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PERMAFROST AND THE ENVIRONMENT

IN ALASKA

by

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ABSTRACT

Although permafrost is estimated to occur on about 20 percent of the land area in the northern hemisphere, it is not a unique substance but frozen, normal geologic materials. Permafrost is caused by the inability of the geothermal gradient to supply heat rapidly enough to prevent deep freezing when mean annual temperatures are below freezing. As most construction problems on permafrost are caused by melting earth materials, this review describes how an understanding of the properties of clastics and principles of soil physics can aid the construction engineer in evaluating factors and predicting the behavior of thawed clastics. Texture and water content are emphasized as being of overriding importance as elements that control how melting clastics behave when thawed. During the construction of engineering works on permafrost terrain thermal properties constitute an added, very important element to be evaluated. The nature and properties of clastic materials governs their thermal properties and a thermal analysis in advance of a project becomes as important as other reconnaissance investigations. It is the interactions of all elements that, when stressed by environmental disturbances, cause a reaction. Computer modelling is now being used to predict how these interacting elements react when various stresses are applied. Several successful engineering works are cited as examples where prior knowledge of clastic behavior and the employment of recommended procedures have resulted in maximum stability while preserving environmental quality.

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INTRODUCTION

Present concern given to the proposed trans-Alaska pipeline has focused attention primarily on one factor of the Alaskan environment--the presence of permafrost (this term was proposed by Muller, 1947, p. 3, for permanently frozen ground). Permafrost is defined as perennially frozen earth material resulting from continued cold climates; in Alaska it ranges in thickness from zero at its southern boundaries to 1300 feet near Barrow. Frozen earth to a depth of 5000 feet has been reported in Siberia. It must be emphasized that permafrost is a condition of earth materials and is not a unique material in itself; therefore, it is the cold environment that imparts unique qualities to problems associated with man's activities in areas where permafrost occurs. Because permafrost is frozen earth materials, properties of these materials, when thawed, control most of the engineering behavior of thawed permafrost. Failure to understand how permafrost behaves, or neglecting to recognize the serious consequences of failing to apply knowledge already known, can result in engineering failure and serious water pollution caused by sediments entering streams as uncontrolled melting progresses. Brown's recent book (Brown, 1970) describing permafrost in Canada provides a good overall appraisal of problems associated with it that are just as valid for Alaska.

The objective of this review is to describe some principles controlling the behavior of clastics (fragments of earth materials), both under frozen and thawed conditions, and to stress that an understanding of permafrost requires some understanding of earth materials and soil physics. No attempt will be made to introduce new material or to use rigorous mathematical treatment proving credibility as this is available in the literature. The objective is to render a practical explanation of permafrost and problems associated with it, and remove whatever mystery may exist to those unfamiliar with, but interested in, what it is, how it formed, and how it behaves.

ORIGIN AND PROPERTIES OF PERMAFROST

Permafrost is a product of cold climate conditions; it covers about 22 percent of North America. These areas are generally divided into two zones, continuous, about 2,950,000 mi^2, and discontinuous, about 2,960,000 mi^2 (Black, 1954). These will be defined later. Figure 1 shows the extent of these zones in Alaska. Because the interior of the earth is hot and the outer crust is cold, a temperature gradient exists called the geothermal gradient that averages about 1°C/40 m (1°F/70 ft) of depth. However, within the uppermost few hundred meters, the temperature is also influenced by local climates and these layers will have different temperatures in the tropics as opposed to polar regions. Moreover, other elements of the environment come into play near the surface such as vegetation, slope direction, moisture content, and nature of the geologic materials that also influence the near-surface temperature of earth materials. Permafrost develops when, under a long continued cold climate, geothermal heat from the interior of the earth is not supplied rapidly enough to prevent permanent freezing at and for some distance beneath the surface.

Figure 2 is an idealized schematic diagram for a homogeneous material that was first developed by Russian workers (Muller, 1947, p. 13) to illustrate and explain some fundamental concepts concerning permafrost and its distribution. In Figure 2, the geothermal gradient is exaggerated to achieve clarity and extends downward from point Z. Above Z, the extended line is the mean annual ground temperature and is under the influence of seasonal variations; this is true for any point on the earth, not just polar regions. With seasonal warming the surface warms and the temperature increases toward E to a maximum,then as cooling commences, the temperature decreases toward A and reaches some minimum before the cycle is repeated. The magnitude of

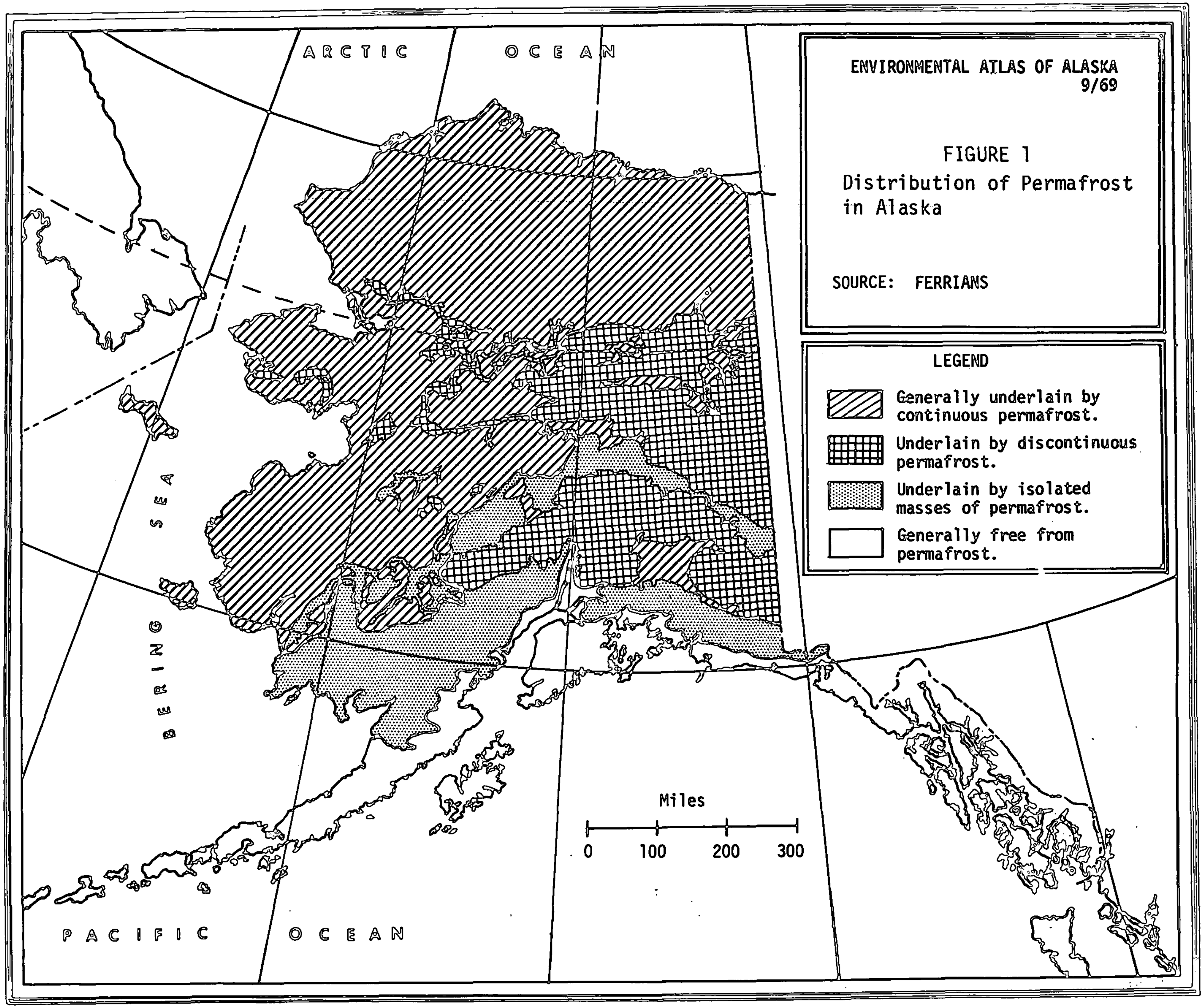

FIGURE 1
Distribution of Permafrost in Alaska

these seasonal variations is called the amplitude of seasonal temperature variation and is transmitted downward with decreasing magnitude until some depth is reached where these variations approach zero. This point, Z, the depth of zero amplitude, is of fundamental importance in the behavior and permanence of frozen ground. Surface disturbance may cause this point to move up or down, depending on the temperature at that point.

Figure 2 also illustrates three hypothetical examples of how such a diagram may be used. If the freezing line AB remains outside the curve (to the left) for minimum temperature as the seasonal temperature reaches its coldest, no ground freezing will occur at any season. Such conditions prevail in warm climates such as the tropics except at high altitudes. If the freezing line were at CD, it intersects the cooling curve and seasonal freezing would occur. However, CD does not intersect the line of mean annual ground temperature below Z so no permanent frozen material is present. Such conditions occur in all areas where seasonal freezing occurs to some depth and at higher elevations of tropical climates.

Line EF introduces some new elements to this description because it shows the various relationships in a permafrost locale. Line EF, the freezing line, now moved to where it intersects the warming curve near its extreme seasonal amplitude, also intersects the geothermal gradient at some distance below the surface at F. Under this circumstance, permafrost would extend to F or a depth of about 190 feet on the scale shown here. All temperatures along the geothermal gradient are below freezing and become colder with decreasing depth. Point G on line EF is where the freezing line intersects the seasonal warming curves and marks the maximum depth of seasonal thaw. The distance between E and G is the thickness of the active layer or the layer of seasonal freezing and thawing, in Figure 2 it is about 1 meter (3.3 feet) thick. At Barrow, in northern Alaska, permafrost extends to 400 m (1300 feet)

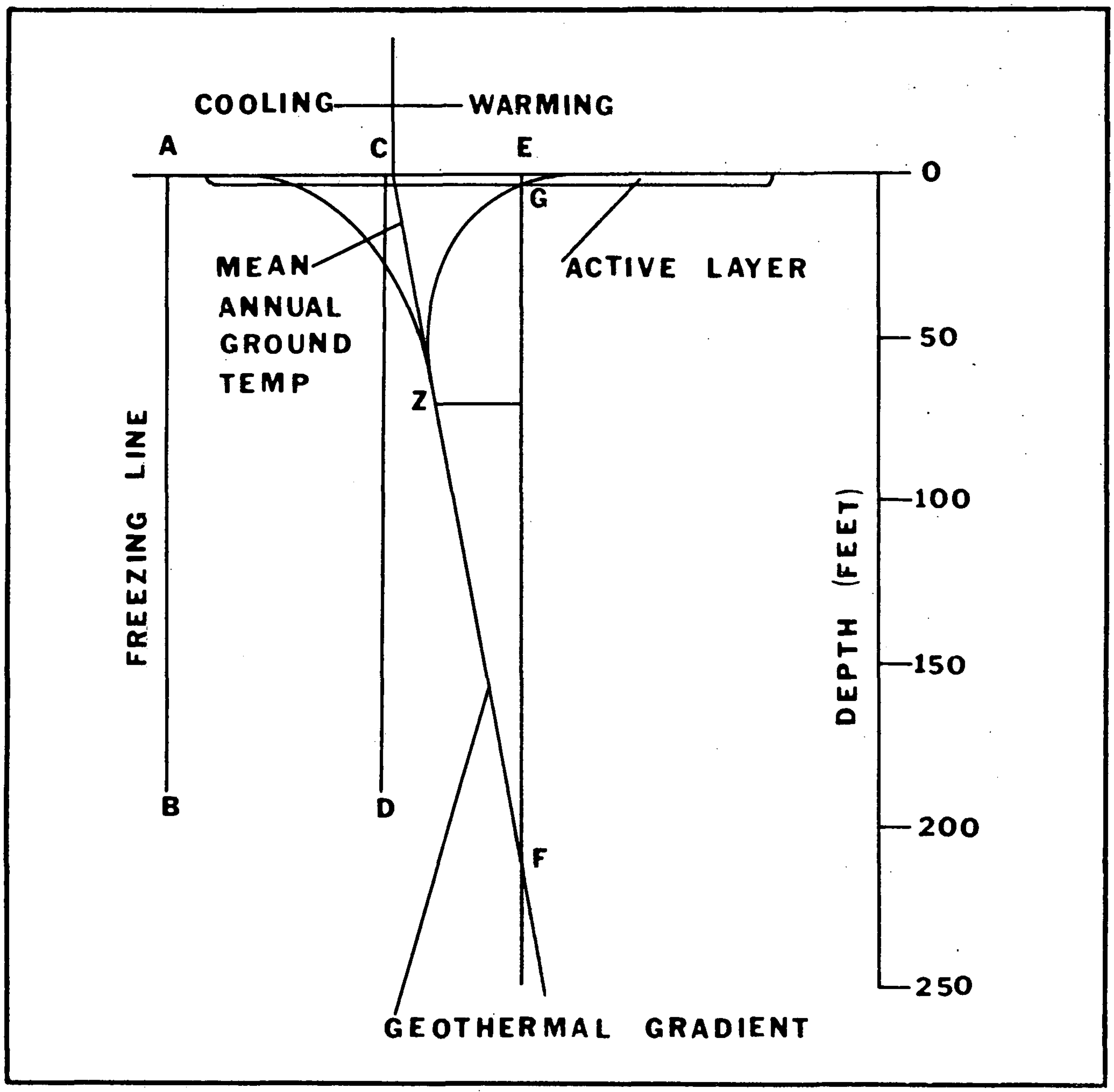

Figure 2

Typical temperature regimens in permafrost and non-permafrost locales. Geothermal gradient is exaggerated to improve clarity.

and the active layer is thin; as the southern boundary of permafrost is approached, point F on the geothermal curve gets closer to the surface and the active layer is thicker because more seasonal heat is available to thaw the subsurface materials.

Temperature at Z, the level of zero amplitude, is fundamental in predicting and understanding the behavior of frozen earth materials. When the temperature at the level of zero amplitude is several degrees below freezing, depth and stability of permafrost is increased. Should the line EF shift nearer Z, that is, the temperature at Z increase, depth and stability of permafrost will decrease. It is under this latter circumstance that surface disturbances can seriously alter the permafrost regimen because it is then in tenuous equilibrium without the added stress of disturbance of an environmental factor. It is the temperature at point Z that is used to define the boundary between continuous and discontinuous permafrost and ranges from about -12°C at Barrow to 0.0°C at the warmer boundary of permafrost.

A prominent surface manifestation of permafrost, as evident from the air, is patterned or polygonal ground (Figure 3). In these patterns, the lines ranging in length from 10-100 m (33-333 ft) are usually ice wedges with the thin edge downward and are the basis for the classification of permafrost by Pewe (1963). These wedges are actively forming in areas of continuous permafrost which, according to Pewe, only occurs when the ground temperature is colder than -5.0°C at the level of zero amplitude. Ice wedges are not actively forming in the zone of discontinuous permafrost where the temperature ranges upward from -5.0 to 0.0°C at the level of zero amplitude. Ice wedges are common in the discontinuous zone but result from former climates colder than at present. Patterned ground may be present without ice wedges in areas where thawing, resulting from recent warming climates, caused the ice to disappear but preserved the patterns; Pewe refers to these as fossil ice wedges.

Figure 3. Polygonal ground. This is the more common form of patterned ground and represents resultant processes that are characterized of climates severe enough to cause permafrost.

Theoretical treatment of heat transfer physics based on these basic concepts has allowed construction engineers to compute the behavior of permafrost under specific treatments. By these calculations, they are able to predict how much fill is required to preserve permafrost during construction activities which use geologic materials for foundations. Using such theoretical treatments, engineers have concluded that in areas of continuous permafrost it is economically feasible to preserve permafrost by placing gravel pads or road overlay directly on undisturbed surface materials. Conversely, in areas of discontinuous permafrost, with its higher temperature, even in the frozen state, it is not economical to prevent thawing by fills of natural materials, and other means to induce stability must be used. Experiments using artificial insulating materials appear promising, and pilings embedded in permafrost for buildings and other structures have long been used in Alaska, Canada, and Russia. To be effective, pilings must be properly installed or repeated freezing and thawing of the active layer can "jack" them out of place and seriously disturb the supported structure. With proper design and construction procedures, these methods produce stable but costly foundations, compared to warmer climates. These additional costs are the price that man must pay when he brings his exotic way of life into this cold environment, if he is to successfully cope with these environmental conditions.

In the zone of continuous permafrost, the ground is unfrozen only under specific conditions. All ground is frozen regardless of slope direction or altitude except under large lakes or rivers. Brewer (1958) places lakes and rivers into two depth classes, those 0.6-1.0 m (2-3 ft) and those 2-3 m (6-9 ft). Shallow lakes and rivers [less than 2 m (6 ft)] freeze to the bottom each winter and are underlain by frozen materials. Deeper waters do not freeze to the bottom and are underlain by unfrozen material. Heat flow calculations suggest that deep lakes wider than twice the depth of regional permafrost are underlain by unfrozen material to the bottom limits of permafrost. Such lakes, therefore, form vertical chimneys of thawed material and may be a source of potable ground water. A similar circumstance is present in deep rivers whose active flood plains are two times wider than the depth of permafrost. Instead of chimneys, unfrozen material beneath rivers consists of channels bordered by permafrost and may act as subsurface streams with gradients similar to those at the surface.

Similar relationships hold in the zone of discontinuous permafrost. However, as temperature of the frozen material rises, slope direction and elevation become important and south facing slopes may be unfrozen. Many recently shifted river-meanders in this zone remain unfroze, whereas adjacent portions of the flood plain may contain permafrost. Vegetation in this zone may frequently be used to delineate unfrozen ground and commercial white spruce is usually restricted to unfrozen slopes and thawed portions of flood plains.

Minor topographic features in permafrost areas, but interesting because of their origin, are "pingos," an Eskimo word for low hill. Pingos are conical hills ranging in height from less than ten to one or two hundred feet and up to 600 feet or more in diameter. They are covered with a thin layer of soil but the interior is nearly pure ice. Their location and mode of formation are believed related to active ground water movement. On the arctic slope they occur on flat terrain (Figure 4) but in the discontinuous zone they usually occur in valleys and many have melted sufficiently to form small circular lakes.

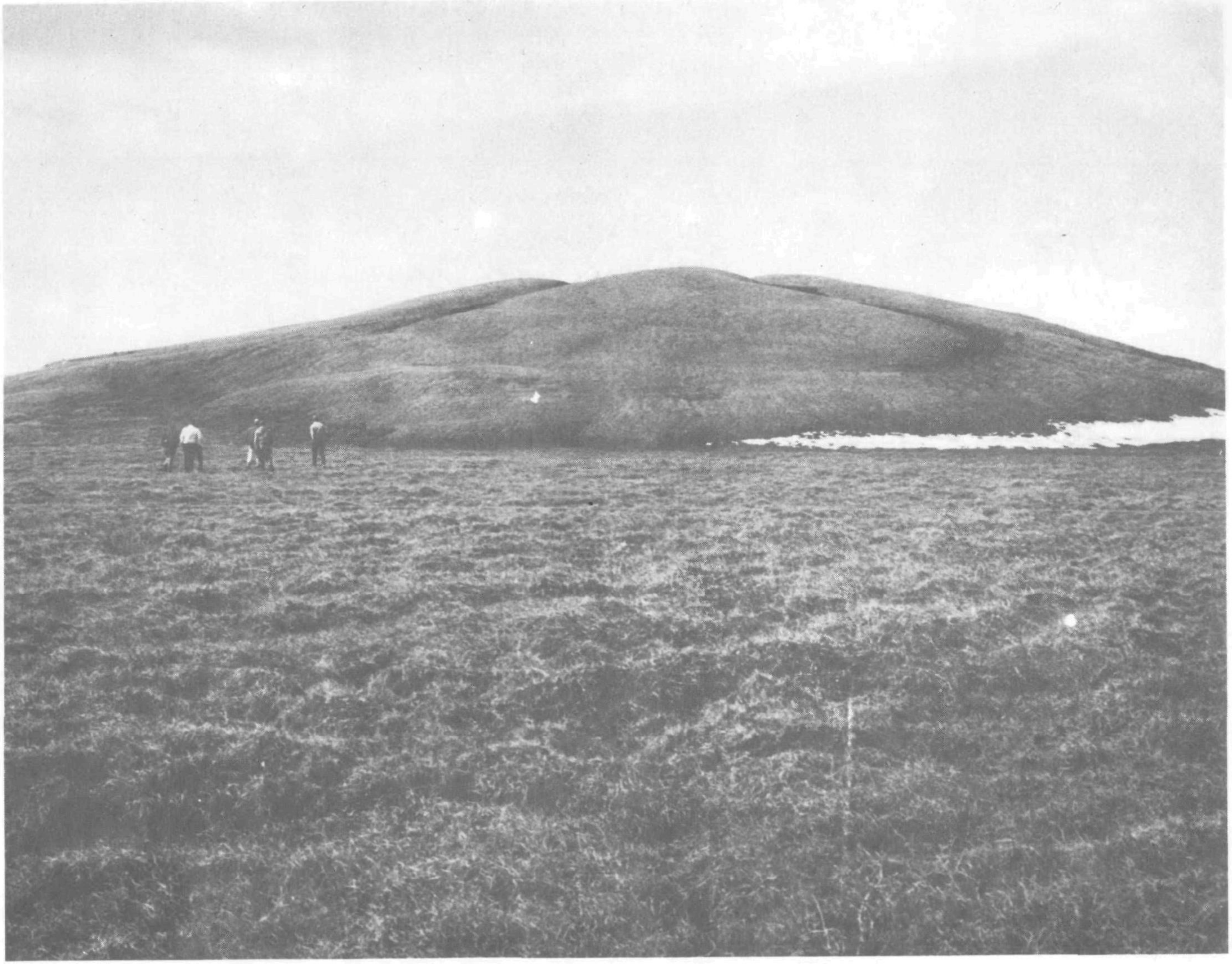

Figure 4. A pingo on the arctic slope of Alaska, about 30 miles south of Prudhoe Bay; this pingo is about 50 feet high and about 200 feet in diameter at its base.

PROPERTIES OF THAWED MATERIALS

Two papers summarizing many of the engineering problems caused by permafrost are those by Pewe (1966, revised from the earlier 1957 version) and a recent discussion by Ferrians, et al. (1969). Pewe cites many examples of failures of engineering works, and probably presents one of the most balanced appraisals of permafrost and how it affects life in the north. Ferrians, et al. presentation was in response to the controversy associated with the proposed pipeline to transport hot oil from Prudhoe Bay on the Arctic coast to the deep-water, ice-free port of Valdez in Southcentral Alaska. Their discussion presents many of the problems caused by improper or insufficient attention to consequences of melting permafrost and cites most of the literature describing the theoretical basis for calculating heat flow and rate of melting under prescribed conditions. However, neither Pewe's nor Ferrians' work stresses the importance of how the nature of unconsolidated clastic materials controls their engineering behavior when thawed.

Basically, two procedures can be followed when dealing with permafrost as an engineering problem: (1) use the frozen material as a foundation by preserving its frozen strength, called the passive method; or (2) permit melting to occur, then design with thawed or imported materials, after excavating thawed material, called the active method. Passive methods are usually superior, especially in continuous permafrost; however, in the zone of discontinuous permafrost extreme care must be taken to prevent thawing because of the higher temperature of the frozen materials. Refrigerated pilings have been designed that may be used in either zone, where the structure warrants the added cost, and offer a satisfactory solution to achieving maximum foundation stability in permafrost terrain.

TEXTURE, WATER CONTENT, AND STABILITY

As discussed in the introduction, permafrost is not a material but a condition of normal geological materials and it is the properties of these materials in the thawed condition that are the concern of construction engineers. Texture, or particle size distribution, is the overriding property controlling the stability and bearing strength of a thawed material. Some related factors of texture are pore size, total porosity, degree of sorting, packing or particle arrangement, and shape. Well rounded alluvial particles pack differently than weathered rock _in situ_, and pore size and channels will also differ. Frozen, fresh bedrock usually does not change properties when thawed. A material dominated by a large percentage of one particle size will transmit or retain water much differently than one with a wide range in particle sizes, where large pores may be filled with smaller particles. All of these physical properties influence the quantity of water held in a material, the rate at which liquid water moves, and the eventual strength when thawed. These factors are taken under consideration by the material specialist and geological engineer when using soil mechanics during the locating and design of engineering works.

Moisture content, which in permafrost is frozen, is another very important factor that determines the behavior of unconsolidated earth materials. Ice in permafrost takes many forms. It may be massive (Figure 5), as in wedges, and be nearly pure ice; it may be intercalated, lenticular seams or horizontal masses up to several feet thick (Figure 6); or it may be fine interstitial ice partially filling pores (Figure 7). Massive and lenticular ice causes the most serious problems because of the relatively high water content and volume occupied by ice which drains upon thawing. Massive ice of any form is usually associated with fine materials (silts and clays) and is rarely

Figure 5. Massive ice in a road cut about 70 miles northwest of Fairbanks.

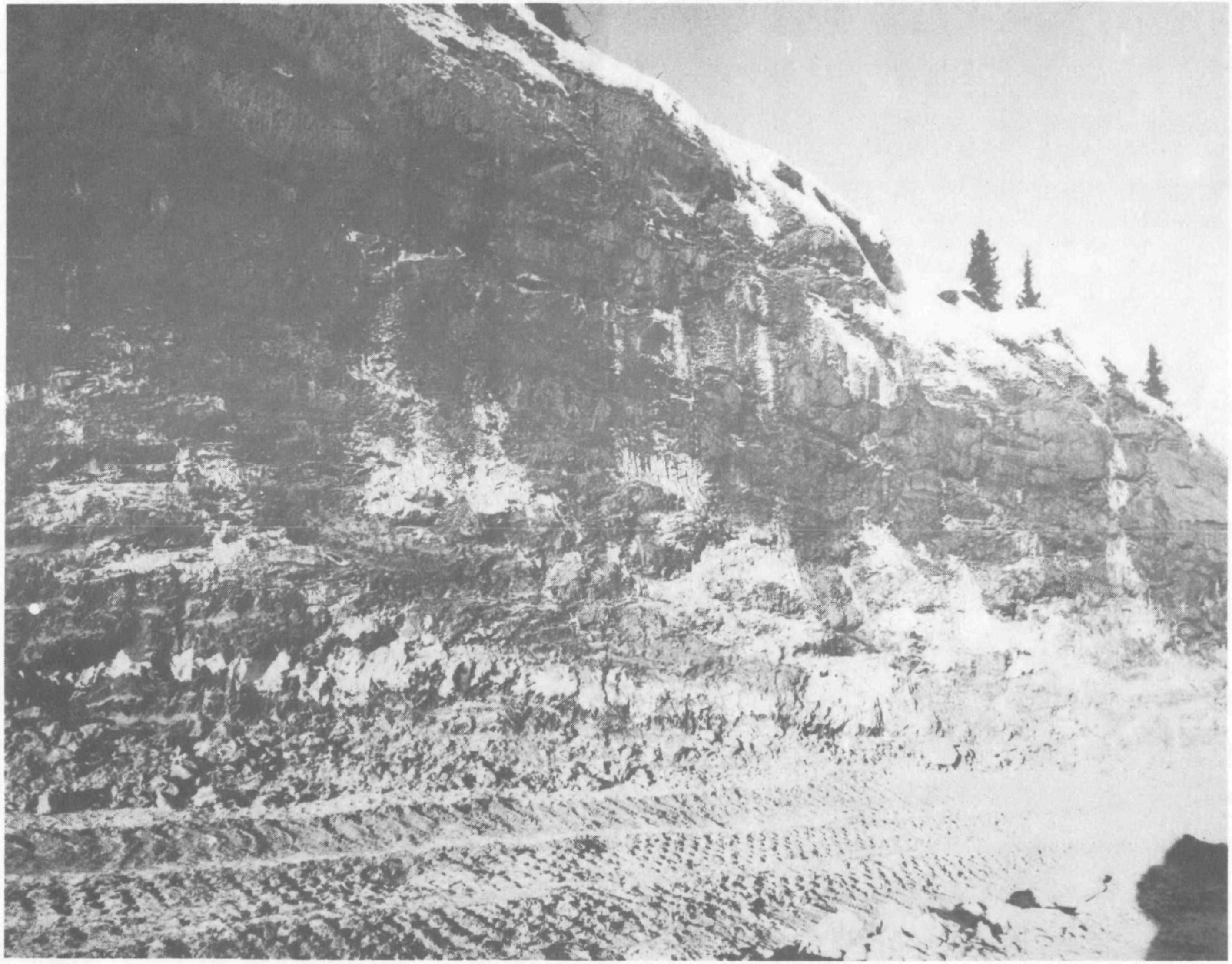

Figure 6. Ice wedges and intercalated ice in a road cut near Figure 5; ice content is estimated to be 40-60 percent

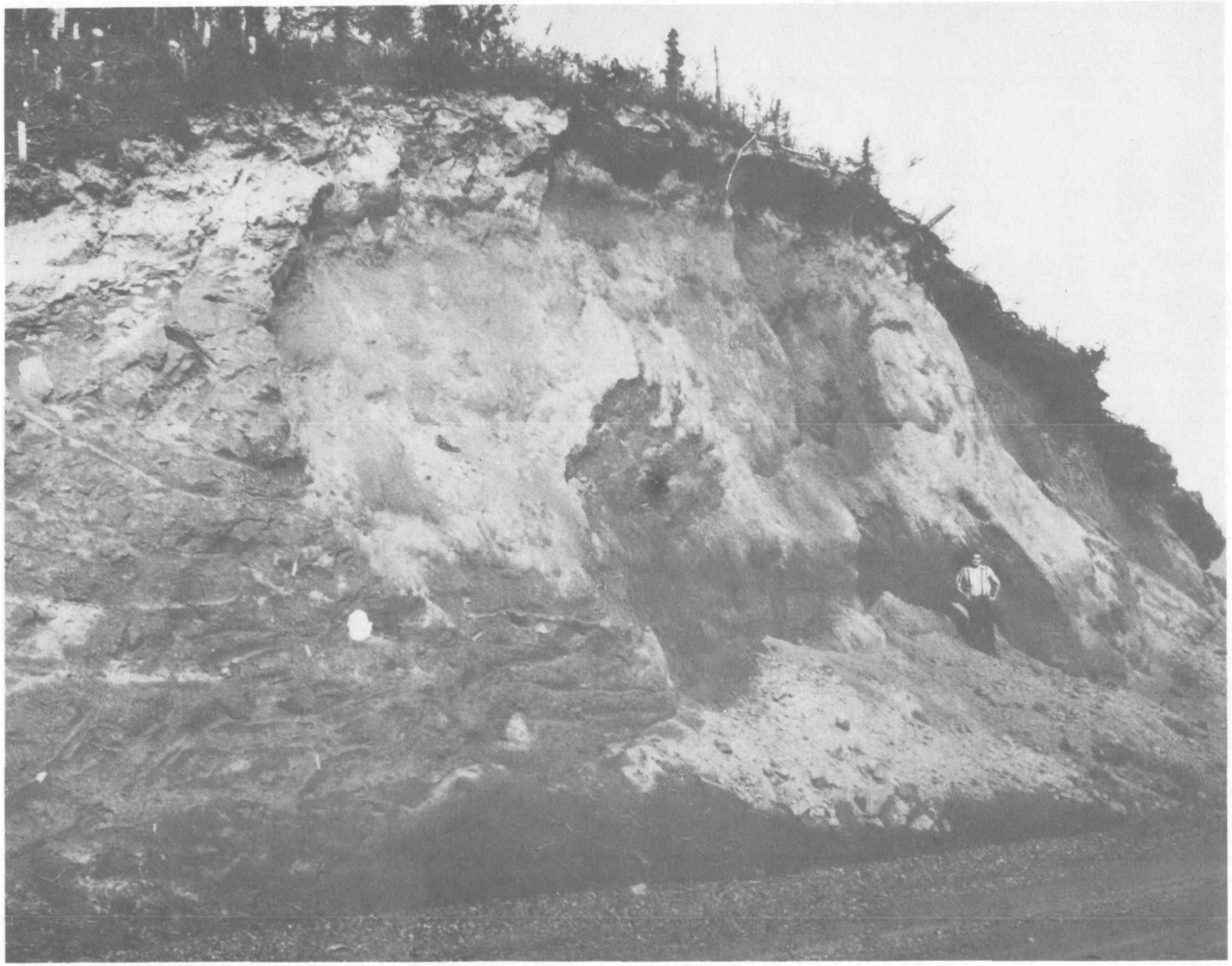

Figure 7. Frozen, unsaturated silt. Although this cut melted on exposure, it remained stable because it was relatively dry. Three to four miles south of the Yukon River (1970).

encountered in sands and gravels, probably because coarse materials drain better and remain dry above a water table.

All frozen materials retain their stability and bearing strength when thawed if their water content is low. Once melting starts and continues, as under heated buildings or a warm pipeline, transfer and disposal of water becomes a vital problem when water content is high. Rapid melting without proper water disposal causes severe thermal erosion and instability, therefore, the problem exemplifies itself through two facets, temperature control and moisture movement. Rarely do sand or gravels lose their bearing strength when thawed if their moisture content is below saturation--such events might occur when these coarse materials are saturated and frozen below a water table. It has long been known that airfields built on coarse subsurface materials were stable even though the construction disturbance caused permafrost to thaw. Structures using coarse materials for foundations should be stable even when the ice melts and drains away because their ice content is usually less than 100 percent of the pore space.

Frozen silts, with moisture contents well below saturation, if free from massive ice, retain their bearing strength when thawed. It is when water content, in the form of ice, approaches or exceeds total pore space that instability becomes a problem. Evidence that thawed silt can be stable is presented by a section of experimental pipeline at the University of Alaska. A 600 ft. aluminum pipe, four feet in diameter, was buried in frozen silt and heated by hot air at 160°F. Soil moisture content at time of installation was well below saturation, ranging from 20 percent to 30 percent by weight. After several months of operation no signs of instability appeared, even though a thawed zone up to 18 ft. from the pipe developed. Even with this evenly distributed heat in the pipe and with 4 feet of backfill with frozen silt removed during excavation, the surface froze during winter under a moderate snow cover. Silts even with a high percentage saturation, gain strength rapidly when the water is removed. Personal observation of slurry-like silt on a new road excavated through permafrost indicates that this fine material rapidly changes in properties after thawing and draining.

Pore size is also important because clastic materials coarser than silt have pore spaces and interstices that are larger than capillary in size, hence, cannot retain water against gravity above a water table. Capillary rise of water is nearly impossible in coarse materials, possibly being a reason why massive ice seldom occurs in these materials. Water may be transfered within a clastic material in two states, vapor and liquid. Ice cannot move except to deform under load but can sublime and move as a vapor. Liquid water moves chiefly by gravity and has limited lateral or upward movement. Stratification, sometimes within narrow textural ranges, may significantly influence liquid water movement. A stratum of fine material overlying a stratum of gravel must be nearly saturated before water moves downward into the coarse material, in accordance with the soil physics outflow principle. Thus, alternating layers of coarse and fine materials behave quite differently from a homogenous mixture in their water transmitting properties. This may be a partial explanation for the usual occurance of massive ice in silts and clays but which is seldom found in sands and gravels.

Transfer of water in the vapor phase may be important in permafrost terrains because colder materials cause lowered vapor pressures and water vapor moves from warmer to colder materials. Thus, during winter, moisture is transferred upward because surface temperatures are lower at that season, condensation and freezing of the vapor then occurs near the surface. This may be one reason why the percentage of ice is greater near the soil surface.

Water vapor may move in any direction in response to a thermal gradient, and in artifically melted materials, may move downward or laterally to condense at the thawed-frozen interface. Such phenomena could cause drainage problems with hot pipelines on sloping terrain, especially in areas of deep silts. Transfer of water released by thawing is an important consideration when predicting or estimating strengths and stability of thawed materials derived from permafrost.

The movement of liquid water in clastic materials has received much attention by soil physicists and materials engineers and the principles of movement are well established. If failures are to be avoided in permafrost terrains, disposal of meltwater becomes all important, because frozen layers may prevent downward movement of liquid water. In warmer climates, excess water usually percolates downward to enter and be included in groundwater. Many times this is not possible in frozen materials and other provisions to dispose of water must be planned. Where permafrost occurs as massive ice, or large percentages of lenticular ice, thermal erosion can be serious if melting is not controlled. It is not the water movement that erodes, it is the removal of large volumes of ice that causes cavities to appear with highly turbid meltwater.

Liquid water released by thawing may move upward only in fine textured clastics and then very slowly. For clastics coarser than sands, water must move downward under the influence of gravity; if an impermeable layer is encountered, lateral movement is possible as hydraulic head provides the energy to move, as governed by the Darcy law. Any engineering structure that acts as a continuing source of heat such as a hot pipeline must remove water, which will move in response to gravity and thermal gradients or laterally downslope on a frozen layer. It is unlikely that much will be lost to the atmosphere as evaporation because gaseous water moves in response to a thermal gradient, and the pipe is warmer than surrounding material. Water must move downward or laterally to colder surfaces where it will condense and freeze at the cold edge of the thawed envelope.

TEXTURE AND HEAT TRANSFER

Physical properties of clastic materials strongly influence the rate of heat transfer mainly by controlling water content and its movement. Since thermal relationships are so important when dealing with permafrost terrains, an understanding of how physical properties influence heat movement becomes necessary. Many factors influence heat transfer: temperature, moisture content, porosity, texture, mineralogy, shape of particles, and degree of packing (Kersten, 1949). Of these, moisture content and porosity are the most important and both are strongly influenced by texture. For dry materials, gravels are better thermal conductors than fine materials. However, under the natural environment most materials are not dry and the presence of moisture increases thermal conductivity. High total porosity--silts are higher than gravels--inhibits heat transfer under dry conditions; however, even small amounts of water greatly increases it. The insulating efficacy of dry silt was strikingly evident during operation of the hot pipeline test referred to earlier. In this test it was noted, after several months operation, that as soon as a thin envelope of dry silt developed in contact with the pipe, the rate of heat transfer slowed significantly. However, when this material was rewetted during breakup the original thermal properties of the silt returned. A clastic material consisting of one grain size conducts heat more slowly than one with a wide range of sizes; conduction occurs at contact points of the material. Thus, it becomes apparent that a complex system of interrelated factors are operating to influence thermal conductivity.

Since thermal phenomena are so important for most engineering works on permafrost, a thorough thermal evaluation of a proposed construction site becomes mandatory. Once the thermal regimen is established, knowledge of controlling factors of clastic materials may be applied to engineering studies. Thus, another environmental element is added to the already complex system that engineers must consider when planning engineering works in cold climates with permafrost.

Although each of these topics has been discussed separately, they do not operate in isolation from one another but by complex interactions which make accurate predictions difficult. Only by previous knowledge, gained through thorough reconnaissance of physical factors, thermal regimen, and moisture content, can reliable predictions be made on how a given structure will perform. Designers can produce a final structure that will serve its designated purpose, with minimum damage to the surrounding environment, if due regard is given to each controlling factor.

SOME EXAMPLES OF CONSTRUCTION PROJECTS ON PERMAFROST

Many examples, both good and bad, can be cited of engineering works on permafrost; only a few good ones will be mentioned here. Engineers can use principles illustrated in Figure 2 as the basis for calculating and evaluating design criteria for a given project. A good example of such treatment is that described by Peyton (1969) and points out the necessity of having certain required information before design can start. A good theroetical prediction of thawing caused by a hot pipeline is given by Lachenbruch (1970) and illustrates the complexity of the system under study. Lachenbruch discusses the role of water but his treatment of its movement under implied conditions is not as thorough as his thermal analysis. In designing the Trans-Alaska pipeline, hundreds of man-years have been expended in data gathering and engineers are using computer models based on these data to solve many problems; however, much of the input to the computer is based on the principles and interactions of factors discussed in this review.

Passive methods of construction are used in Arctic Alaska for drill rig pads and roads by providing enough gravel fill to preserve permafrost. The Naval Arctic Research Laboratory at Barrow is built on wooden piles imbedded in permafrost to maintain the foundation strength of frozen gravels. An example of a major construction project on permafrost is that of the research community of Inuvik on the MacKenzie River delta, Northwest Territories. It was decided to use passive construction methods and support all structures on piling. Careful planning and scheduling of operations consisted of: minimum disturbance (all clearing was by hand), restriction of traffic to thick gravel pads and roads, and installation of piling deep enough and early enough to permit complete freezing before any load was placed on them. (Johnson, 1963). Results are outstanding, with no serious failures after ten years. Although every effort is made to route highways on coarse materials to utilize their superior foundation properties when thawed, some sections must cross frozen silts. Therefore, some sections of highways built in the zone of discontinuous permafrost are expected to be unstable for several years where they cross areas of high-ice, silty materials as the thermal regimen shifts in response to increased thermal inputs from the new dark surface.

SUMMARY

The presence and need for developing natural resources existing in northern North America has focused the attention of engineers and scientists on gaining a better insight of permafrost properties and how it behaves as an engineering material. This review gives a brief, nontheoretical description of permafrost in its various forms, and has, as its primary objective, a discussion of properties of clastic materials in their thawed state and how these influence stability and bearing strength as applied to engineering problems in very cold climates. Attention is drawn to the requirement that to understand the environmental behavior of permafrost, it is vital that the mechanical properties and extent of clastic materials be known prior to design. Water relations are always important controls over engineering behavior of clastic material. In frozen materials, moisture relations are critical and may make the difference between success or complete failure of engineering works. Temperature as a factor seldom requires serious attention by designers in temperate regions; however, in permafrost regions, detailed thermal analysis becomes an overriding consideration of success is to be assured.

A final conclusion is that, without detailed consideration of materials extent and properties, their water content and predicted behavior as its phase changes from ice to water, and thorough thermal analysis, any proposed project may fail. Complicated as these interactions become, failure to properly evaluate each in its role as a factor can only cause additional failures. Modern computer technology has provided planners with a mechanism of testing various models, what remains now is to gather sufficient data from intensive reconnaissance to avoid overlooking some vital factor. Prior to computers, handling of extensive data was limited because of ponderous hand calculations

and some factors may not have received sufficient attention. That day is fast vanishing, and even though more intensive field exploration generates huge quantities of data, they can now be handled by computers; such treatment should result in superior engineering works with minimum damage to the environment.

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