SOME PROBLEMS IN ENGINEERING GEOLOGY CAUSED BY PERMAFROST IN THE ARCTIC COASTAL PLAIN, NORTHERN ALASKA*

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DURING field studies of permafrost from 1945 to 1951[1], especially at a U.S. Navy camp near Barrow, Alaska, the writer was impressed with the controlling influence of permafrost on certain engineering projects. Permafrost has direct and indirect effects on transportation, surface and underground exploration, construction and durability of structures in or on permafrost, water supply, sewage disposal, and petroleum resources. Numerous reviews of the engineering aspects of permafrost are available (Liverovsky and Morosov, 1941; Muller, 1947; U.S. Army, 1950; University of Minnesota, 1950; Black, 1951; Tschebotarioff, 1951; Frost Effects Laboratory, 1952; Johnson, 1952; Terzaghi, 1952; Lovell and Herrin, 1953; Black, 1954; and Schultz and Cleaves, 1955), and no attempt is made herein to present another survey. Only some of those relationships of permafrost to engineering as particularly applicable to the Arctic Coastal Plain Province of northern Alaska are mentioned here. Some of these peculiar aspects are touched upon briefly merely to point them out, or to emphasize them, rather than to present solutions to the problems thereby arising. Some of the unique problems, including drilling, have been met and solved, at least in a limited way, during exploration of U.S. Petroleum Reserve No. 4 in northern Alaska by the U.S. Navy (Fagin, 1947; Wilson, 1949). Others have yet to be met given future projects with different purposes. Complete records have been kept by the Bureau of Yards and Docks, U.S. Navy, on engineering in petroleum exploration in northern Alaska, 1944-54, of which certain results are summarized in U.S. Navy (1948-1949a, b).

Most construction undertaken in areas of permafrost requires individual surveys to determine the most practical method. The Arctic Coastal Plain Province is no exception to that general rule. Because of its large cold reserve (the average minimum temperature is $-10°$ C, and the normal thickness of permafrost is about 1,000 feet), except under the major deep lakes, permafrost should be used as a construction "material" for economy of time and money in most instances. Scheduling of engineering projects must then take into account the time required to thaw and refreeze permafrost in emplacement of foundations. To ignore permafrost in construction is to invite delays, expensive repairs, or later failures.

Nees and Johnson (1951) have reviewed some of the problems in engineering exploration in the Arctic. Such problems generally involve

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logistics more than the direct effects of permafrost, except in extensive subsurface explorations.

Overland transportation

Roads are absent in northern Alaska except for those within the confines of the Navy camp near Barrow and at Umiat, about 175 miles southeast of Barrow. The gravel and sand beach 4 miles long between the Navy camp and Barrow village is used as a road by wheeled vehicles, without improvement except for intermittent grading. Therefore, essentially all overland traffic must follow natural terrain, and tracked vehicles, (or large-tired "swamp buggies" or similar vehicles) are required for year-round transportation. In summer, amphibious vehicles are used to cross the numerous lakes, streams, and marshes resulting from poor subsurface drainage caused by permafrost at shallow depth. Such vehicles can avoid circuitous routes by fording or barging. Cut-banks constitute natural obstacles, many of which must be circumvented. The ridged and furrowed surface of the coastal tundra, caused largely by growth and thaw of ice wedges in permafrost, results in slow and indirect overland movements. For men and light loads, tracked vehicles, such as the Weasel (M29c) and Canadian snowmobile, with ground pressures of less than 2 pounds per square inch, ride over the turf without breaking it, except after many passes. Once the turf is broken, vehicles sink deeper into the supersaturated material, and travel is generally slower. The heavier vehicles, tractors, tanks, and LVT's have much greater ground pressure and commonly cut through the turf and ride on top of permafrost. For these vehicles, angle-dozing may be necessary, especially if sleds are being pulled, to avoid "high-centering" by the vegetal mat that bunches up in front of and under them. Permafrost is of less importance in a sand dune area 30 to 60 miles southeast of Barrow, where the well-drained, thick, active layer supports tractors and sleds well, and ice wedges which are everywhere present, are not indicated at the surface by strong relief.

In winter, low temperatures, drifting snow, darkness, and lack of natural landmarks are the chief obstacles to overland travel, but movement over the snow is faster and easier than over bare ground in summer. Permafrost is not a problem. Movement of heavy equipment in winter is done largely by tractor trains (U.S. Navy, 1948-49a, b; Earle, 1949; and Jones, 1951).

In the Arctic Coastal Plain the fall "freeze-up" and spring "break-up" are the most critical seasons for overland transportation. During "freeze-up", the active layer in many places freezes to permafrost as much as a month later than in immediately adjacent areas, because of differences in moisture content and thickness of the active layer, topography, and thickness of snow cover. Marshes and the low, wet furrows over ice wedges are especially slow in freezing. During "freeze-up", the tracks of vehicles may break the thin frozen crust overlying water or supersaturated fine-grained materials, immobilizing the vehicles which are then supported by ice between the tracks. During "break-up", streams are high and ice in the lakes is weakened by thaw so that vehicles break through easily.

Construction

Bench marks

Only with great difficulty and expense can bench marks be accurately placed for tide levelling or positioning within a millimeter or two in the Arctic Coastal Plain. Ice-wedge polygons are everywhere in the coastal plain, and measurements of ground contraction by Black (1952) indicate that individual polygons move erratically many millimeters during one year. Near-surface temperature surveys, examination of contraction cracks, and fabric studies of ice wedges also show that significant movements take place in permafrost to depths as great as 10 m. annually. Therefore, to insure that a bench mark will stay in place requires (1) the removal of the fine, supersaturated material to a depth of at least 10 m.; (2) back-filling of the excavation with material less subject to thermal changes; (3) permanent draining. Ideally, the bench mark should be a long rod placed inside a tube or cylinder penetrating perhaps 20 m. into the ground with at least the upper 10 m. of ground removed from within the tube, and the whole covered to prevent cold air effects at the base and to exclude foreign material. Thus, the upper 10 m. of the ground that is most subject to movement does not come in contact with the bench mark that is frozen-in below a depth of 10 m. According to the writer's contraction measurements, bench marks less than 10 m. in length, especially in or adjacent to ice wedges, are subject to lateral movements of 1 to 2 cm. and to vertical movements of perhaps 1 to 3 mm. per year. Such movements commonly are cumulative from year to year. Movement of this magnitude has been recorded by the U.S. Coast and Geodetic Survey personnel at their tide gauging stations (D. A. Jones, oral communication) and at their magnetic observatory at Barrow.

Excavations

Excavations or surface pits in the thawed active layer can be made in summer with normal excavating equipment. However, surface thaw commonly is only a few inches deep, seriously restricting the depths to which excavations can be made. Thawing of permafrost by solar radiation is most economical (Patty, 1951) but is effective only for about three months. By frequent removal of the thawed material in borrow pits, excavations to depths of several feet can be accomplished in one summer. Usually any surface excavation fills immediately with water, which must be drained or pumped. In winter, bulldozers, carryalls, and scrapers have essentially no effect on saturated, frozen, fine-grained material. It must be broken up with jack hammers or explosives, or thawed artificially.

Steam jetting is most effective for emplacement of piles and for thawing of small, shallow surface pits, because the size of the thawed area can be controlled most easily. Cold running water (hot water is less economical) is suitable for hydraulic operations or sprays in summer, provided the drainage is good. Hand tools for excavations include the miner's pick and chisels, but they are very slow and labourious to use. Explosives can be used effectively to form shallow pits if a small hole is first drilled. This is done commonly to provide a mud sump for drilling operations.

Ice cellars are convenient and relatively cheap for cold storage in areas of permafrost and have been used by the Eskimos since prehistoric times. Various methods are used to make the excavation. The Eskimos and early miners built fires on the frozen ground or used heated stones to thaw a thin layer of ground that was then scraped off. Thawing by steam or water is much more rapid. The use of steam offers advantages because little water is added to the excavation. Jack hammers are especially effective in supersaturated materials that are below —5° C. Sledge hammers, drill rods, masonry chisels, pick mattocks sharpened to a blunt V-point, and other hand tools are also used. Machines similar to the chain tree saw or coal cutter can be adapted for use in fine-grained frozen ground. Explosives are also practical.

Foundations

Bedrock in the Arctic Coastal Plain lies, on the average, several tens of feet beneath the surface and is thus, too deep to be used as foundations for most structures. The unconsolidated surficial materials must be used,

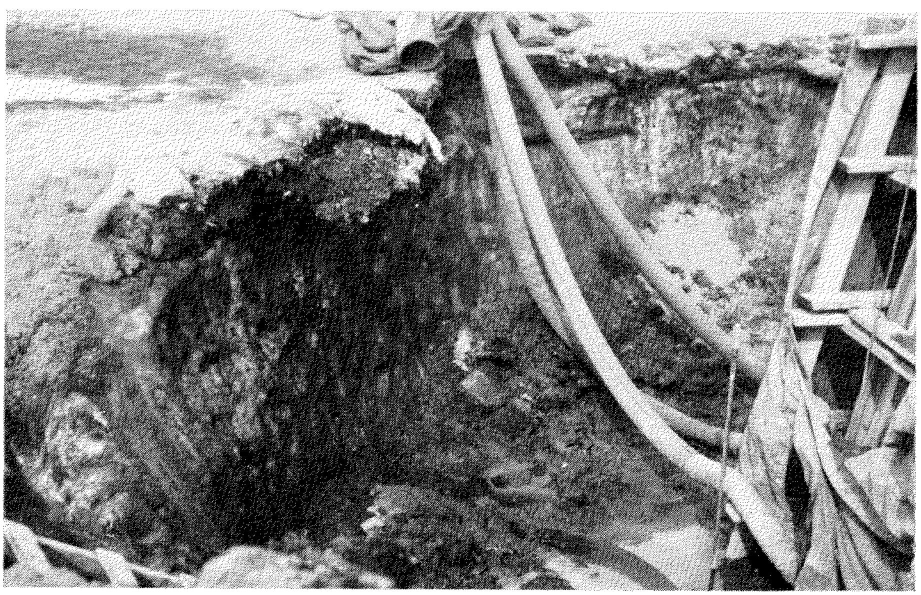

Fig. 1. Excavation near Barrow for large tower foundations that will be "frozen-in" in permafrost consisting mostly of ground ice. Ducts provide heat to the setting concrete. July 15, 1947.

but they are not suitable for foundations unless permafrost is retained (Fig. 1). The fine clay, silt, and sand covering the surface of the Arctic Coastal Plain generally are supersaturated and flow like molasses when thawed. Because of the large cold reserve of the permafrost, which is about $-10°$ C near the surface, it is not difficult to insulate buildings, oil well foundations (Rathjens, 1951), or large structures (Roberts and Cooke, 1950; Nees, 1951) so that heat conduction will not thaw the underlying permafrost. However, concrete foundations for heated buildings, boilers, pumps, or other structures cannot be laid on a few inches of gravel and be expected to hold more than a year or two. In all heated buildings the floor must be elevated above the ground level and insulated to minimize heat flow into the permafrost. Wooden piles have been used effectively for supporting small buildings. These are steam-jetted into place, the ground being thawed only enough to get them in. They are then allowed to "freeze-in" in place prior to loading. Near Barrow, wooden poles used for telephone and power lines seem to have no effect in increasing the depth of seasonal thaw around them.

It is again emphasized that prior to construction an analysis of the heat flow between the earth and the atmosphere must be made, and the effect of the structure on that heat flow should be determined. If necessary, artificial means of refrigeration can be used to prevent undue influx of heat into the ground beneath an important structure. This may be done by mechanical refrigerators (Gordon, 1937), but it is more economical to use the cold reserve of the adjacent permafrost or to utilize the cold reserve of the winter atmosphere (Huttl, 1948; Rathjens, 1951). As is well known, the specific heat, heat conductivity, and thermal diffusion qualities of different natural soils are markedly non-uniform (Kersten, 1949, and 1952) and must be taken into account. Once frozen, the unconsolidated materials, whether saturated or supersaturated, generally have ample strength to support most structures (Kersten and Cox, 1951).

In the emplacement of foundations, care must be taken to insure that very little water is trapped in the excavation to refreeze later. If much water is present, cryostatic pressure from freezing may heave the foundations.

Berger and Saffer (1953) have found that $-6.5°$ C is the lowest possible temperature to which water with an interface of air and solid material can be supercooled. Ordinarily salt and other materials will lower the freezing point of soil mixtures well below that temperature. Brine is found at shallow depths in many drill holes throughout the Arctic Coastal Plain and must also be taken into account in emplacement of foundations. For example, an apparently anomalous situation in northern Alaska is recorded by Terzaghi (1952, p. 14-15) in which soft plastic clay from a depth of 25 to 35 feet and at a temperature of $-15°$ C was unfrozen but separated by ice lenses. The clay became frozen on exposure to slightly warmer air temperature after being removed from the ground. Presumably, brine contaminating the deposit was concentrated by freezing of water into lenses of ice so that the clay was kept from freezing. On exposure to air the brine drained off and permitted the clay to freeze.

Roads and runways

The lack of suitable construction material for roads, except very locally in the Arctic Coastal Plain Province, and the lack of economic incentive probably mean that few if any permanent roads will be built for a long time to come. Within the Navy camp near Barrow the beach gravel required the addition of some turf and silt from the tundra to bind it for use by wheeled vehicles. Without a binder the pebbles rolled like marbles under the wheels of the vehicles. However, the organic and fine-grained material prevented thorough drainage, so that during heavy rains in the summer, the road became a quagmire (Fig. 2).

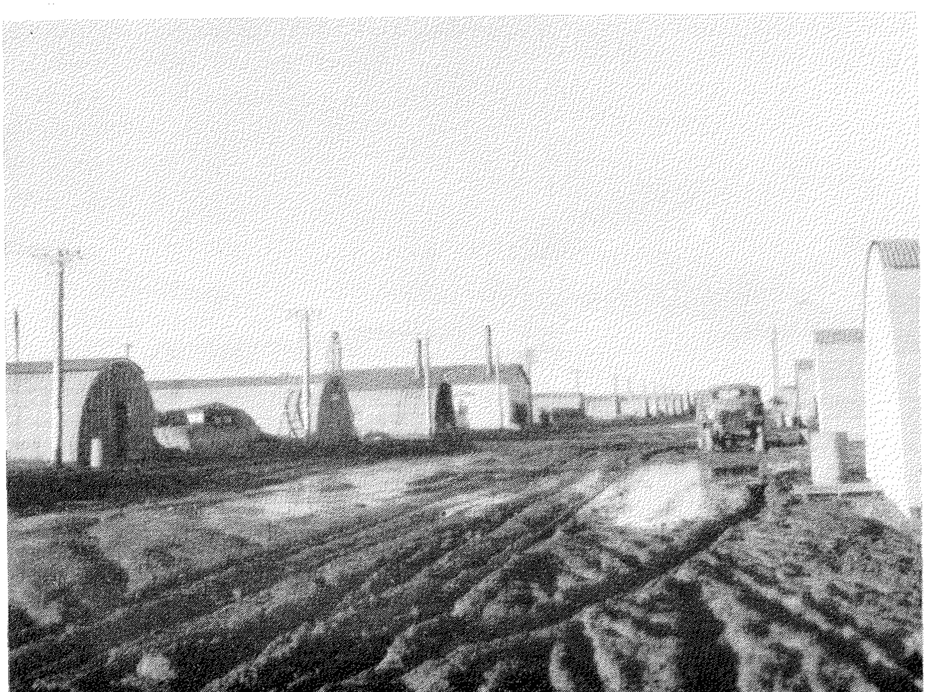

Fig. 2. Main street of the U. S. Navy camp near Barrow after a moderate to heavy rain. August 23, 1946.

A steel landing mat is used on the gravel beach for a landing strip at the camp, but a binder is needed to prevent small grains of sand and gravel from being picked up by propeller wash. Concrete is used at the warm-up apron. Neither affects the underlying permafrost adversely. In an area of sand dunes 30 to 60 miles south of Barrow, small airstrips can be made with little grading and with little danger that permafrost, and therefore foundation stability, will be affected. Former ocean-beach ridges, recently abandoned lake terraces, and other natural bars and beaches with only slight to moderate grading are suitable as airstrips for small planes, which leaves the permafrost essentially unaltered. Stripping of vegetation over areas of much ground ice, however, results in differential thaw and collapse of the ground by as much as several feet (Fig. 3).

In areas removed from a suitable source of gravel or sand, a frozen runway of pycrete (Perutz, 1948) or icecrete (Roberts, 1950) utilizing turf and surface soil as the foundation material and permafrost as a cold reserve in a heat exchanger is recommended for permanent runways.

Pipe lines

Pipe lines on the surface offer no special problems other than those familiar to any engineer, where extreme cold, snow, and rapid spring run-off are found. Pipes buried in the ground present special problems in the Arctic Coastal Plain. The writer has shown by field measurements (Black, 1952) that contraction of the ground takes place each winter as though the ground were composed of pure ice with a thermal coefficient of about 50×10^{-6}. Where contraction cracks are produced, as in all areas of ice wedges, the effects are at least partly cumulative annually. Adfreeze strength of fine-grained saturated materials is sufficient to cause most pipes to be pulled apart by the winter contraction, unless they are protected by material with low adfreeze strength. Slower vertical movements adjacent to ice wedges, over a period of several years, heave pipes out of level.

Steam lines or other heated pipes in the ground thaw permafrost, which results in the collapse of the ground (Fig. 4) if ice is present. Utilidors are required for their protection.

Water supply and sewage

Potable ground water, except in the beds of the larger rivers and lakes, is absent in the coastal plain of northern Alaska (Black, pp. 118-119 in Hopkins, Karlstrom, *et al.*, 1955); shallow wells within permafrost have always encountered saline water in and below permafrost. Potable water is trapped on permafrost in many lakes dotting the coastal plain. Lakes more than 6 feet deep do not freeze to the bottom in winter and can be used, at least to a limited extent, throughout the year. A very small amount of water can be obtained from the active layer during summer, even in some of the off-shore bars, although the water generally contains much organic matter and dissolved salts. The occurrence and development of ground water in areas of permafrost, including especially methods of drilling, are treated by Cederstrom, Johnston, and Subitzky (1953), and need not be reviewed here.

In areas of permafrost the cold climate and low ground temperature present problems in water purification, filtration, and distribution (Alter, 1950a, b; Crockwright, 1947; and Hyland and Reece, 1951). At Barrow it has been found convenient to use a heated wagon and tractor to distribute

Fig. 3. Removal of the turf covering ice-wedge polygons has resulted in the thaw of ice wedges and a slump of the surface of as much as 6 feet. Weasel tracks (M29c) give the scale. Near Barrow, August 25, 1947.

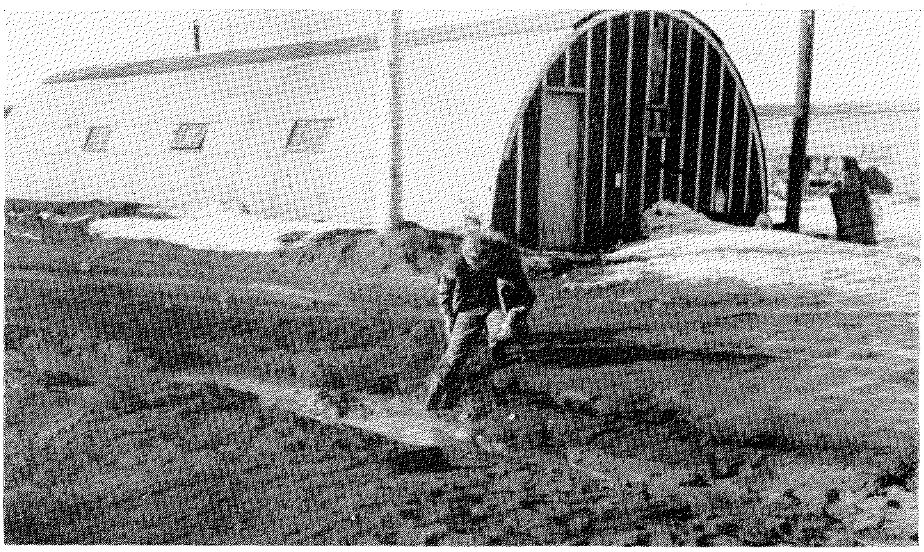

Fig. 4. Slump in the gravel street at the U. S. Navy camp near Barrow along a heated sewage line. The thaw penetrated more than 7 feet and the surface dropped more than 2 feet in 2 years. May 17, 1950.

water to buildings housing from 200 to 500 men. In other places heated utilidors are more convenient or economical for water and sewage lines (Muller, 1947; Roche, 1948; and Hyland and Mellish, 1949). Individuals and small groups of people commonly use melted ice and snow in winter and store ice for summer use.

Because surface water has to be used in northern Alaska, extra care must be exercised to avoid contamination. Sewage disposal presents a problem not now within easy reach of solution. Inland, where natural gas or coal are available in quantity, the liquid sewage can be boiled or evaporated and the solids burned. For installations adjacent to the coast, the ocean offers the only safe outlet. Few rivers can be used as outlets for sewage disposal from large installations, unless the use of drinking water below the sewage outlet is not considered.

Drilling for and production of oil and gas

Drilling for oil and gas in the Arctic Coastal Plain has introduced problems in logistics and in mechanics of operation not encountered in temperate regions (Fagin, 1947). As pointed out earlier, permafrost directly and indirectly creates difficulties in overland transportation in the supplying of well-drilling camps (U.S. Navy, 1948-1949a and b). By virtue of its cold temperature, permafrost also adversely affects drilling operations within it. For example, the cold reduces the viscosity of drilling muds, and during periods of idleness the drill string can "freeze-in". The normal drilling problems in permafrost areas are augmented when the high ground temperatures at depths of several thousand feet are transmitted to the permafrost by the drilling mud, thawing the permafrost adjacent to the hole and under the drilling platforms. Artificial heat exchange then must be resorted to (Rathjens, 1951) in order to maintain the foundations of the drill rig.

Similarly, production of gas and petroleum from below or within permafrost creates problems not generally found outside northern Alaska (or other arctic areas), and the problems require solutions that are not yet available or standardized. For example, moisture within gas tends to freeze on the inside of pipes on passing through permafrost, and the ice eventually seals off the flow. Effective pore space in rocks within permafrost is reduced by ice so that capacity and ability to yield oil and gas are reduced. Furthermore, spicules, cement between grains, and other forms of ice in openings in the rock effectively reduce permeability, and the minute crystals of ice within the oil may be filtered-pressed off around the producing well, preventing delivery of oil to the pipe. However, permafrost may substitute for a cap rock for petroleum and gas where no other cap exists.

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