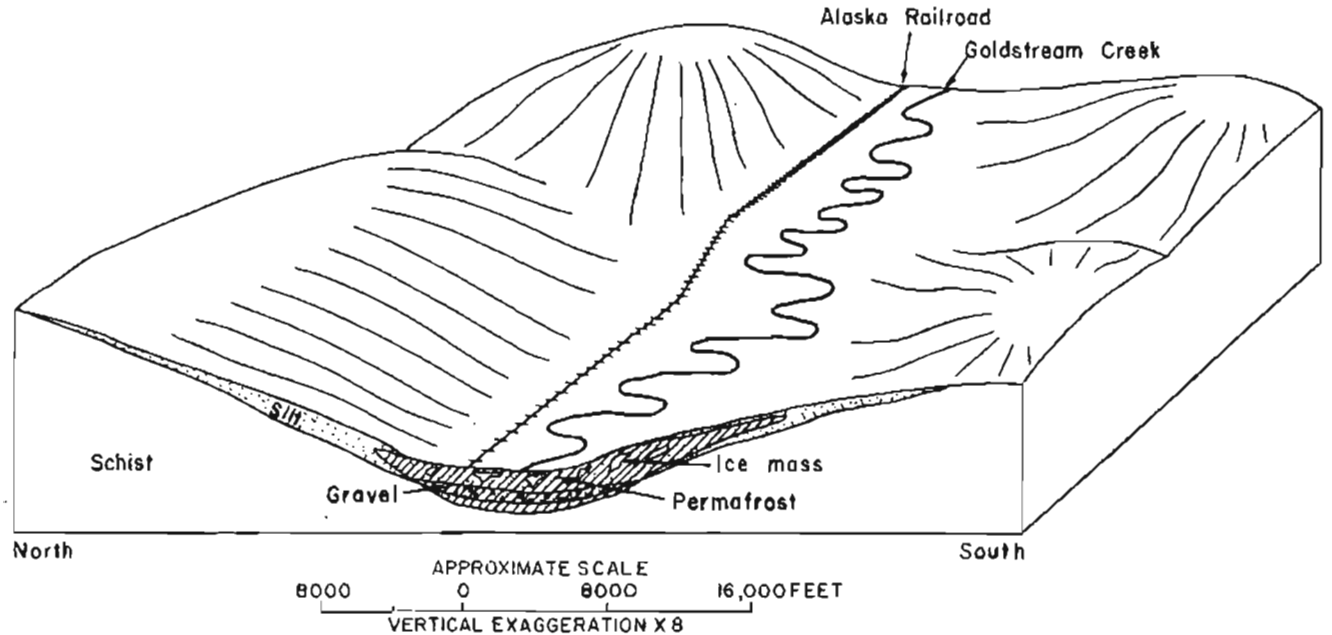

FIGURE 42.—Diagrammatic sketch showing permafrost distribution in Goldstream Valley near Fairbanks, Alaska. (After Péwé, 1949.)

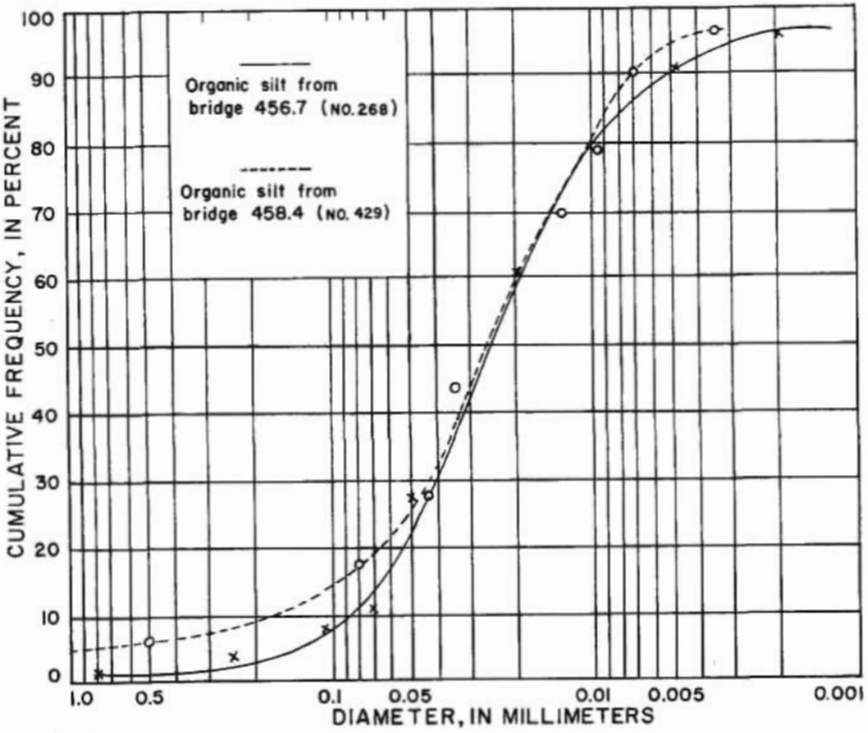

FIGURE 43.—Cumulative-frequency curves of organic silt from The Alaska Railroad bridge sites in Goldstream Valley near Fairbanks, Alaska.

south. Alaska can be divided arbitrarily into three generalized permafrost zones—the continuous, discontinuous, and sporadic permafrost zones (fig. 32). In the continuous zone of the north, permafrost is present nearly everywhere and extends to a depth of about 1,000 feet or more (Brewer, 1958, p. 19–26). In this area the temperature of permafrost at a depth of 50 to 75 feet is less than –5°C. From 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°C. Permafrost conditions at Fairbanks are probably typical of the discontinuous zone. In the sporadic permafrost zone in the south, the perennially frozen ground is confined to local areas, and the mean annual ground temperature is generally above –0.5°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 (pl. 43) (Péwé, 1954, pl. 9). The Tanana River flood plain is underlain by zones of peren-

nially frozen ground interspersed and interstratified with zones in which the sediments are unfrozen. Large ice masses are lacking. The gently sloping alluvial fans (Qsu on pl. 43) that extend from the upland to the flood plain, and also fill the creek valley 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°C.

PERMAFROST OF THE FLOOD PLAIN

Sediments of the flood plain of the Chena (pl. 43) and Tanana Rivers (2 miles south of map area) are perennially frozen to a maximum known depth of 265 feet but permafrost is not found everywhere 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 lenslike 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 (Péwé, 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 partly 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 and organic-silt lowlands probably extends unbroken from the flood plain of the 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 the thickness decreases toward the hills, pinching out at the base of steep southward-facing slopes. Permafrost may extend farther 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 and lowlands is characterized by large masses of ice occurring as horizontal sheets, vertical or inclined sheets, and wedges ranging from ¼ 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 honeycomblike 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 and 1½ to 5 feet in the organic-silt lowland. Large masses of ground ice are not unique to the Fairbanks area, and they have been reported from many other localities in Alaska (Kotzebue, 1821, v. 1; Leffingwell, 1915, p. 635–654, 1919; Taber, 1943b; Frost, 1950; Black, 1951, p. 1423–1424; 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 (Péwé, 1954, p. 329) in cleared fields, and changes in plant cover. The most accurate criteria for determining this boundary are temperature measurements (fig. 40) and well data, which can reliably indicate the presence of permafrost although it may underlie a thawed layer 20 or 25 feet thick. Less reliable indicators for determining the boundary are thermokarst features and vegetation (Péwé, 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. Commonly, 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 (fig. 32 and pl. 43). 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. Where drainage is poor, frost action is locally intense.

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-free 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 (pl. 43). 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 (pl. 43), the highway is damaged by frost action and thawing of permafrost.

The flood plains of the Chena (pl. 43) and Tanana (fig. 32) Rivers support most of the engineering structures in the Fairbanks area —the city of Fairbanks, the International Airport, and Ladd Air Force Base (the latter two are outside the limits of pl. 43). 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 it has been removed before construction.

ECONOMIC CONSIDERATIONS

The engineering-geology problems of frost heaving of bridge piling of The Alaska Railroad are economically important 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 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 crossbraces and other structural members.

It is estimated that it costs $125 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 to reduce speed of a 70-car freight train from 40 to 20 miles per hour 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 on piling are at mileposts 456.7, 458.4, and 460.4 (pl. 43). The milepost 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 power auger, 16 inches in diameter, 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 U.S. Smelting, Refining & Mining Co.

BRIDGE AT MILEPOST 456.7

DESCRIPTION

The wooden bridge is 43 feet long, supported by 4 bents of piles, and spans a small creek that lies in a V-shaped valley 15 feet below the elevation of the track. The creek commonly 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.

PERMAFROST

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

Permafrost is near the surface except in the drainageway; as shown in figure 44, the permafrost table on September 27, 1955, was about 9 to 10 feet below ground surface at the end of the bridge and 10 feet deep under the creek bed. These 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, located 350 feet south of the railroad tract at milepost 459.75, indicates that the temperature of the permafrost at 70 feet was –0.88°C on May 31, 1957 (fig. 40). Moisture content for similar perennially frozen material near Fairbanks (pl. 43) ranges from 40 to 180 percent by dry weight (Linell, 1959, 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 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.

Thick aufeis forms every winter in the drainageway crossed by the bridge at milepost 456.7. In February 1954, the aufeis was 10½ feet thick under the bridge and covered all but the upper 2 feet of the piles. In March 1955, aufeis was only a few feet thick and

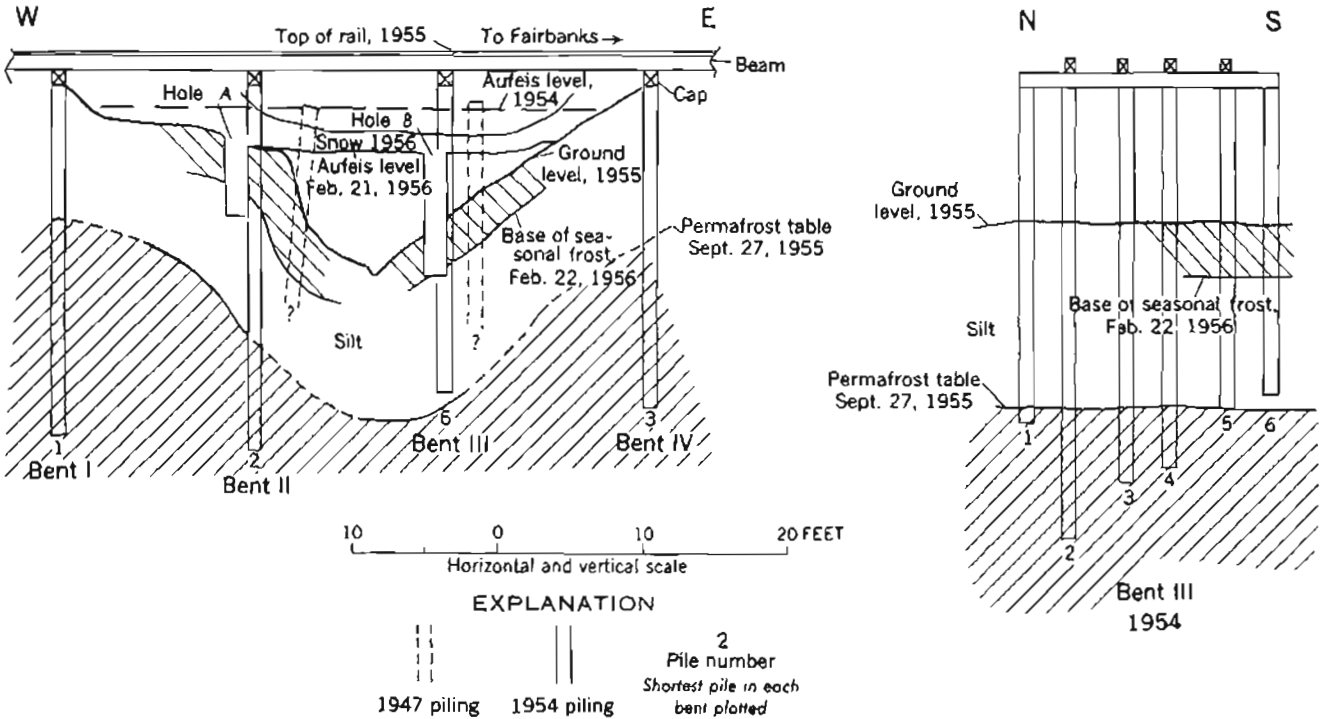

FIGURE 44.—Geologic sections at The Alaska Railroad bridge at milepost 456.7 in Goldstream Valley near Fairbanks, Alaska.

on February 22, 1956, it was about 7 feet thick in the center of the drainageway.

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. 44). 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°0 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 (pl. 44).

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 in 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. 44). This hole went through 4½ feet of aufeis and 3½ 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 74.5 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 43.1 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 64.6 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 was affected every year by frost heaving. 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 inches or more 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 has been partly chopped away to lower the track 2 inches. Figure 45 illustrates the 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, as the piles were frost heaved, they probably did not penetrate permafrost very far.

In February 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 follows. The piles are driven into a steam-thawed hole. Holes are thawed in frozen silt by forcing steam under pressure through a 20-foot steel pipe, three-fourths of an inch in diameter, which has 3 small holes at the end. Steam is applied to the pipe by a rubber hose. 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 2½ to 3 feet apart; however, because of excess thawing the end result is not a series of

FIGURE 45.—Deformation of wood bridge by frost action. Milepost 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. Péwé, February 11, 1954.

holes but a coalescence of thawed holes to form a trench of thawed ground about 2 or 2½ 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 1 day to several days. If a pile is not placed in a hole before quitting time, the thawed hole is covered with snow (in winter) to prevent it from freezing until work is resumed the next day or next week. The piledriver crew on bridge 456.7 reported (oral communication, Feb. 11, 1954) that during a Christmas vacation one year the holes were covered with snow to keep the mud from freezing, and that 2 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. 44). 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. Several piles in the center of the drainageway do not penetrate permafrost, but some of the piles, especially on the end bents, penetrate more than 11½ feet of permafrost.

The bridge at milepost 456.7 was examined during the summers and winters of 1954, 1955, 1956, and no evidence of frost heaving was noticed during the 2 winters since the installation of the piles in 1954.

BRIDGE AT MILEPOST 458.4

DESCRIPTION

The bridge at milepost 458.4 is 71 feet long and is supported by 6 bents of wooden piles. It spans a small creek that drains the hills to the north and empties into Goldstream Creek. This unnamed creek lies in a flat-floored valley 11 feet below track level and flows southward between two gently sloping alluvial fans of silt.

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. The base of

the permafrost was not reached. Permafrost is near the surface, except in the drainageway. On September 29, 1954, the permafrost table was about 11 or 12 feet below ground surface at the ends of the bridge, but was 13 feet deep under the creek (fig. 46). Permafrost 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 given for the bridge at milepost 456.7.

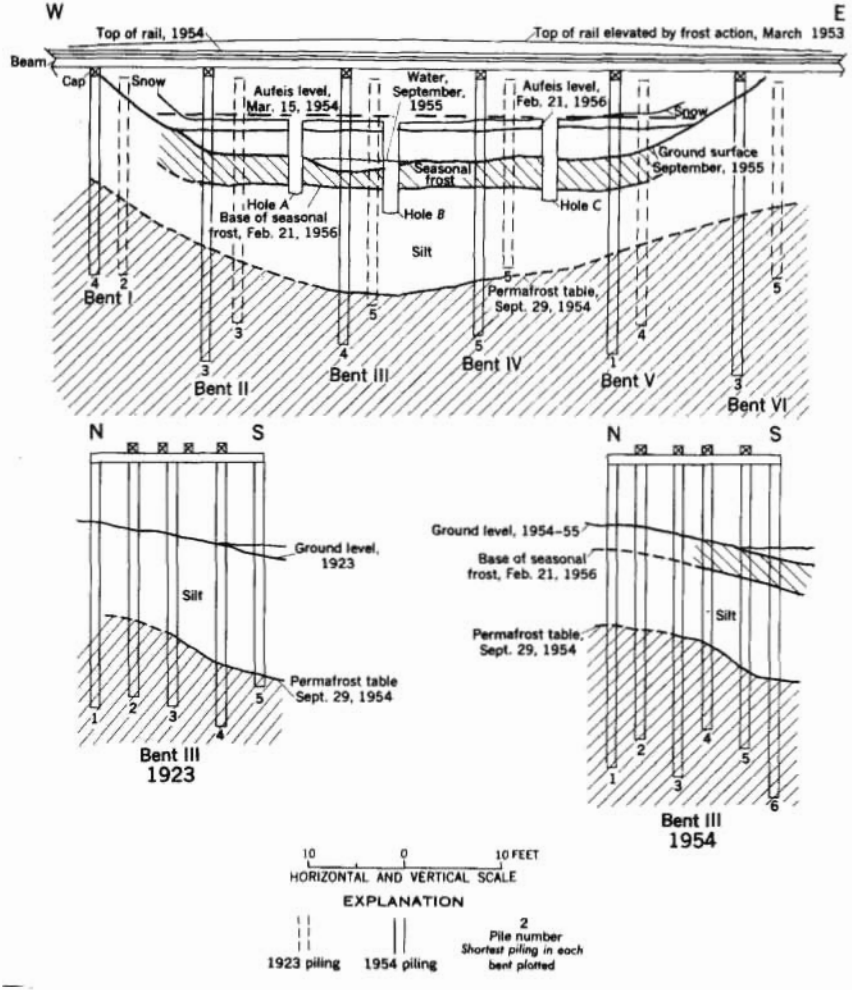

FIGURE 46.—Geologic sections at The Alaska Railroad bridge at milepost 458.4 in Goldstream Valley near Fairbanks, Alaska.

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 penetrated in auger holes *A*, *B*, and *C* was 2 feet 9 inches, 3 feet 3 inches, and 3 feet, respectively (pl. 44).

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. 46). 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 (pl. 44).

Hole *B* was drilled between bents III and IV in the center of the valley. Aufeis, 3 feet 3 inches thick, overlies 3 feet of seasonally frozen organic silt containing a few twigs and wood fragments. The upper 6 inches of the ground contains a few pebbles. A sediment sample taken 10 inches below the surface contained 42.3 percent moisture.

Hole *C* was drilled between bents IV and V on the east side of the valley (fig. 46). The hole penetrated 3 feet of aufeis and 3 feet 6 inches of seasonally frozen silt. As in the previously drilled holes, the upper 6 inches of the ground contained a small amount of gravel. The moisture content of a sediment sample taken a foot beneath the surface was 51.6 percent (pl. 44).

UNFROZEN GROUND

About 10½ 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 57 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 drainageway and the unfrozen ground is very wet. Five inches below the base of the seasonal frost the ground contained 60.9 percent moisture, and a silt sample taken 20 inches below the base of the seasonal frost contained 70.7 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 61.1 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 depths ranging from about 12 to 23 feet. The greatest penetration was under the end bents. These piles were installed by the same method as those on bridge 456.7; some of them penetrated 6 or 8 feet of permafrost, but others, 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 great 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. This displacement produced a sharp hump in the track, sharp enough to uncouple train cars. 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 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. 47). In the latter part of February new piles were installed and the bridge lowered. These piles were installed in the manner described for bridge 456.7; they penetrate the ground to depths ranging from 18 to 30 feet (fig. 46). 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 1954-55.

During the second winter (1955–56) after pile installation, the effect of frost heaving on the bridge was very evident. By February 3, 1956, the bridge had been elevated 3 inches at bent III, and by the end of the winter it was elevated 5 inches.

BRIDGE AT MILEPOST 460.4

DESCRIPTION

The bridge at milepost 460.4 is 91 feet long and is supported by 10 bents of wooden piles. It spans Goldstream Creek, which is 20 feet wide and 4 feet deep at the normal stage of the water. At the normal stage the water is about 18 feet below the track.

GEOLOGY OF THE SITE

A gold-prospect drill hole 800 feet west of the bridge (and 100 ft from Goldstream Creek) penetrates 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 streambed 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. 48).

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

FIGURE 47.—Roadbed and track of The Alaska Railroad bridge at milepost 458.4 in Goldstream Valley near Fairbanks, Alaska. Bridge with hump in center caused by bridge piling being raised 9 inches by frost action. Photograph by T. L. Péwé, February 11, 1954.

depth of the prospect hole. The base of the 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 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 (pl. 44). 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 18.3 and 62.3 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°C. At a depth of 1 foot 6 inches it was–1.7°C, and at 2 feet 3 inches it was –0.6°C. The air temperature when ground temperatures were determined was –23.5°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. A sample taken 1 foot 5 inches below the surface contained only 5.9 percent moisture (pl. 44).

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 30.2 percent moisture. The temperature of the unfrozen ground 2 inches below the base of the seasonal frost was 0.0°C.

In hole *C* about 10 feet of unfrozen silt is present between the frozen silt and the gravel (fig. 48). This silt is moist (moisture

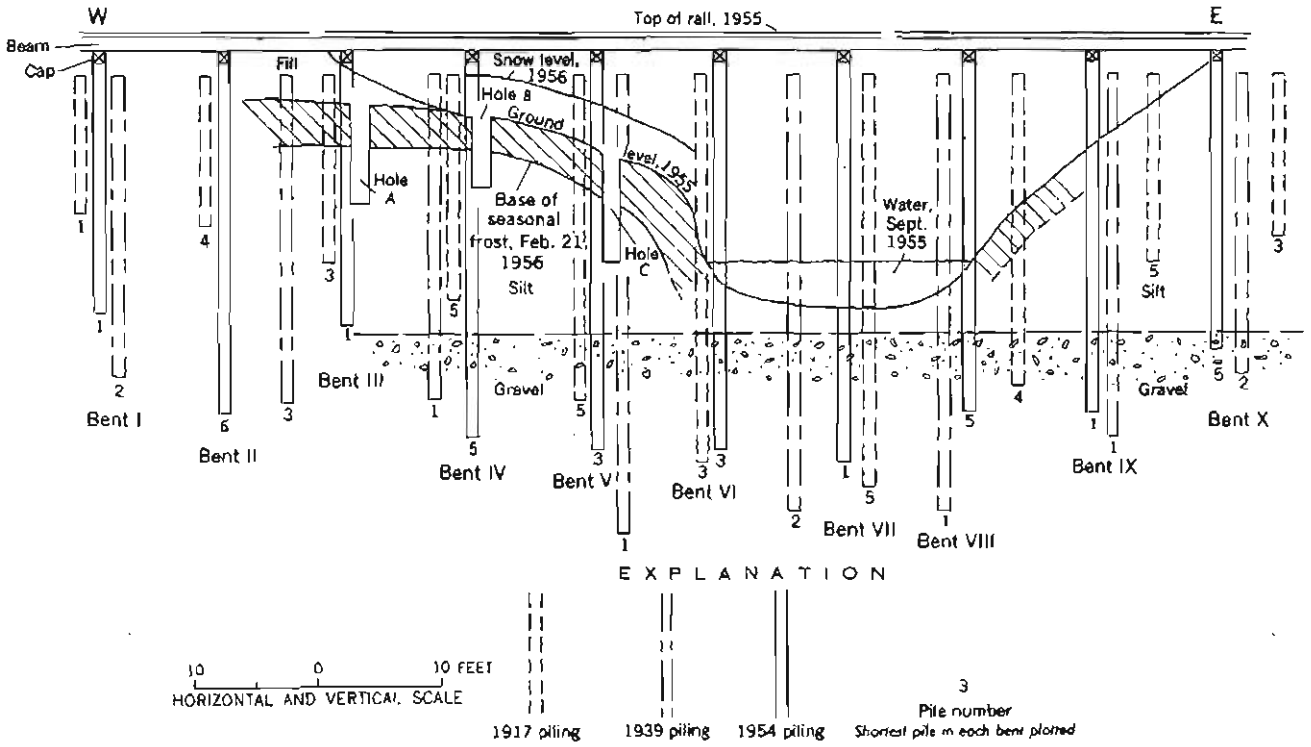

FIGURE 48.—Geologic section at the Alaska Railroad bridge at milepost 460.4 over Goldstream Creek near Fairbanks, Alaska.

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 much deeper.

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

INTERPRETATION

Studies of frost-heaving of bridge pilings on The Alaska Railroad well illustrate the mechanics of frost heaving of piling and also show the position and properties of permafrost that are concerned with frost heaving. As discussed on page 347, the factors affecting frost heaving of piling deal with upward forces (fig. 35). The amount of the upward force on piling depends on (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. 43) and will be used as an example to illustrate the upward and downward forces acting on piles. As discussed on page 350, 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 that is ideal for a source of water during freezing.

The duration and intensity of winter freezing in central Alaska is great (fig. 41). 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 44, 46, and 48 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 on page 363, 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; the circumference 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° to −0.6°C and a moisture content of about 50 to 60 percent. Based on data already reported (tables 1–5; figs. 37, 38) an estimate of 45 pounds per square inch for the tangential adfreezing strength between the wood pile and this silt is considered probable.
Therefore,

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

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 pounds 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 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 pounds and the load is less than 2,000 pounds. This pile extended 8 feet into unfrozen ground and had a perimeter of 40 inches. Skin friction is estimated at 2 pounds per square inch.
Therefore,

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

From this it is evident that the maximum available upward force on this pile (82,080 lb) 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 46, 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 4 of bent III (1954) can be assumed to have a maximum upward force of about 82,000 pounds 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 a 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 wood piles that were placed in drilled holes failed structurally upon extraction, and the full tangential adfreezing strength was not determined. The piles failed at 21 pounds per square inch. However, as discussed on page 361, the plastic flow limit, the limit at which the bond between the frozen ground and the pile fails under slow steady pressure, is probably 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 pounds per square inch seems to be about average for concrete and steel piles. This figure may be too high for creosoted wood piles; however, it will be used for calculations.

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

Therefore about 98,000 pounds of force is the maximum resistance force available to counteract the upward pressure. If these figures are correct, no frost heaving of the piles should occur because the maximum available downward force (97,080 lb) exceeds the maximum available upward force (82,080 lb). However, inasmuch as the pile is elevated by frost hearing, a modification is needed in the magnitude of the factors involved.

The factors that may be incorrectly evaluated are the tangential adfreezing strengths 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 pounds per square inch, but this seems 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 pounds per square inch used above, the maximum upward force would be larger than the maximum resisting force, and frost heaving would occur.

Recent work at the U.S. Army Arctic Construction Investigations Area indicates that a tangential adfreezing strength of 5 pounds per square inch may be near the correct order of magnitude for the Fairbanks area. (K. A. Linell, written communication, Sept. 17, 1957).

Pile 5 of bent III (1954) in bridge 458.4 extends slightly less into permafrost than does pile 4 of this bent and would be frost heaved even if the adfreezing strength were 20 pounds per square inch.

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, owing partly to steam thawing the holes, and perhaps to failure of permafrost to reform around the pile.

FROST HEAVING OF MIDDLE OF BRIDGE

Using the principles of frost heaving of piling outlined (p. 347) and the geologic section of bridge 458.4 (fig. 46), it is possible to gain an idea why the middle bents are elevated and the end bents are not (fig. 47). The two prime factors involved are the intensity of frost heaving, and the depth at which the piles are anchored in the perennially frozen ground.

If none of the piles extend into permafrost, and this was quite possible of the piles in 1917, 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 much greater than that around the end piles; however, the duration of ground temperature below 0°C should be the same around all piles. The sediment that 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 the piles and this dry gravel and silt 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 much deeper into permafrost than piles of the middle bents (figs. 44, 46). This is especially true of the 1954 piles in each bridge. Thus, deeper penetration of the piles (10 to 15 ft) 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 bridges 456.7 and 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 that the effect 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 before 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 the pile and thus reduce the adfreezing bond.

ABSENCE OF FROST HEAVING OF PILES OF BRIDGE AT MILEPOST 460.4

The piles of bridge 460.4 have not been affected by frost heaving so far as is known. The explanation for this apparent anomaly is found in the geologic and topographic conditions of the site (fig. 48). 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. 48) 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. The 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—those which are in the streambed and penetrate only gravel (plus an ephemeral veneer of silt), and those which do not lie in the streambed and penetrate several feet of silt. The piles in the streambed are not subject to frost heaving because the flow of Goldstream Creek is great enough during winter to prevent freezing of the streambed. The remaining piles penetrate 3 to 4 feet of seasonally frozen silt (fig. 48). This silt is the same as that of bridges 456.7 and 458.4 (fig. 43), 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 (pl. 44). For example, the seasonally frozen ground of hole *C* (bridge 460.4), near the break of slope, contained only 5.9 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 seasonally frozen ground 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.

RÉSUMÉ 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. 35): (1) methods devised to decrease the upward force and (2) methods devised to increase the resisting forces in the unfrozen zone and in the perennially frozen ground.

METHODS TO DECREASE UPWARD FORCE

The problem of decreasing upward force may be attacked along two major lines: reduce the intensity of frost heaving or reduce the effect of frost heaving of the pile. The effect of frost heaving may be reduced by reducing the tangential adfreezing strength between the pile and the seasonally frozen ground and reducing the surface area of that part of the pile in the seasonally frozen ground.

REDUCTION OF 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, p. 8–12; 1953b, p. 103–106). Chemical treatment, however, is not a permanent solution to the problem of reducing frost heaving (see also Lambe, 1956, p. 1–23).

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 it would probably be 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, 1949, fig. 26), straw (Lubimoff, 1902, p. 111), snow, or other insulating materials it is possible to decrease the depth of frost penetration. Also chemical treament 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 it 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, p. 28–33). 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, for 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 will probably 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 method.

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 frost heaving successfully.

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

IN UNFROZEN GROUND

Methods to increase downward force in unfrozen ground are (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 modifica-

tions have been devised to anchor the pile (Pihlainen, 1951, fig. 33; Hemstock, 1949, p. 53; and Trow, 1955).

IN PERMAFROST

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

Methods depending on tangential adfreezing strength between permafrost and the pile.—The basic objective is to obtain maximum tangential adfreezing strength; this is achieved by preserving, or reestablishing after pile emplacement, the natural thermal regime of the ground. Any action of pile emplacement that 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 reestablished 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 freezing back or reestablishment 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 reestablishment of maximum tangential adfreezing strength after thawing is quicker in permafrost that has a temperature of -3° to -5°C, for example, than in permafrost that has a temperature of only −1°C. Much of the permafrost in central Alaska is about -1.0°C and the freezing back would be slower here than in regions of colder permafrost, such as near Barrow, Alaska, (Brewer, 1955, p. 503), and near Resolute Bay (Misener, 1955, p. 1059), and Norman Wells (Hemstock, 1949, p. 18), in Northwest Territory, Canada.

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 in 1956 at Fort Yukon, Alaska, the steel structure was supported by many wood piles 10 to 12 inches

in diameter, placed 16 feet into the ground. The piles were placed in dry augered holes, and 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 (Western Construction 1956, p. 24–26). A variant of this method has been used in northern Alaska (Jensen, 1952, p. 152, 154, 157–158).

Piles that necessitate reestablishment of the thermal regime (freezing back) for maximum tangential adfreezing strength should be placed in the ground between March and June so that there will be maximum opportunity for natural freezing back 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 on the magnitude of all the forces acting on the pile (fig. 35); however, Tsytovich calculated that the pile should be embedded in permafrost to twice the depth of the active layer, and this was also established independently by fieldwork conducted at the Skovorodino Frozen Ground Station (Tsytovich and Sumgin, 1937; translation, p. 231). This rule seems 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 that affect the surface area of the pile in permafrost are the method of emplacement of slurry around a pile and the variation in 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 owing to unsuccessful backfilling. Placement of the slurry should be by a tremi-type method to insure maximum surface-area contact (Corps of Engineers, 1954a, p. 10; Scott, 1956, 1959, p. 1–10).

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, p. 4–12, 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 was kept firm by circulating a refrigerant to keep the ground frozen (Robinson, 1956, p. 46).

SUMMARY AND EVALUATION

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 the tangential adfreezing strength between the pile and permafrost and 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, this is achieved by preserving, or reestablishing after pile emplacement, the natural thermal regime of the ground. Inasmuch as the temperature of permafrost in Goldstream Valley is about 0°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 it 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 backfilled 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 on the magnitude of all the forces acting on the pile (fig. 35). The Russians state that piles should be emplaced in permafrost to twice the depth of the active layer. As shown by observations at bridges 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 to 3 or 4 times the depth 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.

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