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PILE CONSTRUCTION IN PERMAFROST

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Permafrost underlies approximately 20% of the land area of the world. Its extensive occurrence in northern regions, including almost one-half of the USSR and Canada and much of Alaska, is of considerable concern to engineers particularly with regard to the foundations for various structures. Although permafrost provides excellent bearing for a structure, it may lose its strength to such an extent when thawed that it will not support even light loads. Substantial settlement can occur when these frozen materials thaw, and differential movements usually result in serious damage or even complete failure of the structure.

Prior to the last war, construction in the Canadian North mainly involved the erection of isolated small buildings and limited engineering facilities. Most structures were supported by foundations which extended to or slightly into permafrost or were placed on the ground surface [1]. Some movement had to be tolerated, therefore, due to frost action and thawing of the frozen ground. Increased northern development in recent years has required the construction of more extensive facilities that made previously used foundation designs unsuitable.

Present construction techniques for large structures favor the use of foundations, such as piles, which are embedded in permafrost. They are particularly useful, and may be the only type of foundation suitable, for sites underlain by materials containing large quantities of ice. Piles are anchored in permafrost thus providing resistance to frost action forces. In addition, because they are well embedded, some thawing of the frozen ground can occur without detriment to the foundation or structure.

Several accounts describing the design and performance of pile foundations in permafrost areas have been published [2, 3,4]. Studies have also been conducted to determine factors affecting the use and design of piles in frozen ground [5,6,7, 8]. There is a great need, however, for additional information on the design of pile foundations.

The development of the new townsite of Inuvik, NWT, in an area of continuous permafrost offered a unique opportunity for members of the Division of Building Research, National Research Council, Canada, to conduct studies of many aspects of construction on permafrost. Pile foundations were used extensively at Inuvik and the experience gained and some observations on their use are reported.

HISTORY

The development of the new townsite of Inuvik near the mouth of the Mackenzie River (68°21'N, 133°44'W) resulted from a decision of the Canadian Government in 1953 to concentrate and enlarge its educational and administrative facilities for the Northwestern Arctic at or near the old settlement of Aklavik located in the Mackenzie River Delta. Aklavik was not a suitable location for the expansion proposed for several reasons including poor subsurface conditions [9]. During 1954, therefore, potential sites for a new town were surveyed [10]. The most favorable site, originally known as East Three but officially named Inuvik in July 1958, was recommended; by a decision of the Federal Cabinet in November 1954, development of the new townsite was approved.

During 1955 and 1956, construction activity was limited to site preparation (building access roads, hand clearing of brush, stripping of borrow pits), stockpiling materials and the erection of a large equipment maintenance garage, some warehouses, and a wharf. The main construction period was from early 1957 to the late fall of 1960 when all major contract work was completed [11]. All major buildings (including most housing) and engineering facilities such as heated oil tanks and utilidors are supported by pile foundations (Fig. 1). All pile foundations were placed, in advance of building construction, by the Federal Department of Public Works.

Fig. 1. Air view of Inuvik under construction, June 1959

DESCRIPTION OF SITE

Inuvik is located on a terrace immediately adjacent to the East Channel which forms the eastern boundary of the Mackenzie Delta [12]. The relief of the area is one of flats at varying elevations, gentle undulations seperated by shallow swales, rounded knolls, hummocky hills, and ridges of varying heights and lengths. Spruce and birch are the dominant tree types with secondary stands of willow and alder. The ground is generally hummocky and covered everywhere with moss from 4 to 6 in. thick.

Below the living moss cover a brown to black peat (average depth about 2 ft) occurs over much of the site. At a few locations it may be as deep as 13 ft. Underlying the peat there is usually a brown gravel with sand or silt which varies in thickness from 1 to 14 ft. This material is, in turn, underlain by a grey gravel with sand, silt or clay. Granular deposits are underlain by various combinations of grey, fine-grained soils, mostly silt size. A typical sequence of subsurface materials found at the Inuvik townsite is shown in Fig. 2.

Ice segregation varies considerably over the site but has been observed in all soils, ranging from fine-hairline lenses or coatings on particles to massive ice concentrations several feet thick. The higher ice contents occur in the peat and the fine-grained soils, generally in the form of thin lenses. The larger ice masses are also chiefly associated with peat and fine-grained soils although some have been observed in granular materials (Fig. 3).

Permafrost occurs everywhere under the ground surface at Inuvik to depths exceeding 300 ft. The mean annual ground temperature at depths of from 15 to 100 ft is approximately 26°F. The maximum depth of thaw observed in the late summer of 1954 (during the site survey), i.e., prior to occupation and disturbance of the area, averaged 1.5 to 2 ft, ranging from 1 ft in peat to about 4 ft in gravel having a 4 in. moss cover.

FOUNDATION SELECTION

It was realized that because of the variable soil and permafrost conditions at Inuvik, every precaution would have to be taken to prevent thawing of the underlying permafrost, or at least to keep thawing to an absolute minimum. In addition, the erection of several very large buildings and important facilities at the site made foundation design particularly critical; the selection of one foundation type that would serve all or

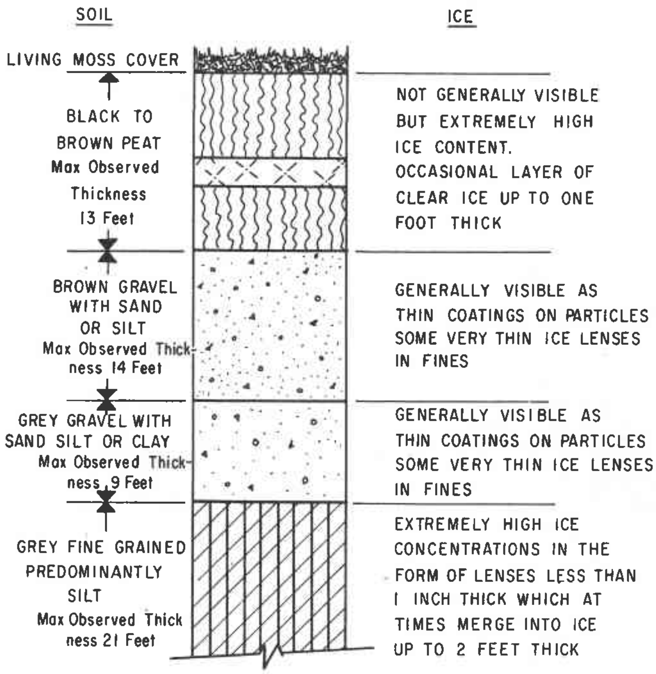

Fig. 2. Typical sequence of subsurface materials at Inuvik, NWT

most structures was most desirable. Under these circumstances it was decided to place all structures on pile foundations.

Five major factors had to be considered with regard to the use of piles in permafrost at Inuvik. These were: Site preparation, type of pile, pile placement methods, depth of embedment, and refreezing characteristics.

PILE FOUNDATIONS

Site Preparation

It was imperative that individual construction sites as well as the area as a whole be disturbed as little as possible in order to maintain the frozen ground condition. Under no circumstances was the insulating moss cover to be disturbed and therefore movement of construction equipment and clearing of brush was under strict control. Any necessary clearing of trees and undergrowth was done by hand methods.

At each construction site a gravel pad from 18 to 24 in. thick was laid over the whole area. For access the pad was connected to an adjacent main road by a gravel fill. Heavy equipment thus moved easily about the site and construction materials were stockpiled on the gravel pads with little disturbance of the moss cover.

Type of Pile

More than 20,000 piles were placed for the foundations of buildings (Figs. 4,5), utilidors, oil tanks, and road bridges (Fig. 6). Because spruce timber was available from the adjacent delta area and thus would affect a substantial saving in cost over material brought in, wood piles were used for the majority of the foundations. Although some timber in 24 and 30 ft lengths was available in the delta, most of the spruce piles obtained locally had a maximum length of 20 to 22 ft with a minimum diameter of 6 in. About 800 pressure-creosoted Douglas Fir piles (30 to 40 ft long), were brought in from Edmonton, Alta., for the foundations for the powerhouse and the two 35,000-barrel heated oil storage tanks. Some 200 reinforced concrete piles (about 20 ft long and 15 in. square) were cast on the site and used for road bridges over the utilidor lines. Approximately 300 steel piles were used, primarily for corners and anchor points along the utilidor lines. Some of these piles were 9 in. dia. pipe and others were wide

Fig. 3. Massive ice deposit in gravel

Fig. 4. Pile foundations for house

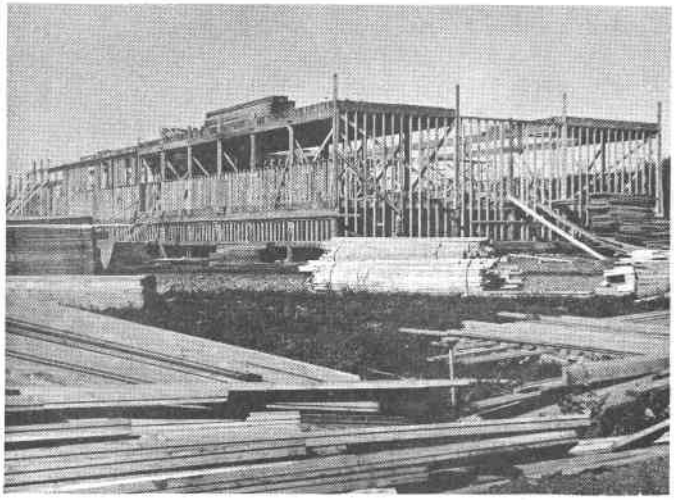

Fig. 5. Pile foundations for hostel. Note airspace, false floor, and crawl space

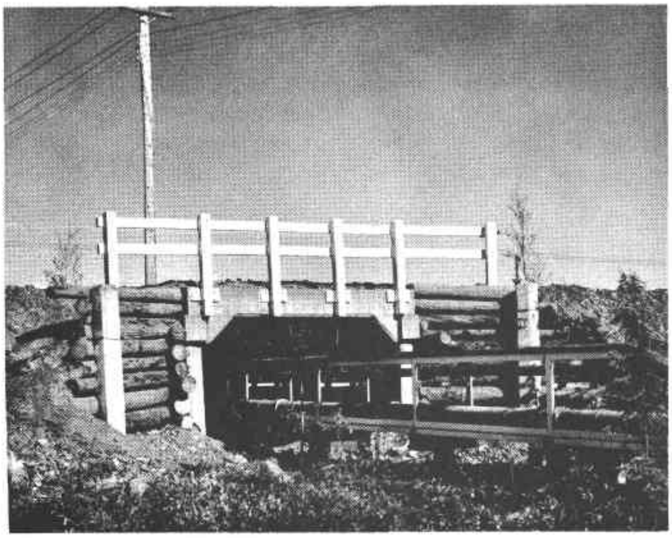

Fig. 6. Concrete and wood piling for bridge and utilidor foundations

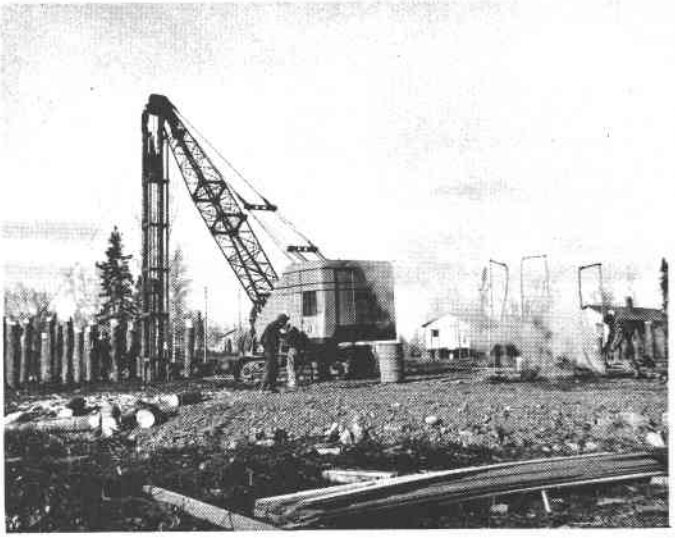

Fig. 7. Pile steaming and driving

flange beams (approximately 12 by 15 in.) about 24 ft long.

Preservative treatment of wood piles is necessary to prevent deterioration of the upper portion of the pile which is in thawed soil. All wooden piles, except the pressure-creosoted ones, were treated at the site using a diffusion process. The bark was stripped from the top 6 to 10 ft of each pile, although initially the first few hundred piles were treated for their full length, and the preservative applied by brush to the timber in the form of a paste.

Pile Placement

Satisfactory performance of pile foundations depends upon adequate anchorage of the pile in permafrost. The method by which piles are placed in the ground can have an appreciable effect on refreezing conditions and ultimately on their performance. Normal procedures entail either steam thawing or drilling a hole into which the pile can be driven. At Inuvik, steam thawing of pile locations was used for virtually all foundations. For the two large oil storage tanks and the powerhouse, however, where the piles were closely spaced because of the heavy loads, the piles were placed in drilled holes.

Drilling— At the location of the structures previously noted a truck-mounted seismic "shot-hole" rig was used to drill pile holes. The gravel pad and active layer were penetrated with a 24 in. auger, and a casing, made of 45 gal gas drums, placed in the hole. From the permafrost table, holes were bored with 18 in. dia. augers, having special, hard metal-faced cutting edges, to depths of about 30 ft. Frozen fine-grained soils and ice were readily penetrated by the augers (e.g., 23 ft in 1.5 to 2 hours) but at many locations concentrations of boulders and, at the 23 ft depth, a cemented layer of gravel, prevented, or caused very slow, penetration. When stones were encountered, carefully controlled steaming (10 to 20 psi) was used in order to enlarge the hole so that the stones could be pushed to the side and thus allow passage of the auger.

Steaming—All other piling, e.g., utilidor and building foundations, were placed in steam-thawed holes (Fig. 7). A 50 hp oil-fired portable boiler supplied steam to as many as five 0.75 in. jetting pipes. Boiler gage pressure varied from 100 to 130 psi but was usually maintained at about 115 to 120 psi. Pile locations were steamed from 10 to 20 ft in depth and averaged about 14 ft. The depth and rate of penetration of the steam jets varied considerably and were directly dependant on soil type. Organic material or massive ice was penetrated so rapidly that the jets had to be held up until the hole exceeded the pile in diameter. In granular materials, which contained many stones, and dense sandy silt the jets had to be forced into the ground. At times stones prevented jet penetration to the depth desired. In these cases a new hole was started immediately adjacent to the old location, or the pile was driven to the depth steamed if the hole was considered deep enough. In some townsite areas, gravels were cemented, at a depth of 8 to 10 ft, by an iron oxide coating which made steaming very difficult.

The difficult steaming conditions encountered in the gravels often resulted in excessive steaming of pile locations at some sites. This oversteaming substantially enlarged the pile holes near the surface (as well as at depth) and caused subsidence of the ground surface due to the thawing of massive ice deposits. The thawed zone surrounding each pile varied, but generally was from 2 to 4 ft in diameter.

Very stony soils also caused trouble during pile driving. Stones were frequently loosened by pile driving and these deflected the pile out of line (as much as 3 ft). In some cases stones were forced to the bottom of the hole so that the pile could not be driven to full depth. A steaming technique was developed by which the steam jet was left at the bottom of the hole to "bell out" or enlarge a thawed area into which stones and boulders could be pushed by the pile as it was driven.

Steaming intervals varied widely over the townsite and even from one pile location to another at one construction site. Observations of steaming intervals, including the time taken for the jet to penetrate to the hole bottom ("sinking" time), the "belling-out" time and the total time, were made during the construction period. Total steaming times for a 14 ft hole ranged from about 1 hour under good steaming conditions in fine-grained soils to about 8 hours at a few locations where steaming was most difficult because of heavy concentrations of stones. In the latter case, because of the excessive steaming, the jet pipe was pulled to the surface without "belling out" the bottom of the hole. Some of the steel piles for utilidor corners and anchor points were placed to a depth of 20 ft and these holes generally required steaming for 4 to 6 hours.

Driving—At the powerhouse and the heated oil storage tanks where holes were drilled, the piles were simply dropped into the hole and a silt- and sand-slurry backfill placed around the pile. At steamed locations a 2000 lb drop hammer was used to drive piles. In most cases the hammer weight was sufficient to force the pile to a depth of from 4 to 8 ft in the steamed hole, and the pile was then driven to refusal. As the pile was driven, the soil slurry resulting from the steam thawing was forced to the surface. Those piles deflected by stones during driving (some more than 12 in.) had to be realigned. The "straightening" operation consisted of resteaming the hole beside the pile, pulling the pile into line with a winch and then inserting long wooden wedges beside the pile to hold it in position until refrozen (Fig. 8). Although many piles were realigned immediately after placement, some piles had to be straightened from 2 to 4 weeks after the pile had been driven, because wedging was ineffective, until the large thawed zone surrounding the pile at the surface had refrozen.

In an attempt to provide additional anchorage against frost-heave, piles were driven butt-end down for the foundations of the first structures erected. Great difficulty was experienced in driving because the local timber tapered greatly from butt to tip, and stones in the hole wall prevented penetration of the pile. Consequently, except for about 200 piles, all piles were driven tip down.

Depth of Embedment

Only limited information is available with regard to the required depth of embedment of a pile in permafrost. Although some of the load on the pile may be taken by end bearing, it is believed that when the pile is completely frozen into the surrounding soil much of the load is transferred to the permafrost by the tangential adfreezing strength developed between the soil and the surface of the pile. Not only does the adfreezing bond distribute the load to the permafrost but it must also resist frost-heave forces in the active layer. Two factors influence the embedment depth: The depth of the active layer resulting from the presence of the structure over a period of years and the adfreezing strength that will be mobilized by surrounding frozen soil. Because of the information lack on these factors the following "rule of thumb" for embedment of piles in permafrost has generally been followed: "Piles should be embedded in permafrost to a depth equal to at least twice the depth of seasonal freezing and thawing during the life of the building" [13].

Only a qualitative assessment of the potential depth of expected thaw under a building at Inuvik could be made. For design purposes, therefore, some increased thawing was assumed that would result in a maximum depth of thaw of between 4 and 5 ft over a period of years. Thus, using the "rule of thumb," piles should be anchored at least 10 ft in permafrost; i.e., placed to a minimum depth of about 15 ft below ground surface.

For most buildings, holes were steamed to a depth of about 15 ft and the piles were generally driven to within 1 ft of the steamed depth. Steel anchor piles for the utilidors were placed to depths of 15 to 24 ft in steamed holes. Wood piles for oil tanks and powerhouse were placed to a minimum depth of 25 ft in drilled holes.

Pile Refreezing

The refreezing period required for piles placed in permafrost is of utmost importance to a construction schedule. Superstructures cannot be erected until the foundations are adequately anchored in permafrost. Refreezing of piles is dependant on many variables, including the time of year when piles are placed, steaming interval, ground temperatures, soil type, and soil moisture content. Of these, perhaps the most important factor is the steaming interval.

Refreezing observations made at Aklavik in 1953 and at Inuvik in 1955 [2] indicated that, with average or moderate steaming, piles would be refrozen at the 20 ft depth within a few days and at the 10 to 14 ft depths within one month. Shallower depths normally took longer than one month to refreeze depending on the time of year. Excessive steaming prolonged the refreezing period considerably—by as much as several weeks. The need for carefully controlled steaming was therefore emphasized.

Observations made at Inuvik during the construction period showed that piles should not be loaded for from 2 to 6 months, or longer, depending on the time of year they were placed. In particular, a full winter period (at least 6 months) was required to ensure that piles placed in the fall were adequately anchored and free of movements caused by freezing of the active layer.

Fig. 8. Straightened piles. Note variability of driven depth, wedges, and ground subsidence

CONCLUSION

Pile foundations have long been used with great success in temperate climates to provide support for structures located on materials that are relatively unstable or have low bearing capacity. They have also had considerable application in permafrost areas where they are used to transfer building loads through the unstable active layer to the more suitable and stable permafrost. Certain aspects of pile placement techniques and design criteria differ considerably for foundations in permafrost however.

Methods of placing piles in permafrost (e.g., by steaming or drilling holes) can have an appreciable effect on their performance. Major design considerations include predicting the effect, with respect to thawing, that a structure will have on permafrost and determining what tangential adfreezing strength can be assumed for distributing the load to permafrost and resisting frost-heaving forces. Factors considered in the use of pile foundations at Inuvik, NWT, have been described as an example of the approach taken at that location.

Pile foundations at Inuvik have performed exceedingly well to date. Observations on pile-placing techniques and refreezing characteristics have shown that careful steaming control, particularly during the latter part of the year, is required because of difficult soil conditions. Excessive steaming of pile locations can result in greatly increased refreezing times. Piles placed early in the year (January to May) can usually be loaded within 2 to 3 months. Those placed later in the year may not be adequately anchored (to resist frost-heave occurring in the active layer during the late fall and winter) for periods of six months or more, depending on steaming conditions and refreezing characteristics of the soils encountered.

The large construction program recently completed at Inuvik has shown the success of preplanning the time of foundation placement so as to allow time for refreezing of piles before the superstructure is erected. Construction schedules were rarely disrupted by pile foundations not being ready for loading.

The selection and use of piles as the most suitable foundation type for the majority of the buildings and facilities erected at Inuvik has been justified. Observations are continuing to assess their long term performance.