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ENGINEERING DESIGN AND CONSTRUCTION IN PERMAFROST REGIONS: A REVIEW

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THERMAL CONDITIONS IN PERMAFROST - A REVIEW OF NORTH AMERICAN LITERATURE

This state of the art review summarizes key points of present knowledge in North America and major problem areas relative to engineering design and construction in permafrost regions. Topics discussed include the special importance of proper site selection and investigation, environmental engineering and protection constraints, current concepts of foundation design including footings, piles, ground anchors, foundations near or in water bodies and control of frost heave, design criteria for roads, railroads and airfields, North American experience with dams and reservoirs, excavation and underground construction studies in frozen ground, drainage, groundwater movement and artesian water conditions and problems, difficulties of providing reliable water, waste disposal and other utilities systems at reasonable cost in permafrost regions and the state of the art in the field of petroleum production and pipelines. Areas in which further research and development are required for improvement of engineering design and construction are summarized in a concluding section of the paper.

PERGELISOL - UN RESUME DES ECRITS NORD-AMERICAINS

Le présent exposé de synthèse résume les points saillants des connaissances actuelles en Amérique du Nord et les principaux problèmes que suscitent les études techniques et la construction dans les régions de pergélisol. Les sujets traités comprennent l'importance particulière d'une étude et d'un choix appropriés de l'emplacement, les exigences de l'aménagement et de la protection de l'environnement, la conception actuelle des fondations, y compris les semelles, les pieux, les ancrages au sol, les fondations dans les nappes d'eau ou près de celles-ci et la prévention du soulèvement dû au gel, les critères de calcul des routes, des lignes de chemin de fer et des terrains d'aviation, l'expérience des barrages et des réservoirs acquise en Amérique du Nord, les études d'excavation et de construction souterraine dans un sol gelé, le drainage, le mouvement des eaux souterraines et l'état et les problèmes des eaux artésiennes, les difficultés d'approvisionnement en eau saine, d'évacuation des déchets et autres commodités à un prix raisonnable dans les régions de pergélisol ainsi que l'état d'avancement de la production pétrolière et des pipelines. Les domaines dans lesquels il importe de poursuivre la recherche et le développement en vue d'améliorer les études techniques et la construction sont mentionnés brièvement à la fin de l'article.

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INTRODUCTION

In North America, development of the permafrost regions is advancing at a rapidly accelerating rate. This creates increasingly intense pressure on the technical community to formulate engineering design and construction principles that will accurately ensure predictable behavior and minimum costs. In North America, research to develop such criteria was started in the 1940's. This has provided an invaluable base and fund of fundamental knowledge to meet this construction need. In the past decade, entirely new construction situations, new and more stringent requirements for structural and environmental stability, and the continuing increase in knowledge of the nature of permafrost have contributed new intensity and scope to the challenge and have provoked especially intense research and investigation efforts. The extent of current activity in applied permafrost research is reflected by the fact that about one third of the total North American papers submitted to the Second International Permafrost Conference appear under Session VII. Also, a large percentage of papers in other sessions are clearly closely supportive of engineering needs.

Because of the large volume of information currently available on construction in permafrost regions, it is impossible to reference all significant literature in this paper. Therefore, references herein have been selected only to be indicative of the current state of the art.

SITE SELECTION AND INVESTIGATION FOR ENGINEERING PURPOSES

The importance of proper selection and investigation of a site or route for construction in permafrost areas, by reconnaissance and detailed site, environmental and material availability studies, cannot be overemphasized. Unfortunately, the fact that rational design requires an adequate base of factual knowledge and that this is doubly important in permafrost regions has sometimes in the past been overlooked or ignored. The record of the past shows many failures of construction on permafrost from lack of this information base. Consequences of encountering unexpected conditions during construction include lost construction time schedules, improvised foundation redesign, carrying of work unexpectedly into severe fall and winter weather, very large cost increases, delay in beneficial occupancy, heavy repair and maintenance expenses, and disruption of operations. During the last several years, however, recognition of the fundamental need for adequate area, route, and site studies prior to engineering design and construction decisions has increased. Existing and new techniques for obtaining the required surface and subsurface information have been increasingly employed on new construction.

Investigational techniques may be divided into two categories: indirect, including aerial photographic and geophysical methods, and direct, including drilling and sampling and allied techniques.

Use of conventional aerial photographic techniques for terrain and site evaluation in permafrost areas was extensively investigated beginning more than two decades ago and results were reported by Frost.[52] The U.S. Army Corps of Engineers has included summaries of these techniques in two engineering manuals.[175,176] The discovery of vast oil and gas and other mineral resources in northern North America in the last few years has greatly spurred the widespread practical use of these aerial photographic techniques. Very extensive application of aerial photographic methods is now being made for both route selection and detailed route and site examination in combination with surface and subsurface investigations on the proposed Alaska pipeline, on several proposed pipelines in northern Canada,[125] and on associated transportation systems and on other projects. In current practice, airphoto analysis is used not only for reconnaissance evaluation of geological, soils, vegetation, drainage, accessibility, and similar factors but also to assist in detailed layout of roads, buildings and other facilities and in detailed engineering evaluation of permafrost conditions in relation to these projects. Engineering design and construction problems may often be enormously simplified by placing the facility in the most favorable location.

An interesting special case is the use of aerial photographs taken during the thaw–melt period to determine topographic positions of maximum snow accumulation, especially from snow drifting. This approach was used by the Arctic Construction and Frost Effects Laboratory in Greenland in the 1950's for selecting route locations for roads and more recently within the continental United States to minimize facility snow removal problems. Granberg, in a paper prepared for this conference, describes a technique for indirect mapping of snowcover to aid in predicting localized occurrences of permafrost.[63]

As outlined by Haugen *et al.*,[68] the current Earth Resources Terrain Survey (ERTS) program promises to give a wealth of information on terrain and permafrost conditions in Alaska and Canada that will be useful for engineering purposes. Information will be obtained on any given location every 18 days on such surface details as vegetation, snow and ice covers, ground temperatures, and geomorphic and other evidences of permafrost, as well as stream levels and sedimentation patterns, forest fires, etc.

Urgent need exists for new geophysical exploration equipment and techniques that will permit large areas or distances (such as for pipelines and roads) to be covered quickly, conveniently, and economically on a continuous basis, with positive capability to detect problem ice-rich locations and isolated permafrost and ice bodies under specific sites, especially in areas of sporadic permafrost. Electromagnetic sensing systems, both airborne and surface-operated and capable of yielding subsurface information to depths of 15 m or more in frozen soil, have been used on an experimental basis. Hoekstra,[71] Frischknecht and Stanley,[48] and Bertram *et al.*[13] have discussed technical approaches in this area. Such equipment is capable of distinguishing, with depth, materials such as soils, ice, and rock having different electrical properties. Although not yet routinely used on major projects, such equipment can be used operationally for some purposes and is in a state of rapid and continuing development As reported by Garg[56] and Hunter[73] in Session VI, both resistivity and refraction types of conventional geographical systems have utility in permafrost areas. Roethlisberger[139] has recently summarized the state of the art of seismic exploration in cold regions. Experiments have been performed with acoustic reflection-type sounding equipment with inconclusive results thus far; however, additional research is in progress.

Special equipment and techniques for subsurface exploration and sampling of frozen soil (including clean gravels well bonded by ice), ice, and bedrock by core drilling are available, although improvements over the last decade seem to have been less rapid than in the previous decade. Sellmann and Mellor are summarizing the current state of the art in a monograph.[151] The frozen condition may actually offer a distinct advantage in gravels or in fractured or weathered rock provided the material is well ice-bonded. Lange has described for this conference techniques by which these materials can be sampled effectively.[100] Frozen bedrock should never be assumed free of ice if thawing of the rock is possible and if the consequences of undetected ice in the rock would be significant. McAnerney has described a case in which thaw sink holes and subsurface drainage channels developed in bedrock thought free of ice on basis of non-refrigerated core drilling.[117]

Though northern development has greatly spurred employment of special equipment and techniques, refrigerated core drilling should be used much more than it is, as undisturbed frozen cores permit visual examinations and accurate measurement and tests of almost completely undisturbed materials. As shown by Smith *et al.*, however, a small degree of disturbance may be present even in frozen cores which has to be taken into account in precise analyses.[160]

In fine-grained frozen soils above $-4\,^{\circ}$C drive sampling is feasible, as has been described by Kitze,[91] and is often considerably cheaper, simpler, and more rapid. Samples are structurally disturbed, but still permit accurate detection of ground ice and measurement of moisture content of specimens. Test pits and power-driven augers of various sizes are also widely used to obtain both disturbed and undisturbed samples and for *in situ* examination of the frozen soil profile.

Restrictions against surface movement and operations on the tundra in summer in order to avoid damage to the arctic environment have resulted in use of helicopters to move exploration rigs from location to location. The rigs have even been mounted on the undercarriage of the helicopter itself.

Both thermistors and thermocouples are used for ground temperature measurements, the choice depending on the degree of precision required.[161] Diodes have also been used occasionally as sensors to measure ground temperatures. Groundwater table measurements are often difficult to obtain on a routine basis, except in summer. Some experiments have been made with systems that use air displacement (Gilman[59]) or kerosine in the groundwater well to prevent freezeup. Methodology of groundwater measurements in permafrost regions is discussed in greater detail by Williams and van Everdingen in their review paper for Session V. Under the stresses encountered on construction projects, soil moisture cells may not always perform reliably.[7]

In both the United States and Canada an extension of the Unified Soil Classification System is in use in detailed or simplified form for engineering classification of frozen material.[107,130,182] During the last decade, significant effort has been applied to development of methods of field and laboratory testing of foundations materials for engineering analysis. For example, Crory,[33] Luscher and Afifi,[111] and Smith *et al.*[160] have reported studies to evaluate thaw-consolidation behavior of foundations. Again, Sayles,[148] Stevens,[164] Ladanyi and Johnston,[95] and Garg[56] have carried out studies to measure the mechanical properties of frozen foundation materials useful for engineering analyses, such as strength, creep, and dynamic response characteristics.

For special structures and facilities and where permafrost conditions are particularly complex, full-scale field tests are necessary and should be carried out in advance of construction to provide information for evaluations of the interaction between the atmosphere, the structure, and the ground.

PRINCIPLES OF ENVIRONMENTAL ENGINEERING AND PROTECTION FOR PERMAFROST TERRAIN

In North America, great public pressure now exists for preservation of the natural environment as well as for correction of pollution and environmental degradation effects where these have been allowed to develop. In the United States, this pressure is backed by laws at the federal level and increasingly at lower governmental levels that require a detailed evaluation and statement of the environmental impact of the construction or facility be submitted to show its acceptability before any new construction is started. In Alaska, these restrictions are further supplemented by a prohibition against operations on the natural tundra surface in summer because experience has shown that even a single vehicle pass may result in uncontrolled permafrost degradation and erosion where conditions are especially fragile. In Canada, similar legislation with regard to pollution and environmental impact is in effect or is being promulgated; Land Use Regulations must be complied with by anyone going anywhere on the lands north of 60° and a specific land use permit is required for every activity that involves going on the surface of the land at any time of the year.

The severe cost and operational penalties that may be encountered if a facility is not environmentally stable serve as further constraints on the engineer. The impact analysis cannot be limited to the structure itself; the total impact of all activities and environmental changes relating to the project must be considered. At a special symposium of the Royal Society of Canada[67] on "The Tundra Environment" some of the factors to be considered were discussed. The fragile nature of the ground thermal regime and the effects that natural and man-made changes can have on the environmental conditions under which permafrost exists have been described by Watmore,[186] Mackay,[113] and Gold *et al.*[60] among others. Wein and Bliss[189] have presented a summary of the effects and of methods of coping with them. Changes in vegetation, drainage, and water quality or temperature will affect animal and aquatic life. Erosion may not only destroy utility of land for future generations but may add siltation in streams, which affects aquatic life. Spills of oil or other substances may destroy many types of vegetation. Wildlife migration patterns may be changed.

In the United States, the need to incorporate environmental protective measures into construction on permafrost was recognized by the U.S. Army Corps of Engineers as early as World War II, and positive control requirements began to be incorporated into construction specifications in Alaska many years before the current public pressures and legal restrictions existed. Construction on difficult permafrost terrain at Kotzebue, Alaska, in 1957 as described by Jensen[78] is a case example. In Canada the Division of Building Research of the National Research Council, as the primary research agency for the Canadian construction industry, translated the results of research and field experience into technical guidance.

These efforts have led to the current situation as described by J. Brown[15] of greatly accelerated effort by scientists and engineers under sponsorship of both industry and government to develop both better fundamental understanding and better technology for utilization of permafrost terrain.

Much research to develop practical methods for predicting thermal effects in construction has been carried out by many investigators and many of the useful results have been summarized in manual form by the U.S. Army.[178] Sanger[145] has been very active in developing computation methods useful for engineering purposes. Research in use and maintenance of vegetative cover to control degradation of permafrost areas is in its infancy, but some relationships are known, as given in papers by Linell,[105] Heginbottom,[69] Brown *et al.*,[16,17] and others. Of particular interest is the indication that in borderline permafrost areas, such as Fairbanks, Alaska, a living cover of low vegetation cannot by itself be relied upon to control permafrost degradation, but in a colder area such as Inuvik, N.W.T., it can be sufficient.

The practical effectiveness of modifying heat exchange at the ground surface on a long-range basis by control of surface color has been demonstrated in pavement applications as reported in papers by Aitken,[1] Fulwider and Aitken,[54] Berg and Aitken,[12] Wechsler and Glaser,[188] and Kritz and Wechsler.[93] In-ground insulation has been found in several Corps of Engineers studies[9,11,55,159,181] to be effective in slowing or delaying permafrost degradation in marginal permafrost areas, but not in preventing it. Esch,[43] in carrying out similar studies, has thus far found similar short-term effectiveness of insulation in degradation control; however, the test duration has not yet been long enough to show long-term behavior.

Numerous research studies have been carried out and/or are currently in progress on environmental engineering for construction of hot and cold pipelines and on effects of, and remedial measures for, oil and gasoline spills in permafrost areas.

FOUNDATION DESIGN AND CONSTRUCTION

Current concepts of foundation design on permafrost are outlined in a manual prepared by the U.S. Army,[177] and Sanger has published a monograph on foundations of structures.[146] On materials identified as thaw-stable under the extension of the Unified Soil Classification System developed for frozen soils,[107,130,182] foundation design is commonly identical with temperate zone practice, even though foundation soils are frozen below the foundation level. Difficulty sometimes is encountered, however, in determining whether or not clean granular soils containing ice will consolidate after thaw, and elaborate sampling, testing, and compaction experiments have sometimes been conducted in an effort to resolve this question. Terzaghi reported more than 20 years ago that shrinkage or settlement per unit depth of thaw of coarse-grained frozen soils at a site in the vicinity of Fairbanks, Alaska, not containing buried bodies of ice, decreased from an upper limiting value close to the ground surface to almost zero at a depth of about 9 m.[170] He concluded that settlement of the surface under these conditions is by no means necessarily negligible. However, it can also be concluded that settlement of foundations supported at depth in such materials may be entirely tolerable; this is confirmed by observations of thaw settlement of actual construction in the Fairbanks area.[180]

On thaw-unstable foundation materials, unlimited challenge and opportunity for design ingenuity are presented. Here design to ensure preservation of the permafrost is by far the most commonly used foundation approach for permanent construction. Normally, acceptance of permafrost degradation, and design therefor, is used only when the foundation materials are thaw stable or where only expedient or short-term construction is involved. Notable exceptions to this approach have been the designs used for the sand fill dikes at the Kelsey and Kettle Generating Stations[19,82,112,115] and the foundations for several buildings at Thompson in marginal permafrost in northern Manitoba. Removal and replacement of unacceptable materials has been used extensively by the Alaska District of the Corps of Engineers at Fairbanks, Alaska where silts up to about 6 m thick overlay thaw-stable sands and gravels. Similar procedures have been used occasionally in northern Canada to obtain suitable bearing for building foundations.[65,149] Excavation of ice-rich materials to limit settlements to an acceptable amount was carried out for the Kettle dikes.[115] Except for steam or cold water thawing of overburden for gold placer mining operations in Alaska and the Yukon Territory, Canada, no documented case is known to the authors where prethawing to completely eliminate permafrost has been used in North America. However, based on water and steam thaw tests and recommendations by Terzaghi,[170] prethawing of sandy gravels to a depth of 9 m below the original ground surface has been used by the Corps of Engineers in the Fairbanks region with and without blasting as described by Waterhouse and Sills[185] to ensure consolidation of the looser upper strata in advance of foundation construction.

It is widely accepted that structures that cannot tolerate differential movements or seasonal vertical displacements must be supported on permafrost rather than on or in the annual zone of freeze and thaw. However, for structures that have very low movement tolerances, designers should be aware that some seasonal movements may occur in permafrost to at least as deep as 10 m and placement to as deep as 20 m may be required.[14]

The time- and temperature-dependent properties of frozen soils that are subjected to loading are important considerations in foundation design. Creep displacement and decrease in strength with increase in ground temperature may be particularly significant. Long-term strengths may be as much as an order of magnitude less than the strength of a soil subjected to a short-term or instantaneously applied load. These aspects have been covered in Session IV and are referred to in the following sections. From a study of building foundations in Canada's permafrost region, R. J. E. Brown has concluded that "anything can be built in any soil and permafrost conditions, provided the conditions are investigated thoroughly and proper design precautions are taken."[18]

Footings

Spread footings, continuous footings, raft or mat foundations, or post and pad construction have been successfully used on thaw-unstable as well as thaw-stable permafrost at such diverse locations as Churchill, Manitoba, Canada[39]; Fairbanks, Alaska[34,134,180]; Fort Yukon, Alaska; Pangnirtung, N.W.T., Canada; and Thule, Greenland, with careful planning for structural and thermal stability as appropriate for the foundation conditions. Principles and techniques for design of footings on permafrost have been expressed in manual form by the Corps of Engineers, including such aspects as creep and dynamic response analysis.[177]

Thermal control provided for footing-type foundations to maintain permafrost usually consists of either a simple ventilation space between the structure and the ground surface or one of various types of duct systems. Costs of providing ducted foundations easily become excessive unless care is exercised, however. Duct-ventilated gravel fills placed on the ground surface are receiving increasing use in Canada to support slab-on-grade construction, e.g., for aircraft hangars, maintenance garages, and heated oil storage tanks. These vary from simple systems where small diameter pipes are placed in the fill and depend on natural air flow during the winter to remove ground heat, to more complex systems incorporating ventilating fans to ensure adequate air flow. One such system utilizing 1.1-m-diameter pipes on 2.6-m centers has been proposed for a huge railroad maintenance building on Baffin Island.[64] In the United States, the U.S. Army Corps of Engineers began to investigate and use this type of construction in the later 1940's[108] and has since made numerous installations of many types and magnitudes in areas of both warm and cold permafrost. Experience has shown that duct systems placed below the ground level tend to collect ice and sediment, which block air flow, causing serious maintenance problems.[174] Steam thawing is required to open frozen ducts, which, in turn, may cause serious ground thermal disturbance. Instead, it is desirable that ducted foundations be sufficiently elevated above, or positioned relative to, the surrounding terrain so as to be self-draining in summer of any accumulation of ice and snow from the preceding winter. It is also essential that ducts be carefully designed to provide proper duct diameter and spacing. Stacks are used when necessary to increase natural airflow or to raise intakes and outlets above snow accumulation levels. Mechanical blower systems to increase volume of air circulation in ducts are generally avoided because of costs, increased mechanical complexity, and the dependence on alertness and care in operation that they introduce. Mechanical refrigeration systems are employed for maintenance of permafrost only in special problem situations or for remedial purposes.

Pile Foundations

Pile foundations incorporating an air space between the structure and ground surface are the most common type of design for permanent construction on thaw-unstable permafrost. Creosoted wood and steel pipe or H-section piles are the most commonly used types. Precast concrete piles are used much less frequently in permafrost in North America and cast-in-place concrete piles only occasionally. Cast-in-place concrete piles have been used at Thompson, Manitoba, where small islands of permafrost were encountered[61]; the designs assumed no support to a depth equal to twice the thickness of permafrost and allowance was made for negative skin friction when the permafrost thawed and the soil consolidated. Cast-in-place concrete piles were also used at the Birch Hill Ski Lodge, Fort Wainwright, Fairbanks, Alaska. Where substantial frost heave forces are experienced, concrete piles with conventional amounts of reinforcement are easily cracked in tension, exposing the steel to corrosion. Cast-in-place piles, of course, have to cope with the problems of setting and strength gain of the concrete and of thaw and refreeze of surrounding materials in the permafrost zone.

Piles are placed either by slurrying in an auger-drilled hole or by driving. Steam thawing is used only occasionally. Slurry may be the same soil as removed by the auger or concrete sand mixed with water. Use of carefully controlled high-quality backfill around the pile is one approach to increasing effective pile diameter under poor ground conditions. By avoiding excessively wet slurries, freezeback is hastened and made more positive in areas of warm permafrost. When piles exposed to below freezing temperatures are placed by slurrying, an ice layer may form on the surface of the pile that may control the allowable tangential shear strength that may be developed. In marginal permafrost areas, circulation of refrigerant through tubing attached to the pile is commonly used to assure expeditious and positive freezeback of slurried piles unless the piles are installed in the spring months (March through early June) when the ground is sufficiently cold to assure natural freezeback. Artificial refrigeration is not considered necessary where the mean annual ground temperature is –4 °C or colder. In fine-grained frozen soils at temperatures down to about –4 °C, both steel pipe and H piles have been installed by driving with diesel, vibratory, or other heavy hammers. Very extensive pile loading test programs have been carried out in Alaska by the U.S. Army Corps of Engineers, only part of which have been reported to date.[7,31,32,35] Newcombe and Rowley *et al.*[141] have performed pile tests at Prudhoe Bay, Alaska, and Inuvik, N.W.T., Canada, respectively, which extend available data into new soil and/or ground temperature conditions. The studies reported by Rowley *et al.* include the first results published in North America on lateral load tests of piles imbedded in permafrost.

Since effective adfreeze bond is the major variable affecting the realizable pile bearing capacity of non-end-bearing piles, many methods for increasing the effective skin friction or surface area or for maintaining values at high levels in the critical period of the year have been examined, including use of thermal piles. Thermal piles of various designs are in use, finding their greatest applicability in marginal permafrost areas where extra assurance of freezeback and/or maintenance of design adfreeze bond strength is needed. The most commonly used types have been the two-phase Long thermopile[109] (patented) and the single-phase Balch liquid-filled pile[80] (patented). Long recommends ring and helix types of thermal piles in combination with ground insulation as methods of maximizing pile capacity at competitive costs.[110] Johnson[80] has studied thermal convection loops, which are thermal pile elements interconnected to provide loop circulation. Babb, Garlid, and Shannon have suggested a "tube-in-tube" concept in which a single phase liquid device is placed within a "cold storage" tube containing ethylene glycol solution in order to increase effectiveness. Reed has demonstrated the potential of forced air circulation piles.[136] U.S. Army Corps of Engineers practice is to neglect end bearing for piles of about 15 cm tip diameter or less; in larger diameter piles or caissons, end bearing is taken into account.[177]

The need for protection of wood and steel piles in permafrost to prevent deterioration has been investigated. Examination of steel pipe and H-piles, installed for periods of 8–11 years at the U.S. Army CRREL, Alaska Field Station, showed that the length of pile imbedded in the permafrost was unaffected by corrosion and only insignificant effects on pile surfaces in the active layer were indicated by metal attack.[140] A study carried out by the Division of Building Research, National Research Council of Canada and the Eastern Forest Products Laboratory, Department of the Environment, Canada, on wood piles installed for a period of at least 10 years at Inuvik, N.W.T., showed that many of the locally cut spruce piles, some untreated and others protected by a diffusion process applied at the site, had superficial soft rot occuring mainly within the annual thaw zone.[150] All pressure creosoted Douglas fir piles and red cedar poles, treated with creosote by the thermal process, that were examined were in excellent condition. It was concluded that treatment of the local spruce is required and recommendations for improving the on-site treating procedure were made. It was also recommended that all important structures should be supported by pressure creosoted piles with extra heavy creosote treatment. Experience in Alaska and Canada shows that untreated poles used for communication and power lines may be destroyed by decay at the ground line in only a few years, even where the annual precipitation is low. Assuming that the portion of a timber member imbedded in permafrost will last indefinitely without preservative, only the portions extending above permafrost require decay-preventive treatment. However, no method exists for pressure creosoting only part of a member. Therefore entire members must be treated, including the portions to be imbedded in permafrost. Since a coating of creosote reduces the tangential shear stress that can be developed below that which would apply for bare wood, tangential adfreeze working stresses must be reduced accordingly.

Without question, a stable pile foundation can be constructed on any type of frozen soil regardless of the ice content, no matter how borderline the conditions, but each situation must be carefully investigated to ensure that all pertinent factors have been taken into account in order to obtain the most economical designs and satisfactory performance.

Ground Anchors

Construction of anchorages for footings, guyed towers, pipelines (either buried and empty or on slopes), and other facilities subject to uplift, thrust, or overturning forces is difficult and challenging because of the tendency for anchors in frozen ground to yield in creep, the risk of thermal instability in permafrost, and frost heave forces add to the normal structural loading.[177] Both the anchored structure and the anchor may be subject to frost heave and/or thaw settlement but to different degrees; therefore, the structure and the anchor must be analyzed as a system. Anchors for power transmission towers commonly must be very economical to construct because of the large number usually involved, yet adaptable in the field to a wide variety of subsurface conditions; the cost of individual subsurface explorations in advance at each tower location is often prohibitive.

Types of anchors that have been used or investigated for construction in permafrost include gravity, grouted rod, pile (ordinary and corrugated), helical screw, plate (various), belled, and metal expanding. In the 1950's, molten lead was used to grout into frozen bedrock the anchors for a 480-m radio antenna at Thule, Greenland, because of uncertainty concerning the behavior of Portland cement grout under the very cold ground conditions. Later, gravity anchors relying on the weight of footings and overlying earth fill were used with good results for an antenna in the same region subject to very high wind forces. In the 1960's, anchorage needs for arctic and subarctic transmission lines, oil field developments, and other construction resulted in extensive programs of study by such agencies as CRREL; the Division of Building Research, National Research Council of Canada; Manitoba Hydro and its consulting engineer agent, Teshmont Consultants Limited; Ontario Hydro; and Golden Valley Electric Assn., Fairbanks, Alaska.[163] These studies were primarily field investigations but also included some laboratory research. Still later, John A. Shuster of Woodward-Lundgren Associates performed field studies in the North Slope area of Alaska, correlated to laboratory triaxial creep tests; these involved six different anchor types in frozen and unfrozen Alaskan soils and included field tests in very cold permafrost. Crory and Tizzard[36] have measured rates of creep deformation in field tests extending longer than 1 year, and Tizzard and Lorber[173] in laboratory studies have shown that failure of plate anchors occurs by punching below a depth equal to six times the plate diameter and by lifting out of a cone of frozen material above this level. This generally agrees with failure behavior observed by Baker and Kondner in unfrozen soils.[8] Crory and Tizzard have also shown that ordinary commercial screw-in-type anchors cannot be installed by direct screwing into hard-frozen silt without breaking and have developed criteria for long-range holding capacity of anchors.[36] Johnston and Ladanyi have investigated in detail the creep performance of grouted rod anchors in marginal permafrost.[85] Jonassen has described a test program conducted by Manitoba Hydro to evaluate a variety of anchors installed in marginal permafrost, including power-installed screw anchors, grouted rod anchors, belled, Malone, plate, and expanding anchors, for the 880-km-long Nelson River HVDC transmission line.[86] Reinart reporting on further studies for design of foundations for the Nelson River line concluded that Portland cement grouted anchors provided the most cost-effective solution for the ground conditions there encountered (nonpermafrost to marginal permafrost with subsurface materials varying from bedrock to fat clay containing ice).[138] However, such factors as the cement type and grout temperature had to be extremely carefully controlled. About 16 000 grouted rod anchors (15 cm diameter) were installed by over burden drilling methods on this project; some were as much as 27 m in length. Construction aspects of the Nelson River line, erected despite formidable climatic, logistic, and terrain problems, are described by Barry and Cormie.[10]

Shallow depth expedient anchors for tying down tents or other temporary facilities have also been investigated by Crory and others. A simple light-weight device for inserting and recovering such anchors has long awaited successful development. Kovacs *et al.* have summarized available information on both expedient and permanent types of anchors for both frozen and unfrozen materials.[92]

Control of Frost Heave

In field measurements of frost-heaving forces at Fairbanks, Alaska, average maximum adfreeze bond stresses as high as 413.7 kN/m^2 have been measured on uncoated steel pipe piles in slurried silt backfill.[35] The stress would be higher except for relaxation of stress resulting from creep. Since 413.7 kN/m^2 is an average value over the area of adfreeze within the annual frost zone, higher unit values undoubtedly were developed in the coldest parts of the adfreeze zone. Unless such forces are anticipated in the design, destructive and progressive frost heaving of footings, piles, towers, walls, and other structures may occur. These displacements are often more apparent when an unheated exterior porch, loading slab, or building extension experiences differential frost heave with respect to the main structure.

The U.S. Army Corps of Engineers has summarized available techniques for controlling frost heave and frost thrust.[177] When the structure is supported on top of the annual thaw zone the foundation readily returns each summer to its original position. However, when a fixed foundation is used that might be subject to progressive jacking, frost action effects may be controlled by providing sufficient anchorage in permafrost so that, together with structure loading on the foundation, frost-heaving forces are completely counteracted or by isolating foundation members from uplift forces by various means.

Anchorage of piles or footings may be achieved by providing sufficient imbedment in permafrost. The old engineering rule-of-thumb that the length of piles imbedded in permafrost should be twice the depth of the annual frost zone has been shown to be unreliable. Instead each case is analyzed on its own merits, but a minimum depth of imbedment in permafrost of 3 m is normally considered adequate. When the anchorage approach is used, care should be taken to ensure that structural members (such as concrete piles) will not be cracked or broken. Installing wood piles butt down has been found to limit frost heave movement, but some upward displacement does occur before full resistance is developed. Heave force isolation has been successfully used since 1945 for bench mark and pile isolation[6,81] and can be applied to footings and other construction. In one of these heave isolation schemes developed in the Arctic Construction and Frost Effects Laboratory, the pile or foundation member is cased, wholly or partly, through the frost zone. The annular space between the pile and casing is then filled with an oil-wax mixture of sufficiently thick consistency to prevent soil, water, or other materials from entering the annular space. To prevent the casing from being jacked progressively out of the ground by frost action, a plate or flange is attached at the bottom of the casing. To avoid the difficulty and cost involved with use of casings a premixed backfill of soil, oil and wax has also been used by CRREL without casing to reduce transmitted frost heave thrust in the upper part of the annual frost zone to acceptable values. Surface coatings such as heavy creosote or red lead reduce the heave force transmitted but are not relied upon for permanent control of heave. Tar paper or plastic film wrappings do not guarantee even temporary effectiveness, although they have sometimes helped under favorable conditions.

Foundations near and in Water Bodies

Foundations for bridges over water bodies or for port and waterfront construction in permafrost areas tend to involve especially difficult foundation problems because the permafrost conditions are substantially altered near and under the water, especially in borderline permafrost areas. The presence of permafrost may be irregular in such locations and where permafrost does exist its temperature tends to be warmer. Investigations conducted in the Mackenzie River Delta have indicated the distribution of permafrost under and adjacent to water bodies and the effect of channel movements.[83,84,156] Unfrozen highly saline strata may be encountered, especially in coastal locations. As indicated by the studies reported to this conference by Carlson, Kane and Bowers,[24] Sherman,[152] and Kane and Slaughter,[88] water moving in unfrozen zones beneath and adjacent to the water body may cause a very complex and variable thermal regime pattern. For these reasons highway and railroad bridge and wharf foundations in permafrost areas have been a continuing source of difficulties.

Piles are the most common type of bridge support. Because permafrost conditions tend to be borderline at water bodies, however, little or no capacity for natural freezeback of piles may be available and the effective tangential adfreeze bond strength may be small. Because of uncertain, incomplete, or weak freezeback, the frequency of serious frost heaving of pile bridge foundations has been very high. Péwé and Paige[129] have reported that frost heave of wood piling on bridges of the Alaska Railroad has reached as much as 35 cm/year, with serious changes in track elevation requiring reduction of train speed to avoid uncoupling of cars or shifting of cargo.

CRREL, the Alaska Department of Highways, and the U.S. Department of Transportation have recently engaged in a cooperative research study of bridge foundations in permafrost near Fairbanks, Alaska. In his analysis to date, Crory has stressed the need to carefully delineate the location of thaw areas in the foundation under the stream for most advantageous selection of bridge pier location.[32] However, possible changes over the life of the structure must also be considered. Other observations in this program have shown that even apparently stable bridge piers are in cyclic seasonal movement as a result of the varying forces acting on the piers. When the design is inadequate, progressive upward or downward displacements occur.

Permanent wharves have been provided at most major settlements along the Mackenzie River. These are usually either timber pile or earth-filled sheet pile structures constructed so that they are submerged by flood waters during spring breakup to avoid ice damage. Piles placed at the shoreline or just inshore penetrate the thin wedge of permafrost occurring at the margins of water bodies. Sheet piling have been anchored to soldier piles installed in permafrost on shore. Although some pile heaving has occurred, no serious problems have been experienced with these structures.

Permafrost is known to occur offshore in northern Alaskan coastal waters and has been reported by Samson and Tordon[144] in the eastern Canadian Arctic and by Mackay[114] and others in the Beaufort Sea. Mackay also estimates that permafrost will be encountered extensively in offshore areas of the Canadian Arctic Archipelago. Offshore permafrost in these areas will pose similar problems to those experienced on land, but they will be more serious and difficult to deal with because of the remoteness, severe climate, and usually permanent ice cover. Hwang *et al.*[75] report on a preliminary study of the thermal regime under a structure forming part of a proposed arctic harbor development in the Beaufort Sea. This structure would support a heated building and consist of a concrete caisson placed on, and retaining, gravel fill on the frozen sea bottom.

Detailed site investigations, including careful subsurface explorations, are especially and absolutely essential when structures are to be built near the edges of, or in, coastal or inland waters. Provided adequate site information has been obtained and the effects of construction and natural changes on site conditions are anticipated and understood, it appears that, in spite of the above-noted difficulties, it is technically feasible to construct stable foundations by fully utilizing available technology, though at the expense of greater initial cost.

ROADS, AIRFIELDS, AND RAILROADS

Roads and airfield pavements constructed on permafrost in North America during World War II encountered difficulties where the subsurface conditions were unfavorable. Since 1950, however, airfield pavements have been constructed on permafrost and operated without problems at various locations such as Thule, Greenland, and Inuvik and Norman Wells, N.W.T., Canada. This good performance is attributable largely to a better understanding of the nature of permafrost and to the greater attention given in design and construction to subsurface exploration and thorough planning of all operations. Very many kilometres of new road construction on permafrost have also been accomplished successfully in recent years in Alaska and Canada and are anticipated in the future as development of the North continues.

Hennion and Lobacz have summarized current design practices of the U.S. Army Corps of Engineers for pavements on permafrost.[70] Three basic design approaches for pavements on permafrost are available[103]: (a) design for the reduced strength of the subgrade during the thawing season, accepting whatever pavement roughness may occur from seasonal frost heave and thaw settlement; (b) limited subgrade frost penetration design, in which the primary objective is control of surface roughness caused by seasonal heave and thaw; and (c) full protection against frost heave or thaw settlement above the current permafrost table. Approach (a) is applicable primarily for low to moderate speed roads, parking areas, etc. Approach (b) is applicable for high-speed surfaces such as airfield runways. Method (c) is used over permafrost only in very cold areas, where depth of summer thaw is small enough to make this approach economically feasible.

It has been shown that the total thickness of section required for confinement of thaw penetration within the non-frost-susceptible base course can be reduced by as much as 35 percent and the summer pavement surface temperature reduced by 5 °C by painting the pavement white.[1,12,54,93,188] As shown by Berg and Aitken, this technique offers significant potential for controlling permafrost degradation even in a marginal permafrost area such as Fairbanks, Alaska.[12] Perimeter thawing effects also need to be controlled; while a few experiments have been performed to investigate techniques for modifying the albedo of unpaved shoulders, unpaved roads, vegetated areas, and other rough surfaces,[5] no satisfactory system has been developed.

Experiments by the U.S. Army Corps of Engineers for control of degradation by use of in-ground insulation under pavements were started in 1947.[181] Full-scale test installations of various types of insulation in roadways and fills have been made in recent years in northern Canada by the oil industry and the federal government and in Alaska by state and federal agencies and oil companies. Current reports of use of insulation for this purpose by Esch,[43] Berg and Aitken,[12] Smith, Berg, and Muller,[159] and others show that in the more northern permafrost areas insulation can be used to replace gravel base course in a ratio that depends on the type of insulation. In the more southern marginal permafrost areas, insulation will delay and may slow the rate of degradation but neither in-ground insulation nor a heat sink material such as compressed peat is capable of preventing thaw degradation.[12]

As reported by Smith[157] and Hennion and Lobacz[70] investigation is also under way to investigate the potential of "wrapping-up" techniques for control of moisture movements. However, much work is needed before positive conclusions can be drawn.

For ice, the thermal expansion coefficient is about five or six times that of mineral aggregates such as granite or slate; for asphalt, it is more than 20 times.[104] Therefore, the more moisture in the soil or the more asphalt in the paving mix, the greater the shrinkage or expansion with temperature change and the more intense the cracking at low temperatures. This is confirmed by field observations. In the Arctic and Subarctic, pavement cracks may extend a metre or more down into the base course materials. Raveling or spalling of the pavement-wearing surface at edges of cracks produces debris that may be hazardous to aircraft. With age, cracks may become wider and raised or depressed. Water that enters the cracks may freeze and accumulate in the base course, reducing its capacity to function as a drainage course. While the basic phenomena of thermal shrinkage cracking in pavement and earth materials are moderately well understood, technology for minimizing such cracking, except by reduction of moisture and bituminous contents or use of steel reinforcement is minimal.

In recent years, numerous temporary airfields and roads have been built in northern areas with minimum investment of effort, to support oil and mineral exploration activities. Difficulties have arisen, however, due to such problems as ingestion of surface particles into aircraft engines and severe rutting of the surface as the ground thaws and softens when attempts are made to extend operations into the summer season. Use of synthetic insulating materials to provide expedient pavements as described by Smith, Berg, and Muller[159] appears to offer a technically feasible solution to these problems. All temporary or expedient construction, including construction working pads and construction haul roads, must be very carefully designed and controlled to avoid unacceptable environmental effects. Environmental impact may indeed be the controlling factor in the engineering.

For construction on permafrost in general, significant technological gains could accrue from advances in soil modification technology. The potential gains from successful development of an inexpensive system for conversion of frost susceptible soils into non-frost-susceptible materials alone are very large. The Frost Effects Laboratory investigated effects of various additives on frost susceptibility in the 1940's.[49–51] Lambe and Kaplar[96,97] continued very extensive studies in this area during the 1950's and early 1960's. They found materials capable of effecting large reductions in ice segregation and frost heave when used in trace amounts. However, these materials have thus far not been widely used in arctic and subarctic construction because available techniques for incorporating such additives are still too costly and some of the materials lack permanence. The possibility of environmental contamination by leachable additives must also be considered.

Placement of embankment material is frequently carried out during the winter months when the frozen surface makes movement most effective.[147] Fills are placed by end dumping, and construction vehicles are prohibited from traveling on or damaging the vegetation mat beyond the limit of the fill itself. Roads are commonly left unpaved either on a permanent basis or for a lengthy period of thermal adjustment; this permits the surface to be maintained at its design grade with a grading machine whenever any thawing of underlying ice may cause settlement. Cutting into the permafrost is avoided whenever possible and pavements are customarily elevated at least 1–2 m above the surrounding terrain, not just to provide bearing capacity and drainage and to aid thermal adjustment under the pavement, or to dampen its effects, but also to minimize snow accumulation and removal problems in winter. Clean sands and gravels are favored for embankments because of their non-frost-heaving qualities, their good subgrade drainage characteristics, and because they can be excavated and placed during freezing weather if they are well drained. Surface and subsurface drainage problems are avoided as far as possible by proper route location. The natural vegetation mat is left in place on the right-of-way and a thick initial layer of fill is normally placed in order to carry the construction vehicles on the soft terrain. As sescribed by Smith and Berg maximum advantage is taken of natural thermal and physical adjustment capabilities of the permafrost terrain.[158]

Most railroads constructed in permafrost areas have typically required heavy and continuous maintenance because roadbeds placed on adverse subgrades heave continuously during much of the winter and settle continuously in summer, differential movement occurring not only in the longitudinal direction but also between rails. Serious consideration is being given to the use of high speed, heavy load unit trains for movement of minerals and oil from the North (maximum railroad grades of 0.5 percent and maximum curvature of 2.5°). Pryer concluded in 1963 that railroads that must carry very heavy ore traffic on a year-round basis require design and construction to modern highway standards, with rigid specifications covering the selection and placement of subgrade soils.[133] The same basic technical approaches applicable for pavements are also applicable for railroads, that is, control of freeze and thaw penetration, control or modification of soil characteristics, and control of moisture accessibility. Although some studies for control of roadbed frost heave in seasonal frost areas of Canada have been performed in the last decade, no current studies aimed specifically at permafrost conditions are known to the writers.

Improvements in methods of economically ensuring smooth, stable grades and alignments requiring minimum maintenance would have application not only in the permafrost areas, but throughout the cold regions, including especially high-speed transportation systems in the temperate zones.

EXCAVATION AND UNDERGROUND CONSTRUCTION

Ability to effectively and economically excavate and handle frozen materials is a basic requirement for effective year-round construction operations in permafrost regions. Significant laboratory and field work has been done over the past decade to investigate methods of penetration, excavation, and handling of frozen ground and ice, including frozen ore, and of underground construction. In a study to develop fundamental concepts for the rapid disengagement of frozen soil carried out by Foster–Miller Associates[46,47] for CRREL, the possible methods for penetrating and excavating frozen ground were considered. A separate investigation of methods of conveying snow, ice, and frozen ground from an excavation to a disposal area was also made.[45] The methods of disengagement studied included such basic processes as the following:

High-velocity droplet impingement
High-speed continuous water jets
High-voltage spark discharge
High-energy pulsed electron beam
Laser beam
Dynamic column unloading
Cantilever-bending fracture
Controlled explosive loading
Shear impacting and vibratory penetration
Air blasting

It was concluded that the most satisfactory primary processes are shear cutting and indentation cutting and, potentially, high-velocity liquid droplet impingement. The most promising secondary processes included cantilever-bending fracture, brittle ridge fracture, and controlled explosive loading. The novel processes considered were found without exception either very low in effectiveness or not sufficiently developed from an implementation point of view to be of practical interest at this time. It was further concluded that liquid droplet impingement requires advances in the state of the art and extensive development to improve the technology sufficiently to make it practical for large-scale material disengagement. Mellor has more recently reviewed most of the principles that can be conceived of for excavating frozen ground. He has concluded that of the conventional techniques within the realm of existing technology, i.e., ripping, shearing, etc., shear or drag bit cutting offers the best present prospects for work in frozen ground. Of the novel concepts investigated, he has concluded that high-pressure water jets offer the most promise.[120]

The internal jet burner described by Browning and Ordway[20] in 1963 has not received wide acceptance for use in frozen ground. Although this burner, which uses kerosine and compressed air, is light enough to be held by two men during operation, it requires large air compressor capacity. It has penetrated frozen silt to a depth of about 18 m in 30 min.

McAnerney, Hawkes, and Quinn have reported adaptation of coal-mining airblast technology to the excavation of frozen ground in lieu of conventional explosives.[119] They have concluded that a tunneling machine incorporating a combined auger–airblast tube is clearly feasible for tunneling in frozen silt. Use of airblasting for trenching is also an efficient technique, as long as it is confined sufficiently to have a surface on which to act. Difficulties were encountered in using the scheme to aid ripping operations because of insufficient confinement of the air blast.

Conventional explosives are, of course, widely employed in every-day construction and mining operations for excavating frozen ground. More or less conventional explosives and drilling and placement procedures are used. In most cases trials are conducted at the site of the work to determine optimum values for amount of explosive and hole spacing to get the best results. However, problems have been encountered in achieving successful stemming of holes in frozen ground and also with failure to achieve complete rupture of the pit face and sufficient fragmentation.[77,99,171] At Schefferville, Quebec, three times as much powder has been required for blasting frozen iron-ore as for unfrozen[190] and the cost of blasting is more than doubled. Costs increased considerably when blasting frozen ground in open pit operations in permafrost at the Cassiar Mine in northern British Columbia.[72]

Mellor has found distinct advantages in use of liquid or slurried explosives for excavating frozen materials.[121] Shot drilling is far less expensive since only small holes are required. Also, coupling characteristics of liquid explosives are superior to those of solid explosives. Some sensitive explosives may be unsafe. However, the slurries have not presented any unusual safety problems.

When excavated materials are moisture free, no difficulties are encountered in handling, processing, or transporting the materials regardless of temperature conditions. However, when rock or frozen ground contain moisture the material may freeze to any surface it touches such as power-shovel buckets, loading hoppers, conveyor belts, or railroad car bodies. The problem is most severe at temperatures between about −9 and −1 °C.[190] Methods of coping with the problem have included heating of surfaces with which the material may come in contact and drying the material to moisture content levels low enough to give satisfactory performance. Dubnie has summarized Canadian mining experience.[41]

Underground openings, shafts, and tunnels in permafrost have long been used for prospecting, mining, and cold storage of food. Construction methods have included pick and shovel, hydraulic sluicing, and conventional drill and blast techniques. Canadian experience with development and operation of mines in permafrost areas has been described by Drewe,[40] Espley,[44] and Kilgour[90] and advantages and disadvantages of permafrost in mining operations have been summarized by Pike.[131] One of the advantages is that the frozen condition permits more economical use of the stopeing process by allowing greater height of lifts.

CRREL has constructed three experimental tunnels in glacier ice and two in frozen ground using professional mining techniques. One of the two tunnels in frozen ground was constructed near Thule, Greenland, in −11 °C glacial till (approximately 85 percent moisture saturation) by conventional drill and blast techniques.[165,166] The degree of difficulty was approximately equivalent to tunneling in granite. In a room with about 10 m unsupported span, no measureable closure had occurred after several years. The second tunnel was constructed near Fairbanks, Alaska, in frozen silt of about −1 °C mean annual temperature.[167] The original tunnel was cut with an Alkirk tunneling machine equipped with drag-bit cutters. Later, comparative excavation experiments were carried out in the tunnel using a variety of other methods such as conventional drilling and blasting and conventional coal cutting machinery.[116] As reported by Pettibone, the Bureau of Mines in 1970 extended a 61-m-long inclined winze down to the gold-bearing gravel and bedrock and constructed a 9 m × 21 m × 2.4 m room.[128] The CRREL and Bureau of Mines studies in this tunnel complex showed that openings in the frozen silt will close progressively by creep at the normal ground temperature of about −1 °C. In the 2.4 m × 4.3 m primary tunnel, the initial rate of closure was about 30 cm/year. It was apparent that the deformation rate of such warm permafrost can be a serious problem.

However, it was found that the closure could be halted by introducing cold air in winter to cool the tunnel walls, using a natural draft system.[118] Although Pike[131] has reported no apparent problems from ventilation of mines in rock with heated air, experience with tunnels in snow, ice, and frozen soil containing substantial ice has shown that all heat released in the tunnels by machinery, lights, people, and/or other sources must be very carefully controlled. Pettibone has concluded that simply protecting the tunnel from entrance of summer heat or providing partial roof support with yielding-type supports may be sufficient in frozen soil for purposes such as mining.[128] However, where substantial amounts of heat are generated or where extended or permanent use of the facility is required, ventilation by circulating cold surface air through the tunnel in winter or by collecting and conducting heated air to the surface with ducts, or mechanical air conditioning or refrigeration systems, are necessary.

Successful techniques have been developed for portal construction to avoid problems of slope instability and moisture infiltration into the tunnel where the tunnel intersects the annual thaw zone. Many frozen soils contain organic material, including vegetation and animal remains, and underground openings in these materials commonly exhibit a penetrating and unpleasant odor. Techniques for control of this odor and of the dust condition, which results from sublimation of ice in the tunnel walls, need further development. Studies of sublimation by Swinzow[166,167] have shown that spray painting, lacquering, or coating with a nondrying petroleum product are successful and water-base paint unsuccessful, in inhibiting sublimation. Water sprayed to form an ice film is successful as long as the film lasts, but it sublimates rapidly at lower levels in the tunnel cross section. The organic frozen soils may also contain pockets of methane gas, which present a hazard to tunneling.

Prethaw of materials by use of cold water probe pipes was common practice in the placer mining gold fields in Alaska and Canada when these were active. With the virtual halt of these mining operations, this method of thawing has nearly disappeared. However, the "thaw and scrape" operation that has been commonly used for obtaining borrow materials, making cuts, or preparing foundation surfaces on frozen ground in summer is still widely employed.

DRAINAGE

Poor drainage is a typical condition of permafrost terrain because of the presence of impervious frozen ground at shallow depth, even in the summer. Saturated ground conditions in the summer and the frozen surface in the winter cause infiltration rates from precipitation to drop to as low as zero. When air temperatures drop below 0 °C, icings form where water emerges on the surface, in turn, tending to block drainage facilities and cause operational obstacles. Even where precipitation is slight, drainage facilities must be provided to accommodate the large and quickly occurring flow of snow and ice meltwater, possibly combined with precipitation, over the frozen ground surface during a few days of breakup. Subsurface drains are effective only for limited portions of the year or under special conditions, as when a talik (unfrozen zone) exists. Nevertheless, subsurface flow of water within the annual thaw zone may be a very significant factor in the design of engineering structures; even in relatively arid climates of the Far North extensive subsurface flow may occur. Difficulties have been experienced both summer and winter from subsurface flow of water in frost-shattered rock at a seismometer vault placed partially underground at Resolute Bay, N.W.T., Canada. At Thule Air Force Base, studies in 1957-1960 verified the fact that large quantities of water move in summer through the coarse granular materials in the upper soil layers.[122–124] Such water movement is capable of producing greater depth of thaw than would be otherwise experienced. During thaw, ordinary gravity flow is the principal mechanism acting. New supplies of water may be added into the subsurface flow section both from surface infiltration and from thaw of ground ice. However, when seasonal freezing begins in the fall, strong moisture movements in the soil may also occur toward the planes of freezing. In fine-grained soils, seepage flow in the annual thaw zone is slow and may amount to only a few centimetres per year under gravity effects, but in very coarse cobble or broken rock materials, flow rates as high as 750 m/h[123] have been measured. It appears to be within the technological state of the art to control the direction and paths of gravity-induced subsurface flow in the annual thaw zone by controlling depth of subsurface thaw penetration. For example, at Thule, Greenland, painting the airfield pavements white as described by Fulwider and Aitken[54] raised the permafrost table under the pavements and created barriers to cross-pavement seepage flow.[124]

A case is reported by Linell in which uncontrolled artesian flow from a subpermafrost source caused serious thaw of permafrost together with icing, a frost blister, and surface subsidence.[106] This occurred in a borderline permafrost area, and artificial refreezing of the ground was required to restore stability. In very cold permafrost areas such an upset of the thermal balance is normally rapidly self-correcting after removal of the cause. However, when the thermal disturbance is long range, as under a hot oil pipeline, thawing of permafrost and flow of resulting groundwater may continue indefinitely on a year-round basis. Lachenbruch has presented an analysis of resulting thermal, environmental and structural stability effects.[94] In their reports on pipeline performance and requirements, Watson *et al.*[187] and Rowley *et al.*[142] have presented some information on groundwater as a factor.

An excellent example of the potential adverse effects of groundwater flow on permafrost stability is the case described by Tobiasson of serious settlement of hangar floors caused by warm groundwater derived from snow infiltrated into cooling ducts, from runoff of snowmelt and rain from pavements roofs, and natural surfaces flowing toward wells installed to keep the groundwater below the foundation cooling system.[174]

In a notable case history described by McAnerney, previously mentioned under "Site Selection and Investigation for Engineering Purposes," it was observed that water was disappearing into sink holes that appeared in the bottom of a drainage ditch cut 2.1 m deep into the shale bedrock.[117] Investigation disclosed massive ice within the bedrock to a depth of at least 14 m. Subsurface channels were being melted out by the drainage waters. The situation was easily stabilized by rerouting the drainage and backfilling the ditch, which re-established the permafrost conditions. However, if uncorrected, the consequences could have been a major failure.

Other case examples have shown that water from other sources, such as waste or condensate discharges and pipe leakages, may also contain sufficient heat to degrade permafrost, and it is important that control be sustained not only during construction but for the life of the facility.

As pointed out by Johnson in 1950, Alaskan mineral soils, which usually are medium textured and single-grain structure, are highly susceptible to erosion when thawed.[79] It is presumed that this may apply in many other parts of the Arctic and Subarctic. Experience shows that merely damaging the natural surface vegetation may be sufficient to lead to catastrophic erosion under adverse conditions.[69,113,186] The damage may be not only to the terrain itself but also to waterways and to fish and wildlife. Where massive terrain adjustments such as described by Smith and Berg are induced by construction,[158] care must be taken to prevent damage to streams by silt-bearing icemelt runoff.

Icings are an engineering and operational problem throughout the cold regions. A bibliography on river, ground, and spring icings has been prepared by Carey,[21] as well as a monograph on icings developed from surface water and groundwater.[22] The latter summarizes current approaches to control icings. Culverts present a special icing problem because of their tendency to become partially or completely blocked with ice during the winter, with the result that flow cannot be handled during thaw runoff. As reported by Carey, Huck, and Gaskin, a cooperative field and laboratory research program to develop methods to improve the control or prevention of icings in culverts has been in progress for several years by CRREL, the Alaska Department of Highways and the U.S. Department of Transportation.[23] Gaskin and Stanley report that carefully controlled applications of electrical heat have been found promising.[57] Criteria for design of culvert foundations for stability against thawing of underlying foundation materials are discussed in a U.S. Army structure foundation manual.[177] During route selection it is desirable to minimize the number of points where drainage must cross roads or other construction. However, little or no research appears to be in progress to improve techniques for recognizing and predicting icing susceptible locations and conditions during planning, design, and construction.

Experience indicates that in areas of relatively warm permafrost such as Fairbanks, Alaska, road fills can be built of very coarse materials to allow surface water to seep through them in lieu of using culverts, provided the amounts of water involved are relatively small. However, experience in very cold permafrost areas near Thule, Greenland, where the mean annual air temperature is about −11 to −12 °C, shows that in such a climate even the coarsest fills become ice-choked within about 3 years; thereafter, the enbankments act as impervious dams rather than drainage fills. As shown by Fulwider, this effect can be exploited to advantage in the design and construction of water supply dams and reservoirs in very cold climates.[53]

Johnson concluded in 1950 that methods for design of storm water drains developed for temperate regions are applicable in arctic and subarctic regions if certain specific limitations are observed.[79] These limitations pertain to such factors as design storm indexes, infiltration rates, and retardance coefficients. The 1950 recommendations were used as the original basis for U.S. Army surface drainage criteria for airfields. These have been supplemented and updated with more recently available information in an Army technical manual.[179]

UTILITIES

The construction and operation of reliable water supply, sewage and solid waste, fuel, electric power, heating, communication, and fire protection systems in permafrost areas at reasonable cost is often difficult and complex. Pollution control and environmental disturbance are particularly important factors to be considered even for the smallest communities at remote locations. The factor of reliability is especially important in areas that are very remote and have very severe climatic conditions; Ryan[143] stresses the need for duplication of equipment, alarm systems, and preventive maintenance for any sanitation facility in the Arctic. Social pressures are constantly increasing for even very small communities to be provided the same water, sewer, and other conveniences as are commonly available in the temperate zones of North America. Ryan has described current efforts of the U.S. Indian Health Service to provide water and sewer facilities to the Alaska natives.[143] Lawrence has outlined the present situation in northern Canada and has described acceptable practices and guidelines that should be followed including handling of oil spills.[101] To best meet needs of the permafrost areas, Clark recommends that particular attention be given to all-purpose, self-contained sanitary facility units capable of shipment to remote places by aircraft.[26]

Economical provision of a reliable year-round supply of potable water, including its securing, storage, treatment, and distribution is still a difficult problem in many areas, particularly in communities that can tolerate only a small capital investment. Alter has recently summarized the state of the art in a monograph.[2] Alter has also pointed out that an evolutionary trend is in progress in Alaska toward improved quality, dependability, and availability of water supply services that are engineered to be fully compatible with the Alaskan conditions.[4] In North America surface sources are the primary means of water supply in permafrost areas, although wells are used at some locations in Alaska and the Yukon Territory, Canada, and seawater is distilled at Kotzebue, Alaska.[2] At a few places, groundwater aquifers in nonfreezing zones of river beds above permafrost have been developed by means of collection galleries. Sherman has described an excellent example of the latter.[152]

The cost and uncertainties of locating, developing, and providing treatment are definite disadvantages in obtaining water from subpermafrost sources. As pointed out by Alter[2] advantages of subpermafrost water are in its reliability and temperature. Water from subpermafrost sources is commonly highly mineralized and may be saline and/or associated with methane or other gases. Conventional chemical processes and reverse osmosis have been used for treatment. A major need still exists for simple, reliable, and economical treatment systems for waters from subpermafrost sources, particularly for very small installations or communities.

Alter[3] has recently summarized in a monograph the state of the art concerning sewerage and sewage disposal in the cold regions. In recent years, significant research and development has been in progress in the United States by the Environmental Protection Agency, Public Health Service, Bureau of Indian Affairs, U.S. Air Force, U.S. Navy, the U.S. Army Engineer District, Alaska, and the U.S. Army Cold Regions Research and Engineering Laboratory and in Canada by the Canadian Department of National Health and Welfare and Central Mortgage and Housing Corporation, to develop improved sewage treatment systems for cold regions use. The knowledge being gained in these studies is yielding rapid advancement of technology benefiting not only cold regions but also temperate region applications. Since temperature has a marked effect on self-purification processes, the effectiveness of systems that depend on the natural BOD reaction vary greatly with temperature, and, when temperature is near freezing or below, the processes are essentially dormant, including those in natural ground or water or in unaerated waste stabilization ponds (lagoons and similar situations). Dawson and Grainge, based on Canadian and other studies, suggest proposed design criteria for several types of waste water lagoons in arctic and subarctic regions.[37] Since numerous waste stabilization ponds are in use in the cold regions of North America, including the permafrost regions, substantial study has been made in recent years for development of mechanical aeration processes for sewage stabilization ponds and other forms of aerobic treatment. Pohl has offered a rational approach to this problem.[132] Reed was the first to show that extended aeration can operate successfully at temperatures down to just above freezing.[135] Reed and Buzzell have developed a special, compact, extended aeration activated sludge system using a floating tube settler.[137] Pohl has under development an inverted tray settler as an alternative way of hastening the settling process.

With increasing development of the Arctic and Subarctic, the need has become pressing for effective systems for disposing of the increasing volumes of solid waste, which tend to resist decomposition under the effects of greatly reduced chemical and biological reaction rates. Cohen[27] is currently summarizing the state of the art in solid waste disposal in regions of low temperature in a monograph; in a paper submitted to this conference, he recommends an incinerator process for disposal of garbage, rubbish, and wastewater sludge.[28] The system is claimed to avoid atmospheric pollution while leaving only an inert residue and to be suitable for remote locations with populations up to several thousand people.

Utilidors and pipe systems, such as gas lines, have most commonly been built above ground in permafrost regions because of often difficult combinations of foundation conditions. However, above-ground systems encounter road-crossing problems, require extra insulation, and present physical barriers that are functionally, aesthetically, and psychologically undesirable with communities. Underground systems require favorable subsurface conditions and must be designed to be safe against damage from thermal ground cracking, permafrost degradation, and, possibly, flooding. Systems for distributing water and for collection of waste are moving more and more away from truck transport systems toward highly engineered pipe systems. Simonen and Heinke, in a detailed studyof five settlements in the Mackenzie River Delta area of Canada found that water supply and collection and disposal of sewage were the services with the most shortcomings and compared the relative merits and costs of utilidors and tank trucks.[153] Cooper has described an experimental low-cost utilidor system at Frobisher Bay, N.W.T., and compared it with a similar system installed at Inuvik, N.W.T.[29] Leitch and Heinke have described and compared the main, elaborate, and extensive utilidor system at Inuvik with a low-cost utilidor system also in use at this community.[102] Grainge[62] and Dawson and Slupsky[38] have described a sanitary pipeline research installation study carried out at Inuvik to assess the performance of insulated and uninsulated buried and above ground pipelines. They conclude, based on heat loss and cost studies, that where conditions permit, shallow burial (up to 1.2 m) offers the best and cheapest method of constructing water and sewer lines in permafrost. The design and construction of a buried, insulated, and electrically heated, 10-cm-diameter welded steel pipe water supply line, 5.6 km long for a mining community in the Yukon Territory has been described by Cheriton.[25] Circulating water distribution systems such as those at Fairbanks, Alaska, offer the distinct advantage over noncirculating systems of being less susceptible to freezeup at points of inadequate frost protection, but they must be carefully engineered and operated. Centralized steam heating systems often go along with the water and sewer-piping systems because they provide a source of heat in utilidors to prevent freezeup. Barrow, Alaska, and Norman Wells, N.W.T., Canada, also have piped community gas systems. There is also a trend toward putting power and communications underground instead of overhead. Some problems have been experienced, however, including difficult excavation, rupture of lines due to thermal cracking of the ground, and moisture or flooding. One must carefully weigh the advantages and disadvantages and site conditions.

There is a tremendous opportunity for application of ingenuity in design of more reliable and less costly, more easily maintained utility distribution and collection systems. Better solutions to these problems may also contribute to solution of the difficult problem of wintertime fire protection in the Arctic and Subarctic.

EMBANKMENTS AND SLOPES

Hardy and Morrison[66] and Isaacs and Code[76] give examples of and discuss the complex stability problems associated with landslides and large-scale sloughing of natural slopes, particularly on river banks. Smith and Berg illustrate problems that may be encountered in cut slopes in permafrost.[158] Creep, sloughing, and solifluction are common on natural and cut slopes in permafrost areas as a result of high-moisture content, reduced shear strength and seepage in the annual thaw zone in summer, seasonal frost raising and lowering, and seasonal thermal shrinkage and expansion effects and must be taken into account by engineers planning construction. Solifluction lobes, stone stripes, and similar forms of patterned ground are easily visible surface evidence of such movements as discussed by Washburn,[184] Frost,[52] Corte,[30] and others. However, existence of such movements is not always so evident. Where structures and facilities must be constructed in areas of such mass wasting, engineering solutions may sometimes be very difficult. A typical example occurs in the gorge of the Nenana River, Alaska, north of McKinley Station where the bed of The Alaska Railroad has had to be reconstructed a number of times at higher elevation as the entire roadbed was gradually displaced down the slope over many years.

Many studies over past decades have demonstrated the large reductions in strength that occur in frost-susceptible soils on thawing.[89] Some, such as Tauscher,[168] have attempted to explore experimentally the detailed variations of shear strength within the zone of thawed material. Tauscher used a miniature shear vane. A number of analytical efforts have also been made over the past two decades. The consolidation of saturated, frost-loosened soil in the thaw zone differs from the classical Terzaghi consolidation approach in that, as thaw occurs, new water is constantly being released at a moving internal boundary. Nixon and Morgenstern have reviewed this problem and have presented a practical extension of the classical Terzaghi theory applicable to this situation.[127] Thompson and Lobacz report on an effort to measure thaw shear strength by means of direct shear and triaxial tests.[172]

Embankments are usually relatively well drained and exhibit detrimental slope effects less intensely than natural or cut slopes. However, embankment toes are susceptible to loss of shear strength during thaw, especially where an un-vegetated embankment contacts the vegetated natural surface, forming a locus of deeper annual thaw penetration into the materials and potential thermal instability, intensified by ponding of surface water as local degradation and settlement occurs. This weakening allows slumping of overlying slope materials. Embankments that are relatively thin may reflect frost heaving and shrinkage cracking of the underlying subgrade.

Maximum advantage should be taken of the existing soil and vegetation mat to assist in providing the protective cover needed for ultimate obtainment of a stable slope. Techniques need to be developed for rapid re-establishment of vegetation cover where this has been destroyed by construction operations. Our knowledge of techniques for rapid vegetation re-establishment under arctic and subarctic conditions is minimal. However, as pointed out by Linell, preservation or re-establishment of a relatively thin cover of living vegetation is not sufficient in marginal permafrost areas to ensure against permafrost degradation.[105]

The technique of slope blanketing with granular material used by Lane in seasonal frost areas can be employed as either a supplementary or complete protection measure.[98] Blanketing with free-draining gravel or similar material not only increases the thickness of mineral cover over the natural slope materials so as to serve as a semi-insulating layer but it also provides surcharge weight to reduce the amount of ice segregation in underlying frost susceptible materials, thus reducing the volume of water to be released from these underlying materials in the spring. It also allows thaw water and seepage to emerge from the underlying soils without erosion or sloughing and through its loading effect serves to assist reconsolidation and rapid regain of strength in frost-loosened materials. This concept was successfully used to stabilize an unstable silt slope at the portal of the experimental tunnel constructed in permafrost by CRREL at Fairbanks, Alaska. Regardless of type of slope cover used, periodic re-dressing of the slope may be needed, if a degrading condition exists.

DAMS AND RESERVOIRS

While the number of dams and reservoirs that have been constructed in permafrost areas of North America is relatively small, our understanding of the technology of such construction is now much more advanced than one or two decades ago. From observations at the Crescent Lake Dam and Reservoir at Thule, Greenland, described by Fulwider,[53] we know that in very cold permafrost areas it is entirely feasible to construct thermally and structurally stable watertight dams with permanent reservoir water storage, even with relatively pervious embankment materials, because through seepage is completely sealed off by freezing of the embankment. As Fulwider points out, it may be necessary to consider building larger earth-fill dams in the Arctic in stages where development of an initial fully frozen condition is needed. The construction of a small, frozen core earth-fill dam for water storage at a new townsite in northern Quebec, Canada, has been proposed[64] and others have been considered in areas of low temperature permafrost in Alaska. On the other hand, dams in areas of relatively warm permafrost, such as the Hess Creek Dam[154] about 80 km north of Fairbanks, Alaska, and the dikes at the Kelsey and Kettle generating stations in Manitoba,[112,115] experience through-seepage under permanent reservoir storage, which may lead to eventual complete degradation of permafrost under the barriers. As has been reported by Johnston and Brown[19,82] for the Kelsey dikes, it is possible to experience rapid thaw settlement of as much as 1.5 m, differentially without failure, but overtopping must be guarded against. This is made possible by employing materials such as sand that can deform as settlement occurs so as to maintain a watertight dam, without occurrence of piping. A system of sand drains in the ice-rich foundation materials was incorporated in the Kelsey and Kettle dikes to assist in maintaining stability during thaw. Adjustment of the structure can only occur, however, when the materials are unfrozen. Failure can occur if the bridging of the frozen outer shell allows the underlying material to separate from it by settlement as was demonstrated by failure of the Loch Alpine Dam near Delhi, Michigan, in 1927.[42] Significant, longitudinal and transverse cracking to depths of about 3 m due to growth of ice lenses in frost-susceptible core material and thermally induced stresses during the winter have been experienced by some embankments in Canada. Although the cracks usually heal each summer, the cumulative effects over a period of years can become increasingly critical. Such cracking must be anticipated and accounted for in design.

The dams that have been constructed thus far on permafrost in North America, including various community and military installation water supply dams, have all been relatively small (height of Hess Creek Dam equals 24 m). For dams that are significantly higher or have different cross sections, or for climatic conditions intermediate between the borderline and very cold permafrost areas, determination as to whether or not a degrading or watertight situation will result under a permanent reservoir will require special and possibly novel analysis.

The paper submitted by George to this conference describes a type of reservoir project unique for the permafrost regions, in which a dam 38 m high will be used to store flood waters on a very infrequent and temporary basis and, therefore, will not experience the permafrost degrading effects of a permanent reservoir.[58] The basic plan is to leave the permanently frozen silt under the left side of the dam in place and to design the dam so that the existing permafrost will be protected against thaw. On the other hand, Simoni and Kitze have concluded that in the Subarctic, large earth-fill embankments do not freeze solidly even during extremely cold winters.[154] Although subsurface temperature measurements under the centerline of Hess Creek Dam show that freezing of the embankment occurs annually to a depth of about 8-10 m, permafrost had not developed in the exposed upper part of the embankment 4 years after final emptying of the reservoir (20 years after completion of the earth fill).

PETROLEUM PRODUCTION AND PIPELINES

Although small-scale production of oil and pipeline transmission of oil, gas, and fuel in permafrost areas of North America began as early as World War II,[18] the recent discoveries of major oil and gas resources in Alaska, northern continental Canada, and the Canadian Arctic Archipelago have given major new impetus to development of special technology for petroleum exploration, development, production, and transport in these areas. Construction and operation procedures must be effective and economical under exceptionally adverse conditions, yet protect the environment from possibly irrecoverable damage. The volume of published and unpublished technical information on this subject generated in research, environmental, and engineering studies over the past 5 years is very large. The environmental impact statement prepared by the U.S. Government on the proposed Alaska pipeline alone comprises six volumes, with a total of 3204 pages.

Four major technical problem areas are evident:

1. Exploration, drilling, and production of oil from wells through up to 600 m of permafrost, with production oil from depths near 3 000 m typically at a temperature of about 90 °C.
2. Transportation of crude oil at temperatures in the vicinity of 60-70 °C.
3. Transportation of gas in pipelines at temperatures below freezing.
4. Construction and operation of coastal and offshore facilities,[169] including exploratory and production oil wells, terminal and port facilities, and undersea pipelines in ice-filled waters. This problem area potentially surpasses all the others in difficulty.

Specific technical problems are summarized by Kachadoorian and Ferrians in relation to the proposed Alaska pipeline from Prudhoe Bay to Valdez, Alaska, a distance of about 1 270 km.[87] Many aspects to be considered in the design and construction of pipelines in northern Canada were discussed at the Canadian Northern Pipeline Research Conference in February 1972.[126]

Many of the specific construction problems encountered in petroleum development in permafrost areas, such as foundation design or environmental conservation, have been covered above. However, some of the oil development aspects of the problems are novel or have special dimensions. Cementing of exploration and production casing to prevent leakage or blowouts at wells in permafrost may pose difficult problems. Thawing and settlement of permafrost around an oil well casing may require special mechanical and installation criteria for the casing and associated well-head structures and equipment to accommodate the anticipated movements, stresses, and pressures without failure. Storage facilities and pipelines carrying hot crude oil at temperatures ranging from 60 to 90 °C require very accurate and reliable analyses of the consequences and costs of various possible construction alternatives. Above-ground hot oil pipelines require far less subsurface design investigation than below-ground pipelines, but require added foundation support systems and thermal insulation, are more easily vandalized or damaged by forest fires, and are less desirable from the point of view of aesthetics and wildlife migration. Lachenbruch has examined some of the potential problems of buried hot pipelines in permafrost.[94] It is estimated that a buried pipeline carrying oil at 70 °C will thaw frozen ground to a radius of about 15 m in 20 years. Some of the possible serious results of this thawing in thaw-unstable permafrost are overstressing and rupture of the pipe from excessive differential settlement, longitudinal overstressing and buckling of the pipe on slopes from anchorage failure, soil erosion and seepage of heated water along the pipeline axis, slope instability, and adverse effects on vegetation, wildlife, and fish. Provisions must be made for automatic limitation and control of oil spills. Gas pipelines designed to operate at temperatures below freezing offer much simpler design and construction problems than hot oil lines. Some areas, particularly in Alaska, have high seismic activity and possibility of pipe rupture from earthquakes must be considered. The design techniques currently employed for nonfrozen soil conditions for earthquake design are applicable to frozen conditions, but the response of frozen soils to earthquake load may obviously be quite different. Frozen soils have greater stiffness and brittleness and overall rock-like behavior as compared with nonfrozen soil. Wave velocities are much higher in the frozen soil and damping is lower. As reported by the U.S. Geological Survey, a problem may arise from sliding of overlying material at the interface between the frozen and nonfrozen layers. Stream and river crossings are particularly difficult engineering problems because of scarcity of hydrological and scour depth information and the need to avoid damage to aquatic life from increased stream sediment load or from alteration of water temperature. The need for revegetation after construction and after oil spills has been pointed out by Wein and Bliss.[189] Construction, operation, and maintenance activities along the pipeline and at production, pumping, and terminal facilities must be carefully controlled for environmental protection.

While the nature and scope of these problems and their solutions are reasonably well understood, there has been a deficiency of full-scale experience records and specific quantitative design data. To fill this void, broad programs of laboratory, field, analytical, and theoretical studies have been carried out by government and by industry. These have included full-scale field tests at Barrow, Prudhoe Bay, and Fairbanks, Alaska, and at Inuvik, Sans Sault Rapids, and Norman Wells, N.W.T., Canada. Several recent papers give details of some of these studies. Watson, Rowley, and Slusarchuk have presented results of an experimental determination at Inuvik of the rate of thaw plug development around a buried 61-cm-diameter hot oil pipeline and of the resulting interaction of pipe and ground.[187] Slusarchuk, Watson, and Speer have described the field instrumentation used for these tests.[155] Rowley *et al.* have presented results of performance evaluation of a 1.22-m-diameter warm oil pipeline supported above ground in a gravel fill and on piles.[142] Speer and Watson conclude from field tests in three types of ground that a 1.22-m-diameter by 12.70-mm-thick pipe can tolerate a differential settlement of up to 1 m at a horizontal span of 36 m.[162] Rowley, Watson, and Ladanyi tested permafrost-imbedded wood and steel piles both vertically and laterally to obtain specific quantitative criteria for a pile-supported hot oil pipeline.[141] Progress reports on gas pipeline test facilities and other studies were presented at the Canadian Northern Pipeline Research Conference by Hurd[74] and Walker.[183]

It may be concluded that it is within the technological state of the art to develop and make available the petroleum resources of land areas of the Arctic with acceptably low environmental impact. However, much further research and cumulative experience is needed to provide the better understanding and data needed for improved and more economical engineering solutions.

RESEARCH NEEDS

Areas in which this review has shown that further research and development are required for improvement of engineering design and construction are summarized below—not in order of priority.

1. Development is needed of new or improved equipment and technology that will permit rapid, but detailed and economical, determination of permafrost distribution and properties of frozen ground for engineering purposes over both large and small areas or distances. Of special interest are equipment and techniques for:

a. airborne or remote sensing;

b. geophysical exploration;

c. drilling and sampling, including refrigerated systems, and apparatus of minimum weight and maximum portability, to obtain undisturbed cores for examination and testing;

d. *in situ* determination of physical, mechanical (particularly rheological) and thermal properties of frozen ground;

e. transporting and preserving frozen cores in the field and in the laboratory to prevent contamination and thermal and physical disturbance.

2. To improve our capabilities for site evaluation and route selection and to assess the interaction between the atmosphere, the structure, and the ground, there is a need to improve our knowledge of the relationships between surface indicators and subsurface conditions to permit more accurate engineering inferences.

3. Detailed studies are required to define more precisely the heat exchange mechanisms at the ground surface under natural conditions and as a result of engineering or other activities. Of particular importance is the determination of surface characteristics and parameters at the air–ground interface for engineering design, including special surfaces such as rock-fill slopes of dams.

4. There is a need for the development of reliable techniques for estimating site design conditions, e.g., air temperature, precipitation, and wind, at locations widely separated from reporting stations, particularly if they have different elevations and environments, e.g., maritime versus mountainous.

5. Theoretical and experimental studies are needed on the strength and rheology of frozen soils with emphasis on "warm temperature" materials.

6. Further theoretical and experimental studies are needed on the thermal properties of frozen, thawing, and thawed soils in the field and the laboratory.

7. Technology is needed for rapid re-establishment and/or maintenance of thermal stability on surfaces other than pavements including technology for control of albedo of such surfaces and for rapid reestablishment of vegetation on construction surfaces to aid in control of permafrost degradation, erosion, and sloughing. More highly trafficdurable albedo-control surfaces for pavements are also needed.

8. Further field experiments are required to determine the magnitude of frost heave forces that can be encountered and must be incorporated in design of different types of foundations. Procedures are also needed for predicting the amount of frost heave which will be experienced by tower footings or similar unheated foundations imbedded in the annual thaw zone.

9. Research is needed to increase our understanding of seasonal thermal shrinkage and expansion effects in permafrost and to incorporate this information into quantitative engineering design and construction criteria.

10. Further analytical and experimental studies are required to better understand and evaluate the processes involved in the settlement and consolidation of thawing and thawed soils.

11. Present limited information on effects of lateral forces in permafrost foundations needs to be expanded.

12. More economical methods of incorporating air spaces or duct systems in foundations need to be developed.

13. Further investigations are required on pile foundations to improve our knowledge of (a) allowable adfreeze bond stresses, (b) the manner in which stresses are redistributed with time along the length of a pile imbedded in permafrost, (c) methods of reestablishing full adfreeze bond in piles in which the bond has been broken by frost heave or overloading, (d) the full potentials of the many possible variations of conventional, thermal, and specially configured piles, and (e) the feasibility of driving piles into permafrost colder than –4 °C. Design procedures should be simplified and more economical designs should be sought with lower factors of safety.

14. Additional study is needed on permanent and expedient anchorages in frozen ground.

15. Technology needs to be developed to permit pavements and railroads to be constructed with minimum added expense to standards of year-round smoothness needed for high-speed transportation systems. This should include research in soil modification technology to improve strength, thermal, frost heaving, and shrinkage-expansion characteristics of pavement and support materials.

16. Continuing research is required to develop faster and more economical methods of excavation, transport, and handling of frozen soil and rock.

17. Research is needed to develop improved techniques for anticipating, evaluating, and coping with thermal, erosional, and icing effects of groundwater flow in and near construction areas and seepage through dams, in permafrost regions.

18. Much more research and investigation are needed to provide simpler, less costly, and more reliable utility systems, in permafrost areas, especially including distribution and collection systems and improved methods of treating and handling water supplies and wastes, with particular attention being given to the economics as well as to the pollution and environmental aspects.

19. Research is needed to develop the most economical methods of controlling embankment and slope stability, and slope deformations, in permafrost regions. This includes research to develop techniques for controlling the localized lowering of the permafrost table at the transition zone between embankment and the natural vegetated surface, with attendant settlement, drainage and slope stability problems.

20. Continuing research is needed for economical design construction and operation of petroleum development systems, especially including those involving hot oil and the Arctic Sea environment.

21. Especially vitai to the success of permafrost construction research efforts are feedback data on the actual performance of facilities and comparison with the design assumptions.

22. The application of utmost ingenuity and persistence is needed to develop design and construction technology that (a) will reduce both the high first costs, including those from construction seasonality constraints, and the high operating and maintenance costs, which are at present major restraints on arctic and subarctic development, and (b) will improve habitability.

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