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ТОМ 2

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РЕЧЬ НА ОБЕДЕ ДЛЯ УЧАСТНИКОВ КОНФЕРЕНЦИИ

GEOLOGIC CONTROLS OF THE ORIGIN, CHARACTERISTICS, AND DISTRIBUTION OF GROUND ICE

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ABSTRACT

The geologic controls of the origin, characteristics, and distribution of ground ice in the permafrost areas of the world are numerous. The review authors are very conscious of the fact that in a brief survey of the more than 300 papers which have been published since 1973, it is obviously impossible to discuss all topics and to do justice even to those topics which are discussed. The sequence of topics, in this summary, are the same as for the longer review paper which contains the bibliographic references omitted in this summary.

Frost Heaving and Ice Lensing

Much attention has been given to the theoretical aspects of ice lensing, the problem of simultaneous heat and mass transfer in frozen and unfrozen soils, and especially to computer modelling. The concept of normal frost heave (primary heave) has been extended to include that of secondary heaving. Theory and experiments suggest that appreciable quantities of water can move through frozen soils in response to thermal or other gradients. The role of overburden pressure on the mechanism of ice lensing remains a controversial question. Of particular interest to the geologic controls of ground ice and laboratory studies on changes in the cryogenic fabric of frozen ground which result from temperature fluctuations and other factors. Field observations on the lower reaches of the Yenisei River have confirmed the results of the laboratory investigations.

Ice Wedges

Important advances have been made on the theoretical aspects of ice-wedge cracking. The theory attempts to predict the temperature field required to induce cracking and the spacing, depth, and width of the resulting cracks. Differences of opinion have been expressed on the structure and origin of some of the thick old Pleistocene ice wedges of Northern Yakutia. In Canada, studies have shown that some ice wedge cracks originate at depth, not at the ground surface. Wedge-like structures have been found in the geologic record, dating back to the Precambrian in Canada, Norway, South Africa and elsewhere, but the field evidence for a permafrost origin is debatable.

Pingos and Palsas

As more data accumulate, it is apparent that pingo ice cores can show every gradation between pure injection ice and ice rich mineral soil. Many pingos have been found in abandoned channels. Large pressurized sub-pingo water lenses, as much as 2.2 m deep and with diameters of at least 300 m, have been identified by detailed drilling. The major focus of palsa research continues to be the life cycle of palsas; whether palsas are favored by ice injection or ice segregation; and whether the features are essentially degradational or aggradational in origin.

Massive Ice

There is a continuing difference of opinion on the origin of some of the massive bodies of ice found in some permafrost areas of Western Siberia. According to one view, some workers believe the ice to be buried glacier ice. According to the opposing view, the ice is injection, injection-segregation, or segregation ice formed in place. In the Western Canadian Arctic water quality evidence favors a non-glacial origin. In some local areas, it might be very difficult to distinguish between buried sub-glacier regelation ice and debris rich segregation ice.

Geochemistry of Ground Ice

The geochemistry of ground ice, including the use of stable isotopes, appears to be a promising research field

for the study of ice lensing, the growth of permafrost, hydraulic conductivity of frozen soils, changes in the thickness of the active layer, and in paleocryologic reconstructions of past environments. Oxygen isotopes have been used to provide paleoclimatic information from three antarctic cores and from the Mackenzie Valley, Canada.

Thermokarst

One major aspect of recent research has been the mapping of thermokarst features over large areas by remote sensing. Detailed investigations have been carried out in the U.S.S.R. on the ages of thermokarst features in many permafrost regions.

Permafrost Distribution

The worldwide distribution of alpine permafrost has been extended in temperate and tropical regions, such as in the Pamir, Tien Shan, Andes, and Hawaii. A great deal of progress has been made in the mapping of submarine permafrost in the arctic waters of Eurasia and North America. Theoretical aspects have been discussed in some detail.

Paleocryological Studies

Paleocryological studies have been developed to the greatest extent in the U.S.S.R. There have been numerous diverse studies such as on the relation between the cryogenic structure and the thermal regime of permafrost, the horizons which might be formed by epigenetic freezing in fine grained soils, and the reconstruction of paleoclimate from present day geothermal data.

Cryogenic Weathering

The interaction of water with different structural groups of rock-forming minerals has been investigated and a theoretical model of mineral stability with respect to rock weathering presented. The results show that the ultimate grain size distributions for the basic rock-forming minerals in a cold area with freeze-thaw cycles are opposite to a warm area without the cycles.

Cryolithogenesis

Although there is no uniformity in the use of the term, many investigators have been concerned with the topic. A cryolithological map of the U.S.S.R. has been compiled on a scale of 1:4,000,000. The map clearly shows the regional occurrence of permafrost and the two main types, epigenetic and syngenetic. The map provides a wealth of information on cryogenic textures, the estimated area of frozen ground, and the relation between the distribution of frozen ground and its genesis in the U.S.S.R.

INTRODUCTION

The geological controls of the origin, characteristics, and distribution of ground ice in the permafrost areas of the world are numerous and the recent published literature is very extensive. At the First International Conference on Permafrost (Lafayette, Indiana, U.S.A., 1963) there was a panel discussion on Massive Ground Ice. In addition, papers relating to ground ice were presented in sessions on soils, vegetation, geomorphology, and phase equilibria and transitions. At the Second International Conference on Permafrost (Yakutsk U.S.S.R., 1973) Soviet and North American scientists prepared two review papers on the genesis, composition, and structure of frozen ground and ground ice. The 1973 Soviet and North American Proceedings also contain numerous papers on various aspects of ground ice with contributions from many countries of the world. This review paper has been a collaborative effort with the two Soviet authors assuming prime responsibility for the literature of the Soviet Union and the Canadian author prime responsibility for the non-Soviet material. In view of the fact that there are frequently no precise English-Russian equivalents for many permafrost terms, some of the English words used in this review do not convey the precise meaning of their Russian counterparts (Brown and Kupsch 1974; Fyodorov 1974; Poppe and Brown 1976; van Everdingen 1976). For this reason, bracketed terms will be used frequently to indicate substitute words which might help to clarify the meaning. In a brief review of the 1973-1978 world literature, which considerably exceeds three hundred publications, the review authors are very much aware of the fact that it is obviously impossible to cite all papers; to give equal emphasis to all topics; and to review adequately even those topics which are discussed. However, an effort has been made to discuss some of the more important recent research and to mention a number of the more specialized review papers and conference proceedings where additional material on ground ice can be found.

GENERAL REVIEWS

Two monographs, the first by Vtyurina (1974) on "The cryogenic structure of the seasonally thawing layer" and the second by Vtyurin (1975) on

"Underground ice in the U.S.S.R." provide in combination an excellent overall review of underground ice. Vtyurina (1974) discusses the cryogenic fabric (structure) of the active layer. Diagrams, cross sections, and photographs illustrate cryogenic fabrics (Jumikis 1977) produced in different soil types by both downward freezing of the active layer from the ground surface and upward freezing from the frost table. Vtyurin (1975) has summarized data on the different regions of the Soviet Union and has proposed a genetic classification of underground ice including primary ground ice (ice cement, segregated ice, ice lenses, ice beds) and secondary ground ice (ice wedges, vein ice, cave ice). Buried ice (river ice, glacier ice) is also considered. Vtyurin has also determined the regional distribution of ground ice in the U.S.S.R. and has estimated its total volume. Nekrasov (1976) has written a regional review on the morphology, thickness, thermal regime, and related permafrost features of a large, mainly mountainous region in the northeast and south of Siberia, complete with a map on a scale 1/2,500,000. Fotiev et al. (1974) have described the general geocryological conditions of a vast, poorly studied region of central Siberia. The authors also show that water, at a negative temperature, is widespread at depth beneath ice-bonded permafrost. Badu and Trofimov (1974) have carried out cryogenic studies in the Yamal Peninsula. The U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, N.H., U.S.A. has published many technical papers relating to ground ice. Jahn's book on "Problems of the Periglacial Zone", originally published in Polish, has been translated into English (Jahn 1975). The book is worldwide in its coverage of periglacial topics and the references are multilingual. Péwé (1975) has written a monograph on the "Quaternary Geology of Alaska", in which ground ice is included, but it is not the main topic. For Canada, a widely scattered literature on ground ice can be found in the numerous reports prepared for the Environmental-Social Committee, Northern Pipelines (Ottawa: Task Force on Northern Oil Development) and in other reports (eg. Heginbottom et al. 1978) dealing with a proposed, but now defunct, Mackenzie Valley Pipeline. The most comprehensive English language book which includes ground ice is Washburn's (in press) "Geocryology: A Survey of Periglacial Processes and Environments".

FROST HEAVE AND ICE LENSING

Theoretical Considerations

Ice segregation and frost heaving have been the topic of several recent international conferences (Aguirre-Puente 1978; Frost Action in Soils, Proceedings of an International Symposium, University of Luleå, Sweden, 1977, Vols. 1 and 2: Soil-Water Problems in Cold Regions, Proceedings of the First and Second Conferences, Calgary, Canada, 1975 and Edmonton, Canada, 1976; International Symposium on Ground Freezing, Ruhr University, Bochum, Germany, 1978). Considerable attention has been paid to the theoretical aspects of ice lensing since 1973. The capillary model for non-colloidal soils has been criticized by Takagi (1977) on the grounds that the model applies to static conditions whereas the freezing of pore water is a kinematic effect which requires a different thermodynamic approach. Miller and colleagues (Miller 1978) have extended the capillary model to include the concept of secondary heaving. This involves a series-parallel transport of moving pore ice and unfrozen water where the rigid pore ice phase and the incompressible mineral particles interact via an intervening water film with properties which tend to drive the ice phase in the direction of decreasing temperature and the granular skeleton in the opposite direction. Although an ice-water fringe is considered to be characteristic of ice lens growth in clay soils, there is disagreement on the presence of an active ice-water fringe below a growing ice lens in non-colloidal soils (Penner 1977).

The problem of simultaneous heat and mass transport in frozen and unfrozen soils has received much attention, particularly in the field of computer modelling (eg. Guymon and Luthin 1974; Outcalt 1977; Sheppard et al. 1978). Studies have shown that appreciable water can move in frozen soils in response to imposed thermal gradients (Anderson 1977; Williams 1976). In this respect, Williams (1977) concludes that under certain conditions the suction at the frost line that determines the migration of water through the unfrozen soil may be consequent upon suctions having their origin well within the frozen zone. Water filled veins can occur in polycrystalline ice (Raymond and Harrison 1975) and in ice lenses. Osterkamp (1975) has observed liquid filled three-grain boundaries developed in ice lenses at an early stage in the melting process and he has stressed their ability to act as channels for water flow during freezing and melting. Williams (1977) has likewise concluded that the existence of ice lenses 2 to 3 cm thick may not prohibit water movement in frozen soils (Penner 1977). Nuclear magnetic resonance (NMR) techniques have been used to study unfrozen water in frozen soils (Kvlividze et al. 1978; Tice et al. 1978. According to Tice et al. 1978) the results show, contrary to previous conclusions, that the unfrozen water content determined by the techniques of pulsed NMR depend upon the ice content.

The role of overburden pressure on the mechanism of ice lensing remains a controversial question (Loch and Kay 1978). According to one school of thought, for each soil there is a shut-off pressure at which the effective stress at the frost front will cause neither flow of water into or away from the freezing front (McRoberts and Nixon 1975). When the shut-off pressure is exceeded water is then expelled in advance of the freezing front (Hill and Morgenstern 1977). Takashi et al. (1978) have found that heaving decreased rapidly with an increase in effective stress and they have proposed a model for suction/discharge at the freezing front. On the other hand, there is experimental evidence that the observed water expulsion in some experiments may be only temporary. Penner and Ueda (1978) have found that the ratio of in situ to migratory water which is frozen can change continuously during a test and has no influence on the heave rate. In their experiments, the significant factor in determining the heave rate was the value of the cold-side temperature which Penner and Ueda consider determines the suction potential at the growing ice lens. The reversal from initial water expulsion to subsequent water intake is not fully understood (Hill and Morgenstern 1977). Loch and Miller (1975) attribute the expulsion to nucleation reflecting volume changes of freezing pore water to form pore ice and intake to the segregation of ice lenses.

Melamed and Medvedev (1974), developing Goldshtein's concept (Goldshtein 1952) of the existence of an optimum temperature of freezing, at which there is a maximum amount of ice segregation with other conditions being equal, have specified the optimum conditions of growth of segregated ice in fine-grained soils (fine-dispersed rocks) and have given a mathematical formulation for computer solving of the problem of ice lensing.

A group of workers under the leadership of Ershov (Ershov et al. 1978a, 1978b) have carried out extensive laboratory investigations in the formation of pore and lens ice by investigating heat and mass transfer in the freezing and thawing of different soil types under a wide range of freezing rates. Ershov (1977) has distinguished between the necessary and sufficient conditions for the formation of cryogenic fabrics (textures) in freezing soils. The necessary conditions are the thermophysical factors of heat and mass exchange. But proceeding from the factors of heat and mass exchange, it is impossible so far, according to Ershov, to explain fully the nature of ice segregation. The sufficient condition for ice segregation is a physical-mechanical ratio between the tensile strength of the soil and the expansion forces attendant upon soil freezing.

Cryogenic Fabrics (Textures)

Recent studies have shown that the cryogenic fabric of frozen ground can change in response to pressure, temperature, and other factors. Ershov (1977) was the first to demonstrate experimentally the change of one cryogenic fabric into another, in particular, the change of a massive texture (cement ice) into an ice lensed (schlieren) type as a soil warms and thaws. Ershov's laboratory experiments have been confirmed by Parmuzina (1977) from field observations in the basin of the lower reaches of the Yenisei River, U.S.S.R. A change from a massive texture of pore ice to a lensed texture was noted in thawing of the active layer.

Important experiemntal research into the dynamics of ice lensing has also been carried out by Zhestkova (1978) and Zhestkova and Guzhov (1976). In one freezing experiment lasting 22 days, a slow but persistent change in ice lenses and soil fabric was observed in the frozen zone. When an ice lens (schlieren) formed and grew, the mineral aggregates broke away from the soil beneath the lens and moved slowly or were forced out by the ice. The movement of the mineral aggregates in the experiment averaged a fraction of a millimetre a day. The probability of an ice-saturated soil layer, given any type of ice fabric, changing into an extensive ice lens increases with the degree of ice saturation of the layer as it forms. Ice lens (schlieren) growth is favoured when the temperature fluctuates in response to variations in the surface temperature. The dependence of the structural characteristics of an ice lens on the mineral composition of the subjacent material has been corroborated experimentally by Golubev and Kabanova (1976). Maksimova (1977) has derived a classification scheme for cryogenic textures in fine grained soils.

Comment

The theoretical and laboratory

studies on frost heave, ice lensing, and changes in cryogenic fabric have made important contributions to our understanding of the genesis of primary ground ice and yet, at the same time, important questions have been raised. Clearly there are scaling problems in transferring laboratory studies to field conditions where freezing rates, time periods, pressures and so forth can vary by several orders of magnitude. For example, a very low hydraulic conductivity of a frozen soil or a slow temperature induced change in cryogenic fabric may be of little consequence in an experiment, but of appreciable consequence given a geologic time scale.

MASSIVE (BEDDED) ICE

Massive bodies of ice are characteristic of some permafrost areas of Western Siberia (Solomatin 1977) and the Western Canadian Arctic (Rampton 1974; Rampton and Walcott 1974). In the U.S.S.R., until recently most of the bedded ice was regarded as injection, injection-segregation, or segregation ice, although in some of the earlier publications, the ice was believed to be buried surface ice, particularly glacier ice (Saks and Antonov 1945). Recently, Kaplyanskaya and Tarnogradsky (1976) and some other workers have revived the suggestion of a glacier origin. Solomatin (1977) has presented data to support the initially superficial origin of the bedded ice. In the Western Canadian Arctic there could well be some buried glacier ice. However, most of the massive (bedded) ice is probably injection, injection-segregated, or segregated ice, because of the stratigraphic association with fossiliferous sediments, the ice petrofabrics, and the ice (water) quality composition. In some cases, it may be very difficult to distinguish between buried subglacier regelation ice (Clapperton 1975) and debris rich segregation ice, because of similarities in appearance.

ICE WEDGES

Ice wedges and wedge structures have long been studied intensively in areas of contemporary permafrost, in periglacial areas, and more recently in the geologic record. Romanovskii (1973, 1977, 1978) has written in considerable detail on ice wedges and related features. He subdivides the structures into two groups. The classification is applicable to both epigenetic and syngenetic forms. The primary structures are those formed by repeated frost cracking, with infilling of the resulting cracks with ice or earth materials. The secondary structures are formed as a result of thawing of the primary structures. Both primary and secondary structures have been divided, by Romanovskii, into subtypes depending upon criteria such as position within the seasonally thawed (frozen) layer and the nature of the infilling material.

Theoretical

Important advances on the theory of ice-wedge cracking have been made by Grechishchev (1975, 1976, 1978). The theoretical solutions are difficult to apply to field conditions because of uncertainties in our knowledge of vertical and horizontal temperature gradients; ice content and soil type; seasonal changes in the rheologic properties of the active layer, wedge ice, and permafrost; and inhomogenieties in the microrelief. Nevertheless, Grechishchev has been able to integrate some of these factors into a theory which attempts to predict the temperature field required to induce cracking, and the spacing, depth, and width of the resulting cracks. Gasanov (1976, 1978) has analysed the basic factors that control the ultimate size of ice wedges (recurrent-vein ice) and has distinguished four possible categories and four variants of ice-wedge (ice vein) growth depending upon:
a) the depth of frost-induced cracking;
b) the depth of seasonal thawing;
c) the rate of sedimentation; and
d) the horizontal growth rate of the annual (elementary ice veinlet.

Pleistocene Ice-Wedge Growth

The most comprehensive data on the structure of the thick old Pleistocene ice wedges (polygonal wedge ice) are presented by Solomatin (1974). Solomatin considers that the structure of the old ice wedges differs essentially from that of the young epigenetic ice wedges in which the structure of the veinlets (elementary veinlets) are distinct and recognizable. Solomatin has come to the conclusion that the lateral migration of water in frozen ground has a determining role in the accretion of ice to the old wedges. These inferences have been disputed by Volkova and Romanovskii (1974), upon the basis of their extensive investigations of the chemical composition of underground ice in the Quaternary deposits of the southern part of the Yana-Indigirka lowland. The mineralization of wedge ice varies from 0.01 to 0.05 gr/l and that of segregation ice from 0.02 to 0.13 gr/l. These data indicate that the wedge ice is formed by freezing of surface water that has a lower mineral content and a more uniform composition than the water of the seasonally thawing layer which forms the segregated ice and eventually becomes incorporated into permafrost in areas of syngenetic ice wedges. Consequently, the source of water is unlikely to be from lateral migration. Tomirdiaro et al. (1975) have suggested that the large Pleistocene ice wedges are mostly subliminal in origin, with the growth of hoar crystals in the cracks, the moisture source being atmospheric air. However, Gasanov (1977) disagrees with the concept. He concludes there would be a vertical air convection in the frost cracks in winter with sublimation and therefore removal of ice from the walls of the crack. The main source of crack infilling to form new veinlets is surface water from melting snow, rain, or runoff. According to Gasanov, sublimation leads only to an inner redistribution within the crack of previously formed vein (congelation) ice.

Dostovalov's model (Dostovalov 1952) of thermal contraction cracking and the simple dependence between the mean annual temperature (T) and the amplitude (A) of the temperature at the base of the active layer ($T = \frac{A}{2}$) has been used by Kaplina and Kuznetsova (1975) to calculate past mean annual temperatures. The authors conclude that the old Pleistocene ice wedges, which are thicker than those of today, were formed at a mean annual temperature ($T = \frac{A}{2}$) of about -20°C.

Numerous radiocarbon dates have been obtained in recent years on the age of the most intensive growth of ice-wedge polygons in Northern Yakutia. According to radiocarbon dating the deposits are 40,000 to 12,000 years old and are mainly of Karginsk-Sartansk age (Konishchev 1974; Tomirdiaro et al. 1975; other authors). In the western North American Arctic, small syngenetic Pleistocene ice wedges of at least early Wisconsinan age (> 50,000 years) are still preserved at Hooper Island, Canada.

Present Ice-Wedge Growth

Kaplina (1976), in a study of the special features of ice-wedge growth in the Kolyma lowland, U.S.S.R., has found a dependence of growth rate on ground temperature. Kaplina has established a coefficient between the width of the incremental ice veinlet (elementary ice veinlet) near the top of an ice wedge to the size of the polygon. Within the Kolyma lowland the coefficient for ground of similar lithology increases as the mean annual ground temperature decreases, and varies from 0.3 to 1.9 mm/m. Measurements of ice-wedge growth for many ice wedges have been made at Garry Island, Canada for the 1976-1978 period (Mackay 1974, 1975). The mean annual air and ground temperatures are -12°C and -8°C respectively. The broad conclusions are: the frequency of ice-wedge cracking averages 30 percent per year with most cracking occurring from mid-January to mid-March; crack frequency varies inversely with snow depth; medium sized wedges crack the most frequently; instrumentation shows that some ice-wedge cracks initiate within the wedges and propagate both upwards and downwards; measurements with probes placed within the cracks show that most cracks close appreciably before meltwater can enter the cracks to grow ice (elementary) veinlets; there is little evidence from probes inserted to the bottom of cracks to show that the cracks progressively deepen as the cold winter temperature wave propagates downward; and in low centred polygons, there tends to be a net outward displacement of the active layer material to form ridges, the movement averaging from 0.5 to 2 mm/yr.

Sublacustrine polygons, considered by Shilts and Dean (1975) to be similar to subaerial ice-wedge polygons, have been described for lakes where there is no evidence of shoreline submergence. If the polygons have indeed formed under water, ice-wedge cracking is then initiated within permafrost rather than at the lake ice surface, because otherwise, cracking could not recur in the identical geometric pattern, year after year.

Ice-Wedge Petrofabrics

Petrofabric studies are proving of great assistance in the understanding of the mechanics of ice-wedge growth and in the differentiation between different types of ground ice. Black (1978) has reported on the ice petrofabrics of four actively growing surface wedges and nine deeply buried inactive wedges near Fairbanks, Alaska. Lineations of optic axes were better developed in the surface wedges than in the buried wedges and the surface wedges displayed more complicated fabrics than did buried wedges. There was evidence of recrystallization of ice in the buried wedges. Gell (1978) has carried out petrofabric studies on ice wedges of several types and has investigated the change in grain size outward from the centre of a wedge, ice at the junction of two wedges, and massive segregated ice cut by ice-wedge cracks.

Wedge Casts and the Periglacial Record

The world distribution of ice and soil wedge casts for the Quaternary is now reasonably well known and detailed references are given by Washburn (in press). The literature is particularly rich for the U.S.S.R. and Europe, but numerous papers have been published for other parts of the world including Argentina, the British Isles, Japan and North America. As ice-wedge polygons only grow in a permafrost environment, identification of ice-wedge casts is then evidence of past permafrost (Black 1976). If the criteria for an ice-wedge origin are unequivocal, then estimates can be made of past temperatures. However, it is very difficult to extrapolate from present to past mean annual air or ground temperatures. Many writers cite Alaskan data (Péwé 1973) where active ice wedges grow in areas with a mean annual air temperature of about -6°C or -8°C and colder and assume this to hold for other areas under different climatic and soil conditions in the geologic past. Romanovskii (1973) states that ice veins may form at ground temperatures of -2°C and colder, depending upon factors such as soil type and geomorphic conditions. In the Mackenzie Delta, Canada, ice wedges are growing on young alluvial islands with mean annual ground temperatures of -2 to -3°C whereas nearby, some old ice wedges rarely crack, even though mean annual ground temperatures are -8°C. Svensson (1977) points out that polygonal frost cracking now occurs in non-permafrost areas of Norden. Inasmuch as mean annual ground temperatures can range from 1 to at least 8°C warmer than mean annual air temperatures, and thermal contraction cracking is not linearly related to mean annual air temperature, ground temperature, or soil type, extrapolation from the dimensions of wedge casts to paleotemperatures is difficult.

Wedge Casts and the Geologic Record

In view of the indubitable evidence of past glaciation in the early geologic record, it is not surprising that some wedge-like structures, found in association with tillites, have been interpreted as ice-wedge casts and therefore indicative of past permafrost. The geologic evidence is difficult to assess because the wedge structures are small, good polygon patterns have not been observed, and a wedge structure is no proof by itself of permafrost. Young and Long (1976) have described wedge casts, >2.3 b.y. old, north of Espanola, Ontario, Canada. The wedges were exposed only in section, so it was impossible to determine if a polygonal pattern was present. In view of the evidence, an ice-wedge origin is questionable. Nystuen (1976) describes an ice-wedge cast from a Late Precambrian tillite in southern Norway and compares the conditions with wedge casts suggestive of permafrost in the Precambrian in Scotland, Spitsbergen, and Finnmark. The apparent width of the wedge is 5 cm at the top, the presumed depth is 70 cm, and the adjacent bedding in the adjoining sandstone contact is bent slightly downwards. The feature is so small that it may have been formed only by cracking in a seasonally freezing layer and therefore does not give proof of permafrost. Narrow clastic dikes, generally less than 10 cm in width, have been found within the basal tillite of Late Ordovician to Early Silurian glaciations of South Africa. Daily and Cooper (1976) regard the dikes as sand wedges, genetically similar to the sand wedges of McMurdo Sound, Antarctica, where the climate is dry and cold. However, the polygonal forms described by Daily and Cooper are much smaller than those of McMurdo Sound, and the intersection patterns are atypical of thermal contraction cracks. In addition, Daily and Cooper also suggest that a three-dimensional crack pattern in sandstone may be the cast of a reticulate three-dimensional ice vein network, such as frequently occurs in fine grained tills and lake and marine clays in present permafrost areas. But such reticulate ice vein networks are found in fine grained sediments rather than in sands (sandstones).

PINGOS

Pingos, although localized in distribution, are of interest because pingo growth is a dynamic response to changes in the ground thermal regime and ground water hydrology. More and more studies show that pingo ice can range from pure injection ice, injection-segregation ice, segregation ice, to segregation ice interlayered with a preponderance of mineral and/or organic matter (Evseev 1976; Mackay 1977; Pissart and French 1977; Rampton 1974). Evseev (1976) in his paper on the main characteristics, occurrences, ages, and cryogenic structures of pingos in the European part of the U.S.S.R. and Western Siberia, discusses segregation ice in the pingos.

Pingo Growth

Field studies on Banks Island, Western Canadian Arctic (Pissart and French 1977) show that some pingos have grown on low terraces following the lateral migration of a river channel and the freezing of a talik which had formed beneath the channel. On Prince Patrick Island, Canada, elongate pingos located near the coast are believed to have formed following fluctuations of sea level and the inundation of river valleys. Other pingos in the central parts of Prince Patrick Island appear related to the presence of deep faults in the underlying bedrock at a time when permafrost was aggrading. Kowalkowski (1978) has also described pingos, with ice lensed cores which have formed in abandoned channels in a basin of the Khangai Mountains, Mongolia.

Pingos in bedrock are frequently reported in the literature (eg. Ahman 1973: Balkwill et al. 1974). The pingos are of both closed and open system types and bedrock has been domed 35 to 40 m above the surrounding ground level, so the uplift pressures have been considerable. As extensive ice segregation is unlikely to occur in bedrock, injection ice cores can be inferred for pingos with a bedrock overburden. In an endeavor to determine the characteristics of pingo waters, a detailed study (Allen et al. 1976) has been carried out on waters in Scoresby Land, northeast Greenland. Samples of different waters (eg. glacier, stream, pingo) were analyzed chemically for their principal solute ions, and isotopically for their deuterium and oxygen isotope contents. It was concluded that all of the waters from the pingos are of recent meteoric origin.

The growth of pingos along the Western Canadian Arctic coast has been measured by precise levelling (1969-1978) of bench marks installed into permafrost (Mackay 1977). Drilling has shown that the hydrostatic head of a growing closed system pingo may rise far higher than the top of the pingo. Pressure transducers, installed beneath aggrading permafrost surrounding growing pingos, show that the pore water pressures generated by pore water expulsion can exceed 80 percent of the total overburden pressure, even beneath permafrost 40 m thick. Drilling has also shown the presence of large subpingo water lenses as much as 2.2 m deep and with basal diameters of up to 300 m (Mackay 1978). There is some field evidence to suggest that there may be downslope creep of the overburden and ice core of some of the older and larger pingos. Two theories have recently been proposed for the origin of pingos. Bleich (1974) suggests that a pingo grows with a water supply from a lake fed through ice-wedge cracks. Ryckborst (1974) believes pingos originate as upward-growing ice lenses above the water table in the active layer in unsaturated sand. However, both theories are contradicted by abundant field data.

Pingo Scars

The identification of thawed pingos is difficult, because circular forms with ramparts may also result from other processes than pingo collapse, eg. from glacial, thermokarst, eolian, and anthropogenic causes. The recognition of pingo remnants, in former periglacial areas, is widespread (eg. Bastin et al. 1974; Cailleux 1976; Flemal 1976; Svensson 1976; Watson 1976). Many of the identifications have been based upon detailed mapping of the stratigraphy, structure and palynology of ringed depressions. As pingo-like remnants have been recognized from the lower Paleozoic in the Sahara desert, pingo scars, like ice-wedge casts, can contribute to our understanding of the geologic record.

PALSAS

The major focus of palsa research continues to be the life cycle of palsas; whether palsas are formed by ice injection or ice segregation; and whether the features are essentially degradational or aggradational in origin (Jahn 1976; Seppala 1976). Ahman (1977), in a detailed palsa investigation in Fennoscandia, has classified them into palsa plateaus, esker palsas, string palsas, dome-shaped palsas, and palsa complexes. The primary prerequisite for palsa formation according to Ahman is a soil suitable for ice segregation. Genetically, no difference was found in the starting point or further development of a pure peat palsa on one extreme to that of a pure mineral soil palsa at the other extreme. According to this view, a palsa is a hillock formed by segregated ice in soil, peat, or a combination of them.

GEOCHEMISTRY OF GROUND ICE

The geochemistry of ground ice, including the use of stable isotopes, appears to be a promising research field for the study of ice lensing, the growth of permafrost, hydraulic conductivity of frozen soils, changes in the thickness of the active layer, and in paleocryologic reconstructions of past environments (Anisimova 1978). Hallet (1978) discusses some of the problems of redistribution of solutes in freezing soil solutions and points out that there are implications on the nucleation of ice lenses, the rhythmic spacing of ice lenses, and the heaving characteristics of the soil. Oxygen isotope ratios have been used to provide paleoclimatic information and chronology of three cores from Antarctica (Stuiver et al. 1976). Although the interpretation of the oxygen isotope record from permafrost is more complicated than for glacier ice cores, because the accumulation of sediments is not necessarily continuous, and a portion of the ^{18}O record may be missing because of replacement by younger waters or for other reasons, the Antarctic record shows great promise. Michel and Fritz (1978) have studied oxygen isotope ratios for sediments in the Mackenzie Valley, Canada and have interpreted the more negative values at depth as reflecting deep inactive permafrost possibly as much as 7,000 to 10,000 years old. They consider that tritium and ^{18}O data can be used to distinguish between active and inactive (relic) permafrost. Van Everdingen (1978) has used oxygen-and sulphur isotopes and water quality analyses to study the source of water and freezing processes of frost blisters near Fort Norman, N.W.T., Canada.

THERMOKARST

Since thermokarst features reflect natural changes, whether geomorphic, climatic, or vegetational, a study of thermokarst is a study of change (Brown 1974; French 1974; Rampton 1974; Shur 1974; Ugolini 1975). One aspect of recent research has been the mapping of thermokarst features over large areas by means of remote sensing imagery. Sellman et al. (1975) have studied thaw lakes on the Arctic Coastal Plain, Alaska using sequential satellite imagery by means of which, for example, lake depths could be estimated from the extent of ice cover, and deductions made on ground ice volumes and basin genesis. In Quebec, Canada, Thibodeaux and Cailleux (1973) have mapped thermokarst terrain over very large areas using air photographs. Features such as circular lakes, beaded streams and string bogs, presumably of thermokarst origin, were shown to vary along north-south sampling areas. On an interplanetary scale, Gatto and Anderson (1975) have compared an Alaskan thermokarst terrain with a possible thermokarst analog on the plant Mars.

Gravis (1978), from radiocarbon dating of alas, alluvial, and marine deposits of the same age, together with palynological data, shows that most thermokarst depressions on the Maritime Plain and Novosibirsk Islands, U.S.S.R., are of pre-Holocene age. Thermokarst occurred mainly during cold glacial epochs (Zyran and Sartan) and coincided with a lowered sea level. Shur (1974) has concluded that at present thermokarst is formed mostly as a result of local conditions of heat exchange in the system (soil, underground ice, environment) and changes in the climate may either accelerate or retard thermokarst development. Velikotsky (1974) has presented data which show a relation between tectonic jointing in the north of the Yana-Omoloi interfluve, U.S.S.R., and the development of thermokarst (alas) forms of relief. Rampton (1974) believes that many of the thermokarst features of the Western Arctic Coast, Canada have developed during the postglacial warm period which culminated about 8,000 years ago. Rampton and Walcott (1974) have used gravity profiles across ice-cored topography to determine the amount of excess ice and probable thermokarst subsidence if the area were thawed.

REGIONAL GEOCRYOLOGY

Alpine Permafrost

Alpine permafrost with limited amounts of ground ice exists in many temperate mountainous areas of the northern and southern hemisphere and even in the tropics, such as Hawaii (Woodcock 1974). Fujii and Higuchi (1978) have attempted to map the distribution of alpine permafrost in the northern hemisphere and have suggested that the lower limit of alpine permafrost corresponds to the altitude where the mean annual air temperature is in the range of -1 to -3°C. Although such a correlation between mean annual air temperature and permafrost may exist in some areas, other factors, particularly snow cover (Haeberli 1978), make correlation between mean annual air temperatures and permafrost distribution on a world scale difficult.

Considerable research has been carried out on alpine permafrost in the Pamir and Tien Shan. Gorbunov (1976, 1978) has found some regularity in the formation of permafrost and the cryogenic structures in mountain environments. Gorbunov has distinguished three main types of layered permafrost in mountainous areas of the world, namely a single-layer of permafrost (thawing and degrading); two-layered permafrost (thawing and frozen); and aggrading permafrost (single-layered). The extent to which Gorbunov's three main types occur elsewhere in alpine regions still needs field confirmation.

Investigations of alpine permafrost in the Canadian Rocky Mountains by Harris and Brown (1978) show that permafrost may extend to a depth of 100 m or more, the upper portion having adjusted to the present climate and the lower layer being relic. Rock glaciers (Barsch 1978; Corte 1978) are also local indicators of permafrost. In general, except for the ice in rock glaciers, ground ice in areas of alpine permafrost is probably negligible because of the abundance of bedrock at depth.

Submarine Permafrost

Considerable progress has been made in the delineation and mapping of submarine (offshore) permafrost since 1973 but comparatively little is known about the contained ground ice. According to Are (1976, 1978) offshore permafrost extends over the greater part of the shelf of Asia and the Arctic Basin. He has identified two zones over the bottom of the Arctic Basin, viz. a deepwater zone with temperatures below 0°C and a zone between 200 and 900 m with waters above 0°C. The seawater temperature in the abyssal trough situated between the Lomonsov Ridge and the Barents-Kara shelf is at about -0.7 to -1.0°C, this suggesting permafrost under the bottom of the trough. The bottom deposits probably do not contain ice, i.e. the deposits are not ice-bonded. Permafrost, according to Are, is absent in the upper portion of the continental slope, in the deepest parts of the arctic seas, and probably also in the zone of warming of large rivers where depths are less than 20 m. Relic permafrost can occur in that part of the shelf which was exposed during the last glacial sea level lowering. In these areas, ground ice might occur at depth as it does in some nearby land areas. Detailed large-scale studies of submarine permafrost of the Vankina Guba (Bay) in the Laptev Sea show that the permafrost conditions are complex (Zhigarev and Plakht 1974). Kudryavtsev et al. (1978) give a map showing submarine permafrost for Eurasia. Numerous investigations have been carried out on offshore permafrost along the North American Western Arctic Coast (eg. Hunter et al. 1978; Iskandar et al. 1978). Seismic and drilling records have shown that ice-bonded permafrost may occur beneath non ice-bonded sediments whose saline pore water is below 0°C. In some areas, initially ice-bonded permafrost has had the interstitial fresh-water ice dissolved by saline water at a negative temperature (Iskandar et al. 1978).

PALEOCRYOLOGICAL STUDIES

Paleocryologic studies have been developed to the greatest extent in the U.S.S.R. In North America, a substantial percentage of the area now with permafrost was beneath glacier ice only 15,000 years ago and since near surface bedrock is widespread, old underground ice is necessarily difficult to identify or generally absent. The history of permafrost in the eastern part of the Bolshezemelskaya Tundra, U.S.S.R., and the relation between the cryogenic structure and the thermal regime of permafrost has been studied by Tumel (1977). She has drawn interesting conclusions on the long term effect of the thermal regime of the ground on the fabric of ground ice (cryogenic structure) in permafrost in the region. The paleocryogenic reconstruction shows that permafrost grew in the past in different subsurface materials but under similar ground thermal regimes. Hence the epigenetically frozen permafrost although of different ages has a similar composition, water content, and cryogenic fabric. Tumel has also shown that the association of the cryogenic fabric of the upper part of permafrost with the modern mean annual ground temperature at the depth of zero annual temperature change or with other modern temperature values is absent in the surface loams of the Bolshezemelskaya Tundra.

Gravis et al. (1974) in a recently co-authored publication on "General Geocryology" has discussed the processes of ice segregation of fine-grained soils under conditions of epigenetic freezing. He distinguishes three horizons of ice formation which are, from top to bottom: 1) the horizon of ice formation with ice lenses (cryogenic fabric of a segregational type) where the water which migrates to the freezing front is under a suction; 2) the horizon of ice formation with injection or intrusive ice (cryogenic fabric of an injection type) where the water which migrates towards the freezing front is under pressure; and 3) the horizon of passive ice formation with the cryogenic fabric reflecting that of the host material. According to Gravis, if there are several deep-lying water bearing horizons with water under pressure, several horizons with cryogenic fabrics of an injectional type will be formed. The three horizons, discussed by Gravis, were observed by him in Mongolia (Gravis 1974). The extent to which the three horizons can be recognized elsewhere remains to be determined. For example, the occurrence of horizon two is probably absent in many regions where no build up of water pressure was possible. Katasonov (1975) has attempted to associate the contemporaneous cryogenic forms of relief with the genesis of underground ice and the enclosing deposits.

Studies of the relief features due to underground ice (cryogenic forms of relief) in the area of old permafrost (paleocryogenic area) of the Russian Plain have continued to develop. Berdnikov (1976) has discussed in detail the geomorphological characteristics of the relic cryogenic relief in the Upper Volga Basin and he has discussed some characteristic features of the morphology of wedge-like features and asymmetric aspects of their structure. Koreisha (1976) has shown the importance of paleographical research in his analysis of the ground ice in the extreme Northeast area of the U.S.S.R. where the concentration of underground ice is the greatest for the entire permafrost area of Eurasia. The Northeast area comprises only 25 percent of the whole permafrost zone but up to 40 percent of the total underground ice is concentrated there. This is a region where the great range and close interrelationships of different underground ice types (veined, segregation, and injection) and surface ice types (icings, glaciers, etc.) are exposed the most vividly. Koreisha has shown, in a general way, the relationship between underground and surface ice of the Northeast and the climate, altitudinal zones, and tectonic development.

The reconstruction of paleoclimate from present day geothermal data can be of considerable assistance to paleocryological studies (Balobaev 1978; Sharbatyan and Shumskiy 1974). By using geothermal data for disequilibrium permafrost thawing from below, Balobaev (1978) has concluded that during the last cold period (glaciation) in the northern part of the Asiatic continent, about 20,000 years ago, the climate was colder by about 10 to 13°C.

CRYOGENIC WEATHERING

One of the most important problems involving ice on a micro scale is the degree to which there are compositional and textural changes in different types of materials when they undergo freeze and thaw. A second and related problem is the degree to which changes may take place through geologic time at below 0°C temperatures. In fine-grained soils which can have considerable unfrozen pore water below 0°C, temperature fluctuations in the below 0°C temperature range can cause changes in the cryogenic fabric, ice/water content, frost heave, and hydraulic conductivity. Konishchev (1977, 1978) has investigated the interaction of water with different structural groups of rock-forming minerals and has suggested a theoretical model of mineral stability with respect to factors of rock weathering. According to the model, the resistance of common rock-forming minerals, such as quartz, feldspar and mica form a series. Experimental studies of the resistance of primary and clay minerals have confirmed the theoretical model (Konishchev et al. 1974, 1978). In the experiments, the resistance of quartz was lower than that of non-weathered feldspars. Thus, for example, the lower particle size limit for disintegration by freezing of quartz is from 0.05 to 0.01 mm, and that for feldspar from 0.1 to 0.05 mm. Consequently, the ultimate grain size distribution for the basic rock-forming minerals in a cold area with freeze-thaw cycles are opposite to that of a warm area without the cycles. Konishchev et al. (1973) have also shown that certain microstructures of fine grained soils can form in response to repeated freeze-thaw cycles.

White (1976) has raised the question as to whether some products attributed to frost action may not be the result of hydration shattering where the pressure of absorbed water (hydration) may generate forces sufficient to free grains and disintegrate rock. The process, experimentally supported, may be significant even without freezing.

New and interesting data have recently been published on cryogenic weathering beneath glaciers. Subglacial regelation weathering without any temperature change has been discussed by Troitsky et al. (1975) and Moskalevsky (1978). Hallett (1978) has discussed cryogenic chemical deposits which can form in freezing soils. The study of cryogenic weathering and related features can serve as an aid in understanding present processes and the interpretation of paleocryologic conditions.

CRYOLITHOGENESIS

The term "cryolithogenesis" refers to the genesis of permafrost materials with some ice content. The word derivation is from lithogenesis, the origin and formation of rocks, especially sedimentary rocks. Popov (1973, 1976) uses the term in a broad context to include the complex interrelated geologic and associated processes involved in the study of frozen ground through space and time. By way of contrast, Gasanov (1976, 1978) restricts the term to sedimentary processes of a hydrothermal type. Popov, Rozenbaum and Vostokova (1977, 1978) have compiled a cryolithological map of the U.S.S.R. on a scale of 1:4,000,000. The criteria for the map legend are based upon a recognition of the major genetic types of permafrost, the spatial associations of the genetic types, and the processes by which the genetic types were formed. The map clearly shows the regional occurrence of the two main genetic types of permafrost, epigenetic and syngenetic. The map also shows whether the frozen ground is composed primarily of ice (i.e. a cryolite such as the ice core of a pingo or wedge ice) or is frozen ground with some ice (eg. a cryolitite such as frozen sands or frozen peats). The map provides a wealth of information on cryogenic textures, the estimated age of the frozen ground, and the relation between the distribution of frozen ground and the type of cryolithogenesis. The cryolithological map is an excellent example of the application of theory to the generalization of extensive geocryologic data for the U.S.S.R. Vtyurin (1978) advocates the genetic approach in the cryolithological regionalization of permafrost areas; i.e. the distribution should be mapped, both areally and at depth, according to genetic types.

In the opinion of the reviewers, the study of cryolithogenesis in the broad sense is the integrating factor in our understanding of the geologic controls of the origin, characteristics, and distribution of ground ice, the theme of this review paper.

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МЕРЗЛОТНО-ГИДРОГЕОЛОГИЧЕСКОЕ РАЙОНИРОВАНИЕ ВОСТОЧНОЙ СИБИРИ

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ВВЕДЕНИЕ

Выход в свет многотомной монографии "Гидрогеология СССР", ряда монографий по морфологии криолитозоны, обобщающих работ по распространению наледных явлений, наряду с теоретическими разработками вопросов изменения гидрогеологических параметров структур при глубоком их промерзании, доложенных в докладах на П Международной конференции по мерзлотоведению (1,2) , позволяют поставить на обсуждение региональные вопросы мерзлотной гидрогеологии, рассмотрев их на примере Восточной Сибири. Прежде чем перейти к обсуждению по существу, целесообразно остановиться на принятой терминологии, имея в виду рассмотрение лишь тех терминов, которые недостаточно широко используются в печати, имеют различные трактовки или необходимы для понимания принципиальных позиций авторов.

Анализируются две категории структур - гидрогеологические массивы (ГМ) , которые в литературе часто синонимизируют термином бассейны трещинных вод, и артезианские бассейны (АБ) , со свойственным им двучленным строением и наличием в чехле пластовых вод и в фундаменте - трещинных (3). Промежуточные категории структур определены как адартезианские (АдБ) бассейны и гидрогеологические адмассивы (АдМ) . Эти структуры характеризуются наличием и трещинных и пластовых вод в примерно равных соотношениях, однако по морфологическим признакам они тяготеют соответственно либо к артезианским бассейнам, либо к гидрогеологическим массивам.

В числе АБ представляется целесообразным выделить платформенные и межгорные. Они всегда различны по размерам, а, кроме того, по строению чехла, гидрохимическому разрезу, условиям питания, т.е. целому ряду дополнительных признаков, во многом определяющих гидрогеологические параметры этих структур.

В особую категорию вынесены также вулканогенные гидрогеологические структуры. Будучи наложенными на различные геологические образования, эти структуры получили название вулканогенных супербассейнов (ВсБ) .

В основу анализа мерзлотных характеристик положено, в первую очередь, состояние прерывистости мерзлой зоны, по которому выделена сплошная мерзлая зона, где мерзлые породы имеют площадь распространения 80% и более, прерывистая мерзлая зона, где мерзлые породы имеют площадь распространения 40-80%, и островная мерзлая зона, где острова, занятые мерзлыми породами, составляют менее 40%. При этом под мерзлыми породами понимаются такие, для которых мерзлое состояние (отрицательная температура по шкале Цельсия и наличие в составе льда-цемента) является характерным и длительным, многолетним.

Из анализа многочисленных гидрогеологических материалов следует, что в пределах территорий островного и прерывистого распространения мерзлых пород последние не оказывают решающего воздействия на характер гидрогеологических структур или на их гидродинамические параметры. Поэтому для таких территорий дальнейший анализ не осуществляется. Для территорий сплошной мерзлой зоны решающее значение приобретает вопрос мощности мерзлых пород и глубины промерзания недр в условиях различных гидрогеологических структур. В качестве специфических структур по условиям промерзания выделяются (4) :

- криогеологические массивы, в которых мощность мерзлой зоны значительно больше мощности возможного регионального распространения подземных вод, причем последние могут быть приурочены соответственно к зонам наиболее глубоких разломов или участкам, поддающимся карстованию мраморизованных пород;
- криогеологические бассейны, представляющие собой артезианские структуры, в которых осадочный чехол полностью проморожен и подземные воды могут быть сосредоточены лишь в фундаменте;
- криоартезианские бассейны, в которых проморожен пояс пресных вод и непосредственно под мерзлыми породами залегают соленые воды и рассолы;
- артезианские бассейны сплошного глубокого промерзания, характеризующиеся региональным развитием сплошной мерзлой зоны, пресных и слабо солоноватых подземных вод в ее основании.

Наряду с перечисленными, использованы термины :

- криопэги - соленые воды и рассолы, имеющие постоянно отрицательную температуру;
- деятельный слой - сезоннопротаивающий или сезоннопромерзающий слой;
- мерзлые породы - породы, мерзлое состояние которых продолжается много лет.

Районирование Восточной Сибири осуществлено на структурно-гидрогеологической основе, отображенной в обобщающих сводных работах (1,5) и на карте к ним.

В качестве структур первого порядка на территории Восточной Сибири выделены Восточно-Сибирская артезианская область, Восточно-Сибирская, Верхояно-Чукотская и Камчатско-Корякская гидрогеологические складчатые области. Ниже переходим к последовательному их рассмотрению в тех границах, в которых процессы криогенеза определяют условия формирования гидрогеологических структур и содержащихся в них подземных вод.

1. Восточно-Сибирская артезианская область по геологическим условиям представляет собой достаточно сложную структуру, характеризующуюся развитием нескольких впадин, выполненных осадочными отложениями различного возраста, генезиса и состава, разделенных между собой структурными поднятиями фундамента. Структурные впадины образуют крупные АБ платформенного типа : Ангаро-Ленский, Тунгусский, Котуйский, Якутский, Оленекский и Хатангский. Наиболее крупное из структурных поднятий - Анабарский массив-представляет собой обширный по площади выход кристаллических и метаморфических пород фундамента на поверхность. На юге АБ Восточно-Сибирской области сочленяются с Саянской и Байкало-Алданской гидрогеологическими складчатыми областями.

Чехол АБ Восточной Сибири сложен разновозрастными образованиями, отличающимися, кроме того, еще и литологическим составом пород, их геохимическими характеристиками. На значительной территории Ангаро-Ленского, в западной и юго-западной части Якутского и в восточной и юго-восточной части Тунгусского АБ широко распространены верхнепротерозойские и палеозойские (кембрий - девон) терригенно-карбонатные и карбонатные образования, часто галогенные или с существенно сульфатной минерализацией. Центральная часть Якутского АБ-Лено-Вилюйский АБ второго порядка-сложен мощной толщей терригенных мезозойских образований существенно континентального происхождения.В отличие от Лено-Вилюйского- Тунгусский АБ представлен терригенно-вулканогенными отложениями значительной мощности. В разрезе Хатангского АБ песчано-глинистые отложения мезозойского и верхнепалеозойского возраста подстилаются галогенными образованиями среднего палеозоя.

Существенное разнообразие в составе и сложении пород, слагающих Восточно-Сибирскую артезианскую область, подчеркивается и морфоструктурными различиями. На большей части территории ее поверхность представляет собой в той или иной мере расчлененное плато, уровень которого в целом понижается в бассейне Вилюя и Лены, где оно переходит сначала в высокую, а затем - низкую эрозионную и эрозионно-аккумулятивную равнины.

Наиболее возвышенная часть поверхности - плато Путорана- представляет собой лавовое тектоно-денудационное образование, которое по мощности формирующих его базальтовых покровов, достигающих 2-2,5 км , может рассматриваться в качестве вулканогенного супербассейна.

В пределах полей распространения терригенно-карбонатных, существенно галогенных образований чехла, в условиях сравнительно глубокого дренажа этих образований, возникали условия, не благоприятствующие формированию значительной мощности пояса пресных вод, и на сравнительно незначительных глубинах в пределах первых 200 метров от поверхности залегали уже соленые воды или рассолы. Обратная картина наблюдалась в пределах полей распространения преимущественно континентальных образований, например, Вилюйской синеклизы, где в отложениях мела и верхней юры мог формироваться мощный, измеряемый многими сотнями метров пояс пресных подземных вод. Вероятно, близкие гидрохимические условия были и в пределах плато Путорана, гидрогеологическая структура которого была осложнена тектоническими долинами, выполненными мощными рыхлыми молассоподобными отложениями. Промежуточное положение занимали территории, где в составе карбонатно-терригенного комплекса галогенные или гипсоносные фации отсутствовали, как, например, на северном крыле Алданской антеклизы, где на сравнительно небольших глубинах можно было ожидать наличие слабо солоноватых сульфатных или хлоридных вод. Наряду с различиями гидрохимических параметров, учитывая значительную расчлененность рельефа поверхности платформы и неоднородность в сложении пород чехла, их тектоническую нарушенность региональными и оперяющими разломами, можно предположить и существенное различие гидродинамических условий.

Все сказанное позволяет заключить, что ко времени начала формирования мерзлой зоны, глубокого промерзания чехла артезианских структур, в пределах Восточно-Сибирской артезианской области существовала довольно неоднородная гидрогеологическая и гидрохимическая ситуация (6). В целом она представляется следующим образом.

Очевидно, что промерзание недр, связанное с общим похолоданием климата и увеличением его континентальности в плейстоцене, должно было протекать по-разному, в зависимости от конкретной геоморфологической, гидрогеологической и геохимической ситуации.

В условиях мощной зоны пресных подземных вод и пониженных элементов рельефа, в частности центральной части Лено-Вилюйского АБ,в процессе охлаждения недр шло промерзание водоносных горизонтов, сопровождаемое выпаданием из замерзающих подземных вод наиболее трудно растворимых солей кальция и магния, некоторой карбонатизацией разреза, дистилляцией подземных льдов и концентрированием растворенных солей перед фронтом промерзания. В этих условиях ее мощности достигли максимальных значений- до 650 метров, и все верхние водоносные горизонты остались проморожены на полную мощность.

Обратная картина наблюдалась на площадях распространения карбонатных и карбонатно-терригенных галогенных пород, относительно слабо дренированных и на небольших глубинах содержащих соленые воды и рассолы. Охлаждение недр в таких условиях привело к сравнительно быстрому промерзанию верхней, обычно до 200-300 м , части разреза, после чего началось медленное и длительное охлаждение соленых вод и рассолов. Их температура снизилась до отрицательных величин, и охлаждение постепенно охватило мощность верхней части гидрогеологического разреза до глубины 1450 м .

Охлаждение бассейнов, сложенных терригенными и карбонатными отложениями, не содержащими в составе верхних горизонтов рассолов и высококонцентрированных соленых вод, привело к постепенному промерзанию верхней части разреза, аналогично промерзанию пресноводных отложений, однако,мощности мерзлых пород оказались несколько ниже, и в основании их тоже возник пояс отрицательнотемпературных вод - криопэгов, однако,не столь значительной мощности, как это имело место в галогенных разрезах.

Одновременно с возрастанием глубины промерзание охватывало все большие территории, постепенно продвигаясь от наиболее возвышенных к пониженным участкам и с севера на юг, сокращая площади таликов, коренным образом меняя условия взаимосвязи подземных вод с поверхностными, гидродинамическую структуру зоны свободного и затрудненного водообмена артезианских структур Сибирской платформы. На севере Восточно-Сибирской артезианской области эти процессы охватили все артезианские структуры, вне зависимости от слагающих их пород; на юге, в пределах полей распространения карстующихся карбонатных отложений, мерзлая зона сохраняла прерывистый характер, а подземные воды - достаточно интенсивное питание.

В соответствии с характером гидрохимического разреза на обширной части территории Тунгусского АБ, в западной части Якутского АБ, Котуйском, Оленекском и, частично, Хатангском АБ зона пресных вод была полностью проморожена, сформировалась мощная толща криопэгов и артезианские бассейны перешли в криоартезианскую фазу развития.

Рассматривая феномен глубокого промерзания артезианских структур и их переход в криоартезианскую фазу развития, нельзя не подчеркнуть того обстоятельства, что последняя представляет собой качественно новое гидроструктурное образование, свойства которого определяются :

- наличием регионального мерзлотного водоупора, мощность которого непостоянна во времени;
- отсутствием регионально-выдержанной зоны свободного водообмена и свойственной ей пресных подземных вод;
- наличием пояса криопэгов - отрицательнотемпературных вод и рассолов в основании мерзлой зоны и линз криопэгов в ее пределах;
- гидрохимическими и гидродинамическими процессами, вызываемыми колебаниями нижней поверхности мерзлой зоны, ее оттаиванием и промерзанием, следующим за периодами потепления или похолодания;
- низкими пьезометрическими уровнями подземных вод, обладающих, помимо низкой температуры и высокой минерализации, часто и высоким газовым фактором ;
- связыванием подземных вод в криогидратной форме.

Все эти особенности, свойства или процессы, протекающие в криоартезианских структурах, были освещены в трудах П Международной конференции (7) и ряде других работ советских гидрогеологов (8,9), что позволяет остановиться лишь на некоторых аспектах формирования подземных вод этих структур.

Один из наиболее сложных и мало разработанных вопросов- гидродинамические условия формирования подземных вод. Мы не имеем в виду доложить новую теорию формирования низких пьезометрических уровней подземных вод, характерных для этих структур и по-разному объясненных исследователями, занимавшимися этим вопросом. Мы хотим лишь подчеркнуть то обстоятельство, что питание подмерзлотных вод с поверхности в условиях криоартезианских структур исключено.

Действительно, даже в самых глубоко промороженных артезианских бассейнах, для многих из которых также характерны низкие пьезометрические уровни, наличие сквозного проницаемого талика является достаточным условием для взаимосвязи поверхностных и подземных вод. В криоартезианских структурах высококонцентрированные соленые воды и рассолы обладают достаточно низкими отрицательными температурами, в отдельных случаях достигающими -14^0(Нордвик), и пресные подземные воды, проникающие в подобные условия с поверхности, неизбежно должны замерзнуть. Сказанное подтверждается экспериментами, проведенными Институтом мерзлотоведения СО АН СССР на одном из месторождений на юге Сибирской платформы. Казалось бы, в условиях отсутствия питания с поверхности в описываемых АБ должна наступить стабилизация гидродинамической обстановки. В действительности, отсутствие возможностей поверхностного питания не свидетельствует о гидродинамической стабильности рассматриваемых структур. Более того, наличие соленых источников в бассейне р. Вилюя, Большой и Малой Тунгуски свидетельствует о значительной мощности сравнительно активного гидродинамического режима.

Одной из причин его возникновения может стать протаивание мерзлой зоны снизу и возникновение в этой связи так называемых дефицитов напоров. Как показывают фактические данные, полученные в последние годы, это протаивание мерзлых пород от нижней границы происходит неравномерно. Во всяком случае, мощность мерзлых пород над зонами региональных разломов фактически оказывается на 60-80 метров меньше, чем вне влияния этих зон. Однако, если протаивание мерзлых пород происходит неравномерно, значит неравномерно должны быть распределены и дефициты напоров; они должны быть максимальны там, где это протаивание достигло максимальных значений. Следовательно, в этих зонах максимального протаивания и максимального дефицита напоров должны существовать также зоны возможного поглощения. Фактические данные, полученные при разведке подземных вод на ряде объектов в западной части Якутского артезианского бассейна, подкрепляют высказанные соображения. Отсюда можно сделать несколько неожиданное общее заключение - мерзлая зона, являющаяся региональным водоупором, возникшим на месте зоны свободного водообмена, в силу динамичности своего развития стимулирует активизацию гидродинамических процессов в верхних подмерзлотных горизонтах. Исключая свободный водообмен с поверхностью, она способствует активизации внутреннего водообмена.

Какова же должна быть направленность этого внутреннего водообмена? Для того чтобы ответить на этот вопрос, следует остановиться на двух обстоятельствах.

Первое состоит в том, что дефицит напоров возникает всегда в верхних подмерзлотных водоносных горизонтах. Это было хорошо показано в томе XX "Гидрогеология СССР" (10). В результате напоры подземных вод водоносных горизонтов, залегающих ниже по разрезу, как правило, оказываются выше верхних. Следовательно, возникновение и развитие дефицита напоров приводит к общей тенденции перетекания подземных вод из нижних горизонтов в более верхние, если возникают пути, дающие возможность подобного перетекания. Следовательно, возникновение дефицита напоров способствует возникновению тенденции вертикальной миграции флюидов гидрогеологического разреза снизу вверх.

Второе обстоятельство состоит в том, что наибольшее оттаивание мерзлой зоны прослеживается по линейно-вытянутым зонам, отвечающим зонам разломов. Нужно заметить, что в этих зонах возрастает на один-два порядка и водопроводимость пород. Следовательно, возникновение и развитие дефицита напоров приводит ко второй общей тенденции перетекания подземных вод по пласту из зон наименьшего протаивания в зоны наибольшего протаивания.

Все это позволяет сделать еще одно общее заключение: динамика развития мерзлой зоны, наложенная на сложный геоструктурный фон, способствует дальнейшему осложнению региональной гидродинамической структуры криоартезианских бассейнов, неравномерности обводнения верхней части разреза подмерзлотных вод, существенно осложняет возможности инженерного освоения подземного пространства.

Сказанное, однако, относится не только к подмерзлотной части гидрогеологического разреза. Гидрогеологические съемочные и специальные разведочные работы показали, что и в верхней части разреза, в пределах регионального распространения мерзлых пород остались талыми зоны особо высокой водопроводимости. Природа таких зон связана либо с переуглубленными долинами первично тектонической природы, выполненными молассоподобными песчано-галечными отложениями, либо с разломами, пересекающими массивы карбонатных пород и речные долины различного уровня (бассейн р. Вилюй). В последнем случае высокая потенциальная водопроводимость сочетается с особо благоприятными условиями круглогодичного питания, что препятствует промерзанию этих зон и способствует сохранению их таликовой природы. Есть основание ожидать, что подобные высокообводненные зоны могут быть также связаны с отдельными особо трещиноватыми телами траппов, возможно, дайками. Косвенным тому признаком являются мощные наледи, выявленные в верховьях некоторых речных долин, берущих начало на трапповых возвышенностях.

Артезианские бассейны сплошного глубокого промерзания такие, как Лено-Вилюйский, на значительной площади - Хатангский, частично, в западной части - Тунгусский по ряду признаков и происходящих в них процессов напоминают криоартезианские. Они отличаются в основном отсутствием пояса криопэгов и всех тех особенностей развития, которые связаны с этим поясом и рассмотрены выше. Кроме того, преимущественно терригенный состав пород, образующих чехол этих артезианских бассейнов, обусловливает более равномерное протаивание мерзлой зоны, соответственно и более равномерную водопроводимость пород по пласту.

Анализ статических уровней первого подмерзлотного водоносного горизонта показывает, что многочисленные таликовые окна, образовавшиеся в результате теплового взаимодействия мерзлых пород с реками или озерами на поверхности, не являются очагами питания подмерзлотных водоносных горизонтов, хотя мерзлотные условия не могут тому препятствовать. Причиной отсутствия взаимосвязи являются литологические водоупоры, хорошо выполняющие свою изолирующую роль на ограниченных площадях развития сквозных таликов. Вместе с тем, данные режимных наблюдений и радиоизотопных исследований указывают на происходящую в настоящее время интенсификацию водообмена, которая связывается с формированием и расширением области дефицита напоров и отсутствием гидродинамического равновесия между отдельными элементами сложной водонапорной системы этих артезианских бассейнов (9, с.9-14). Следовательно, как и в криоартезианских бассейнах, формироваие и характер гидродинамической структуры АБ сплошного глубокого промерзания определяется во многом динамикой развития мерзлой зоны. Она определяет также характер верхней части гидрогеологического разреза: над мерзлой зоной и в ее пределах. Он более сложен в описываемых структурах из-за наличия многочисленных озерных впадин и озер, реликтовых или новообразованных, термокарстовых, но во всех случаях приведших к образованию водоносных подозерных таликов. При благоприятных литологических условиях - наличие пород высокой водопроводимости, обычно в пределах четвертичного комплекса отложений, подозерные талики сочетаются с долинными и в пределах мерзлой зоны возникают дополнительно сложные над- и межмерзлотные бассейны грунтовых и субартезианских межмерзлотных вод, преимущественно озерного или конденсационного питания. Разгрузка этих вод проявляется формированием высокодебитных родников, обычно образующих крупные наледи (9, с.35-45).

По мере движения с севера на юг криоартезианские бассейны и артезианские бассейны сплошного глубокого промерзания сменяются бассейнами с прерывистым развитием мерзлых пород: Алданское крыло Якутского АБ, Верхне-Ленский АБ, южная и юго-западная окраина Тунгусского АБ. Их гидродинамические условия близки к АБ, не затронутым глубоким промерзанием, и только гидрохимические характеристики свидетельствуют о некогда существовавшей здесь иной, более суровой мерзлотной обстановке, отвечавшей рассмотренным выше гидрогеологическим структурам.

Значительный интерес в мерзлотно-гидрогеологическом отношении представляет Анабарский щит. Теплофизические расчеты, выполненные Ю.Г.Шастkевичем, показали, что мощность мерзлой зоны там превышает 1000 м . В условиях развития кристаллических и метаморфических пород ожидать на этих глубинах ощутимых ресурсов подземных вод оказалось весьма маловероятным. На этом основании Анабарский щит был отнесен к криогеологическим массивам. Однако геофизические данные, полученные в последние годы в Институте мерзлотоведения СО АН СССР, показали, что в основании мерзлой зоны Анабарского щита вода все-таки может быть.

2. Восточно-Сибирская гидрогеологическая складчатая область включает в себя обширную территорию Прибайкалья, Забайкалья, Байкало-Патомское нагорье и Становой хребет. По устройству рельефа - это сложно построенная горная страна, в которой на фоне нагорий и плоскогорий различной степени расчлененности развиты впадины различной тектонической природы и возвышаются альпинотипные хребты с вершинами-гольцами, имеющими абсолютные отметки 2-3 тысячи метров.

Подавляющая часть области сложена кристаллическими и метаморфическими древними породами, меньшие по площади территории - молодыми вулканогенными и интрузивными образованиями и около 8% составляют нормальные осадочные комплексы, образующие артезианский чехол межгорных бассейнов. По времени образования и своей природе последние делятся на три основные типа: забайкальский, южно-якутский и байкальский.

Впадины забайкальского типа характеризуются чехлом мощностью до 2000 м, сложенным континентальными и эффузивными образованиями юрского и нижнемелового возраста, четвертичные отложения в них составляют незначительную мощность и не образуют артезианских водоносных горизонтов. На крыльях впадин могут быть развиты обрамляющие их разломы.

Впадины южно-якутского типа имеют особую тектоническую природу, асимметричное строение с крутыми падениями и значительной метаморфизацией пород на южных бортах и пологими - на северных; выполнены они юрскими угленосными отложениями мощностью до 4 тысяч метров, подстилаемыми с северных бортов нижнекембрийскими образованиями. Южное крыло таких впадин осложнено зоной разломов.

Впадины байкальского типа связаны с крупными перемещениями тектонических блоков и сочетают в себе структуры прогиба и грабена, обычно обрамлены разломами и выполнены мощными толщами четвертичных отложений озерно-флювиогляциального и аллювиального происхождения.

Гидрогеологические условия рассматриваемой складчатой области существенно осложнены промерзанием недр, весьма неравномерным как по площади, так и по мощности зоны мерзлых пород. Основные закономерности формирования мерзлой зоны состоят в увеличении ее общей мощности с юга на север, однако эта общая закономерность существенно осложена высотной мерзлотной поясностью, отражением которой является глубокое, на многие сотни метров, промерзание горных массивов, снижение мощности и возникновение прерывистости мерзлой зоны на плато и нагорьях, поверхность которых относительно понижена.

В пределах Предбайкальской впадины и Приленского плато, в поле развития карбонатных пород мерзлая зона носит прерывистый характер, хотя мощность мерзлых пород здесь достаточно велика и достигает не менее 300 м . Прерывистость мерзлой зоны на этой территории определяется отепляющим воздействием инфильтрации атмосферных осадков сквозь карстовые полости различного рода. И хотя окна таликов не имеют регионального значения, взаимосвязь поверхностных и подземных вод формируется непосредственная, а условия восполнения ресурсов подземных вод весьма благоприятны. Сходная обстановка может быть отмечена и для южной части Учуро-Майского плоскогорья, хотя там можно ожидать еще больших мощностей мерзлых пород, а водопоглощающие талики, связанные с карстовыми полостями, по-видимому, еще более локализованы по площади.

В пределах станового нагорья и северной части Витимского плоскогорья преобладает сплошная мерзлая зона, мощность которой в горных хребтах приближается к 1000 м , а местами и превышает эту величину, а в речных долинах и межгорных впадинах снижается до 130 м . В западной, предбайкальской части Станового нагорья мощность мерзлых пород понижается до 100 и менее метров, прерывистость возрастает, и непосредственно в прибрежной полосе мерзлые породы приобретают островное распространение.

В южной части Витимского плоскогорья и в средневысотных горах Олекминского Становика мощность мерзлой зоны снижается в горах до 300-100 м , на юге - водоразделы и южные склоны часто талые, а в межгорных впадинах мощность мерзлой зоны наоборот возрастает до 200-300 м . В целом мерзлая зона приобретает здесь прерывистый характер.

В пределах Алданского нагорья мощность мерзлой зоны является прямой функцией высотных отметок. На высотах более 900-1000 м мощность сплошной мерзлой зоны повсеместно превышает 200 м, причем на водоразделах возрастает до 800-1000 м , на меньших отметках она снижается до 50-150 м , мерзлая зона приобретает прерывистый характер. Преимущественно прерывистая мерзлая зона мощностью 200-100 м распространена и на южном склоне Станового хребта и только в горных хребтах и системах она местами вновь приобретает сплошной характер, увеличиваясь по мощности до 300 м .

Учитывая громадную площадь территории Восточно-Сибирской гидрогеологической складчатой области, сложность мерзлотной и геологической обстановки, большое число гидрогеологических структур - одних только артезианских бассейнов здесь насчитывается более 60 - представляется целесообразным охарактеризовать гидрогеологические условия по типам гидрогеологических структур и в соответствии с теми водоносными комплексами, которые их характеризуют.

Гидрогеологические массивы по условиям формирования подземных вод подразделены на а) массивы, сложенные кристаллическими и метаморфическими породами,и б) массивы, верхняя часть которых образована карбонатными разностями пород.

а) Гидрогеологические массивы, сложенные кристаллическими и метаморфическими породами, в гидрогеологическом отношении тоже неоднородны, условия формирования в них подземных вод во многом зависят от характера мерзлой зоны. Здесь многое определяется соотношением мощности мерзлой зоны с мощностью зоны региональной трещиноватости, которая обычно в такого рода породах лежит в пределах первых 100 метров, условиями дренированности и промерзания, характером прерывистости мерзлой зоны. По этим условиям намечаются следующие типы гидрогеологических массивов.

Гидрогеологические массивы, выраженные в рельефе горными сооружениями, сильно расчлененные, расположенные в условиях сплошной мерзлой зоны, мощность которой составляет не менее 300-400 м и превышает мощность региональной трещиноватости.

Такие условия характерны для гидрогеологических структур Станового нагорья и северной части Витимского плоскогорья, в пределах Алданского нагорья на высотах более 900 м , в приводораздельной части Станового хребта, возможно - в приводораздельных частях хребтов Янкат-Тукурингра-Джагды и горной страны, образованной хребтами Турун-Буреинским и другими.

В пределах такого рода гидрогеологических массивов подземные воды не имеют регионального распространения. Они бывают приурочены только к днищам речных долин, где формируются в толще рыхлых аллювиальных, флювиогляциальных или иных долинных отложений и трещиноватой зоне в подстилающих коренных породах. Приуроченность зон повышенной трещиноватости кристаллических и метаморфических пород в этих условиях именно к речным долинам связана с двумя обстоятельствами. Во-первых, с выборочной эрозией речного потока, наиболее действенной как раз в породах повышенной трещиноватости и пониженной устойчивости к агентам выветривания, и во-вторых, процессами криогенной переработки кристаллических и метаморфических пород при формировании и развитии мерзлой зоны. Поскольку трещиноватость, в свою очередь, возрастает обычно в зонах тектонических нарушений, то и речные долины здесь часто заложены по зонам разломов или оперяющих их разрывных дислокаций.

Устойчивые водоносные горизонты в аллювиальных и трещиноватых породах, подстилающих днище долины реки, могут сформироваться лишь при достаточной водно-тепловой энергии потока, способной образовать мощный надмерзлотный или сквозной талик. Такие потоки реально возникают лишь при определенных площадях водосборов, в пределах от 50 до 200 квадратных километров, а в ряде случаев и большей площади. Таким образом, в приводораздельных участках рассматриваемых массивов подземных вод не следует ожидать даже в речных долинах.

Другим важным фактором формирования в речной долине талика и надежного таликового водоносного горизонта являются геологические условия накопления рыхлых отложений и характер последних, прежде всего - мощность этих отложений и поперечное их сечение, водопроницаемость, коэффициенты фильтрации и изменения этих параметров вдоль долины реки. Как правило, в горных долинах Восточной Сибири и в пределах рассматриваемой территории также параметры эти вдоль по долинам рек существенно изменяются. В частности меняются мощности рыхлых отложений, их простирание поперек долины, вплоть до полного выклинивания, меняется интенсивность и глубина зон трещиноватости, меняются коэффициенты фильтрации аллювиальных отложений. В конечном итоге меняется потенциальная емкость подрусловых водоносных горизонтов и, следовательно, естественные ресурсы подземных вод, формирующиеся в этой емкости при талом ее состоянии.

Приходится также иметь в виду, что в долинах с широким развитием наледей наледеобразовательные процессы способствуют сработке запасов подземных вод в критический водный период.

Гидрогеологические массивы, выраженные в рельефе средневысотными горами, плато, плоскогорьями, относительно слабо расчлененными, расположенные в условиях сплошной или прерывистой мерзлой зоны, мощность которой составляет 100-300 метров, реже более, и близка или менее зоны региональной трещиноватости. Такие условия характерны для гидрогеологических структур южной части Витимского плоскогорья, Олекминского становика, Алданского нагорья на отметках менее 900 м , южных склонах Станового хребта, на значительной части территории хребтов Янкан-Тукурингра-Джагды и других горных сооружений.

В пределах такого рода гидрогеологических массивов подземные воды приобретают региональное распространение в силу более благоприятных условий питания сквозь фильтрационные талики и в связи с появлением в основании мерзлых пород зоны криогенной дезинтеграции - глубинного выветривания, вызванного неоднократным замерзанием и оттаиванием пресной воды в трещинах горных пород. Тем не менее, и в этих структурах водоносность кристаллических и метаморфических пород вне речных долин весьма незначительна.

б) Гидрогеологические массивы, верхняя часть которых сложена карбонатными породами, распространены значительно менее широко, преимущественно в восточной части рассматриваемой территории. В гидрогеологическом отношении они изучены весьма слабо. Однако значительное число наледей, зафиксированных в притоках р.Гонам и Учур, а также высокая водоносность карстовых горизонтов Учуро-Майского артезианского бассейна, многочисленные формы проявления активных карстовых процессов свидетельствуют о высокой потенциальной водоносности карбонатных пород гидрогеологических массивов. Новообразованные карстовые воронки указывают также на прерывистый характер мерзлой зоны в пределах гидрогеологических массивов, сложенных карбонатными образованиями.

Артезианские бассейны по условиям формирования подземных вод подразделяются на а) межгорные и б) срединные.

Условия формирования подземных вод артезианских бассейнов рассматриваемой территории, помимо геолого-структурных признаков, во многом определяются мерзлотной обстановкой, прежде всего прерывистостью и мощностью мерзлотной зоны и соотношением мощности мерзлой зоны с мощностью осадочного чехла бассейна, отдельных водоносных комплексов, слагающих этот чехол, и мощности зоны пресных вод. Здесь имеют место следующие соотношения.

1. Бассейны, в которых мощность мерзлой зоны меньше мощности осадочного чехла и верхнего водоносного комплекса и меньше мощности зоны пресных вод. Это относится к Баргузинскому, Верхне-Чарскому, Верхне-Ангарскому межгорным бассейнам и некоторым другим. Это наиболее благоприятные для формирования и использования пресных подземных вод гидрогеологические структуры.

2. Бассейны, в пределах которых мощность мерзлой зоны больше мощности верхних водоносных комплексов, но меньше мощности зоны пресных вод. К этим бассейнам относится Юхтино-Ыллымахский, в котором полностью проморожен юрский водоносный комплекс, многие мелкие артезианские бассейны, приуроченные к межгорным впадинам Олекминского Становика и Витимского плоскогорья, где существенно проморожены кайнозойские отложения, а подмерзлотные водоносные горизонты распространены лишь в породах мезозойского возраста. Мерзлотные условия этих бассейнов предопределяют исключительное питание их за счет перетекания вод из гидрогеологических массивов по трещиноватым зонам и обрамляющим разломам.

3. Бассейны, в которых полностью проморожен осадочный чехол, в пределах рассматриваемой территории немногочисленны. Это небольшие структурные впадины Алданского щита, выполненные юрскими угленосными отложениями. Наиболее крупная из них - Гонамский бассейн.

Таким образом, рассматривая в целом влияние глубокого промерзания недр на гидрогеологические условия артезианских бассейнов, следует отметить, что промерзание артезианских структур в подавляющем большинстве случаев не исключает наличия и возможности использования подземных вод осадочного чехла, хотя и затрудняет восполнение водных ресурсов, а также уменьшает естественные их запасы за счет промороженной части потенциально водоносных пород.

3. Верхояно-Чукотская гидрогеологическая складчатая область представляет собой весьма сложное геоструктурное образование, в плане которого выделяются Яно-Колымская и Анюйско-Чукотская складчатые системы и Охотско-Чукотский вулканогенный пояс.

Яно-Колымская складчатая система включает в себя Верхоянский антиклинорий, морфологически выраженный цепью гор, сложенных преимущественно терригенными образованиями пермского и каменноугольного возраста, Сетте-Дабанский горстантиклинорий, в сложении которого участвуют также карбонатные породы нижне-среднего палеозоя, обширную Яно-Сугойскую синклинальную зону, выраженную одноименным плоскогорьем, переходящим к югу в сильно расчлененное нагорье. Восточнее расположен Колымский срединный массив. С севера и юго-запада он обрамлен сложно построенной Момо-Полоусной антиклинальной зоной, характеризующейся интенсивной блоковой тектоникой и контрастным характером неотектонических движений. Центральной обрамляющей Колымский массив структурой является Момо-Селенняхская рифтовая депрессия. В сложении рассматриваемых структур широко развиты терригенные и вулканогенные образования мезозойского и верхнепалеозойского возраста, карбонатные закарстованные породы среднего палеозоя и гранитоидные тела, образующие обычно водораздельные возвышенности.

Сложное геологическое строение подчеркивается сложно построенным рельефом Яно-Колымской складчатой системы, сочетанием плато, высоких альпинотипных водоразделов и межгорных депрессий, приуроченных к речным долинам. Только в пределах погруженной части Колымского массива рельеф выравнивается, переходит в наклонную приморскую низменность.

Анюйско-Чукотская складчатая система представляет собой горную область, включающую в себя складчатые нагорья, участки среднегорного и горстового-глыбового рельефа, сочетающиеся со впадинами и аккумулятивными холмистыми равнинами. В их сложении преобладают терригенные и вулканогенно-терригенные складчатые образования преимущественно мезозойского и верхнепалеозойского возраста; значительно меньше распространены карбонатные и интрузивные породы.

В пределах Охотско-Чукотского вулканогенного пояса доминируют вулканические плато и нагорья, сложенные эффузивами преимущественно среднего и основного состава, перекрывшими сложные блоковые структуры подстилающего их основания.

Общий тектонический план всей территории Яно-Чукотской гидрогеологической складчатой области весьма неоднороден и состоит из областей относительно стабильного неотектонического режима (Колымский срединный массив), испытывающих медленные пологие погружения, областей, испытывающих малоконтрастные неотектонические поднятия (Яно-Сугойская, Олойская синклинальные, Анюйская - антиклинальная зоны и, наконец, областей контрастных неотектонических блоковых движений значительной амплитуды, тяготеющих к зоне Момо-Селенняхского рифтогенеза (12). Ряд структур занимает промежуточное положение по активности неотектонических процессов.

Столь сложное морфологическое, геологическое и тектоническое строение Яно-Чукотской гидрогеологической складчатой области предопределило и сложные мерзлотные условия. Почти на всей рассматриваемой территории мерзлая зона носит сплошной характер, мощность мерзлых пород в горах возрастает, достигая под водоразделами величин 400-600 и более метров, во впадинах - понижается до 200-400 м. И только в полосе шириной около 200 км, простирающейся вдоль побережья Охотского моря, мерзлая зона приобретает сначала прерывистый, а затем - островной характер, и мерзлотная специфика гидрогеологических структур постепенно сходит на нет.

Рассматривая воздействие фактора глубокого промерзания недр на гидрогеологические структуры этой части Восточной Сибири, можно констатировать, что процессы промерзания затронули здесь преимущественно гидрогеологические массивы различного сложения, тектонического и морфологического строения.

По тектоническому строению и неотектоническим особенностям среди ГМ выделяются: 1) горст-антиклинорий, интенсивно тектонически нарушенные, разбитые на отдельные блоки, отвечающие зонам контрастных неотектонических движений. К ним относится ГМ хребта Черского, ГМ Сетте-Дабан, Омулевский ГМ; 2) антиклинорий и антиклинальные зоны, отвечающие крупным монолитным поднятиям. Это, в частности, массивы Верхоянский, Момский, Приколымский, многие массивы Анюйско-Чукотской складчатой зоны; 3) синклинорий и синклинальные зоны, отвечающие слабым недифференцированным поднятиям и выраженные в рельефе относительно слабо расчлененными плато и нагорьями. Это Яно-Сугойская синклинальная зона, Олойская синклинальная зона и некоторые другие.

По морфологии ГМ принадлежат к высокогорным альпинотипным сооружениям, средне- и низкогорным, расчлененным в той или иной мере плато и нагорьям.

По составу пород все массивы можно подразделить на сложенные карбонатными и терригенно-карбонатными породами, терригенными и вулканогенно-терригенными и кристаллическими и метаморфическими.

Из сказанного явствует, что геологическое строение ГМ рассматриваемой территории, равно как и их морфология, весьма многообразны. Характер гидрогеологической структуры как природной емкости, содержащей подземные воды, осложняется также процессами промерзания как таковыми и высотно-поясным строением мерзлой зоны. Таким образом, даже единые в морфоструктурном и тектоническом отношении структуры оказались существенно неодинаковы по своим мерзлотно-гидрогеологическим характеристикам в различных их частях. Однако остановимся на этом подробнее, акцентируя внимание на региональных последствиях процессов промерзания.

Рассматривая ГМ первого типа, следует отметить, что высокая контрастность блоковых новейших тектонических движений привела к некоторым очень важным мерзлотно-гидрологическим последствиям перестройки их структурного плана. Речь идет, во-первых, о "не залеченных" промерзанием разломах и, во-вторых, об узких долиноподобных грабенах и древних погребенных долинах, выполненных мощными толщами грубых песчано-галечных отложений. И те и другие последствия молодой блоковой тектоники привели к формированию в пределах этих структур высокообводненных зон, являющихся надежными путями взаимосвязи подземных и поверхностных вод. Особенно четко это прослеживается в ГМ, сложенных карбонатными и терригенно-карбонатными породами, активно раскарстованными вдоль зон региональных разломов и на их пересечении с оперяющими. Таким образом, общая мерзлотно-гидрогеологическая структура подобных ГМ представляется следующим образом. В пределах мощной мерзлой зоны развиты межмерзлотные высокообводненные талики, приуроченные к трещиноватым зонам разломов, погребенным и ныне существующим речным долинам, выполненным мощными толщами гравийно-валунных отложений. Эти талики обычно пересекаются,и в точках их пересечения возникают условия, наиболее благоприятные для разгрузки подземных вод или их перетекания из одной обводненной зоны в другую. Следствием этого иногда является несовпадение водоразделов поверхностных и подземных вод и высокая активность водообмена, оцененная для некоторых гидрогеологических массивов методом изотопного анализа подземных вод (13), высокие показания величины относительной наледности, достигающие для этих структур первых процентов.

В основании мерзлой зоны водопроводимость горных пород также весьма неравномерна, увеличиваясь в зонах разлома, имеющих характер растяжения, и снижаясь в блоках, заключенных между этими разломами. В пределах наиболее глубоко промороженных водоразделов, где они сложены монолитными породами, подмерзлотные воды могут и вовсе отсутствовать или обнаруживаются в количествах, не имеющих никакого практического значения.

Описанная гидрогеологическая ситуация особенно характерна для ГМ хребта Черского.

ГМ второго типа, представляющие собой крупные монолитные поднятия, отличаются от описанных выше более спокойной тектоникой и в этой связи зоны разломов перестают играть ту заглавную роль, которую они играли в ГМ первого типа. Соответственно, в мерзлотно-гидрогеологическом плане основную роль начинают играть таликовые зоны, связанные с долинами рек и отепляющим влиянием водных потоков. В разрезе эти таликовые зоны имеют обычно двухъярусное строение: верхний ярус сложен аллювиальными отложениями, нижний- подстилающими трещиноватыми терригенными, кристаллическими или метаморфическими породами. Поскольку речные долины имеют тенденцию наследовать наиболее ослабленные зоны, приуроченные часто к разломам, именно по речным долинам возрастает водопроводимость коренных пород, возникают и сохраняются условия для миграции подземных вод и сохранения содержащих их емкостей в талом состоянии.

Морфология долинных таликов достаточно сложна. Как правило, имеет место чередование по долине реки надмерзлотных и сквозных таликов. Однако мощность мерзлой зоны в долинах рек обычно значительно меньше, чем под соседними водоразделами, а трещиноватость пород, наоборот, больше. Такая обстановка приводит к относительному возрастанию водопроводимости подмерзлотной трещиноватой зоны в речных долинах в сравнении с водораздельными пространствами, где зона региональной трещиноватости (выветривания) обычно бывает проморожена полностью. А в конечном итоге - к разобщению единой водоносной системы гидрогеологических массивов, локализации водопроводимости пород по долинным зонам, формированию водонапорных систем, ограниченных территориями речных бассейнов.

Этим, однако, не ограничивается мерзлотно-гидрогеологическая специфика описываемых структур. Конвективная природа таликовых зон предопределяет решающую роль в распределении подземных вод фактора высотной поясности. Действительно, для начала формирования и устойчивого развития таликов, в том числе сквозных, необходимых для питания подмерзлотных вод, требуется достаточно мощный тепловой и, следовательно, водный поток. Последний может сформироваться лишь при определенной площади водосбора, в среднем составляющей для ГМ Верхояно-Чукотской гидрогеологической складчатой области от 50 до 200 км^2. На этих площадях, образующих водораздельные пространства, талики отсутствуют, мощность мерзлой зоны предельно велика, равно как и дренированность породного массива. Все это вместе взятое указывает на значительную проблематичность обнаружения ощутимых количеств подмерзлотных вод в пределах водораздельных пространств. И поскольку мощность водных потоков, а, следовательно, также и мощность потенциально водоносных аллювиальных отложений возрастает вниз по склону гор, в этом же направлении растут и параметры таликовых зон, а, следовательно, и обводненность пород ГМ в региональном плане. Таким образом, морфология ГМ глубокого сплошного промерзания дважды определяет характер и степень обводненности ГМ- через высокую зональность и через строение (морфологию) речной сети.

Следовательно, мерзлотный фактор, наложенный на геологическую структуру, и морфологический план ГМ определяют в совокупности специфику гидрогеологического строения пространства ГМ. Однако эти же обстоятельства в условиях наледного регулирования во многом предопределяют также и режим формирования подземных вод.

Изменчивость живого течения таликов и неравномерность фильтрационных свойств пород, слагающих таликовые водоносные зоны речных долин, вызванная сменой литологического состава аллювиальных или подстилающих коренных пород, приводит к весьма характерному для ГМ Верхояно-Чукотской гидрогеологической складчатой области изменению водопроводимости по длине таликовой зоны. Это явление, в свою очередь, приводит к тому, что на участках относительного снижения водопроводимости происходит разгрузка межмерзлотных, а в сквозных таликах - и подмерзлотных вод в долину реки, восполнение ими ресурсов поверхностного стока, а на участках относительного увеличения водопроводимости таликовых зон наступает явление, обратное описанному. Летом взаимодействие поверхностного и подземного потока в таких условиях отмечается постоянным колебанием расходов водотока, от створа к створу, при сохранении общей тенденции его возрастания вниз по долине реки. Зато зимой, в условиях весьма низких температур, на участках разгрузки подземных вод начинают развиваться процессы наледообразования, фиксирующие подземные воды и выводящие их из кругооборота до последующего весенне-летнего сезона. Следствием процесса наледообразования является в этом случае снижение естественных ресурсов подземных вод и, соответственно, снижение уровней последних. Следовательно, наряду с неравномерностью пространственной, правомерно говорить и о временной неравномерности распределения подземных вод рассматриваемых мерзлотно-гидрогеологических структур. Характерными представителями такого рода структур являются Верхоянский ГМ, Анюйский гидрогеологический АдМ, ряд более мелких структур низших порядков.

Несколько иные последствия формирования мерзлой зоны возникли в структурах, которые по характеру слагающих их пород близки к гидрогеологическим массивам или адмассивам, но по условиям рельефа выражены плато, где глубина вреза речных долин сопоставима с мощностью мерзлой зоны (ГМ 3-го типа) . Колебания нижней поверхности последней в процессе ее формирования и развития привели к подмерзлотной дезинтеграции, своего рода глубинному морозному выветриванию. Эта выветрелая зона, сравнительно небольшой, первые метры, редко - десятки метров мощности, является основной водоносной зоной, взаимосвязанной с поверхностью через таликовые окна речных долин. Следовательно, мерзлотные процессы, приводящие к промерзанию значительных емкостей артезианских структур, разобщающие единую водонапорную систему ГМ, в определенных условиях являются фактором, формирующим водоносную зону, определяющим ее водопроводимость и напорность содержащихся в ней вод, иначе говоря,- генетическим фактором формирования мерзлотно-гидрогеологической структуры. Это обстоятельство и позволили определить их как криогенные бассейны напорных трещинных вод. В пределах Верхояно-Чукотской гидрогеологической складчатой области наиболее крупные из них - Яно-Сугойский, Иньяли-Дебинский, Ольджойский.

Аналогичные последствия глубокого промерзания могут быть отмечены и для других структур Охотско-Чукотского вулканогенного пояса, мощность вулканогенного чехла которых превышает глубину вреза речной сети и мощность мерзлой зоны. Можно предполагать лишь, что в основании последней в той или иной мере развита первичная контракционная трещиноватость, свойственная эффузивным породам и, следовательно, даже в условиях глубокого промерзания вулканогенные супербассейны сохраняют свою региональную обводненность.

Наряду с гидрогеологическими массивами и вулканогенными супербассейнами, составляющими основную часть Верхояно-Чукотской гидрогеологической складчатой области, значительное развитие получили в ней и артезианские структуры платформенного и в особенности межгорного типа. Артезианские бассейны платформенного типа, Колымский и Восточно-Сибирского моря, в гидрогеологическом отношении не исследованы. Можно лишь предполагать, что в основании мерзлой зоны этих структур распространены слабо солоноватые и низконапорные водоносные комплексы. Межгорные артезианские бассейны исследованы значительно лучше.

По структурному положению межгорные АБ приурочены к грабенам и наложенным структурным впадинам или к современным речным долинам и эрозионным впадинам. По сложению осадочного чехла выделяются бассейны, чехол которых сложен исключительно неоген-четвертичными отложениями, и АБ, чехол которых сложен преимущественно мезозойскими терригенными и угленосными отложениями преимущественно верхнеюрского - мелового возраста.

По соотношению мощности осадочного чехла с мощностью мерзлой зоны межгорные АБ Верхояно-Чукотской гидрогеологической складчатой области подразделяются на две группы : АБ, мощность чехла которых больше мощности мерзлой зоны и, соответственно, артезианские бассейны не утратили характерного для этих структур основного признака - наличия напорных пластовых вод в породах осадочного чехла, и АБ, мощность осадочного чехла которых меньше мощности мерзлой зоны. Соответственно, рассматриваемые структуры потеряли основной признак артезианских и определены как криогеологические бассейны или, иначе, бассейны, промороженные на всю мощность осадочного чехла.

В приморских районах Верхояно-Чукотской гидрогеологической складчатой области развиты также криоартезианские бассейны, с полностью промороженным поясом пресных подземных вод.

Степень прерывистости и глубина промерзания межгорных АБ определяет не только характер гидрогеологической структуры и гидрохимического разреза, но, в значительной мере, также и условия питания этих структур. Действительно, водоносные горизонты АБ островной или прерывистой мерзлой зоны Сингланский, Ланковский, Ямский, Пареньский имеют возможность получать устойчивое питание на крыльях структур путем перетекания подземных вод из верхней трещиноватой зоны гидрогеологических массивов непосредственно в горизонты осадочного чехла. В условиях сплошного распространения мерзлых пород значительной мощности эта трещиноватая зона бывает полностью проморожена. Более того, в краевых частях АБ и на крыльях ГМ в результате процессов промерзания нередко наблюдается выклинивание таликов и заключенных в них подземных вод, возникают мощные линии разгрузки подземных вод, фиксированные наледями. Пример тому - краевые части АБ Момо-Селенняхской системы впадин, Раучуанский АБ и ряд других. Следовательно, в ряде случаев питание артезианских бассейнов со стороны обрамляющих их гидрогеологических массивов бывает затруднено. Оно оказывается возможным в бассейнах-грабенах по обрамляющим тектоническим зонам, в иных случаях - по сравнительно редким таликовым окнам или напорными водами фундамента.

4. <u>Камчатско-Корякская гидрогеологическая складчатая область</u> простирается на территорию Восточной Сибири своей северной, Корякской частью. Ее западной границей является граница Охотско-Чукотского вулканогенного пояса, на востоке структуры области простираются под уровень Берингова моря.

В пределах рассматриваемой части Камчатско-Корякской гидрогеологической складчатой области выделяются две крупные системы гидрогеологических структур : на западе - Пенжинско- Анадырская артезианская область и на востоке - Корякская система гидрогеологических массивов и вулканогенных супербассейнов.

Пенжинско-Анадырская артезианская область простирается от Анадырского залива Берингова моря на запад и юго-запад до Пенжинского залива Охотского моря и включает несколько смежных артезианских бассейнов, чехол которых сложен кайнозойскими отложениями, частично разобщенных друг от друга гидрогеологическими массивами. За исключением Пенжинского, все АБ этой области глубоко проморожены, мерзлая зона носит сплошной характер, однако по долинам рек и под озерами развиты устойчивые сквозные талики, обеспечивающие водообмен подземных вод с поверхностными и формирование достаточно мощной подмерзлотной зоны свободного водообмена. Тому немало способствуют значительные превышения очагов питания артезианских бассейнов, входящих в описываемую область над очагами разгрузки. И только в приморских зонах непосредственно под мерзлой зоной залегают солоноватые воды.

Корякская система гидрогеологических и вулканогенных супербассейнов характерна преимущественным развитием меловых, в меньшей степени - среднепалеозойских терригенных, сильно дислоцированных и окремненных пород, образующих горную страну Корякского нагорья. В тектоническом плане Корякское нагорье характеризуется блоковым строением, в наиболее опущенных блоках, выполненных палеоген-неогеновыми и четвертичными отложениями, сформировались артезианские бассейны, часто линейной формы, с унаследованными речными долинами. Часть артезианских бассейнов открыта в Берингово море.

В мерзлотном отношении центральная часть Корякского нагорья исследована слабо, вдоль побережья мерзлая зона носит прерывистый характер. Из распространения наледей можно предположить, что мерзлотно-гидрогеологическая ситуация на большей части ГМ рассматриваемой области аналогична остальным гидрогеологическим структурам Северо-Востока. Однако, учитывая климатические отличия, здесь должно быть несколько больше таликов, они должны быть более устойчивы в плане и в разрезе и, следовательно, обеспечивать лучшие условия взаимодействия поверхностных и подземных вод и восполнения последних.

Заканчивая описание мерзлотно-гидрогеологических районов Верхояно-Чукотской и Камчатско-Корякской гидрогеологических складчатых областей, нельзя не отметить тот факт, что типизация некоторых из выделенных структур произведена условно в порядке прогноза. Причиной тому является их недостаточная изученность. Это относится,в частности, к криогенным бассейнам напорных трещинных вод : некоторые из них рядом авторов относятся к адартезианским (14). Не исключено, что и некоторые межгорные артезианские структуры тоже близки к адартезианским в силу значительного литогенеза слагающих их чехол пород и преобладающей роли трещиноватости в формировании водопроводимости гидрогеологического разреза. Наконец, далеко не выяснены все детали питания межгорных, да и платформенных артезианских структур в условиях сплошной мерзлой зоны значительной мощности. Многие положения, касающиеся питания подземных вод, носят пока гипотетический характер.

Краткие выводы

Из рассмотрения гидрогеологических районов Восточной Сибири можно видеть коренные изменения, произошедшие с гидрогеологическими структурами в результате их глубокого промерзания и в результате развития мерзлой зоны как таковой. Подводя итог этому рассмотрению, можно заметить, что последствия глубокого промерзания недр оказались различны для артезианских бассейнов и гидрогеологических массивов. Эти различия в характере изменения водоносности и другие особенности двух основных групп гидрогеологических структур артезианских бассейнов и гидрогеологических массивов рассмотрены выше.

Произошедшие с гидрогеологическими структурами изменения потребовали разработки специальных методов исследования мерзлотно- гидрогеологических условий, начиная от постановки дистанционных аэрокосмических и геофизических работ и кончая гидрогеологической съемкой, поисками и разведками подземных вод. Эти методики нашли отражение в ряде монографий и специальных методических руководствах, в содержании многих исследований, осуществляемых ныне. Многие вопросы продолжают дискутировать. Одним из дискуссионных вопросов, в частности, является объект гидрогеологического картирования. Традиционное картирование водоносного пласта, горизонта или комплекса, приемлемое для немерзлотной обстановки, в условиях сплошной мерзлой зоны и расчленения разреза на надмерзлотные, межмерзлотные и подмерзлотные воды явно не удовлетворяет ни требованиям теории съемки, ни практическому использованию ее результатов.

Произошедшие в результате промерзания гидрогеологических массивов упрочение взаимосвязи поверхностных и подземных (подмерзлотных) вод через таликовые окна и зоны позволило заострить вопрос об особых условиях охраны подземных вод и о необходимости предъявлять в описанных мерзлотно-гидрогеологических районах Восточной Сибири повышенные требования к охране поверхностных вод. Наоборот, в артезианских структурах мощная сплошная мерзлая зона является надежной защитой подземных вод от загрязнения, позволяет использовать подмерзлотные воды (при их удовлетворительных свойствах и ресурсах) в качестве основного источника питьевого водоснабжения.

Эти и многие другие вопросы теории и практики мерзлотной гидрогеологии получат новые возможности разрешения с выпуском в свет разрабатываемой карты мерзлотно-гидрогеологического районирования Восточной Сибири, принципы составления которой и схема мерзлотного районирования освещены в настоящем докладе.

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VEGETATION AND REVEGETATION WITHIN PERMAFROST TERRAIN

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INTRODUCTION

Permafrost, both continuous and discontinuous, covers vast areas within circumpolar lands. All of the arctic tundra, polar semi-deserts and polar deserts are underlain by continuous permafrost (Fig. 1). To the south, the forest-tundra transition and the northern portion of the open forest, generally a spruce-lichen woodland in North America and a larch-lichen woodland in Siberia, occur on continuous permafrost. The northern portion of the taiga or closed boreal forest is also underlain by continuous permafrost. Much of the remaining taiga is found on discontinuous permafrost, especially in uplands and poorly drained areas.

The relationship of vegetation to permafrost on a macro-scale and plant communities to depth of the active layer on a micro-scale, has been of interest to ecologists for a number of years. Studies of vegetation in relation to permafrost and terrain have taken on a new meaning with the increased pace of northern development.

The objective of this paper is to describe the vegetation patterns within the taiga, Low, and High Arctic as they relate to topography and drainage as influenced by permafrost and depth of the active layer.

The role of species useful in rehabilitating surface disturbed northern lands will also be discussed in relation to northern development.

VEGETATION OF SUBARCTIC AND ARCTIC LANDS

TAIGA

Introduction

The taiga or boreal forest covers an estimated 9.9×10^6 km^2 circumpolar. Of this total, 2.5-3.0 $\times 10^6$ km^2 comprise the forest-tundra and open boreal woodland (Weck and Wiebecke 1961). Here, as in the Arctic, the forest lands are subdivided into zones (Table 1). As will be discussed below, this is largely based upon tree density, plant growth form or physiognomy, and species present. The taiga has been classified in various ways, resulting in confusion for ecologists, let alone engineers unless the terms are clearly defined. Zonation systems of classification were discussed by Blüthgen (1970), Hustich (1970), and Tikhomirov (1970) at the symposium on "Ecology of the Subarctic Regions" in Helsinki. The classification used here follows Hare and Ritchie (1972). The forest-tundra (lesotundra) consists of isolated or small clumps of deformed trees set in a tundra landscape, generally shrub tundra or cottongrass-heath tundra. These areas grade into open woodland in which scattered upright trees occur with a ground cover of lichens or shrubs. The lichen woodlands of Ontario, Quebec, and Newfoundland typify these communities (Hare 1951, Hustich 1951, Ahti 1951, Rouse and Kershaw 1971, Kershaw 1978). To the south tree density increases until closed boreal forest is encountered. Tree line occurs at the northern edge of forest-tundra and forest line at the northern edge of the closed forest. An annotated bibliography on the relationship of vegetation, wildlife, and landform to permafrost covers the earlier literature (Roberts-Pichette 1972).

Closed Forest

The closed boreal forest contains relatively few plant and animal species, single tree species often dominating the landscape for many square kilometers. The forests, usually of conifers, often have an understory of feather mosses and a few scattered herbs and low shrubs. The forested pattern is broken in poorly drained lands where fens and bogs are common (Hustich 1957, Ritchie 1959, Sjörs 1959, 1965a, Osvald 1970, Vitt and Slack 1975). Fig. 2 depicts the general vegetation pattern in relation to topography, soils and depth of the active layer near Sans Sault Rapids, NWT.

Most of the closed forest lies south of discontinuous permafrost. Within the discontinuous zone of permafrost in Canada, forests of *Picea mariana* predominate. This species is most common in poorly drained lands, but to the north and west, black spruce is found in uplands as well. *Picea glauca* is more common on warmer and more deeply thawed soils, though white spruce is found at higher elevations than black spruce in Alaska (Britton 1957) and the Yukon, further north along arctic flowing rivers (Drew and Shanks 1965, Hettinger et al. 1973, Hettinger and Janz 1974), and in more extreme maritime conditions in the Hudson Bay Lowland (Ritchie 1957, Hustich 1957).

Table 1. General classification of Taiga, Tundra, and Polar Desert

North America (Bliss 1979)	USSR (Aleksandrova 1970)
Taiga closed forest	Taiga forest
Taiga woodland	Taiga woodland
Forest-Tundra	Lesotundra
Arctic	
Low Arctic	Tundra Zone
Tundra	Subarctic - Southern
tall, low, sub shrub,	forest-tundra
Hummocky (cottongrass)-sub shrub,	shrub tundra
wet sedge-moss	
	Subarctic - Northern
	sub shrub tundra
	hummocky (cottongrass)
High Arctic	Arctic - Southern
Tundra	sedge-moss tundra,
wet sedge-moss (miror)	cushion plant tundra
Polar semi-desert	Arctic - Northern
cushion plant, moss-herb,	herb-moss, moss sedge
lichen-herb	
	Polar Desert Zone
	Southern and Northern
Polar Desert	herb-moss, herb-lichen
herb (few cryptogams)	

Trees of lesser importance include *Abies balsamea* in eastern and central Canadian forests, *Pinus banksiana* in sandy soils and dry rocky soils west to the Great Bear Lake region and *Larix laricina* scattered throughout. The latter species reaches its maximum importance in the Hudson Bay Lowland where it forms pure stands in poorly drained soils (Hustich 1957, Rowe 1972).

The deciduous tree species *Populus tremuloides*, *P. balsamifera*, and *Betula papyrifera* comprise a relatively minor portion of these northern boreal forests. These species grow best where the active layer is relatively deep and the soils are both warmer and better drained than in nearby sites with *Picea mariana* (Rowe 1972).

In Alaska, Viereck (1975) has classified taiga vegetation along temperature and moisture gradients. Here, *Picea glauca* rather than *P. mariana* delineates the taiga. The latter species is generally found in poorly drained soils with a shallow active layer. *Larix laricina* is more limited in its distribution and importance as a forest species. It is rare in the relatively warm Yukon River Valley (Viereck 1975). As in Canada, *Populus tremuloides* is found in areas of higher degree-day accumulation. *Pinus* and *Abies* are not part of these northern forests.

Only discontinuous permafrost extends across northern Fennoscandia, mainly in the mountains. The closed forest consists mostly of *Picea excelsa* with open stands of *Pinus silvestris* and *Betula tortuosa* at higher elevations (Sjörs 1965b, Rune 1965), the latter forming tree line at 600 to 800 in Lappmark.

The most extensive regions of discontinuous and continuous permafrost in association with closed boreal forest are in Eurasia (Fig. 1). Forests of *Picea obovata*, *Pinus sibirica*, and *Abies sibirica* extend from eastern Europe across Siberia with *Picea* dominating vast areas of continuous permafrost terrain. *Abies sibirica* is important in the taiga of eastern Europe to 63-65°N. In the more continental lands, east of the Yenisey River, *Abies* is important in the forests south of 60-62° N (Hustich 1966); most of this area is underlain by discontinuous permafrost. On better drained soils, often without permafrost, *Pinus silvestris* and *P. sibirica* predominate; the latter species having a distribution pattern more like *Abies sibirica*.

In North America closed forests of larch are uncommon, most stands of *Larix laricina* occurring in fens as sparse and open grown forests (Hustich 1957, Rowe 1972, Ritchie 1960, 1962). In contrast, *Larix* forms vast closed forests across eastern Siberia and it is an important genus in the closed forests of European and central Siberia. *Larix sibirica* predominates in European USSR, *L. sibirica* and *L. dahurica (= L. gmelinii)* in western and central Siberia and *L. dahurica* without *Picea* and *Abies* in eastern Siberia (Hustich 1966).

The previous discussion has centered on the large scale pattern of vegetation in relation to large scale permafrost conditions. Let us look briefly at a meso- or micro-scale relationship of topography, permafrost features, and vegetation.

Near the southern limit of discontinuous permafrost, palsas (ice mounds) typically form where surface peats dry in summer, effectively reducing thermal conductivity. With fall cooling and precipitation, the peats become saturated which increases thermal conductivity. This annual cycle results in more winter cooling than summer heating, the net result being a negative heat balance resulting in ice formation and preservation (Brown 1970, Tyrtikov 1959). These palsas with their elevated peats are better drained and often thinly treed (Zoltai 1972, Zoltai and Pettapiece 1974, Zoltai and Tarnocai 1975). The relationship of permafrost and annual soil temperature regime to a successional pattern of forest vegetation (15 to 20 - 250 yr) has been presented for central Alaska (Viereck 1970a, b). Viereck (1965) also discussed the relationship of *Picea glauca* to the local occurrence of ice lenses that develop with canopy closure. Similar cycles of vegetation in relation to permafrost have been described by Benninghoff (1952) and Drury (1956).

These northern closed forests are low in biological production, except in the specialized habitats of river terraces, deltas, and wetlands near lakes. Muskrats, beaver, moose, and waterfowl are the most productive animals; all of these in wetlands. The closed forests produce limited numbers of woodland caribou, wolf, fox, wolverine, marten, hare, and birds.

Open Woodland and Forest-Tundra

As climate becomes more severe poleward, permafrost becomes more continuous and the rooting zone less favorable for tree growth; forests are more open grown and trees are of lower stature. This region of "subarctic" forest stretches in a broad arc across Canada, varying in width from ca. 150 to 550 km (Rowe 1972). In Newfoundland and Quebec, open stands of black spruce-lichen predominate in uplands. *Picea glauca* and *Abies balsamea* occur locally as closed forests. Lowlands and poorly drained soils are generally covered with stunted *Picea mariana; Larix laricina* forms strips along lake shores and streams. *Carex* dominated fens and shrub dominated bogs with scattered black spruce cover many square kilometers (Hustich 1951, Sjörs 1959). Similar areas of lichen-woodland occur west of Hudson Bay, north of Great Slave Lake to Great Bear Lake and to the lower delta area of the Mackenzie River (Hustich 1957, Ritchie 1959, Maikawa and Kershaw 1976, Kershaw 1978).

Fire plays a major role in these lichen-woodlands and forest-tundras (Rowe and Scotter 1973, Maikawa and Kershaw 1976, Black and Bliss 1978). Without fire, a closed canopy forest with a feather moss understory develops in ≃ 200 yr. Following fire, woodlands dominated by the lichens *Cladonia stellaris* or *Stereocaulon paschale* develop. Extensive lichen mats reduce soil temperature to levels that may limit true root growth, thus conserving the open nature of the woodlands. These lichen mats also reduce water flux and thus maintain soil water levels favorable to tree growth where soils might otherwise be too dry to support these open stands (Kershaw 1978). The development of lichen mats plays a key role in maintaining these open stands of *Picea mariana*.

In the lower Mackenzie River region, lichen-woodland is more restricted due to the longer time required for lichen cover to develop (150-200+ yr), the domination of low shrubs in the understory for many years due to finer textured till soils, and the presence of cold soils due to permafrost (Black and Bliss 1978) (Fig. 3). Active layer depths averaged 100 ± 17 cm in "stands" 8 yr following fire, 51 ± 22 cm in stands 30-115 yr, 43 ± 4 cm in stands 130-190 yr and 52 ± 19 cm in stands 240-285 yr after burning. Repeated fires within these subarctic woodlands have little effect on the understory vascular plant composition but a major impact on the lichens and mosses for many years (Black and Bliss 1978). Fire also plays a major role in the life history of *Picea mariana* by preparing a seed bed (Ahlgren 1959), opening the semi-serotinous cones (Vincent 1965), and altering the thermal regime of the soil (Rouse and Kershaw 1971). Fire in the forest-tundra can eliminate tree establishment provided the general climate is in a cooling cycle (Nichols 1975, Black and Bliss 1978). Black (1977) calculated that only a 6-7 yr "window" occurs for seedling establishment following fire near tree line. Since relatively high surface temperatures are necessary for seed germination, seedling establishment can be prevented during cooler climatic periods (Black 1977). Massive fires could effectively force tree line 50-100 km south, which helps to explain forest and tree line oscillation in addition to forest advance during the warmer Hypsithermal Interval and the cooler climates which have followed (Ritchie and Hare 1971, Ritchie 1974). More recently, Ritchie (1978) has described vegetation change since deglaciation near Inuvik, NWT that is based upon sequential invasion of species (plant succession) rather than regional climatic change. Additional research is needed in order to determine the relative roles of the failure of tree re-establishment following fire vs. climatic oscillation in explaining post forest and tree line boundaries in the North.

In many areas the transition from forest-tundra to shrub tundra results in only the loss of *Picea glauca* in better drained uplands and river terrace locations (Drew and Shanks 1965) or the eventual failure of *Picea mariana* to maintain itself in more poorly drained, cold soils with a shallow active layer (Larson 1965, 1971, 1972; Black and Bliss 1978). Because of this patterning, Soviet ecologists have generally considered shrub tundra a past of the subarctic (Andreev 1966, Aleksandrova 1970) or hypoarctic (Yurtsev 1966, 1972).

The transition from closed forest to tundra in Alaska is complicated by the Brooks Range in the north that prevents the normal transition to open woodland and forest-tundra, and the low net radiation values of western Alaska when a broad band of tundra occurs where general climate indicates that forest should be present (Hare and Ritchie 1972).

In the northern mountains and upland plateaus of Fennoscandia, *Betula tortuosa* predominates in the forest-tundra. Open grown *Pinus silvestris* generally occurs as the next lower elevation woodland (Rønning 1960, Sjörs 1965b, Blüthgen 1970, Kallio 1975). Permafrost plays a minor role in vegetation pattern, except in mires where palsas occur, providing elevated and somewhat drier habitats (Rosswall et al. 1975).

In European USSR, the forest-tundra (lesotundra) is formed by communities of *Betula tortuosa* and *Picea excelsa* (western section) and *P. obovata* and *Larix sibirica* in the eastern section (Tikhomirov 1970). On the western slopes of the polar Ural-Mountains *Betula tortuosa* dominates with an understory of *Juniperus sibirica, Rosa acicularis, Betula nana, Salix glauca, S. arbuscula* and various dwarf shrub heath species. To the south *Pinus obovata* dominates at tree line (700-800 m) with lesser amounts of *Betula tortuosa* and *Abies sibirica* (Gorchakovsky and Shiyatov 1978).

Larix dahurica dominates in western and central Siberia. On the eastern slopes of the Urals, *L. sibirica var. sukaczewii* predominates with an understory similar to that of the open forests on the western slope (Gorchakovsky and Shiyatov 1978). The northern limit of trees occurs near Ary-Mas along the Novaya River (72°30'N) on the Taimyr Penninsula (Norin and Ignatenko 1975). In this continental climate (January mean -33.8°, July mean 13.1°C), open larch woodland (redkolesja), and very open woodland (redina) occur on the valley slopes with bog and spotted tundra (soil-boils) on ridges and poorly drained slopes. Active layer depths are closely correlated with nano- and micro-relief and plant community patterns. In open larch thaw averages 50-70 cm in late August, 30-50 cm under trees, and 40 cm (cracks and depressions) to 65 cm (bare soil) in the spotted tundra (Norin and Ignatenko 1975).

In eastern Siberia *Larix dahurica (L. calanderi)* predominates except in Translenian Siberia where the low stature *Pinus pumila* occurs on mountain slopes and the deciduous trees *Chosenia macrolepis* and *Populus suaveolens* in valleys (Hustich 1966, Tikhomirov 1970). In the mountains of Kamchatka the tree line is dominated by *Betula ermani* at elevations of 700-850 m. In places there are some *Larix dahurica* and *Picea jezoensis* trees to a height of 8-16 m. The shrub layer consists of *Pinus pumila, Sorbus sambucifolia, Alnus fruticosa, A. kamtoschatica* and *Juniperus sibirica* (Gorchakovsky and Shiyatov 1978).

Within the open woodland and forest-tundra, wildlife is even more restricted, due to the reduced plant production base. The most characteristic animals are barren ground caribou and reindeer which overwinter in the open forests where there is an abundance of lichens, sedges, and low shrubs. River deltas are productive in waterfowl, muskrats, moose, and beaver.

ARCTIC

Introduction

Historically, Arctic has referred to those lands beyond the northern climatic limit of tree growth. Scattered islands of trees may occur 20 to 100 km poleward on southern slopes and along rivers where soils are somewhat warmer and the active layer is deeper in summer.

Classification of the Arctic has been based upon zonal concepts in the USSR (Aleksandrova 1970) and North America (Polunin 1951). While zones of climate and associated vegetation are more pronounced in the Soviet Union (Andreev and Aleksandrova 1979) because of greater continentality than in North America, more recent studies in the Canadian Arctic reveal a mosaic pattern (Bliss 1975, 1977). The mosaic results from differences in summer solar radiation and resultant temperature regime, the amount of water retained on the land following snowmelt, and soil texture and soil development as influenced by bedrock geology.

In mainland North America and presumably across Eurasia, the boundary between forest and tundra coincides with the summer position of the Arctic Front (Bryson 1966). Another important component of the bioclimate of the North is net radiation. The northern limit of forest occurs near the 75-80 kJ cm -2 isoline in Canada and the 65-70 kJ cm -2 isoline in Alaska (Hare and Ritchie 1972). Net radiation for the growing season decreases rapidly in going from closed boreal, even with spring land, and finally to tundra. The low albedo of closed forest, even with spring snow, vs. the tundra and the structure or roughness of vegetation (forest vs. shrub tundra), all influence the radiation balance and therefore the bioclimate potential for plant growth and net plant production (Hare and Ritchie 1972).

For purposes of this paper, the Arctic is divided into Low and High Arctic based upon climatic differences, permafrost characteristics, vegetation structure, and wildlife diversity (Table 2).

Low Arctic

The Low Arctic is characterized by closed vegetation of shrubs, herbs, mosses, and lichens; bare ground is generally a minor feature. In most plant communities there is some component of woody vegetation, ranging from tall shrubs (2-5 m high) of *Salix, Betula,* and *Alnus* along streams and steep banks to dwarf shrubs (5-20 cm high) of *Ledum, Vaccinium, Salix,* and *Empetrum* on elevated sites with little winter snow cover. The dwarf shrubs also occur as a component within cottongrass tussock communities and low shrub lands. These landscapes with their continuous or near continuous cover of vascular plants and crypotogams, often with a strong component of tall to dwarf shrubs, are generally called tundra (Fig. 4).

Table 2. Physical and biological characteristics of the Low and High Arctic

Characteristic	Low Arctic	High Arctic
Mean annual temperature (°C)	-12 to -9	-19 to -16
July mean temperature (°C)	7 to 10	3 to 6
Length of growing season (months)	3 to 4	1 to 2.5
Accumulated degree days (0°C)	300 to 1000	150 to 600
Mean annual precipitation (mm)	150 to 350	50 to 200
Mean annual temperature of permafrost (-10 to -20m)	-4 to -2	-13 to -10
Active layer depth - gravels (m)	1 to 2	0.7 to 1.2
- peat and clay (m)	0.3 to 0.6	0.2 to 0.6
Plant cover - tundra (%)	80 to 100	80 to 100
polar deserts (%)	------	0 to 10
Flowering plants (#species)	300 to 600	50 to 150
Mammals (# species)	6 to 20	3 to 8
Breeding Birds (# species)	40 to 70	5 to 30

Tall Shrub Tundra

Large rivers in arctic Alaska, mainland Canada, southern Greenland, and mainland Eurasia have sand and gravel bars as well as steep slopes that are typically covered with tall shrubs. *Salix alaxensis* predominates in western Canada and Alaska on coarse gravels and sands (Bliss and Cantlon 1957, Drew and Shanks 1965, Gill 1973). Associated shrubs on fine textured soils, and often as an understory to the feltleaf willow, include *Salix lanata, S. richardsonii, S. glauca, Betula glandulosa,* and *Alnus crispa.* These communities are strongly correlated with warmer soils in summer, soils with better drainage and deeper active layers (1-2m). These communities have deep winter snow that melts early in spring. There is often a rich understory of grasses and herbs. Moose and arctic ground squirrels as well as ptarmigan and arctic hare are commonly found in this lush arctic vegetation.

Communities of tall shrubs (hyoarctic shrubs) are a conspicuous feature along rivers and steep slopes within the Siberian and Chukotka provinces or divisions of the Arctic (Andreev and Nakhabtseva 1974, Andreev and Aleksandrova 1979). In the Yara-Indigirca subprovince, *Betula exilis, Salix glauca, S. lanata,* and *Alnus fruticosa* occur along rivers. In the Kolyma subprovince with increasing snow cover, shrub communities of *Betula exilis* and *Alnus fruticosa* occur along rivers in the southern section while willow scrub of *Salix alaxensis, S. pulchra, S. glauca,* and *S. lanata* predominate in the middle section. *Salix pulchra, S. alaxensis* and *Betula exilis* are common in the far eastern province of Chukotka. Note the strong floristic ties in the tundra vegetation of northeastern Asia and Alaska, the Transberingian floristic element (Yurtsev 1972).

Low Shrub Tundra

Within the forest-tundra, birch and willow shrubs 40-60 cm in height are common. Beyond the limit of trees, low shrub tundra predominates as the first type of tundra vegetation in many upland sites. In western Alaska and the Mackenzie River Delta region of Canada, various combinations of *Betula nana* ssp. *exilis, Salix glauca, S. pulchra* and *S. lanata* ssp. *richardsonii* provide an open canopy. Interspersed are clumps of *Carex bigelowii, Eriophorum vaginatum,* scattered grasses and forbs. Within the moss and lichen mat, varying amounts of dwarf (sub-shrubs) shrubs (10-20 cm high), mostly heath species, are common. These include *Vaccinium vitis-idaea, V. uliginosum, Empetrum hermaphroditum, E. nigrum, Ledum palustre* ssp. *decumbens, Arctostaphylos rubra, A. alpina, Caasiope tetragona, Rubus chamaemorus* and *Salix* ssp. (Hanson 1953, Hettinger et al. 1973, Corns 1974). These communities are common on moderately well drained uplands and slopes where there is typically 25-50 cm of snow cover. With a thick vegetation mat, the active layer is seldom more than 35-50 cm deep by August.

In the central and eastern Canadian Arctic, low shrub tundra is less common, the result of thinner snow cover and strong abrasive winds in winter (Savile 1972). The predominate shrubs are *Betula glandulosa* and *Salix glauca* along with the dwarf shrub heath species as in the west. These shrub communities are found on steep warm slopes with 0.5-1 m of snow cover in the Chesterfield Inlet area west of Hudson Bay, northern Quebec, and southern Baffin Island (Polunin 1948). Similar shrub communities dominated by *Betula glandulosa* and several species of *Salix* extend to 74°N in west Greenland, but only to 62°N in east Greenland, due to its colder climate away from the Labrador Current (Böcher 1959, Sørensen 1943).

Across the USSR, low shrub tundra is common in the rolling uplands beyond forest-tundra (subarctic zone). Low shrubs (50-60 cm) of *Betula nana, Salix lanata, S. glauca,* and *S. phylicifolia* and many of the dwarf shrub heath species previously described for North America predominate (Andreev and Aleksandrova 1979). Since these communities of the southern tundras are dominated by species common to the boreal forest, Soviet scientists refer to these shrub and related communities as comprising the subarctic (Aleksandrova 1970, 1971, Andreev and Nakhabtseva 1974). Species common to the boreal forest and tundra are referred to as hypoarctic species (Yurtsev 1966).

Throughout the range of low shrub tundra reindeer or caribou are common in summer. These lands are also important habitat for small rodents (microtine) and many species of ground nesting birds including ptarmigan.

Cottongrass Tussock - Sub Shrub Tundra

Across western North America and Siberia there are vast areas of this community. In the USSR these are called hummocky tundra and in North America tussock tundra. *Eriophorum vaginatum* tussocks are generally 15-30 cm high, 15-25 cm across, and spaced 15-60 cm apart. Large areas of western and northern Alaska (Hanson 1953, Churchhill 1955, Bliss 1956, Britton 1957, Johnson et al. 1966), and limited areas of the Northwest Territory (Larsen 1965, Corns 1974) are covered with this community. These communities are commonly found on rolling topography and small basins and valley floors where soil drainage is intermediate and the active layer in August is 30-50 cm deep. Prostrate shrubs of *Betula nana* ssp. *exilis* are common along with numerous dwarf shrubs of various species of heath *(Ledum, Empetrum, Vaccinium, Empetrum)*. Mosses including *Sphagnum* species and lichens form a dense carpet between the tussocks. The sedges *Carex bigelowii* and *C. lugens* are common along with the arctic grass *Arctagrostis latifolia* and numerous species of forbs.

These communities are some of the richest in plant species diversity. They are also favorite feeding grounds in early summer for caribou and reindeer which relish the tender and nutrient rich new shoots of *Eriophorum*. Arctic mice (lemming), and voles are common to these areas, as are several species of ground nesting birds.

Across Siberia *Eriophorum vaginatum* hummocky tundras are restricted to the southern subarctic zone (Andreev and Aleksandrova 1979). In the Kolyma subprovince of the Siberian Province and in the Chukotka Province *Carex lugens* is an important component as are the dwarf heath shrubs.

Sedge-Moss and Sedge-Grass-Moss Tundra

The Finnish word tundri and the Soviet word tundra were originally used to describe wetland areas dominated by sedges and grasses. Only limited wetlands occur in the mountains and upper foothills of arctic Alaska and the Yukon Territory (Britton 1957, Hettinger et al. 1973). They dominate on the Coastal Plain in Alaska (Britton 1957, Webber and Walker 1975) and the coastal areas of the Yukon Territory and the Mackenzie Delta of the Northwest Territory (Hettinger et al. 1973, Corns 1974). Eastward across the NWT, wet sedgelands occur, but with the dominance of rocky Precambrian lands, this tundra type is localized (Larsen 1965, 1972). Where drainage is impeded, deep peats 2-10 m develop and on these surfaces *Carex aquatilis, C. chordorrhiza, C. rariflora, C. rotunda, C. membranacea, Eriophorum angustifolium* and *E. scheuchzeri* predominate. The grasses *Arctagrostis latifolia, Poa arctica* and *Deschampsia caespitosa* occur in the best drained sites, *Dupontia fisheri* and *Alopecurus alpinus* in moist sites to shall water and *Arctophila fulva* in standing water. Common herbs include *Caltha palustris* ssp. *arctica, Chrysosplenium tetrandrum, Pedicularis sudetica, Petasites frigidus* and several species of *Saxifraga* and *Pinguicula* (Britton 1957, Corns 1974).

The shallow waters of lakes and ponds contain *Menyanthes trifoliata, Equisetum variegatum, Potentilla palustris, Arctophila fulva* and *Hippuris vulgaris* with species of *Carex* and *Eriophorum* where water is only 10-20 cm deep.

These sedge and grass wet meadows have a nearly continuous cover of mosses including several species each of *Sphagnum, Drepanocladus, Alacomnium, Calliergon* and *Ditrichum*. Other common mosses are *Meesia triquetra* and *Tomenthypnum nitens;* lichens seldom occur other than *Peltigera aphthosa* on hummock tops.

In many areas, raised center or raised rim polygons occur. The troughs (top of ice-wedges) are dominated by sedges and the elevated sites (30-200 cm) are covered with dwarf shrub heath species, and prostrate or low shrubs of *Salix* and *Betula*. Species distribution varies greatly over short distances in relation to soil water content, soil aeration, active layer depth, and depth of winter snow cover.

Across Siberia there are vast wetlands of sedges. In the Ob-Yenisei subprovince, wetlands (mires) are dominated by *Carex globularis* in the southern portion, *C. rotundata* in the middle, and *C. chordorrhizae* in the northern portion of the subarctic zone. To the north in the arctic zone where woody vegetation is minor, *Carex stans* dominates. To the west in the Yana-Indigirka subprovince, mires are dominated by *Carex stans* and *Eriophorum angustifolium*. In many areas *Arctophila fulva* occurs in shallow waters of lakes and ponds (Andreev and Aleksandrova 1979).

These wetlands are very important feeding and nesting sites for numerous species of waterfowl and shore birds. They are also important summer range for caribou. Because of the wet soils, thick moss cover and deep saturated peats, the active layer is seldom more than 20-30 cm deep by late August.

Cushion Plant-Herb-Lichen

In the mountains of the Yukon Territory and Alaska, wind-swept slopes and ridges are often dominated by *Dryas octopetala, D. integrifolia*, numerous grasses, sedges, and small clumps or rosettes of species of *Draba, Saxifraga, Arenaria*, and *Cerastium* (Britton 1957, Drew and Shanks 1965, Johnson et al. 1966, Hettinger et al. 1973). Species of the lichen genera *Cetraria, Cornicularia*, and *Alectoria* are also important. Plant cover is much less as is plant production when compared with the previous communities. *Dryas* dominated communities in upland granitic rock are common in the uplands of the Boothia and Melville peninsulas of the Northwest Territories, Canada.

In the Ural Mountains and other nothern mountain systems of the USSR, *Dryas* and lichen dominated communities are common. The arctic zone is often characterized by hummocky tundra with *Carex ensifolia* ssp. *arctisibirica, Dryas octopetala,* mosses, and lichens in the Ob-Yenisei Subprovince (Andreev and Aleksandrova 1979). In the Kolyma Subprovince *Diapensia obovata, Salix polaris, Dryas punctata,* and *Alopecurus alpinus* along with small herbs, mosses, and lichens are common. On the Taimyr Peninsula extensive areas are covered with a moss-*Dryas*-sedge tundra in a "frost-boil" or "spotted tundra" pattern (Matveyeva 1972, Pospelova 1972, Norin and Ignatenko 1975).

These communities dominated by *Dryas,* dry site species of *Carex,* and prostrate shrubs of *Salix,* mosses, and lichens form one of the most common communities in the High Arctic as discussed below.

High Arctic

In contrast with the continuous cover of vegetation of the Low Arctic, the High Arctic is characterized by its limited plant cover, sparseness of wildlife except in localized areas; a general appearance of biological barrenness (Table 2.). The High Arctic, mostly in Canada (Fig. 1), can be divided into small areas of tundra (sedge-moss, dwarf shrub heath, and cottongrass tussock), large areas of sparce vegetation (polar semi-desert), and large areas of little or no vegetation (polar desert) (Bliss et al. 1973, Bliss 1975). As a result of less plant cover, the patterned ground features (Washburn 1956) of a permafrost dominated terrain (sorted and non-sorted polygons and stripes, solifluction terraces, massive ice-wedge patterns, and soil hummocks) are a more conspicuous feature.

Tundra

Only small areas of sedge-moss tundra occur in the Queen Elizabeth Islands (> 2%) (Babb and Bliss 1974). Lowlands with impeded drainage and coastal areas with series of raised beaches retain snow melt waters, this permits the extensive growth of the sedges *Carex stans, C. membranacea, Eriophorum scheuchzeri* and *E. triste* (Polunin 1948, Savile 1964, Brassard and Longton 1970, Muc 1977, Bliss and Svoboda 1979a, b). Mosses of the genera *Distichum, Mnium, Ditrichum, Tomenthypnum, Drepanocladus, Aulacomnium* and *Hypnum* are abundant (Vitt 1975, Vitt and Pakarinen 1977). Lichens are very minor in these wetlands. With saturated, peaty soils, the active layer is more shallow in these areas (Fig. 5). These meadows, biologically the most productive sites in the High Arctic, support muskox, Peary's caribou, brown lemming in the southern arctic islands, and numerous species of waterfowl and shore birds.

Small meadows of grasses, sedges, and mosses occur on Svalbard (Rønning 1965). Herb-grass meadows of *Poa alpigena, Alopecurus alpinus, Luzula confusa,* and several species of *Saxifraga* in interfluve communities and sedges in stream valleys are present in the northern Taimyr Peninsula, USSR (Matveyeva et al. 1975).

Dwarf shrub heath communities with various combinations of *Cassiope tetragona, Vaccinium uliginosum, Rhododendron lapponicum, Salix arctica,* and *Dryas integrifolia* occur to 72°-73°N in east Greenland and to 75°-76°N in west Greenland (Siedenfaden and Sørensen 1937, Sørensen 1943, Oosting 1948). Heath communities are species poor in the Canadian High Arctic, typically dominated by *Cassiope tetragona* and lesser amounts of *Salix arctica, Dryas integrifolia,* and *Carex misandra* (Brassard and Longton 1970, Beschel 1970, Bliss et al. 1977). These communities occur where snow melts 1-2 weeks later than average and on warmer south or west-facing slopes (Fig. 5).

Polar Semi-desert

Plant communities dominated by cushion plants (*Dryas, Salix, Saxifraga oppositifolia),* cover about 55% of the Canadian mainland High Arctic and the southern arctic islands. Cover of flowering plants generally averages 10 to 20%; lichens and mosses provide an additional 30 to 50% cover. These communities occur on rolling slopes and exposed uplands where winter snow cover is shallow and the soils in summer are well to imperfectly drained (Bliss and Svoboda 1979b).

In the eastern and central Queen Elizabeth Islands, areas dominated by *Dryas integrifolia, Salix arctica, Saxifraga oppositifolia, Carex nardina,* and lichens occur on sandy and gravelly raised beaches near the sea and on warmer slopes with winter snow cover of 50-100 cm (Savile 1964, Brassard and Longton 1970, Beschel 1970, Babb and Bliss 1974, Svoboda 1977).

Dryas dominated communities occur on Svalbard (78°N) in wind exposed sites and in areas of deeper snow *Cassiope, Salix polaris,* and *Dryas octopetala* occur (Rønning 1965).

Although these communities are less productive than the tundra sedge and grass meadows, they do support Peary's caribou and limited numbers of muskox, collared lemming, and a few species of nesting birds.

In the western Queen Elizabeth Islands where silty loam to clay loam soils predominate, moss-lichen-herb communities predominate (Fig. 6). The number of species is reduced, as is plant height. Much more open ground is present and crustose lichens become more important (Bliss and Svoboda 1979a). The dominate flowering plants include *Luzula confusa, L. nivalis, Papaver radicatum, Alopecurus alpinus, Cerastium arcticum, Ranunculus sabinei,* and numerous species of *Draba* and *Saxifraga.* The forbs are mostly tiny clumps or rosettes with compact stems and flowers within 1-2 cm of the soil surface. The woody species *Salix arctica* and *Dryas integrifolia* are restricted to only the warmest sites. Although total plant cover is limited (> 20% flowering, 50-70% lichens and mosses) in biomass, the active layer is as deep as in many tundra communities of the Low Arctic (compare Figs. 4 and 6).

Vegetation somewhat similar to this has been described for Cape Chelyuskin at the tip of the Taimyr Peninsula (77° 43'N) (Matveyeva and Chernov 1976). These authors termed the area polar desert though it is richer in species than most areas examined to date in the Canadian High Arctic.

Polar Deserts

The most barren landscapes of sandy soils, alkaline clay flats, coastal and upland sites with massive sorted polygons and stripes have 1-5% total plant cover. In many areas vascular (flowering) plants are spaced 1-5 m apart and each plant is 0.5-2cm in surface area. The most common species are *Papaver radicatum, Cerastium arcticum, Draba corymbosa, Saxifraga cernua, S. oppositifolia, Phippsia algida, Alopecurus alpinus,* and *Puccinellia angustata.* Only in small areas (1-2ha) below snowbanks are there mats of moss (10-30% cover) with 8-12 species of flowering plants (Fig. 7) (Bliss et al. 1979). Eleven species of flowering plants were recorded at 350 m on Somerset Island and 10 species at 900 m at Lake Hazen, Ellesmere Island (Savile 1959).

At 26 sites sampled on five islands within the Central High Arctic, vascular plants averaged 2% cover, lichens 0.9%, and bryophytes 0.3%. Only in snowflush sites was total plant cover more than 0.5 to 5%. Plant cover was more similar to semi-desert lands, vascular plant cover 10%, lichens 10%, and bryophytes 12% (Bliss et al. 1979). Polar deserts with their sparce plant cover have been described for Novaya Zemlya (Aleksandrova 1959) and the northern portions of Franz Josef Land and the New Siberian Islands (Severnya Zemlya) (Aleksandrova 1970).

Under such barren conditions insects are greatly reduced and birds and lemming are rare, although a few do occur near snowflush sites. Peary's caribou, muskox, arctic fox and other larger mammals are found only as they move across these barrens seeking areas of higher biological production. The active layer is often 50-60 cm in depth by mid-August, the result of relatively well drained so little or no plant cover and organic matter accumulation, yet soils that are only 2°-3°C at -10 cm.

Summary

From this discussion it should be apparent that subarctic and arctic lands have a low diversity of species and a low biological production. There is a very significant poleward reduction in plant production within these vast areas (Table 3). With reduced biological production there is a corresponding reduction in thickness of the organic layer. Although the polar semi-deserts and polar deserts of the High Arctic have less energy input and colder soils in summer, depth of the active layer is as great as in the Low Arctic. Some plant communities (tall shrub tundra, isolated forest stands) can be correlated with a deeper active layer, but in general arctic plant communities seem to be poorly correlated with depth of the active layer.

REVEGETATION OF SUBARCTIC AND ARCTIC LANDS

Introduction

Revegetation and general rehabilitation of disturbed lands have been practiced for years in temperate regions. It is only within the last 8-10 years that a corresponding technology has begun to be developed to restore northern lands. This results mainly from petroleum exploration and production, though more recently some mining operations, road and airstrip construction, and community development are beginning to use these techniques. Although the literature on revegetation in the taiga and tundra is not large, two reviews on North American research have been prepared (Johnson and Van Cleve 1976, Peterson and Peterson 1977). The annotated bibliography on permafrost, vegetation and wildlife (Roberts-Pichette 1972) contains references to some of the early studies.

To date, the most successful restoration programs

Table 3. Net primary production for different Arctic Environments. Data are aboveground estimates only

	Net plant production ($g\ m^{-2}$)		
Plant Community	Vascular Plants	Bryophytes	Total
	Polar Desert		
Rosette plant	0.1-1	-	<1
	Polar Semi-desert		
Moss-herb	3-15	1-30	5-35
Cushion plant-moss	5-50	1-20	5-50
	Arctic Tundra		
Wet sedge-moss	35-100	15-100	50-150
Cottongrass-dwarf heath	40-75	30-130	100-175
Low shrub-dwarf heath	75-150	30-50	100-200

have started by determining the role of native species in plant succession, and where possible incorporating some of these species in the seed mixes. As will be seen, the use of native species is important in the northern boreal forest and forest-tundra, and becomes more important in the tundras of the Low Arctic and the polar semi-deserts of the High Arctic.

The primary objectives of these studies have been to determine: 1) what species and species mix will provide an adequate cover to hold the soil, 2) successfully overwinter and regrow in successive years; and 3) maintain populations of the species through natural reseeding. Seeding and fertilizer levels have also been determined.

Taiga

Within the northern closed boreal forest and open woodland, the grasses *Calamagrostis canadensis*, *Arctagrostis latifolia*, sedge species of *Carex* and *Eriophorum*, fireweed (*Epilobium angustifolium*) *Ledum groenlandicum* and *Arctostaphylos rubra* and the shrubs *Alnus crispa*, *Salix* ssp. are the typical pioneer species in disturbed lands (Reid 1977, Hernandez 1974). *Calamagrostis canadensis* forms extensive grasslands in south central Alaska (Mitchell and Evans 1966) and in western Alaska (Hanson 1951).

Revegetation studies were initiated at eight sites within forested lands north of Fairbanks, Alaska in 1970 and 1971 (Van Cleve 1973), and at the buried heated pipeline test site at Fairbanks in 1970 (McCowan 1973). In Northern Canada similar research was initiated at Norman Wells, NWT in 1971 (Wein 1971, Hernandez 1973a), at Sans Sault, NWT in 1971 (Dabbs et al. 1974, Younkin 1976), and at Inuvik, NWT in 1971 (Younkin 1971, 1976).

After two summers of growth, the grasses Arctared and Boreal creeping red fescue *(Festuca rubra)* and Nugget Kentucky bluegrass (*Poa pratensis*) grew best on the berms of cold (-9.5°C) and hot (18°C) simulated gas pipelines at the test facilities at Norman Wells (65°17'N) (Hernandez 1973a). The tests at the Sans Sault site (65°40'N) also within the boreal forest, about 90 km north of Norman Wells showed that after five years the grasses Durar sheep fescue (*Festuca ovina)*, Meadow foxtail (*Alopecurus pratensis)*, Frontier reed canary - grass (*Phalaris arundinacea)*, Meadow fescue *(Festuca elatior)*, Boreal creeping red fescue (*Festuca rubra)* Kentucky bluegrass (*Poa pratensis)*, and Fowl bluegrass (*Poa palustris)* grew best (Younkin 1976) (Table 4).

At the end of the seventh growing season a thick mantle of grasses covered the test plots at Norman Wells. The most abundant grasses were the fescues and the native bluejoint grass (*Calamagrostis canadensis)*.

The revegetation plots at Inuvik, NWT (68°20'N) showed the following results after three summers of growth. Plant cover was greatest (65-85%) for Boreal creeping red fescue, Meadow foxtail, Arctared creeping red fescue, and Nugget Kentucky bluegrass. Engmo timothy (*Phleum pratense)* and Slender wheatgrass (*Agropyron trachycaulon)* produced about 50% or more cover (Hernandez 1973a). This site is near the northern limit of the open woodland (Black and Bliss 1978).

Data from the simulated hot oil pipeline study at Fairbanks, Alaska (64°49'N) indicated that Manchar brome (*Bromus inermus)*, Boreal creeping red fescue, Engmo timothy, and Nugget Kentucky bluegrass grew well and survived at least one winter both over the heated line and at a distance of 10-13 m from the center of the pipe (McCown 1973).

Fertilizer studies at Sans Sault and Inuvik showed that in these cold, nutrient deficient soils, phosphorus and nitrogen are most limiting (Younkin 1972, 1976, Hernandez 1973a, Dabbs et al., 1974). The recommended levels of a fertilizer mix were 112:235 kg/ha of N and P_2O_5 near Inuvik and 39:79: 79 kg/ha for a N:P:K mix at Sans Sault (see Younkin 1976). A follow-up fertilization program the second or third year appears necessary to maintain higher rates of plant growth. Within the boreal forest a species mix of Boreal creeping red fescue, Frontier reed canarygrass and Sheep fescue (ratio 1:1:1) was recommended for high erodibility sites (56 kg/ha) and Boreal creeping red fescue, Meadow foxtail, and Frontier reed canarygrass (ratio 1:2:2) for sites of low erodibility (28 kg/ha). In the forest-tundra, a 2:2:1 ratio of Nugget Kentucky bluegrass, Arctared creeping red fescue and Meadow foxtail (28 kg/ha) was recommended for high and low erodibility sites respectively (Younkin 1976).

Johnson (1978) has recently shown that where a rapid cover is desired to prevent erosion, annual rye planted alone is best. However, if a perennial grass cover is desired, the best biomass was achieved by planting Canada bluejoint alone with a high level of N:P:K (228:57:114 kg/ha) rather than a mixture of Arctared creeping red fescue and bluejoint. Where annual rye and fescue were mixed, biomass was higher the second year for fescue where 114 rather than 228 kg/ha of N was used. These results indicate that the selection of species as well as fertilizer level is important in revegetation programs, at least in the Fairbanks, Alaska area.

The combination of results from these studies and the successful reseeding work by Alyeska Pipeline Co. within the forest zone shows that soils can be stabilized and that with time, the permafrost table may be stabilized through a detailed revegetation program.

Low Arctic Tundra

Prior to petroleum exploration in the Arctic, there had been little if any technology developed for rehabilitation of disturbed surfaces. Revegetation studies were initiated at Prudhoe Bay, Alaska (70°15'N) in 1969 and at Tuktoyaktuk, N.W.T. (69°25'N) in 1970. Sedge-moss tundra predominates at Prudhoe Bay and low shrub-dwarf shrub heath tundra near Tuktovaktuk. Most of the species

Table 4. Boreal agronomic and native boreal and arctic species potentially useful in revegetation of disturbed soils in permafrost lands, North America

Region	Species
	Agronomic Species - northern varieties
Taiga closed forest	18 species tested - Sans Sault, NWT Durar sheep fescue Meadow foxtail Frontier reed canarygrass Meadow fescue Boreal creeping red fescue Kentucky bluegrass Fowl bluegrass
Forest-tundra	16 species tested - Inuvik, NWT Nugget Kentucky bluegrass Arctared creeping red fescue Meadow foxtail Boreal creeping red fescue Engmo timothy
Low Arctic	
Low shrub and cottongrass tundra	16 species tested - Tuktoyatuk, NWT Nugget Kentucky bluegrass Arctared creeping red fescue Boreal creeping red fescue
High Arctic	
Sedge-moss tundra	100 species and varieties tested - Prudhoe Bay Alāska Arctared creeping red fescue Nugget Kentucky bluegrass
Cushion plant polar semi-desert	10 species and varieties tested - Rea Pt., Melville Island, NWT none
Polar Desert	none
	Native Species
Taiga forest - Forest tundra	Canada bluejoint
Low Arctic	Canada bluejoint Tall arcticgrass
High Arctic	
Tundra	Tall arcticgrass, dwarf hairgrass
Polar semi-desert	Alpine foxtail, *Phippsia algida*
Polar Desert	none

planted were the same as in the northern boreal forest sites, agronomically developed varieties of northern boreal grasses.

Of the 60 grass species and varieties established by ARCO (1972) at Prudhoe Bay, creeping red fescue seemed the most promising. Other studies at Prudhoe Bay by Mitchell et al. (1973) and by Wein (1971) and Hernandez (1973a) in the Mackenzie Delta region showed that Arctared and Boreal creeping red fescue and Nugget Kentucky bluegrass grew well and survived the longest. Some species grew for one or two years, then suffered severe winter kill (redtop, Reed canarygrass, meadow foxtail, Engmo timothy, Durar sheep fescue, Canada bluegrass).

At the climatically less severe site at Tuktoyaktuk, only Arctared creeping red fescue and Nugget Kentucky bluegrass showed good growth for three summers (Hernandez 1973a). These two agronomic grasses were selected and developed by the Agricultural Research Station, Palmer Alaska; Nugget originated from a selection at Hope, Alaska (Hodgson et al. 1971) and Arctared from the Matanuska River Valley, Alaska. For many sites within the open woodland, forest-tundra, and shrub tundras, the native grasses *Calamagrostis canadensis* (bluejoint) and *Arctagrostis latifolia* (tall arcticgrass) grow well. Agronomic aspects of these two species have been studied by Klebesadel (1965, 1969) and ecological aspects by Younkin (1974). *Calamagrostis canadensis* is more common to the northern boreal forest and *Arctagrostis latifolia* to the Low Arctic. Both species are common pioneer species of seismic lines and abandoned winter roads and well sites in the Mackenzie Delta and uplands to the east (Hernandez 1973b).

Seed mixes have proven successful in seeding old well sites and winter roads in the tundra (Younkin 1976). The first seed mixes contained Nugget Kentucky bluegrass, Boreal creeping red fescue, Climax timothy, Frontier reed canarygrass, and Prolific spring rye in a 2:2:2:1:1 ratio of 56 kg/ha (Younkin 1976). More recent mixes used Nugget Kentucky bluegrass, Arctic creeping red fescue, and Engmo timothy in a ratio of 2:2:1 or 2:5:2. These mixes did not include the native grasses because of lack of seed, though in many sites they began to establish the second year provided a local seed source was available. Fertilizer levels used by ARCO (1972) at Prudhoe Bay, Alaska were 56:161:165 kg/ha of elemental $N:P_2O_5:K_2O$. Mitchell and McKendrick (1975) recommended 112:66:101 kg/ha of N:P:K at Prudhoe Bay and Younkin (1976) recommended 56:112:56 kg/ha of N:P:K in the general Mackenzie Delta region. In sites of medium to high erodibility, reseeding and refertilization in one or two years is recommended (Younkin 1976).

Following the experimental field plot studies, 22 old well sites and winter roads were seeded in 1973-1975 from the outer reaches of the Mackenzie Delta in low shrub tundra to open forest and forest-tundra on the Peel Plateau, ca. 320 km to the south. The results showed that seeding on gravel drill pads results in very low grass establishment (<1%). Engmo timothy, though not winter-hardy in the tundra, provided 40 to 50% of the plant cover the first year. Nugget Kentucky bluegrass and Boreal creeping red fescue became well established the second and third year; especially when the latter two species were sown in 1:1 mix. Both seed mixes and fertilizer can be successfully spread with a Sling-King seed bucket hung from a helicopter flying at 48 km/hr. This seeds at the rate of 0.6 ha/min for seed and 1.25 ha/min for fertilizer (Younkin 1976). The native grasses *Arctagrostis latifolia* and *Calamagrostis canadensis* will establish naturally where less winter-hardy species such as timothy are used. The native grasses do not easily invade a well established cover of bluegrass and red fescue.

The selection of a seed mix is dependent upon the particular site requirements. Where erosion control is needed, mixes high in Engmo timothy should be applied. Where a slower establishing and longer lived cover is needed, Nugget Kentucky bluegrass or Arctared creeping red fescue sown separately or in combination is recommended. If rapid establishment and longer lived cover is desired, the 2:2:1 mix of bluegrass, red fescue, and timothy is best. In the boreal forest the proportion of timothy can be increased because there is less winter kill (Younkin 1976).

Shrub cuttings tested over a three-year period show a high survival (> 95%) for *Salix alaxensis* and *S. arbusculoides*, 40% survival for *Alnus incana* and no survival for *A. crispa*. These plantings at Sans Sault, N.W.T. give promise for replanting at least limited areas to shrub vegetation (Younkin 1976). Alyeska Pipeline Service Co. is currently testing the feasibility of planting rooted cuttings of *Salix alaxensis* on gravel and sand bars in northern Alaska.

The natural regrowth of low and dwarf shrubs on sites that were hand or machine-cleared of trees and shrubs prior to constructing test snow-ice winter roads, attests to the feasibility of using this technique for pipeline construction on permafrost terrain (Adams and Hernandez 1977, Younkin and Hettinger 1978). The regrowth of sedges, grasses, and low shrubs on the winter snow-ice roads used for several years in the sedge-moss, cottongrass tussock and low shrub tundras northeast of Inuvik, NWT also shows the potential for natural recovery (Campbell and Bliss-unpublished data). In these areas the 10-15 cm peat layer provides considerable insulation with the result that permafrost melt seldom occurs, provided vehicles do not start snow road construction too early in the winter nor operate too late in spring when the surface begins to thaw.

There is a considerable body of literature on the general impact of industrial development in the Soviet North (Brown and Grave - this volume, Andrews 1977, 1978). However, few of these papers give detailed information on restoration procedures being used. Andreev (1979) has outlined in general terms the literature on the influence of human factors, including the impact of reindeer grazing, on tundra vegetation. Revegetation on gold mining spoils requires 8-10 years and graminoids become established in vehicle tracks in 3-4 years. Weedy species have increased in the North due to land clearing and increased transportation routes (Dorogostaiskaya 1972). She reported 298 weedy species of disturbed soils around towns, along railways, and mining sites from arctic and subarctic lands. Of these, 2 species are introduced weeds of agricultural lands and 42 species have the potential for spreading more widely as human activity increases. In the western Taimyr Peninsula at the settlement of Kresty, Matveyeva (1978) has described native species that invade disturbed soils. Of the local flora (~ 200 species) of vascular plants, 89 species occupy disturbed habitats. Yurtsev and Korobkov (1978) list species occupying disturbed soils near the village of Yanrakynnot on the Chukotka Peninsula.

The results of these various studies, including the uniformity of results using native wild and northern agronomic species, show that considerable success in stabilizing soil can be achieved under arctic conditions (Table 4). Limited success in reseeding the arctic portion of the Alyeska Pipeline has occurred, though a program of reseeding and refertilizing for a number of years is probably necessary.

High Arctic Polar Semi-Deserts

More than 50 wells have been drilled in the Western Canadian Arctic Archipelago. In relation to well clean-up operations and preliminary plans for a gas pipeline on Melville Island, a limited revegetation program was initiated. Three sites were established on Melville Island and one on Ellef Ringnes Island. After five years of work the main conclusions are: 1) none of the 10 agronomic species tested survived over winter; 2) hydroseeding was more successful than broadcast seeding; and 3) fertilizer (ratio 1:4:4) applied at the rate of 245 kg/ha stimulated growth of native species as well as the agronomic species under test (McGillivray 1976). These studies vividly demonstrate the futility of planting boreal forest species well beyond their climatic limit.

In a separate study, *Calamagrostis canadensis* and *Arctagrostis latifolia* native to the Tuktoyaktuk and Inuvik areas were planted at the Truelove Lowland, Devon Island (75°N) and on King Christian Island (78°N). There was limited seed germination and plant establishment for at least four years on the Truelove Lowland. Survival was much greater in *Arctagrostis*. At the more severe site with its shorter growing season on King Christian Island, only a few seeds germinated and no plants survived over winter (Bliss and Bell - unpublished data). At the latter site *Phippsia algidia* and *Alopecurus alpinus* seeded in naturally in the fertilized plots, indicating again the practicality of using native species rather than agronomic races of species physiologically adapted to different environments.

Unless there are major breakthroughs in our knowledge of high arctic species, there seems little or no hope of revegetating the true polar deserts. The shortness of season, low soil temperatures, and dry surface soils seem to negate success. Only very limited success appears possible in revegetation work in the norther polar semi-deserts (Table 4).

Summary

The data available indicate that northern races of agronomic species are well adapted for use in revegetating northern boreal forest lands. A few of these species and two grasses native to the northern forests and tundra have been used with reasonable success in the Low Arctic. Few studies have been done to date on revegetation in the High Arctic, but the limited results show little promise for reseeding surface disturbed soils. All soils are nutrient deficient and require high applications of nitrogen and phosphorus (100-200 kg/ha). There are examples of successful revegetation in these northern permafrost lands, but those north of 72° hold less promise for soil stabilization through seeding programs.

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FIGURE CAPTIONS

Fig. 1. Permafrost distribution based on recent revisions by T.L. Péwé and the boundaries of the Low and High Arctic.

Fig. 2. Pattern of forest, fen, and mountain tundra in relation to topography, soils, and depth of the active layer, Norman Wells, NWT, Canada.

Fig. 3. Pattern of forest and tundra wit in the lichen-woodland open forest near Inuvik, NWT, Canada.

Fig. 4. Idealized pattern of low arctic tundra communities in relation to topography, soils, and depth of the active layer in the Foothill province of the North Slope Alaska.

Fig. 5. Pattern of dwarf shrub and sedge moss tundra communities and cushion plant communities of man polar semi-desert areas, Truelov Lowland, Devon Island, Canada.

Fig. 6. Pattern of moss-herb communities and limited areas of dwarf shrub heath and sedge-moss tundra, wit in a polar semi-desert landscape Rea Pt., Melville Island, NWT, Canada.

Fig. 7. Limited pattern of "plant communities" in relation to soil active layer, and topography wit in the polar desert landscape, ne Resolute, Cornwallis Island, NWT, Canada.

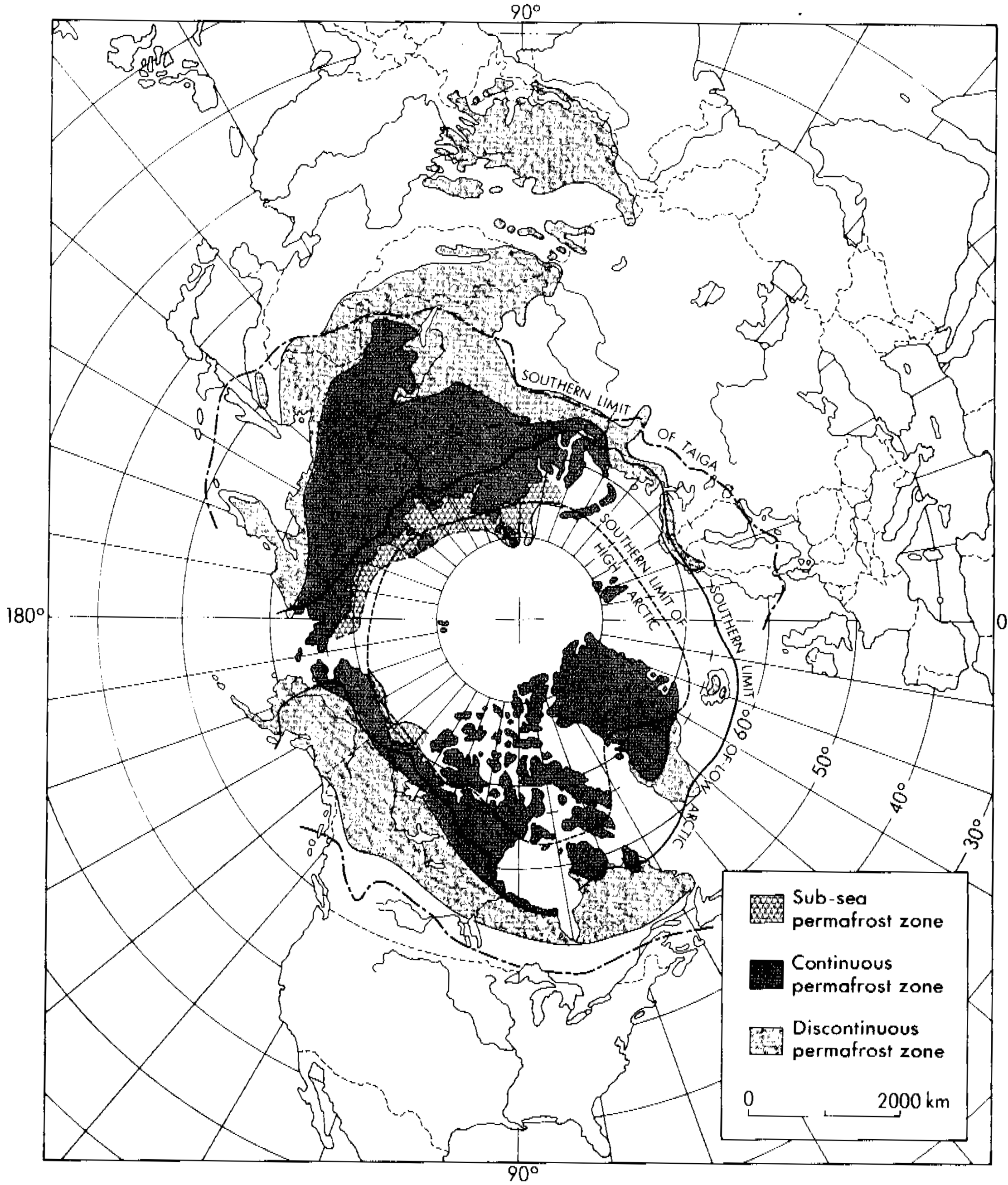
90°
180°
0°
90°
SOUTHERN LIMIT OF TAIGA
SOUTHERN LIMIT OF HIGH ARCTIC
SOUTHERN LIMIT OF LOW ARCTIC
60°
50°
40°
30°
Sub-sea permafrost zone
Continuous permafrost zone
Discontinuous permafrost zone
0
2000 km

Figure 1

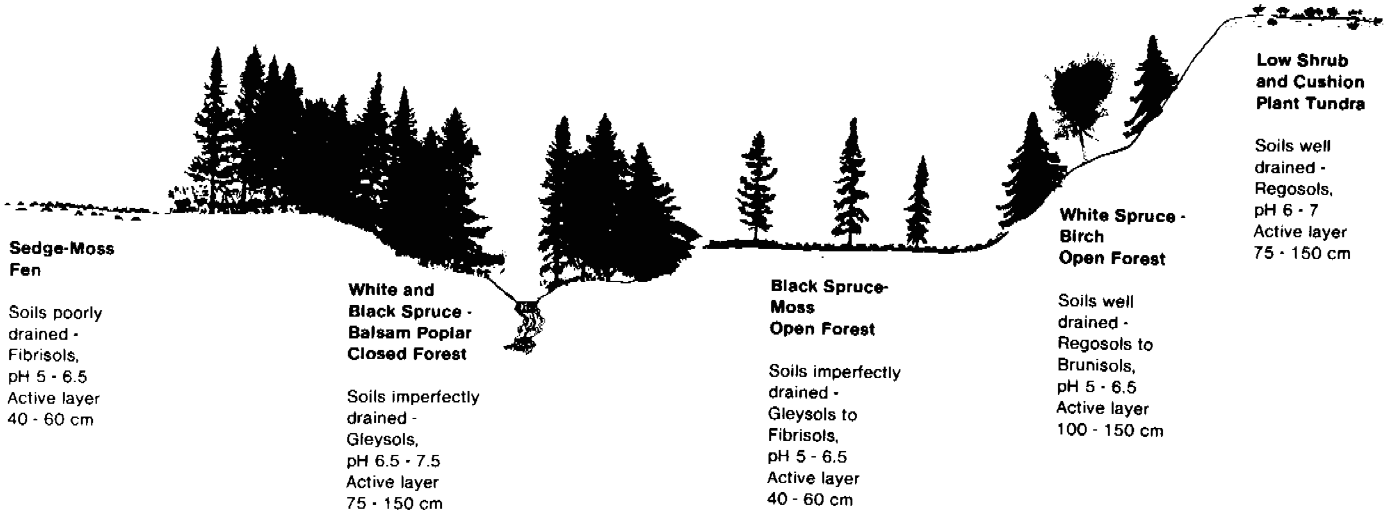

Figure 2

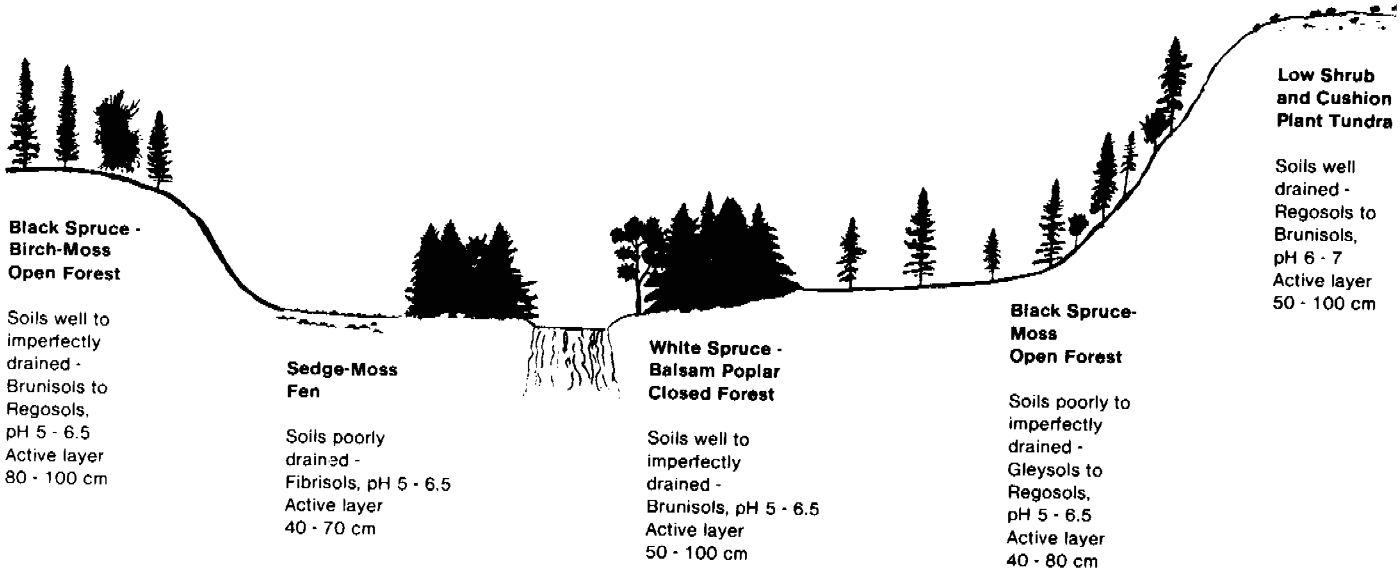

Figure 3

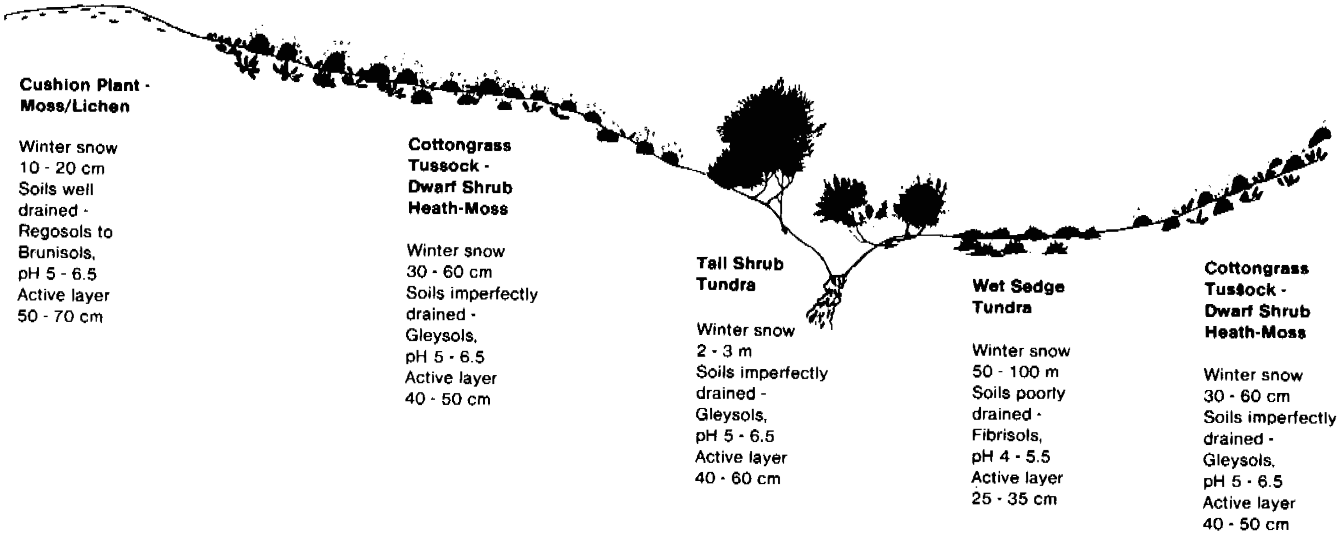

Figure 4

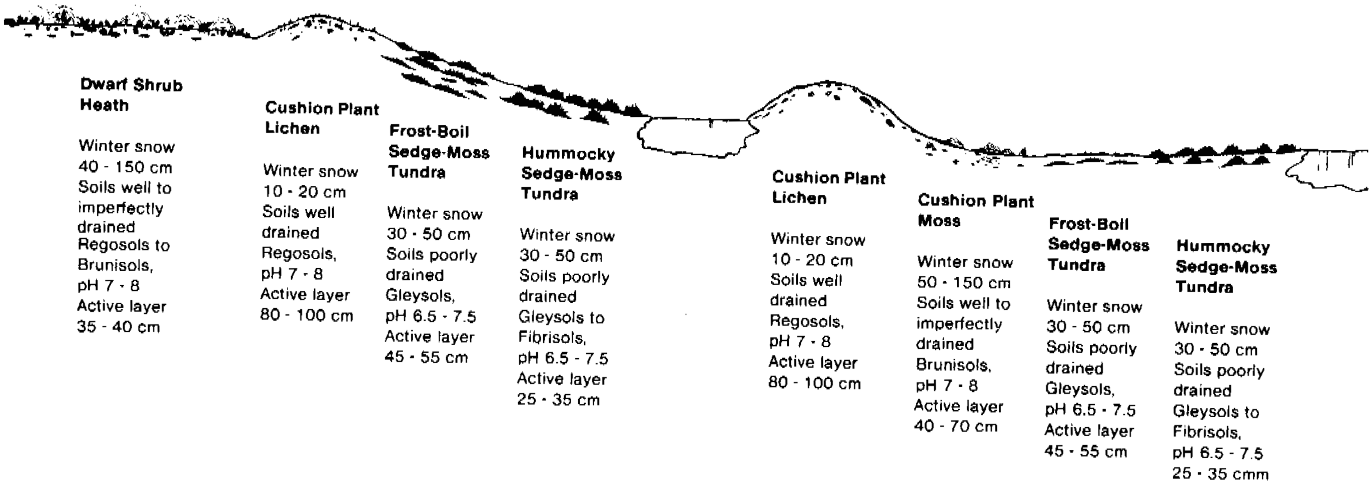

Figure 5

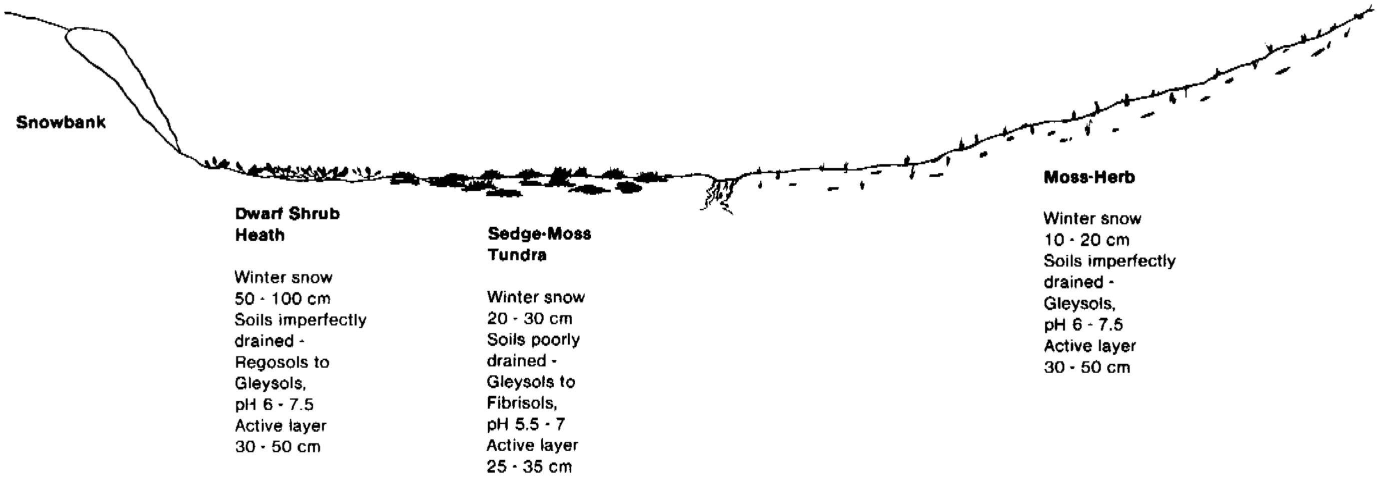

Figure 6

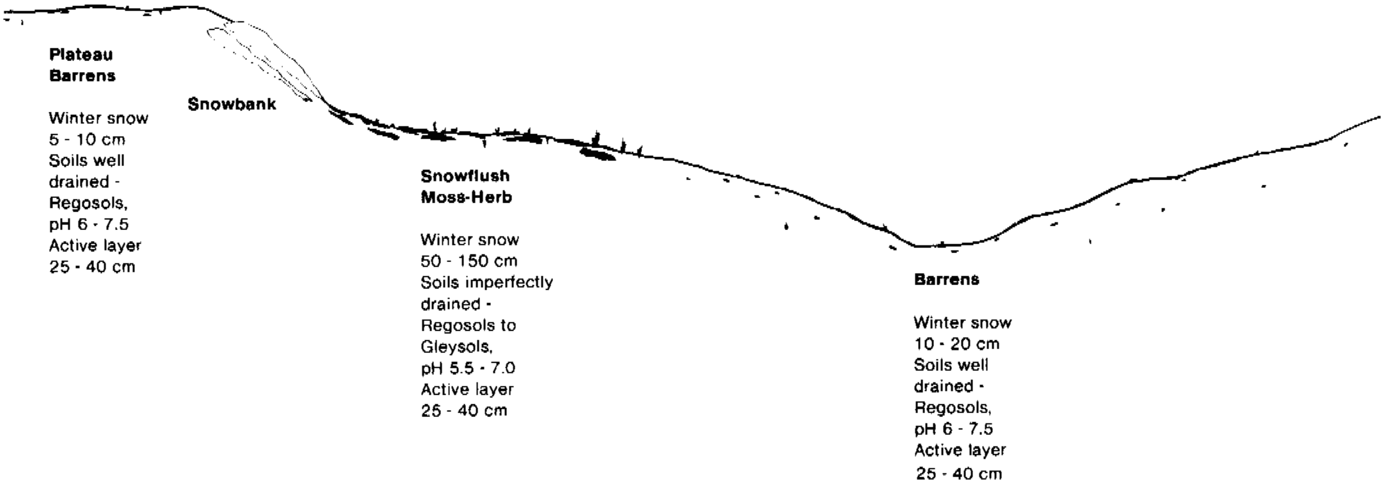

Figure 7

PHYSICAL AND THERMAL DISTURBANCE AND PROTECTION OF PERMAFROST*

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INTRODUCTION

Since 1973 the trans-Alaska pipeline has been constructed, the limits of subsea permafrost in the Beaufort Sea have been investigated, the route has been selected for a large-diameter natural gas line running south from northern Alaska, construction of the Baikal-Amur Railroad (BAM) has progressed, and exploration for oil, gas, coal and other resources has continued throughout the mid- and high-latitude circumpolar regions. Those who have undertaken these massive construction and planning projects have considered many of the environmental impacts and hazards associated with permafrost and the problems involved in protecting and restoring the terrain (for instance Berger 1977a, b, Eddy 1974, Lysyk 1977, Mel'nikov 1976, National Energy Board 1977, Weller and Norton 1977).

Disturbance of the terrain, whether by natural or artificial causes, is bound to result in an acceleration of natural processes (Jahn 1976). Most factors that tend to disturb the natural environmental equilibrium are associated with human activity. But natural catastrophes occur as well: torrential rainfall, earthquakes, and fires. Terrain disturbance tends to increase the mean annual surface temperature. The active layer may become thicker and the thickness of the permafrost may decrease. The increase in thaw may be a few centimeters and be of little practical consequence, or we may observe gully formation, thermokarst development, landslides, and other forms of mass wasting. The magnitude of the disturbance depends mostly on the amount and type of buried ground ice, its proximity to the surface, the sediment type, and the time since disturbance.

This paper reviews the major findings of site and regional investigations dealing with human-induced and natural disturbances. Since the review paper by Bliss in this volume discusses the distribution and characteristics of arctic and subarctic vegetation, its relationship to permafrost, and natural and artificial revegetation, this review deals extensively with the physical and thermal aspects of terrain disturbance. A recently published paper by Webber and Ives (1978) discusses many aspects of tundra damage and recovery. It has not been possible to reference or discuss all available literature. In general, the references cited were published since 1974, although there are some earlier citations where considered pertinent.

Closely associated with terrain disturbance are subjects related to ground temperature regimes. Gold and Lachenbruch (1973) presented a major review on thermal conditions in the permafrost of North America. An update on ground temperature literature, mainly from North America, and associated microclimatic, energy exchange, and computer modeling studies are summarized in Appendix I. Microclimatic studies were an integral part of the investigations at the International Biological Program Tundra Biome sites at Barrow (Alaska), Devon Island (Canada), Niwot Ridge (Colorado) and several Scandinavian countries (Rosswall and Heal 1975). These studies, and the interest in modeling thermal processes associated with heated oil pipelines and proposed refrigerated gas pipelines and embankments, gave rise to many publications on computer modeling of soil thermal regimes and coupled heat and mass transfer processes (see, for instance, American Geophysical Union 1975, 1976). Specific aspects of the Soviet literature on ground thermal regime are presented in the text.

The first half of this report deals with literature from North American and other circumpolar regions, excluding the Soviet Union. The second half of the report contains the discussion of the Soviet literature.

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REGIONAL STUDIES, MAPPING AND TERRAIN SENSITIVITY IN NORTH AMERICA

Environmental assessments and design considerations associated with large regional projects such as oil and gas pipelines have resulted in several major programs to study their potential impact upon permafrost. In Canada these efforts were accompanied by government-and industry-sponsored terrain and ecological investigations of the Mackenzie Valley and the Arctic Islands. The Mackenzie investigations began in the early 1970's and during the period of this survey a large number of government reports have been published in several series (reports of the Task Force on Northern Oil Development, Arctic Land Use Research (A.L.U.R.) and the *Environmental Studies* Series). In Alaska, preconstruction terrain mapping along the trans-Alaska pipeline was undertaken by industry (Kreig 1977). The Prudhoe Bay oil field provided an opportunity for developing a mapping scheme for evaluating various types of impacts (Everett et al. 1978).

Strang's (1973) study on the effects of disturbance at a wide range of sites in the Mackenzie Valley differentiated between non-damaging and detrimental changes. Change was deemed damaging if its effect extended beyond the area of initial impact. A change in floristic composition, a shallow depression, or a slight lowering of the permafrost table was rated not damaging. Accelerated bank erosion, siltation of a stream bed, and other outward spreading of a disturbance were considered harmful. Surface disturbance increased the average active layer thickness in the Mackenzie Plain by 23 cm, in the Peel Plateau by 21 cm, and in the Old Crow area by 10 cm. Causes of serious damage were the exposure of subsurface frozen soil on sloping ground (>5%), the intersection and diversion of drainage channels, travel on unfrozen wet ground, and the reuse of old roads or seismic lines. Several conclusions from these observations are: 1) sites underlain by ice-rich strata close to the surface are most vulnerable to disturbance, 2) any activity which modifies or destroys the organic layer causes some degree of damage, 3) sites undergoing recolonization are vulnerable to further disturbance, and 4) it is during the thaw season that the surface is most susceptible to disturbance.

A series of reports and maps describe the surficial deposits and landforms in the Mackenzie Transportation Corridor. They include rankings of the susceptibility of various terrain units to thermokarst, slope failure, gully erosion and other hazards (Hughes et al. 1973, Rampton 1974, Rutter et al. 1973, Zoltai and Pettapiece 1973). The distribution of terrain hazards related to thermokarst gullying and slope failure is controlled by the occurrence of high ice materials and massive ice beds. The hydraulic and thermal erosion resulting from the concentration of drainage along or adjacent to pipelines and roads constitutes a major hazard. The till plains afford the best potential routing and the glacio-lacustrine plains the most difficult, because of potential thermokarst conditions and highly unstable slopes. Slope failures are attributed to the thawing of frozen sediments, either due to thickening of the active layer or the undercutting of a slope. In the southern portion of the Mackenzie Corridor, areas of thick organic matter consisting of unfrozen fenland and ice-rich bogland pose the most significant problems in pipeline construction.

Kurfurst (1973) prepared preliminary terrain sensitivity maps of the Norman Wells area based on observations of terrain response to natural and human-induced disturbances. These included fire and removal of trees, surface vegetation and soils. Many of these activities were associated with exploration and drilling. He emphasized that the susceptibility of the terrain to disturbance is controlled by ground ice or moisture content, material type, slope, and relief. Bedrock, sands and gravels are least susceptible, till and organic sediments moderately susceptible, and clay and clayey silts most susceptible.

The results of many of these Mackenzie Valley investigations have been compiled and synthesized into two terrain sensitivity maps (1:1,000,000) in a report of the Environmental-Social Committee on Northern Pipelines (1975). The maps show surficial deposits, ecoregion, terrain sensitivity, disturbance level, and type of reaction. An ecoregion consists of land characterized by a distinctive regional climate. Terrain sensitivity was divided into seven classes based on the degree of reaction to terrain disturbance, and is dependent on ground ice, slope, material, and insulating cover. The mapped sensitivity ratings are indicative of maximum deterioration response. The presence or absence of permafrost and the type of ground are the two most important factors. Based on soil data from over 11,600 bore holes in the Mackenzie Valley, Heginbottom et al. (1978) concluded that the major factors controlling permafrost conditions were location (latitude) and soil texture.

An interdisciplinary mapping scheme for terrain characterization and evaluation was developed by Barnett et al. (1977) and illustrated for eastern Melville Island. The map scale is 1:250,000 and data are presented on a photomosaic base at three levels of detail: 1) landscape type (regional), 2) geobotanical facies (intermediate), and 3) terrain units (local). The subdivision into terrain units is based on criteria such as soil moisture, surface material, plant community, degree of dissection, and slope. The mapping scheme evaluates ground ice and engineering properties, trafficability, and sensitivity to overland travel and trenching. The approach provides a mechanism for combining natural subdivisions of the landscape (ecological, geological, pedological) on a single map and considers surface materials as a key element of potential disturbance. Units are rated for sensitivity to several types of impacts.

Babb and Bliss (1974b) prepared a provisional map of the Queen Elizabeth Islands which emphasized the susceptibility of soils and vegetation to surface disturbance. Four broad categories were mapped: 1) Polar desert (31% of the land area), 2) Polar semi-desert (25%), 3) Diverse terrain (22%), and 4) Large meadows (<2%). Precautions or limitations for activities in each unit were presented. Although the Barnett et al. (1975, 1977) and Babb and Bliss (1974b) approaches differ considerably, both present useful information to planners when initial decisions are required for terrain utilization.

A more detailed approach to terrain sensitivity mapping has evolved at Prudhoe Bay which integrates soil and vegetation with respect to landform units at a scale of 1:6000 (Everett et al. 1978, Webber and Walker 1975). Ten landform units, six soil units and thirteen vegetation units are recognized. Soils and vegetation are displayed within the same landform boundaries and the result is referred to as a master map. Master maps provide the basis for generalization or for preparing very specialized interpretations. Depending upon the user's need, information may be extracted to form a derived map, for instance a map reflecting the thickness of the peat layer or the active layer for use in oil spill clean-ups. The most complex derived map is used to evaluate terrain sensitivity. A scheme for rating the impact of off-road, low pressure balloon-tired vehicles on vegetation was developed which described the type of disturbance and estimated the immediate and long-term impact (Walker et al. 1977). Oil spill sensitivity maps are being field-evaluated in conjunction with controlled and uncontrolled spills (Walker et al. 1978). Follow-up reports will evaluate the accuracy of the technique, and a terrain atlas of the Prudhoe Bay region is being prepared at CRREL by the same authors.

Terrain or landform analyses were an integral part of the design and construction of the trans-Alaska pipeline. Kreig (1977) and Kreig and Reger (1976) described the terrain unit map approach utilized in assessing the occurrence of thaw-unstable permafrost for purposes of locating material sources and evaluating slope stability conditions, and for other design requirements. The maps were prepared on a photomosaic base at a scale of 1:12,000 to show the landforms expected in a 3.5-kilometer-wide strip along the proposed oil pipeline route. Soil data from 3500 boreholes and numerous field observations were utilized. A 15-m depth profile was prepared of the geotechnical conditions anticipated along the pipeline centerline. An important contribution of the TAPS landform approach was the computerized data bank of soil and terrain conditions that was developed.

Several relationships governing the distribution of permafrost and the thickness of the active layer were evaluated by Dingman and Koutz (1974) in a small drainage area (1.8 km^2) in interior Alaska. A solar radiation index, based on the concept of equivalent latitude and a function of slope and aspect, was shown to be closely related to vegetation and permafrost distribution. The boundary of permafrost in this region of discontinuous permafrost appears to coincide with an isopleth of 365 calories/cm^2-day. The thickness of the active layer correlated significantly with the solar radiation index. Vegetation characteristics appeared to be at least as important in controlling active layer thickness. Also, in interior Alaska, Haugen and Brown (1978) indicated that the lower and cooler tundra-covered slope below timberline also favored the development of cold permafrost. This was associated with fine-grained soils and a shallow active layer (<60 cm as compared to >1 m on the upper slopes).

Several other permafrost-related mapping activities were also published. Sellmann et al. (1975), employing Landsat satellite imagery as an aid, developed a classification scheme for the thaw lakes of the Alaskan Arctic Coastal Plain that refined previous descriptions for these oriented lakes. It consists of six lake units and three non-lake units based on size, development of orientation of the elongated axis, lake density (percent water coverage), and controlling parameters such as regional or local relief and structural control. Methods were also discussed for estimating depth of water and potential maximum depth of thaw settlement and refinement of the transgressive history of the region. Using Landsat data, Tarnocai and Kristof (1976) developed a computer-aided classification and map of the terrestrial and aquatic environments on Richards Island, Canada. Spectral data were grouped into 14 terrestrial and 8 aquatic classes. Lathram (1974) was able to identify vehicular scars at Umiat, Alaska, using enlargements (1:80,000) of Landsat imagery. These tracks, which resulted from drilling activities in the period 1945 to 1952, were examined in the field in 1973. Well-developed beaded streams have formed on the ice-rich lowlands.

NATURAL PROCESSES

The development of natural thermokarst features has been summarized by Brown (1973) and Rampton (1973). Rampton concluded that thermokarst processes are still active in the Mackenzie-Beaufort region, but have slowed down, possibly reflecting a deteriorating climate in the area over the past 5000 years.

French (1974) described active thermokarst processes in eastern Banks Island. Broad and shallow ground ice slumps with a regional density of 0.5/km^2 are retreating at 6.0 to 8.0 m/yr. It is estimated that the slumps become stabilized within 30-50 summers. In the same area, thermal melting and erosion along ice wedges are resulting in the development of badland terrain (*baydzherakh*). Since the climate is probably not undergoing an unusual general warming, it was concluded that the active thermokarst is the result of local, nonclimatic factors.

Mackay (1978) measured radiant surface temperature data for thawing headwalls in ice-rich permafrost on

Gary Island. Headwall retreat had been active from 1963 to 1971 at a rate of 6 m/yr. All temperatures on the thawing headwall were above 0°C under bright sunshine. Surface temperatures increased rapidly as muddy water flowed downslope, rising 5° to 10°C in less than one minute.

Thie (1974), using aerial photography acquired over a 20-year period, measured the degradation of permafrost in the southern part of the discontinuous permafrost zone in Manitoba. The observations were based on peripheral and central collapse in palsas and peat plateaus. Retreat due to edge collapse was as much as 20 m. Up to 60% of the land portion of this area once contained permafrost; now only 15% does. This degradation apparently has been active over the past several centuries.

Priesnitz and Schunke (1978) reported on the permafrost of central Iceland, where both degradation and aggradation processes are or have been active. The permafrost is up to 6 m thick. Thermokarst depressions, valleys and mounds are described as degradation forms. Over 1200 palsas have been mapped and are considered to be indicators of aggrading permafrost.

Ugolini (1975) described an unusual form of thermokarst along the Noatak River Delta in Alaska. He suggested that upon melting, ice-rafted sediments deposited a layer of mud on the permafrost terrain, which in turn resulted in increased thawing, subsidence and subsequent pond formation.

The quickest way to measure thaw is to force a small-diameter rod into the soil to the point of refusal. However, these determinations of thaw depth are subject to error. Mackay (1977a), using a temperature probe and metal probes of varying diameters, evaluated the results obtained this way under different soil and ice conditions on the Tuktoyaktuk Peninsula. Firm resistance to probing corresponded to the 0°C isotherm in icy, organic soils, ice-bonded coarse-grained soils, and ice-lensed fine-grained soils. But in fine-grained soils free of ice lenses, probes could usually be pushed beyond the 0°C frost table. The large unfrozen pore water content of silty clay and clay soils can lead to overestimates of several decimeters in the depth of the frost table. In such soils, larger diameter probes may give a better physical estimate of the 0°C isotherm.

The depth of thaw along the coast of northern Alaska has been investigated at several sites, e.g. Peard Bay (Harper et al. 1978, Owens and Harper 1977) and Pingok Island (Fisher 1977). Thaw measurements along four profiles across a 55-m-wide barrier pit and a beach backed by a tundra bluff revealed that the spit experienced the greater thaw. In the gravel of the spit the rate of thaw increased during late summer, with 0.6 to 0.7 cm/day being measured as opposed to the more usual rates of 0.2 to 0.4 cm/day in soils. This greater rate was attributed to the nearshore water with its higher heat capacity and salinity. Total mean seasonal thaw ranged from 93 to 131 cm across the four profiles.

In a related detailed investigation of thaw depths on Pingok Island in the Beaufort Sea off Alaska, the normal exponential seasonal decrease in thaw was noted (Fisher 1977). Here the base of the active layer generally conformed to surface polygon configuration. An inversion of surface topography developed beneath hummocks and over the ice wedges that were close to the surface. Slope exposure was found to affect the thickness of the active layer significantly, whereas moisture content and sediment size had only minor effects. The southwest slopes had thicker active layers than the southeast slopes, which were about the same as the north-facing slopes. The vegetation cover was the dominant factor in influencing the thickness of the active layer; unvegetated sites had over 100 cm of thaw, while vegetated areas had 30-60 cm.

Brown et al. (1975) presented thaw data for major soil conditions at Prudhoe Bay: <30 cm for dry organic soils, 40 cm for silty dry meadow tundra, 60 cm for sandy dry meadow tundra, and >90 cm for sandy upland tundra. From the same area, Walker and Webber (1979) reported thaw increases as a function of distance from the cold bay: 22 cm near the bay and 33 cm inland. A strong summer air temperature gradient exists from the shore of the Arctic Ocean inland several tens of kilometers (pers. comm., R.K. Haugen, CRREL).

Peterson and Billings (1978) investigated the interaction of vegetation patterns and geomorphic processes along sandy bluffs in northern Alaska. Maximum depth of thaw occurs near the edges of the bluffs and exceeds 100 cm. Within 50 m of the edge, values decrease to less than 40 cm. The sand deposits were observed to be stabilized by the presence of the permafrost table, which rises as vegetational cover increases.

Nicholson and Lewis (1976) investigated the deeper thaw (10-12 m) under drainage lines in Schefferville, Quebec. Normal active layer thicknesses in the region range from 2.4 m under continuous vegetation to 3.6 m under bare ground. Nicholson (1978b) indicated that permafrost is actively developing in mine waste dumps (8-10 m in 10 years) at Schefferville and that areas deforested by fire and having shallow snow cover may develop 10-20 m of permafrost over a 25-30 year period of revegetation.

Hannell (1973) correlated depth of thaw with the 1-cm-deep daily temperature. The emphasis was on slopes of approximately 30° on the southwest coast of Devon Island. Contrary to accepted principle, active layers on north-facing slopes were consistently 5-10 cm thicker (20-40 cm on the south-facing slopes and 25-45 cm on the north-facing slopes). Active layer thickness increased as the slope of the surface declined, with 52-cm depth found on an 18° slope as opposed to 40-47 cm on a 29° slope.

Ponds and lakes on the Colville Delta, northern Alaska, are dynamic features of that landscape. Walker and Harris (1976) described perched intradune ponds with depths of up to 1.3 m. The restricted thawing of the active layer insures maintenance of the pond level above the regional "water table" throughout the summer. Total thaw beneath the pond is only about 60% of that beneath the exposed sand dunes. Maximum depth of thaw in the ponds is about 110 cm. These ponds are relatively short-lived as either filling by the blowing sand or drainage by headward erosion leads to their extinction. Walker (1978) describes the process of lake tapping. As the lake enlarges and the river erodes lakeward, thawing of ice wedges creates channels through which the river can overflow. Further erosion results in partial or complete draining of the lake. Other papers on the Alaskan lakes discussed the role of lineament control in lake orientation (Short and Wright 1974) and compared the origin of the Carolina Bays with the Alaskan oriented lakes (Kaczorowski 1977).

Erosion of permafrost along river banks and shorelines is a natural form of terrain disturbance. Cooper and Hollingshead (1973) reported on several cases of bank erosion in the Yukon Territory and emphasized that the active layer annually provides an easily erodable and unstable slope material. Newbury et al. (1978) concluded that shoreline erosion in reservoirs on permafrost occurs through a combination of thermal and mechanical processes that cause a deep niche to form immediately below the waterline, which then leads to slumping. Ritchie and Walker (1974) identified nine forms of river banks along the Colville River, four of which were erosional, four depositional, and one neutral. Thermal erosion and thawing result in the development of niches along the bases of the banks. Bank collapse and block sloping are common. Harper (1978) indicated that the average rate of coastline retreat between Peard Bay and Barrow, Alaska, is 0.31 m/yr. Code (1973) mapped the stability of river banks along the Mackenzie River and its tributaries.

In several papers, McRoberts and Morgenstern (1974a, b) emphasized the important role thawing plays in a wide range of landslide types associated with permafrost. The most common landslides of thawed materials are flow-dominated and are subdivided into solifluction, skin flows and bimodal flows. Slope failures on frozen soils were classified and analyzed as block and multiple retrogressive.

Zoltai et al. (1978) sampled a large number of earth hummocks from the Canadian Arctic and reported radiocarbon dates from the buried peats and organics. Most of the samples were 3000 to 4000 years old. These dates correspond to a climatic change toward colder and moister conditions about 4500 years ago, conditions which presumably would favor an intensification of frost action and peat burial.

HUMAN-INDUCED DISTURBANCES

Human activities which initiate disturbance can be divided into 1) point activities and 2) extensive activities (Barnett et al. 1975). Point activities include airstrips, staging areas, drill sites and town sites. Extensive activities include survey lines, pipelines, winter roads and all-year roads. Disturbance can be quantitatively evaluated in several terms of reference or combinations: 1) visual impact, 2) physical terrain modifications such as an increase in active layer thickness, settlement, and compaction, and 3) ecological impact and ability to recover. How (1974), in an assessment of the effects of the proposed gas pipeline construction on the terrain found in the Mackenzie Valley, summarized the major causes of human-induced impacts and the mechanism and consequences of each (Table 1). Brown et al. (1978) discussed the following causes of tundra disturbance, many of which are found in the western U.S.: grazing, recreation, mining, roads, pipelines, powerlines and reservoirs.

Heginbottom (1973, 1974-75) discussed three main causes of disturbance as being related to human settlements, forest fires, and oil and gas exploration activities. Where bulldozers cleared trails in summer by simply pushing over trees and leaving the forest mat in place, thaw conditions under it and the adjacent undisturbed sites remained essentially the same. When the vegetation mat was pushed aside, deep thaw and slumping occurred. Surface disturbance results in compaction of the surface soil, which in turn alters the soil thermal properties, while removal of the surface alters the albedo. The downward flux of heat in summer increases following physical disturbance, causing warming of the permafrost and deeper thawing. Subsidence occurs as excess ice melts and water drains. On sloping terrain, slope failures, mass movement and landslides occur. Coarse-grained soils are more resistant to these forms of disturbance.

The following sections discuss the response of permafrost terrain to a variety of human activities. Fire disturbance, although generally considered a natural phenomenon, is included in this discussion primarily because it is frequently compared with other forms of human-induced disturbances.

Off-road transportation

In the absence of established roads, surface transportation is now restricted to environmentally nondestructive modes. In winter this is accomplished using over-snow tracked vehicles or, on snow and ice roads, by more conventional wheeled vehicles. In summer, experimental machines such as low pressure balloon-tired vehicles (Rolligons) and air cushion vehicles (ACVs) are being used. Rickard and Brown (1974) reviewed much of the available literature on summer off-road vehicular impact. The U.S. Bureau of Land Management sponsors and publishes surface protection seminars (Evans 1976, 1977) at which numerous individual reports are presented on problems and their solutions associated with off-road impact, transportation, and protection of the terrain. A number of experimental investigations have been undertaken to observe the performance and potential impact of both summer and winter vehicles. The physical damage to the terrain that results from off-road vehicular movement is potentially more serious on the wetter, ice-rich permafrost terrain than on drier terrain, where visual impact may be the extent of the damage.

Table 1. Summary of terrain impacts in North America (after How, 1974).

			Severity of problem	
Cause	*Mechanism*	*Possible consequence*	*South of latitude 65°*	*North of latitude 65°*
Clearing	Removes trees and shrubs, compresses peat slightly, increases depth of thaw	Thermokarst subsidence, ponding, slumping	Minor subsidence, local slumping	Minor subsidence
Grading (cut)	Exposes mineral soil to increased heat input, increases rate and depth of thaw	Subsidence, slumping, gullying	Gullying by mechanical erosion, minor subsidence	Subsidence, slumping, gullying (active for more than 5 years)
Traffic on winter roads	Reduces vegetation cover, compresses peat layer, increases depth of thaw	Subsidence, ponding, slumping	Minor subsidence, local ponding and slumping	Short-term effects: minor subsidence and ponding; Long term effects uncertain
Traffic in summer	Compresses, damages, and strips off peat layer, increases rate and depth of thaw	Rutting, thermokarst subsidence, ponding, slumping	Minor subsidence mechanical erosion of slopes to form gullies	Short-term effects of multiple passes of vehicles: rutting and subsidence; Long-term effects: subsidence, gullying and slumping
Roads and airstrips	Keeps surface generally clear of snow, allowing greater frost penetration	Ground icings, choking and diverting of drainage during breakup	Icing problem can be reduced or solved with use of proper control measures.	

Winter roads and trails

This section reviews studies concerned with the effects of winter road construction on the terrain and does not discuss methods of construction or the properties of ice and snow roads.

Adam and Hernandez (1977) described the Norman Wells forested test loop, which was built in March 1973 and was subjected to 36,000 passes by several types of tracked vehicles. For comparison, thaw depths were also obtained from adjacent plots that were cleared by hand and by machine, and areas that were slash-burned. A nearby seismic line, cleared in October 1971, was also used for comparison. Measurement of the active layer thickness the first summer (1973) showed that clearing of the land by hand and by machine had increased thaw to 44 and 59 cm, respectively, as compared to 36 cm in the undisturbed forested site. The ice and ice-capped portions of the snow road had 59 and 63 cm of thaw, respectively. The seismic trail, which had had several summers of increased thaw and additional foot traffic during access to the test site had a thaw depth of 82 cm. Subsidence of the surface of the seismic trail was about 30 cm. This area, however, is not underlain by excessively ice-rich sediment. The second year (1974) of thaw showed increases of 10 cm in the control area, 14 cm in the ice road, and 13 cm in the ice-capped snow road. The depth of thaw in the seismic trail in the fourth year was essentially the same as in prior years, suggesting a thaw equilibrium or recovery on that site. The conclusion of the study was that snow roads could be constructed in a way that would protect the permafrost. However, additional precautions would be needed on ice-rich subsoils.

Haag and Bliss (1974a), in their energy budget investigations of upland tundra at Tuktoyaktuk, reported on a winter road from which all the vegetation and most of the surface peat had been removed or compacted. Thaw on the winter road was 55 cm compared to 33 cm for the undisturbed surface. The surface subsided approximately 15 cm.

Younkin and Hettinger (1978) presented results from the Inuvik processed snow road which was built in winter 1973-74. This road received 1000 vehicle passes, mainly with a tandem tractor and trailer. Before the test the active layer thickness averaged 42 cm. The mean active layer thickness in the road and the cleared area decreased 2 cm and 1 cm respectively in 1974 and increased 4 cm in 1975 where it remained in 1976. No significant change in elevation was noted. These results substantiate other similar findings that the peat layer has a greater influence on depth of thaw than either albedo or the effect of living vegetation (Haag and Bliss 1974a).

Kerfoot (1974) described topographic disturbance resulting from cross-tundra movement of tracked vehicles on the Tuktoyaktuk Peninsula and winter road in the vicinity of Sitidgi Creek. For topographic features which resulted from the 1965 blading of ice-rich tundra, 63.5 cm (41%) was the result of thermokarst subsidence, and the remainder of the relief was due to removal and redistribution of debris. Subsidence or decrease in ground surface elevation along a winter snow road (1964-1965) was estimated to be 84 cm, while the actual observed was 64. By summer 1966 field evidence indicated that a new quasi-equilibrium condition in the thickness of the active layer had been attained.

Racine (1977) reported on surface disturbance (and subsequent recovery) resulting from a 1974 winter oil exploration and drilling operation on the northern part of the Seward Peninsula. The snow road caused less damage to the vegetation than did the activities at the drill storage pads, which were located in stabilized sand dunes and beach ridges.

Summer off-road traffic

Rickard and Brown (1974) summarized the results of off-road vehicle experiments initiated in 1968-71 at Barrow and Prudhoe Bay, and in the Mackenzie Delta and the Arctic Islands.

Hernandez (1973) compared the disturbance caused by winter roads and summer seismic lines in the Mackenzie Delta and the Tuktoyaktuk region. In the forested and shrub communities north of Inuvik, silty soils thawed 60-70% deeper in the disturbed areas than in the controls (16-22 cm in the control and 27-40 cm in the disturbed areas over three summers of observations). In a tall shrub community near Tununuk Point, thaw doubled in the disturbed areas (29 cm in the control and 60 cm in the center of a seismic trail in early July). For tundra communities near Atkinson Point, the depth of thaw under trails increased only slightly, although the thaw under an old airstrip on which 1-2 m of sand had been placed in the mid-1950's more than doubled. In a tussock tundra community near Reindeer Station, a trail made by a vehicle train resulted in erosion, slumps and more than doubling of the thaw depth by early July. In the Tuktoyaktuk region winter roads used for several winters produced thaw 27 to 44% deeper under the center of the road than in the adjacent undisturbed areas. Where the surface peat had been worn down over ice wedges, thermokarst and gullying occurred. A comparison was also made of summer and winter seismic lines through similar plant communities. Thaw averaged 58 cm under the summer seismic line and 29 to 38 cm under the three winter lines (controls ranged between 19 and 30 cm in mid-July). Subsidence of the bladed summer trail was estimated at 25-30 cm and thermokarst ponds formed where ice masses were exposed. Winter trails did not result in massive thermokarst subsidence since only a small amount of soil was exposed. For this region, thaw generally increased 80 to 100% where mineral soil was exposed, 30 to 50% if the peat remained intact, and 10% if the plant cover was little altered.

Addison (1975), Babb (1977), Babb and Bliss (1974a) and Barrett (1975) reported on a series of controlled surface manipulations and observations of disturbances at a number of extensive sites in the Canadian Arctic Islands. Multiple passes (10, 40 and 60) of a vehicle with rubber tracks (Ranger) on a meadow site resulted in no significant thaw differences during the first season. A simulated blading experiment in which the top 3 cm of peat was removed resulted in only a small increase in thaw (approximately 5 cm). It was concluded that erosion and thermokarst resulting from increased soil heat flux in disturbed surfaces are relatively minor problems in the High Arctic.

Abele (1976) and Abele and Brown (1976) presented long-term results of multiple-pass testing of air cushion and tracked vehicles (Weasel) and low pressure tired vehicles at Barrow. For the worst case, thaw continued to increase for several years following 50 passes of the tracked vehicle and the air cushion vehicle. The maximum increase in thaw was 11 cm for the Weasel and 5 cm for the air cushion vehicle. The area contained relatively low amounts of ground ice. Visual deterioration began to improve during the second growing season following the tests, and in areas that received 25 and 50 passes signs left by the vehicles were barely perceptible after 4 years. The visual impact is more severe in wet tundra than in dry, polygonal tundra.

In a related study Abele et al. (1978) initiated another multiple vehicle test at Lonely, Alaska, the current base camp for oil and gas exploration in the National Petroleum Reserve, Alaska. This test involved 1, 5 and 25 passes of several types of Rolligons and a Nodwell tracked vehicle. After two seasons, differences in thaw depth were negligible in all test lanes. In a related test at Prudhoe Bay single and multiple passes were made by a Rolligon across a range of vegetation and soil types early in the summer (Everett et al. 1978, Walker et al. 1977). The tundra was extremely wet and thaw still shallow (12-28 cm). Thaw observations were made and impact ratings assigned at 32 stations. By mid-July of the second summer (1977) following the test, differences in thaw between the track and the control surface were either negligible or the thaw averaged 3 cm deeper in the trail (pers. comm., Walker). In these observations no damage had spread from the Rolligon test area to the adjacent tundra. This is in agreement with the Muskeg Institute's observations (Radforth and Burwash 1977) that rarely did deterioration of the terrain go beyond the immediate tracks.

Radforth (1973) reports on the long-term effects at tracked vehicle test sites at Tuktoyaktuk and Tununuk, N.W.T., and Shingle Point, Yukon Territory. Thermokarst development was related to the level of initial disturbance, although all terrain types tested stabilized within two years. It was concluded that vehicle traffic in excess of 40 passes should be avoided to minimize surface disturbance.

Gersper and Challinor (1975) reported on physical changes in an old Weasel trail at Barrow. Soil bulk densities and temperatures were higher, thaw was deeper, and moisture was lower under the track than in the adjacent undisturbed tundra. Thaw in the control area was 30 cm while at several positions in the track it averaged 42 cm. The wetter sites had greater thaw. Where the trails intercepted ice wedges close to the surface, shallow thermokarst pits had formed.

Sparrow et al. (1978) studied five trails on alpine soils and vegetation in central Alaska and found that in mid-July thaw depths were more than 1 m under the trails and ranged between 40 and 70 cm in the undisturbed tundra. The wetter areas and side slopes, which are highly erodable, showed the greatest visual impact.

Rickard and Slaughter (1973) monitored permafrost degradation and erosion on a tractor-cleared trail and on a hand-cleared access trail near Fairbanks. Under the severely eroded tractor-cleared trail depth of thaw had increased to between 132 and 189 cm while thaw in the adjacent undisturbed area was 36-48 cm. On the hand-cleared trail thaw had increased from control values of 54-59 cm to 127-182 cm. The hand-cleared trails had been used for four summers while the bulldozed trail was used once.

Linear transportation systems and other activities

Roads, railroads and pipelines have considerable potential for modifying the highly variable permafrost terrain they traverse. The response of the permafrost environment varies, depending on physical and thermal conditions. Proper route selection, drilling programs, and design can eliminate much potential terrain disturbance. Recent experience along the Livengood to Prudhoe Bay haul road, the Dempster, Alaskan and Mackenzie highways and the old Canol road (Fradkin 1977) has produced numerous documented examples of terrain disturbance due to road construction. Major causes of disturbance due to linear placement of gravel for road beds and pipelines are:

1. Concentration of sheet flow through drainage structures and subsequent downslope thermal and hydraulic erosion in ice-rich permafrost.
2. Cuts through massive ground ice and subsequent accelerated melting and thawing, with production of sediment and potential for rapid headward erosion.

Secondary effects are:

1. Local surface impoundments where ponding may accelerate thaw adjacent to and beneath the roadbed and result in local impact on vegetation.
2. Increased snow accumulation due to drifting and potential warming of the permafrost.

Isaacs (1974) investigated the thermal modifications caused by the Canol road, which was built in 1943 between Norman Wells and Whitehorse. As a result of surface warming the underlying permafrost has warmed considerably. Calculated thaw depths, assuming conduction processes only, underestimated the depth of thaw as observed in drilling. In one area thaw was calculated to be 15 m but no permafrost was found in the 25-m-deep hole.

Pufahl et al. (1974) reported on a field reconnaissance of road cuts in northwestern Canada and parts of Alaska. It was noted that the greatest risk of initiating unstable slope conditions arises in areas of glacio-lacustrine silts and clays which contain large amounts of ground ice. They concluded that instability of natural slopes is the best indicator of potential instability of cut slopes. Their observations indicated that cut slopes need not be a serious impediment to routing transportation arteries across permafrost.

Berg and Smith (1976) reported on the slope stabilization of the TAPS road over a 6-year period. They concluded that natural processes of slope stabilization in ice-rich cuts can be enhanced if: 1) lateral drainage ditches are wide enough to allow deposition and removal of material, 2) backslope cuts are cut nearly vertically and 3) the tops of cuts are hand cleared to a width equal to one and one-half times the height of the cut.

Berg et al. (1978) reported on the initial thaw performance of the Yukon River-Prudhoe Bay haul road and indicated that concentration of sheet flow through culverts on the ice-rich slopes is a serious design and terrain problem.

McPhail et al. (1976) also reported on stabilization of cuts along the haul road. The Happy Valley road cut is cited as an example in which thawing of gravelly silt caused considerable maintenance problems. Special restoration techniques were required. The adjacent cut with massive ground ice healed naturally.

Huculak et al. (1978), reporting on the Dempster Highway construction, said that the prime design concern was to preserve the permafrost to a tolerable degree of grade distortion.

Considerable attention has been devoted to erosion control and related revegetation during and after the construction of the trans-Alaska pipeline. In an initial report Johnson et al. (1977) documented the summer 1975 performance of initial revegetation and erosion control techniques and presented illustrated examples of slides, slumps, thermokarst, and thermal erosion along the route. The natural folding over of the organic mat on road cuts was successful in stabilizing cuts.

The Arctic is not the only tundra region where pipeline construction activities may cause temporary disturbance (Brown et al. 1978). As an example, Marr et al. (1974) described placement of a gas line which crossed the alpine tundra of Colorado. Erosion potential during spring runoff when the ground is frozen was considered high and the routing was selected to intercept a minimum of existing drainages. Construction was delayed until the turf vegetation was dry to avoid damage, and techniques for placing the turf back over the trench were experimented with for purposes of restoration.

The experience gained in road and pipeline construction across permafrost and muskeg terrain has led to revised environmental design and construction guidelines for roadways on permafrost (Murfitt et al. 1976, Lotspeich and Helmers 1974, Curran and Etter 1976). Some major points are listed: 1) The vegetation mat should remain in place to minimize thermal erosion and thermokarst. 2) Grading, particularly in ice-rich soils, should be avoided and fills used as an alternative. 3) Natural drainage should be maintained and additional drainage for runoff considered. 4) Design should incorporate tolerable amounts of settlement. 5) Surface and groundwater seepage areas and frost-susceptible materials should be avoided where possible. 6) Drainage structures should be designed to minimize water-related erosion. 7) Embankment surface drainage must be accounted for in the design and maintained during construction.

French (1975) described a case history of human-induced thermokarst due to construction of a gravel airstrip at Sachs Harbour on Banks Island between 1959 and 1962. Hummocky-type terrain with maximum relief of 100-150 cm has been created by progressive subsidence and thermokarst modification. Thaw depths were 10-20 cm greater under the disturbed sites. After 10-12 years, the thermokarst process continued but at a lower rate, although thermokarst forms were well-developed several years after the initial disturbance.

Price et al. (1974) described wet spots found on surfaces scraped for runways and other access sites on the Queen Elizabeth Islands. The spots are associated with non-sorted polygons. As the underlying ice-rich zones around the margins of the polygons thaw, due to the disturbance, moisture is drawn to the surface. Over the course of several summers the excess ice is removed and the spots dry out.

Walmsley and Lavkulich (1975) examined the effects of organic matter removal on the active layer over a period of one year in an area 80 km east of Fort Simpson. In a peat plateau, thaw in a trench increased from 30 cm in July 1971 to 90 cm in July 1972. The disturbance influence was still measurable 2 m from the trench, with thaw 40-60 cm deep. In a polygonal bog, lateral thaw along an ice wedge increased the disturbed area to more than 4 m.

In a study of a 1949 exploratory drill site in northern Alaska Lawson et al. (1978) observed thaw as a function of intensity of disturbance; mean thaw depth was 53 cm on intensely disturbed sites as compared to 32 cm on the least disturbed.

Oil spills

Research on experimental terrestrial crude oil spills started in 1970 at Barrow (Deneke et al. 1975) and at three locations in the Mackenzie Delta (Wein and Bliss 1973b). Additional experimental spills were conducted in Fairbanks (Jenkins et al. 1978), Barrow (Everett 1978), Prudhoe Bay (McKendrick and Mitchell 1978, Walker et al. 1978) and in Canada (Hutchinson et al. 1976, Mackay et al. 1975a, b). Although the intent of many of these spills was to evaluate the fate of the crude oil and its effect on biological components, soil temperature and thaw depth were also measured to evaluate the potential effects of the movement of the oil on the permafrost table.

Hutchinson and Freedman (1975) and Freedman and Hutchinson (1976) reported insignificant differences in the active layer under spills at Norman Wells and Tuktoyaktuk compared to their controls. During a three-year period of measurements the only exception was a wet meadow spill at Tuktoyaktuk which had much deeper thaw than the control in both 1974 and 1975. Summer spills are more harmful to vegetation than winter spills. Oiled plots tend to have higher surface temperatures due to increased radiation absorption on the surfaces darkened by the oil (Haag and Bliss 1974a). However, these higher surface temperatures do not generally lead to increased depth of the active layer on the oiled sites. Extra energy absorbed apparently is lost as latent heat of evaporation and the resulting drier surface forms an effective thermal barrier.

Dickman and Lunardini (1973) observed thaw depths one year after applying crude oil to hummocky terrain at Inuvik. Thaw increased between hummocks and decreased under the hummocks. These results indicated the rather complex behavior of oil in the active layer.

At Barrow, Everett (1978) observed a marked increase in thaw depth during the first two summers after application of crude oil (1975 and 1976). The effect diminished in 1977 and it was suggested that the effect is probably of short duration, on the order of five years or less.

Hydrocarbons persist in the active layer for more than 30 years as observed on 1948 and 1949 drill sites in northern Alaska (Lawson et al. 1978) and along the Haines-Fairbanks pipeline for a period exceeding 20 years (Deneke et al. 1975). In the latter, the permafrost table receded where vegetation had been killed, but where a thick moss layer existed changes in active layer thickness as well as erosion were minor or not detectable. At the Fairbanks 1976 winter and summer spills of hot crude oil there was little movement of oil downslope after the first season (Jenkins et al. 1978). An increased rate of thaw in July and August was noted for the summer spill as compared to the winter spill. Natural oil seeps at Cape Simpson indicated thaw in the seeps was 40-50 cm deep and diminished abruptly to 25 cm adjacent to the seep (Deneke et al. 1975). Temperatures were 3 to 5°C warmer in the seeps during the day at 10-cm depth and 1-2°C warmer at night compared with the adjacent tundra.

Containment of spills by damming in permafrost and damage by vehicles could result in increased disturbance. Greene et al. (1975) proposed a portable corrugated metal sheeting which could be installed by hand to contain the oil. Other techniques involve cutting narrow trenches (30 cm wide) which intercept the oil, which can then be pumped. It is suggested these techniques might be less degrading to the environment than burning, although McKendrick and Mitchell (1978) report no significant thermal or thaw changes resulting from burning spilled oil in Alaska.

Mackay et al. (1975a) indicated that some effects of oil on the thermal regime could be: 1) an albedo increase that would increase the mean surface temperature by 10%, 2) an increase of 10-20% in thermal conductivity if the oil was physically trapped in voids contained in mosses, 3) an increase in thaw if oil occupies the voids instead of ice since the latent heat to melt ice would not be required, and 4) an increase in the soil temperature due to reduced evaporation caused by the oil film.

Raisbeck and Mohtadi (1974) developed a simple model to predict the movement of oil on permeable and impermeable surfaces. Oil is likely to spread above the groundwater table. The question was raised whether the oil's ability to absorb extra energy would in fact result in greater thaw. Oil-inundated soils have a lower thermal conductivity, which reduces heat transfer. This may be the reason for the lack of strong evidence that oil in soil increases thaw.

Fire

Fire in the tundra and northern coniferous forest (taiga) is a common natural process frequently initiated by lightning storms. Viereck (1973, 1975) states that "fire is undoubtedly one of the most important environmental factors affecting taiga ecosystems." In Alaska, of the 400,000 hectares burned between 1940 and 1969, nearly half was treeless bogs, fens and tundra. Hernandez (1974) reported that one million hectares burned in the period 1962-71 in the District of Mackenzie, N.W.T., and the Yukon Territory north of 67° latitude. Wein (1976) reported on over 50 tundra fires, mostly in western North America. Shilts (1975) added to the list of tundra fires for the eastern Arctic, aided by the use of satellite imagery. Generally tundra fires are smaller than forest fires because of the lack of combustible materials.

Following fire, the active layer undergoes some modification and usually increases in thickness. Secondary effects of fire on the permafrost terrain result from erosion and gully formation, particularly where fire lines have been bladed or cleared with bulldozers (Evans 1976).

Rowe et al. (1975) and Johnson and Rowe (1977) investigated the characteristics of forest fires and related vegetation responses in the upper Mackenzie Valley and Caribou Range. The rapid response of permafrost to fire was seen in the form of silt and earth flows which developed within a year of the fires.

Wein et al. (1975) examined slumps in the area of the 1968 Inuvik fire and found that most of them had occurred since the fire. They concluded that fire does initiate slumps or soil flows when the landscape is unstable. Vehicle tracks caused more damage on burned areas than on unburned areas (Wein et al. 1975). First season active layer depths resulting from tracks on the burned areas increased about 10 cm (20%) in a black spruce community and almost 20 cm (25%) in a birch community.

Mackay (1977b) followed change in the active layer in the Inuvik fire which burnt an area of forest and tundra. The depth of thaw at five sites was measured in August of each year from 1968 to 1976. On a hillside site consisting of ridges and depressions, the active layer thickened rapidly for the first 4 or 5 years and was still increasing slightly after 8 years. The active layer on the hillside site under depressions thickened 57 cm to approximately 90 cm, and under ridges it thickened from 54 cm to approximately 115 cm. Due to its high ice content the hillside site has subsided nearly 50 cm. However, with time, as the vegetation changes and the permafrost aggrades upward, the ground surface will likely rise. Therefore, the long-term disturbance to the permafrost at this and other fire sites remains to be fully evaluated.

Viereck (1973), however, reported that depth of thaw under burned and unburned sites in four black spruce stands near Fairbanks was not significantly different (total thaw about 45 cm). Hall et al. (1978) noted a slight increase in thaw one month after a tundra fire in northwestern Alaska. In cottongrass tussock tundra at four fire sites in Canada and Alaska, Wein and Bliss (1973a) observed a 35-50% increase in thaw in June with an overall late summer increase of 15-25%. Cottongrass recovers rapidly after fire, and unless the organic mat has been consumed, long-lasting disturbance of cottongrass tundra in the form of thermokarst or erosion is unlikely. Haag and Bliss (1974a) reported results of an experimental controlled fire on tundra at Tuktoyaktuk. Thaw increased from 36 to 46 cm by the end of the first summer.

Recently, McKendrick and Mitchell (1978) reported that the soil did not warm appreciably during controlled burning of oil. In three burns at Palmer, Fairbanks and Prudhoe Bay, soil temperatures stayed below lethal levels for the vegetation at the 4-cm depth. Viereck (pers. comm.) similarly indicated that soil temperatures immediately after an experimental burn in the Fairbanks area did not increase below a depth of 15 cm. The heat of the Inuvik fire did not contribute to the initial thawing (Mackay 1977a).

Rouse and Mills (1977) summarized a three-year study of microclimatic changes which accompanied burning of lichen woodland in the Northwest Territory. Summertime soil temperatures were 3.0 to 5.5°C warmer in the burned areas; however, there was apparently no long-term soil warming. The soils in burned areas are drier and remain so for many decades. Kane et al. (1975), in a study of soil moisture and temperature near Fairbanks, concluded that the thermal and moisture regimes of soils undergo considerable alteration because of fire. These changes are related to long-term changes due to modification in the surface layers.

The rapidly burning fires on old lake beds and polygonal ground are unlikely to produce long-term disturbance since the underlying wet organic soils have not been drastically modified (Shilts 1975). The more intense and hot fires which do burn the peaty materials are likely to alter the depth and configuration of the permafrost surface. This is particularly so around mineral frost scars, where thaw increases adjacent to the scars. It has been suggested that the intensity of frost action and the formation of frost scars may be a function of the frequency of tundra fire (Viereck, pers. comm). Pettapiece (1974) described the role of fire in cyclic aspects of hummocky soils. The loss of the surface organic layer due to fire initially promotes the downward retreat of the ice-rich upper permafrost. A loss of volume creates settlement in the center of the hummock. Subsequently the increase in the vegetative mat results in an aggrading permafrost table, which in turn results in an elevation of the hummock.

CRYOGENIC PROCESSES AND REGIONAL DISTRIBUTION OF PERMAFROST IN THE USSR

Human disturbance of permafrost terrain gives rise to cryogenic and other geological processes which alter the landscape in undesirable ways. The damage which results is generally slow to heal, a characteristic of the northern environment (Kriuchkov 1976). The cryogenic processes such as frost heaves, fractures and icings are associated with increased freezing of soils in permafrost areas. Thermokarst, thermal erosion and subsidence, solifluction, and landslides are associated with thawing. The specific causes and rates of cryogenic processes are dependent upon many environmental factors (Romanovskii 1978a).

The newest geocryologic map of the USSR, including the arctic shelf, provides the basis for delineating areas where cryogenic processes are probably active (Kudriavtsev et al. 1978b). Offshore over most of the arctic shelf and basin, permafrost is widespread, with the exception of the continental slope under 200-900 m of water and in zones influenced by the warming effects of discharges from large rivers. The thickness of the frozen sediments in the shelf area of deep water can be up to 30 m (Are 1978a).

In the southern part of the permafrost region of the USSR there is island permafrost. Farther north the size of these islands increases, as does the thickness of the frozen stratum. Its temperature is 0° to −2.0°C. In the northern regions there is continuous permafrost with temperatures −3° to below −15°C and thicknesses up to 500-700 m. The greatest thickness of ground with negative temperatures (800-1500 m) is to be found in the Paleozoic stratum of central Siberia, where ground containing supercooled salt solutions below 0°C underlies the frozen layer (Kudriavtsev 1978b). In the high altitude regions (Tian Shan, Pamiro-Alai) permafrost covers an area of more than 100,000 km². Sporadic permafrost begins to appear at altitudes of 2200-3200 m; at altitudes of 2700-3700 m islands of permafrost occur; discontinuous permafrost is to be found at 3200-4100 m; and continuous permafrost at altitudes above 3500-4400 m. The greatest permafrost zone thicknesses (more than 860 m) and the lowest negative temperatures (−19°C) are found in rock massifs (Gorbunov 1978). Significant depths of bedrock freezing are found in the Pai-Hoi ridge (Polar Urals), where the frozen layer may be up to 800 m thick (Oberman 1978).

The rates of seasonal thawing and freezing of soils to which cryogenic processes are closely related are found in the schematic map by Vtiurina and were also investigated by Cherniad'ev (1976). Cryogenic processes may exist beyond the southern limit of permafrost, which is not only sensitive to climate but to human disturbances (Makeev 1977). The cryogenic processes develop differently in various zones (polar deserts, tundra, taiga, forest-steppe and continental or maritime climates). The regional climate determines the features of the cryogenic processes in the northern permafrost zones, whereas meso- and microclimates are more influential in the southern and discontinuous zones (Gavrilova 1978).

The type and thickness of the organic cover greatly influence the depth of seasonal thawing. Research in northern Tyumen Oblast on seasonal thawing under various types of tundra vegetation indicated that a moss-lichen cover exerted the greatest influence on the thermal regime of the ground, whereas a sedge-sphagnum cover had the least influence (Skriabin 1978).

The presence of underground ice is the main condition necessary for large scale cryogenic processes such as the formation of thermokarst features and thermal erosion. The distribution of underground ice is irregular (Vtiurin 1978) with separate areas of sheet ice, ice wedges, and other types of ground ice. Ice wedges have the largest areal distribution (see Figure 1). The character of cryogenic processes depends on the relationship between the landscape components. The composition of the soils and their ice contents, the topography, and the climate are related to the microclimate, vegetation, snow cover, and ground temperature regimes. Human-induced changes in these regimes determine the character of the resulting technologically produced landscape (Balobaev 1978, Fel'dman 1977, Mel'nikov 1976, Mel'nikov and Tolstikhin 1974, Shvetsov 1973).

Cryogenic processes resulting from natural causes such as changes in climate, plant succession, and geomorphic processes take place slowly and can be measured over many years. Thermokarst in northern Yakutia has a long and complicated history (Gravis 1978, Konishchev 1974) and is related to cooling and warming during the Quaternary. New cryogenic processes occur in northern sections of West Siberia as a result of swamp formation in the taiga and its replacement by sparsely forested sphagnum and lichen bogs. Deep freezing occurs on the growing hillocky peat bogs which are more snow free as a result of wind exposure in these open areas. Soil temperatures are decreased by 4°C (Belopukhova et al. 1976).

Natural cryogenic processes have been investigated in detail: thermokarst (Gravis 1978, Romanovskii 1977, Shur 1974, 1977, Sukhodrovskii 1976); processes on slopes (Sukhodrovskii and Gravis 1976, Zhigarev 1975b); frost action (Grechishchev 1978, Podbornyi 1978; Romanovskii 1977b, 1978a, b, Romanovskii and Liebman 1975), frost heaving (Nevecheria 1975, Romanovskii 1978b) and gully formation (Kosov and Konstantinova 1975).

Human-caused surface disturbance increases the rate

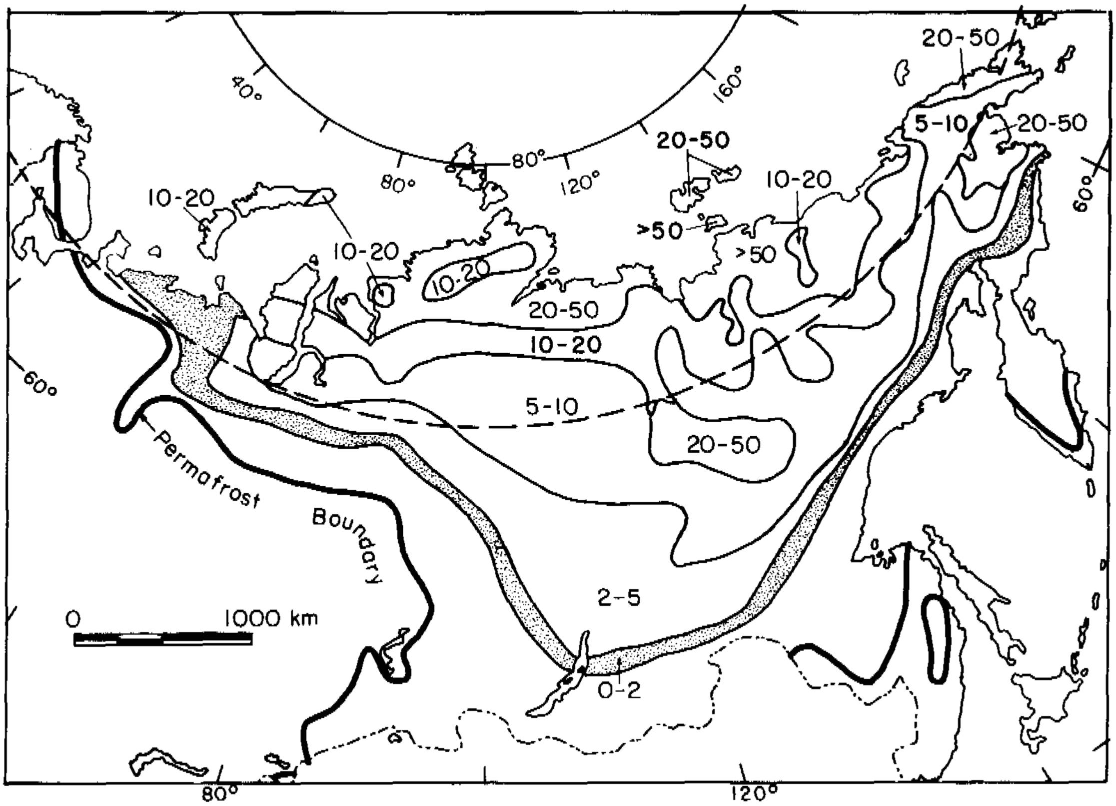

Figure 1. Ice wedge distribution in percent of area for permafrost regions of the USSR (Vtiurin 1975).

of cryogenic processes. After the active phase following disturbance, which usually takes 2-3 years and results in topographic changes, changes are more gradual and may cease after about 10 years. The result is the formation of a new landscape (Grave and Sukhodrovskii 1978, Grigor'ev 1977, Kriuchkov 1976, Mel'nikov et al. 1977).

The direct cause of changes in the cryogenic processes in permafrost regions is modification of the surface heat balance. Partial or complete removal of the surface organic layer in the northern section of West Siberia increased the radiation balance by 5-15%, the mean ground temperature by 0.7 to 2.0°C, and the depth of seasonal thaw by 2-3 times (Pavlov 1978). Human activity results in greater changes in the surface heat balance than do natural causes (Mel'nikov et al. 1977a, Sergeev and Skriabin 1978).

The modification in the surface heat balance can be either negative or positive and depends on the particular permafrost zone and the type of impact. Surface disturbance in one area can cause an increase in ground temperature, followed by the appearance or further development of thermokarst, thermal erosion and solifluction, while the same disturbance in another area can cause frost heaving, icings, and cracking of the ground (Alekseev 1977, Belopukhova et. al. 1976, Fel'dman 1977, Lisitsyna 1977, Makeev 1977, Moskalenko 1975a, b, c, Moskalenko et. al. 1978, Romanovskii 1978a, b, Romanovskii et al. 1978).

Human-induced cryogenic processes have not been well investigated. Their classification and some features have been investigated in a regional approach (Adushkinov and Borishenko 1975, Arkhangelov et al. 1975, Chizhov et al. 1977, Efimov and Efimova 1975, Kulakov 1977, Leshchikov 1975, Maksimova 1977b, Maksimova et al. 1975, Nevecheria et al. 1975, Neizvestnov and Postnov 1975, Poltev et al. 1975, 1978, Stepanov 1977).

HUMAN-INDUCED TERRAIN DISTURBANCE AND CHANGES IN GROUND TEMPERATURE REGIME

The principal types of disturbance, including the destruction of topography, can be treated as part of the study of the formation of human-induced landscapes. The specific features of these landscapes are determined by the type of disturbance, the consequent cryogenic and other geological processes, and the characteristics of the original landscape. There are only partial references to this subject in the literature (Ermakov et al. 1977, Kondrat'ev et al. 1977, Leshchikov 1975, Poltev et al. 1975, 1978, Serdiukova and Vnukov 1975, Serdiukova et al. 1975, Sokolov 1975, Sukhodol'skii, 1975).

The disturbance of plant and soil covers

The polar deserts have a very thin and discontinuous plant cover, with areas of exposed mineral soil that usually are larger than the areas covered by vegetation (Matveeva and Chernov 1976). Disturbance of this type of cover by vehicles or reindeer herds has little effect on the depth of summer thaw, and in spite of high ice content in the ground, little melting occurs. The main disturbance is destruction of reindeer pasture (Andreev 1977). The same is true in the taiga where damage to the moss cover leads to loss of plant cover in treeless sites (Belyi 1977).

In the forest-tundra and northern taiga zones (fluvio-lacustrine plains) of Western Siberia the removal of the surface moss cover from hummocky peat land and muskeg which are underlain by frozen sand and silts does not lead to significant increases in ground temperatures or depth of seasonal thaw. This is explained by the low thermal conductivity of the peat, which usually dries out at the beginning of the summer. However, once the peat cover is removed, the sands and silts thaw deeper, thermokarst occurs, and lakes and bogs develop (Moskalenko 1975b, c, Nevecheria et al. 1975, Slavin-Borovskii 1975).

Investigations from different locations in the tundra and forest-tundra of Western Siberia during 1974 and 1976 have shown that the differences in moisture content of the ground and the depths of seasonal thaw are not so much conditioned by zonal climatic factors as they are by ecological conditions. These ecological conditions are the factors which determine the degree to which vegetation and soil cover disturbance will affect ground temperatures, moisture and summer thaw (Table 2).

Removal of the tree cover in the southern taiga and forest-steppe zones of Western Siberia decreases the depth and increases the density of the snow cover on the treeless sites, which results in a lowering of the ground temperatures. Islands of permafrost develop and "short-term" permafrost appears where there was none previously. Landscapes are created with characteristic processes of frost heaving and frost cracking (Makeev 1977, Tshigir et al. 1977).

In both the tundra and taiga of Western Siberia, where removal of vegetation and surface soils exposes frozen sands, the newly thawed, dry sands are blown by strong winds, forming human-impacted landscapes termed "sandy arenas." The sand storms damage populated areas (Shilova and Mamaev 1977). Naturally occurring extensive areas of blowing sands or *tukulans* occur in central Yakutia.(Shepelev 1976).

In the northeastern Siberian lowland, with its massive ice wedges, the disturbance and removal of the plant cover and soil mantle increase summer thaw, and thermokarst and thermal erosion are widespread. Hillocky terrain with water-filled depressions and cemetery mounds (*baydzherakh*) is nearly impassable and gullies form (Efimov and Efimova 1975, El'chaninov and Shor 1975b, Zhigarev 1975a, Tyrtikov 1975). The shores and slopes of thermokarst lakes and sea coasts formed from ground containing ice are also subject to erosion (Are 1978b, Troitskii 1977).

In the taiga of Central Yakutia, where there are extensive masses of ground ice, clearing of vegetation, removal of tree stumps and disturbance of the soil mantle cause thermokarst. This process is slowed by the hot and dry summer climate and is limited to the area in which the vegetation was damaged. The surfaces of the sites cleared for agriculture soon become hummocky and boggy (Zamolotchikova and Smimova 1974). Systematic observations at various sites in the region around the city of Yakutsk (Zabolotnik 1978) have shown that clearing of trees while maintaining both the snow and moss cover results in considerable warming of the ground. Four years after forest removal, ground temperatures had increased by 1.3°C at the 3-m depth. However, simultaneous removal of the forest, moss and snow covers leads to considerable cooling of the ground. Over a four-year period of observation, ground temperatures decreased by 1.7°C in comparison with natural conditions.

In drained and dried sites, sodium sulfate and sodium chloride salinization of the soil frequently occurs and about 30% of the agricultural land becomes unusable (Elovskaia et al. 1977a, b). Where fire occurs and massive ground ice is present, "pyrogenic tundra" forms (Kriuchkov 1976, Kurbatskii 1977). In mountainous areas, altiplanation terraces become more active following the disturbance of the plant cover (Kudriavtsev et al. 1977).

Destruction of ground and underlying rock

Excavation during construction and mining, and building of dikes, embankments and spoil piles cause intensive surface disturbance. These activities influence all permafrost zones and particularly sites with high content of ground ice.

During open pit or underground mining and associated construction activities, not only are the soil and plant covers destroyed, but shocks and vibrations from machinery disturb soil structure. Runoff water from mining results in erosion. Changes in topography and the increased chemical and sediment loading of rivers and lakes lead to impacts far beyond the boundaries of direct activity. In areas with soils of high ice content, especially in northeastern USSR, human-impacted landscapes form consisting of cemetery mounds, landslides of thawed earth materials, and other forms of thermal denudation and erosion, and slopes are lowered (Zhigarev 1975a).

Waste rock piles formed during mining activities and construction of embankments are heat insulators. In areas where the permafrost temperatures are relatively high, taliks form within 2-3 years. Piles and embankments disrupt the hydrological regime of adjacent areas and stagnant surface waters accumulate. The taliks form as a result of stagnant waters which coalesce with those formed under the waste piles and embankments, and thermokarst may develop if sufficient ground ice is present.

Table 2. Temperature-moisture regime of soil and ground under natural and disturbed conditions (modified from Moshalenko and Shur 1978).

Natural ecological complex	*Avg ground temp (°C)*	*Avg moisture in 50-cm soil layer (mm)*	*Max summer thaw (m)*
Southern Tundra (1974)			
1. Spotty tundra on sandy loam deposits			
a. Sandy loam spot	−6.2	179	1.15
b. Grass-shrub cover	−5.7	167	1.06
2. Shrub-moss tundra on peaty sandy loam deposits	−6.8	193	0.52
3. Polygonal tundra on peaty sandy loam			
a. Shrub-lichen-sphagnum polygon	7.3	224	0.35
b. Grass-sphagnum trough	−7.2	—	0.43
Forest Tundra (1976)			
4. Spotty polygonal tundra on sandy deposits			
a. Sandy spot	—	35	1.8
b. Shrub-lichen polygon	−1.3	49	1.7
5. Spotty larch shrub on peaty loam			
a. Loamy spot	—	171	1.49
b. Shrub-lichen cover	−2.3	165	1.3
c. Loam with vegetation removed	—	160	1.62
d. Peaty loam with vegetation removed	−2.5	172	1.52
Northern Taiga			
6. Shrub-sphagnum-lichen peat moss			
a. Hummock	−0.8	260	0.63
b. Depression between hummocks	—	285	0.57
c. Same surface with vegetation removed	−0.8	248	0.7
7. Peat-mineral mound with shrub lichen cover			
a. Mound	−0.7	200	0.92
b. Depression	—	220	0.65
c. Same surface with vegetation removed			
Mound	−0.7	160	1.43
Depression	—	180	1.3

Human-impacted terrain, and specifically waste rock piles, is unsuitable for land use; it is also the cause of chemical pollution of water and requires restoration and rehabilitation (Bol'shakov 1975, El'chaninov and Shor 1975a, b, Krylov et al. 1975, Neizvestnov and Postnov 1975, Peretrukhin et al. 1975, Sever'ianov et al. 1975).

Long, deep quarries in the southern part of the permafrost zone are a source of new permafrost formation and accompanying cryogenic processes, if water does not accumulate in them (Klimovskii 1978).

Experience with coal mining operations in permafrost areas has shown the danger of icings and shaft cave-ins where the surface has collapsed to a depth of 60 m. Air and water which enter through the shaft lower the stability of the ground (Sever'ianov et al. 1975, Sever'ianov and Popov 1975). It has been shown that roof thaw depends on the number of galleries and the distance between them (Fedorov 1976).

The influence of urban development

Towns and villages represent a particular type of human-impacted terrain which results from very complex geological and engineering processes. A classification has been drawn up of factors related to human impact and conditions that influence the temperature regimes at the air/ground interface, and of ground waters in populated areas. Both direct and indirect factors that contribute to increasing or lowering the temperature are indicated (Kotlov 1977).

L.N. Khrustalev (1975) studied the influence of large buildings on changes in the geocryological conditions. In the northern and central permafrost zones, it was established that the properties of the snow cover exerted the greatest influence on heat exchange on ground that has been built upon. In southern regions, destruction of peat moss cover, use of artificial surfaces, and the distribution of buildings significantly influence the heat regime, since they change the conditions of moisture movement into the ground (Porkhaev and Shchelokov 1973). Changes in the thermal balance at the ground surface resulting from human impact in the city of Vorkuta led to partial degradation of permafrost for 80-90% of the region (Gorbacheva 1975). Within the main areas of permafrost, towns and villages generally lower the

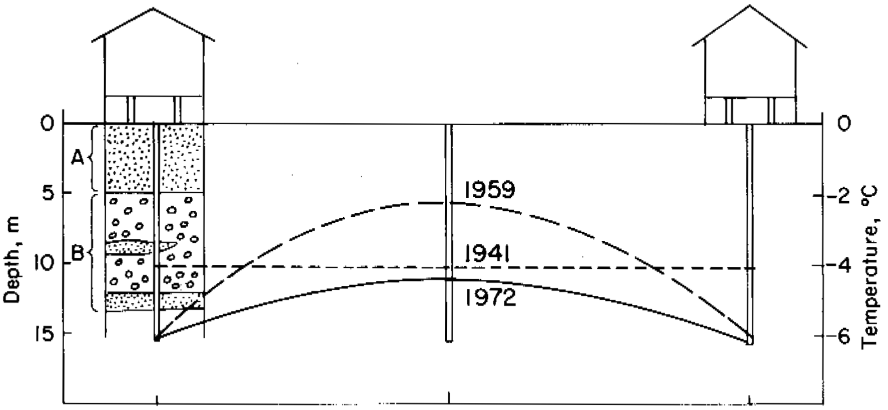

Figure 2. Idealized cross section of buildings and road in Norilsk showing the changes in ground temperature resulting primarily from differences in winter snow accumulation and related methods of snow removal. A is fine icy sand with moisture of 25%, and B is clayey loam gravel with sand lenses. (Bobov and Lapochkin 1974.)

ground temperature (Porkhaev and Shchelokov 1973). Long-term measurements of ground temperature in Norilsk began in the tundra prior to construction and were then taken at various sites and different times as the city building progressed. Three to nine years after building commenced, ground temperatures in the city rose, but 19 to 30 years later they were lower than they were before development (Figure 2). The reason for the decrease was increased removal of snow within the city area when mechanization was introduced (1950-60). Until that time, snow was removed manually and remained in the yards (Bobov and Lapochkin 1974).

In Yakutsk, apart from decreases in ground temperature, particularly below old sections of the city, intensive salinization of groundwater and of the silty loam soils by chlorides of sodium and magnesium has been observed as a result of the penetration of saline water of less than 0°C (about 100 grams per liter) into the active layer and taliks below lakes. Salinization is associated with higher rates of evaporation and low precipitation during the hot summers in a city with insufficient drainage and other amenities (Anisimova 1975).

FORECASTING, MODELING, AND EVALUATION OF TERRAIN SENSITIVITY

The problem of geocryological forecasting, which should be considered as part of ecological forecasting, is very complicated. Most of the investigations represent individual solutions that are related to specific types of construction and that have been based on limited evaluations of isolated geocryological features of the natural environment (Kudriavtsev et al. 1978d, Shvetsov et al. 1973). The prediction of human impact is important to environmental protection (Kondrat'eva 1978, Maksimova 1977a). Working out a theory for human-impact forecasting is a very complicated matter. The thermal regime of the ground and fluctuations in the depth of seasonal freezing and thawing are of great importance in forecasting these processes. Phase transitions of water play the greatest role in these cryogenic processes. It has been established that albedo and radiation balance are the major factors in determining the energy budget of natural terrain. Relationships between the radiation budget and the mean annual temperature of the ground have been established (Pavlov 1975, 1978a, b).

The changes in the temperature regime of ground of various compositions and thermal conductivity and under various geological conditions are determined by the structure of surface heat balance (Balobaev 1974, 1978, Dostovalov 1978, Kondra'teva 1978, Moskalenko 1975c). G.M. Fel'dman (1977), following the ideas of V.A. Kudriavtsev (Kudriavtsev 1974, 1978, Kudriavtsev and Maksimova 1978, Melamed and Medvedev 1974), has developed techniques for forecasting the temperature regime of the upper layer of permafrost in relation to specific geological and geographical conditions. There are various possible approaches for conducting investigations at a particular building site (Alekseev 1977, Garagulia et al. 1975, Konstantinov et al. 1977, Kulakov 1977, Nevecheria 1975, Peretrukhin 1975, 1978).

Geological surveys furnish much of the information necessary for qualitative and quantitative forecasting (Kudriavtsev and Maksimova 1978, Kudriavtsev et al. 1978c). As a result of these surveys, an engineering-geological map of permafrost is prepared and predictions of changes to the natural environment and a forecast map or chart are compiled. A regional classification of soil and rock types and a comprehensive land use evaluation of natural and human impact development have been prepared (Kudriavtsev et al. 1978a, d, Badu and Trofimov 1977, Veisman 1977, Gorbylev et al. 1977, Mel'nikov et al. 1978, Nevecheria and Moskalenko 1977, Nefedova and Chizhov 1975).

In order to accelerate the investigation of new areas that are being considered for development, the method of "preconstruction impact studies" has been proposed. On the basis of surveys at scales of 1:100,000 and 1:200,000, an evaluation of permafrost conditions is made, and the terrain sensitivity resulting from damage to the vegetation cover, to excavation, and to the warming influence of buildings is evaluated. Optimum building methods are chosen, bearing in mind environmental protection measures (Baulin et al. 1978).

Methods have been developed for making rapid engineering and geocryological surveys in oil- and gas-bearing areas and pipeline routes of northern West Siberia (Mel'nikov 1973, Mel'nikov et al. 1974). Most important is the landscape indicator method, which includes widespread application of aerial photography and topographic maps. An example of evaluating the territorial complexity of a gas pipeline route is presented in a graphic model of the gas line in relation to landscape features (Mel'nikov et al. 1975). Compilation of the forecast mapping approaches for the regions of the Poluy-Nadym and Pur-Nadym in Western Siberia have been presented (Mel'nikov et al. 1978). Methods for interpretation and application of aerial and satellite photography, including spectrazonal photography, are being perfected (Gavrilov and Ershov 1977, Gavrilov et al. 1978, Eliseev 1977, Lynov et al. 1977).

Experimental application of thermal aerial photography in permafrost regions produced promising results for mapping geocryological features (Gornyi and Shilin 1978).

An indicator-interpretive scheme has been compiled on the basis of research carried out in the northern taiga and forest-tundra landscapes of northern West Siberia. The scheme includes interpretive features for 16 terrain indicators and their corresponding geocryological conditions (Moskalenko 1975a).

Information received from permafrost surveys is used to define characteristics and conditions when performing quantitative forecasting which includes mathematical and physical modeling. Mathematical models of thawing and freezing processes employ the Stefan solution. Computer modeling of this problem has been suggested and it has good prospects for solving multi-dimensional problems (Melamed and Medvedev 1974, Kudriavtsev 1974). Kudriavtsev has derived a formula for heat circulation within the layer of annual temperature fluctuation which takes into account phase transitions of water during seasonal freezing. It is based on the annual temperature at the bottom of the freeze-thaw layer, and the composition and moisture content of the soil (Melamed 1978). G.M. Fel'dman has proposed solutions that more closely approximate actual environmental conditions (Fel'dman 1973, 1977). Through experimental research, he derived the quantitative dependence of seasonal freeze-thaw depth, temperature of the frozen ground, and heat circulation in the ground on the combined parameters of air temperature and the composition and properties of the snow, vegetative cover and ground (Fel'dman 1977). Thermal conductivity of tundra cover in its natural and disturbed states has been researched by Mandarov and Skriabin (1978). Similar quantitative relationships have been published for Western Siberia (Grechishchev et al. 1975).

A model has been proposed for calculating ground temperature and summer thaw depth in relation to changes in heat balance of the diurnal surface conditions; this model permits one to study the influence of the meteorological regime on geocryological conditions (Palagin and Natanzow 1975). A model and algorithm have been developed for determining the quantitative influence of vegetation and snow cover disturbances on the depth of seasonal thaw, and on ground temperature in the BAM zone (Pal'kin 1975). Analytical solutions have been derived for areas disturbed during road construction (Savko 1978). For the BAM zone forecast estimates or calculations have been made using a statistical model and 1-2 dimensional calculation scheme for heat exchange in soils (Tutkevich and Gorodnova 1977). A solution to the Stefan problem is given in order to choose a method for thermal amelioration of frozen ground (Smorygin and Fandeev 1977).

Analytical solutions are available for predicting the results of cryogenic processes: reworking of shores of lakes and reservoirs (Balobaev and Shastkevich 1974, Gogolev 1977, Savko 1977, Tomirdiaro and Riabchuk 1974), icings or *naled'* (Sokolov 1977), slope processes (Kudriavtsev et al. 1977, Chubarova and Lavrent'eva 1977) and thermokarst (Fel'dman 1977, Shur 1977).

In contrast to the existing solutions to the problem of ground freezing under a snow cover, a different method of solving the problem has been proposed; it takes into account the dependency of the thermal conductivity of snow on temperature. A computer program has been developed for three- and four-layered media using the EVM-M-222 computer (Shipitsina 1978). Solutions to problems concerned with the temperature field of frozen ground around mines and mine shafts have been studied and calculations have been made (Fedorov 1976).

Critical changes of parameters of such systems as soil-frozen ground and thawed ground-groundwater due to industrial development of the territory, and catastrophic changes due to disturbance of the natural environment, have been studied from the thermophysical aspect (Khrustalev 1975).

Physical modeling using electro- and hydrointegrators is being widely implemented in forecasting. This type of modeling has been used for environmental protection purposes in one of West Siberia's regions to evaluate methods for improving water quality (Novikov 1977) and to determine the influence of surface cover and topography on the freezing and thawing of the ground (Ershov 1971a, b, Ershov et al. 1978).

Techniques for evaluating terrain sensitivity to technological impact are being developed. It has been suggested that terrain sensitivity should be estimated on engineering-geological maps (Demidiuk 1977), landform-permafrost maps (Lynov et al. 1977), ice-content maps (Lur'e 1977), and on regionalization maps according to type and intensity of thermokarst, thermal erosion and frost heaving (Chizhov et al. 1977, Smirnov et al. 1975, Stepanov 1977). Systematic photogeological mapping of the territories under development is in progress (Eliseev 1977).

It is recommended that estimates of rates of cryogenic process development and landscape changes be made, and that the effectiveness of environmental protection measures in regions of planned pipeline routes be evaluated. Pipeline route conditions are considered under two different categories: 1) complex, where there is frozen ground, and the temperature of the discontinuous permafrost is high, and 2) simple, where ice content is low and the temperature of the permafrost is low (Baulin et al. 1978). L.N. Maksimova (1977a) has presented the following classification for the engineering-geological evaluation of permafrost areas under development:

1. Regions where development disturbs permafrost conditions and ecological systems, and irreversible cryogenic processes are set into motion, disturbing existing landforms.
2. Regions where development does not cause catastrophic changes in landscape, and where it is possible to partially reestablish natural processes, through natural or artificial means.
3. Regions where changes in permafrost conditions lead to favorable changes in the geological environment.
4. Regions where changes in permafrost conditions have practically no effect on the geological environment.

A ten-point scale of probability for activating cryogenic processes as a result of changes in surface heat balance resulting from territorial development is suggested. However, factual observations necessary for developing this sensitivity scale are insufficient at present (Shur 1977).

A territorial evaluation has been made according to the degree of complexity of engineering undertakings needed to improve permafrost-engineering-geological conditions (Gavrilov et al. 1978). Three categories have been designated:

1. Those conditions that do not need complex measures.
2. Those requiring complex measures.
3. Those which require extremely complex measures.

PROTECTION OF TERRAIN DURING DEVELOPMENT

The main protection measures emphasize prevention of the thawing of permafrost. These measures include thermal and hydro amelioration of soils, biological recultivation where the surface was disturbed during development, and other measures for specific types of developmental activity such as mining, landfill and agricultural development.

Methods have been proposed for ground heat amelioration, control of ice sublimation and desublimation in frozen soils by means of changes in gas medium parameters, and controlled changes on the surface of ground masses (organic film, surface coating) (Ershov et al. 1974, 1978).

Practical measures for environmental protection have been developed during the construction and operation of trunk pipelines, mostly in Western Siberia. Environmental protection measures must adhere to the following requirements: excavation and pipelaying operations should be carried out during the period of stable negative air temperatures; tree stump and root removal is prohibited in areas of high ice content; traffic is possible only with maximum maintenance of the vegetative and soil covers and without disturbance of the soil surface on the right-of-way (Bol'shakov 1975, Ivanov and Friman 1975, Mikhailovskii and Lolua 1975, Serdiukova and Vnukov 1975, Serdiukova et al. 1975). The use of natural and artificial insulating materials is recommended for covering areas that have been denuded of vegetation or soil cover and leveled during construction (Mikhailov 1975). Complex areas requiring costly environmental work and materials are best avoided during pipe-laying due to economic considerations (Sukhodol'skii 1975). During road construction, apart from the above-mentioned measures, it is recommended that fill be placed over the natural vegetation and organic layer or onto artificial thermo-insulation (synthetics, peat, slag, wood flooring). It is desirable to paint the fill surface white (Bol'shakov 1975, Kaganovskaia 1975).

Special techniques and technology are recommended during mining activity such as excavating the producing strata and reinforcing the roofing of galleries and shafts. To prevent surface subsidence over mine shafts it is recommended to use short-face systems (of mining) and to plug the worked-out sections (Fedorov 1976, Krylov et al. 1975, Sever'ianov et al. 1975).

Areas with near-surface, ice-rich soils are considered to be entirely unsuitable for agricultural development within the taiga region if they require uprooting of trees and plowing. Apart from bog formation that may take place, the surface that has been cleared of trees and plowed becomes hummocky as a result of uneven subsidence. Drainage can be introduced where more homogeneous subsidence due to thaw occurs (Vidiunina and Khudiakov 1974). However, drainage is not always effective in cold climate and permafrost areas. Wide experience with drainage and flushing of saline soils has been gained in Central Yakutia (Elovskaia et al. 1977b).

In order to control permafrost conditions in agricultural areas so that cryogenic process development may be avoided and to increase soil fertility, thermal and water amelioration techniques are introduced. Significant amongst these are snow enhancement techniques, which, depending on the conditions, either allow thawing of the underlying permafrost or prevent new permafrost aggradation and pereletok formation. The regulation of snow cover in West Siberia serves as a basis for modifying the temperature regime and freezing and thawing of the soils. Recommendations have been developed for snow retention in fields and a system of techniques for thermal improvement of areas with varying natural conditions has been developed in West Siberia (Tshigir et al. 1977).

Table 3. Depth (meters) of seasonal thaw of sandy loam in Yakutia, under various surface modifications (modified from Pavlov 1978a, b).

Type of cover	*1972*	*1973*	*1974*	*1975*	*1976*
Natural	1.89	1.99	1.80	1.85	1.83
Wooden paneling	1.75	1.78	—	—	—
Wooden panel and foam insulation layer (1 cm)	—	—	0.64	0.73	0.63
Foam insulation (7 cm)	1.01	1.09	0.97	1.00	—
Foam insulation (20 cm)	—	0.42	0.35	0.39	—
Foam insulation (30 cm)	—	—	—	—	0.26

A scheme for land reclamation of Far Northern regions has been developed that holds promise for the future. It includes techniques of drying, irrigation, erosion control, and cultivation among others (Kriuchkov 1977).

Irrigation and drainage techniques for agricultural land in the permafrost zone are treated in numerous papers (Bogushevskii 1977, Elovskaia et al. 1977a, Gavril'ev and Mandarov 1976, Kamenskii 1976, Kriuchkov 1977, Lomakin et al. 1977). Other papers deal with artificial surface cover for purposes of temperature regime control and regulating of the thawing and freezing of soils in the permafrost regions (Demchenko 1978, Pavlov 1978a, Rashkin and Shuvalov 1970, Skriabin 1976, Smorygin and Vediaev 1977, Smorygin et al. 1978).

Several synthetic and natural materials have been tested for protecting soil from thaw. Long-term research in Yakutia and in the northern Tyumen has indicated that foam insulation has high insulating properties compared to other materials, particularly wood paneling (Table 3). The relationship of thaw depths beneath a foam insulation covering of varying thickness and under natural conditions was presented and a formula was suggested for the corresponding calculation (Pavlov 1978a, b). An approximate method for calculating ground thaw dynamics under the insulating layer has been developed using the EVM M-222 and different combinations of insulating layer properties and ground and ambient conditions (Demchenko 1978).

The effectiveness of a water-air foam as a heat insulator is being investigated (Smorygin et al. 1978). Synthetic transparent film is used to increase thawing of frozen soils. A model has been developed which will allow one to compute the ratios of thaw and freeze depth under various plastic film covers in order to determine the optimal time span required to cover the ground and to define how soils will thaw under the film as a result of changes in solar radiation. For more practical application, graphs and charts have been developed (Smorygin and Vediaev 1977). Field observations have shown that the film coverings raise ground temperature by 4 to 4.5°C, speed up the date of onset of thaw by 15 to 20 days, and increase the depth of summer thaw by 0.5 to 1.5 m (Rashkin and Shuvalov 1970, Skriabin 1976).

One of the measures used to restore the disturbances caused during development of territories is the recultivation of vegetation and restoration of terrain. These measures are not only of technical consideration—slope stabilization and recovery of vegetation to favorably affect the ground thermal regime—but are also of aesthetic importance. Difficulties of recultivation are, to a great extent, associated with the very slow natural recovery process of vegetation in the North.

Moss-lichen cover damaged by reindeer movement or destroyed by man is restored only after several decades. Partial meadow formation in denuded sites is arrested after a few years as a result of increased moss and shrub growth and bog formation (Kriuchkov 1977, Vital' 1975). Such phenomena have been observed in the tundra on the bottom of lake basins which have been drained in order to induce meadow formation (Tomirdiarov 1975). In Chukotka, the slow and partial regrowth of grasses on drained basins started to slow down after seven years because of moss growth and permafrost aggradation (Tatarchenkov 1977).

In northern West Siberia grass-moss bogs are the more quickly rejuvenated areas; it is here that bog formation increases when surface cover is disturbed. Shrub-lichen communities of flat peatlands are more slowly restored. Where soil cover is maintained, cloudberries, *Ledum* and cottongrass will grow back within 3 or 4 years. In cases where the peat layer is damaged and thermokarst depressions appear, grass-moss communities will develop. Vegetation, practically speaking, does not regrow on forest-covered hillocks and ridges underlain by frozen sands following the removal of the forest shrubs and peaty horizon. In order to accelerate and maintain growth of the recolonizing vegetation, special agrothermal techniques are applied (Bol'shakov 1975, Ivanov and Friman 1975, Liverovskaia 1975, Mikhailovskii and Lolua 1975, Serdiukova and Vnukov 1975, Serdiukova et al. 1975). In addition, problems of recultivation of human-impacted landscapes have been investigated (Kolesnikov 1974, Potemkin 1975, Razumovskii 1975, Smolianitskii 1976, Shcherbatenko and Kandrashin 1977 and Trofimov 1974).

A regional scheme has been developed for recultivation of impacted areas of Siberia and the Far East. Each zone is characterized by a description of its type of impacted terrain and the type of recultivation to be performed (Ragim-Zade and Trofimov 1977). On the basis of investigations into human impact on the natural complexes of Siberia, studies on the resistance to various levels of disturbance, and their influence on ecological conditions of human life, environmental protection programs have been developed, including recultivation. The optimal scheduling of work has also been considered (Ragin-Zade and Trofimov 1977).

In summary it is possible to classify human-induced terrain disturbance according to type and cause (Shur 1977, Smirnov et al. 1975, Trush and Chizhov 1977). These types, causes, sensitivities, and recommendations for environmental protection and recovery are presented in Table 4.

Table 4. Main types of human-induced terrain disturbances in permafrost regions of USSR, their causes and probable consequences, and general recommendations for environmental protection measures, depending on the surface sensitivity and type of disturbance (1, 2, 3). Based on N.A. Grave (in Gerasimov, in press).

Type of disturbance	*Causes of disturbance*	*Probable consequences of disturbance (according to region's sensitivity)*	*Recommended measures for environmental protection*
I: Compaction and damage to vegetative cover.	Movement of heavy vehicles, particularly in summer; intensive reindeer pasturing; light construction activities.	1 Development of thermokarst-eroded relief with "sunken" lake depressions and gullies. Thermal abrasion of shorelines.	(1) Limitation and regulation of vehicle movement and reindeer grazing; improvement of drainage; filling of upper reaches of gullies; thermo-insulation of surface cover; recultivation.
		2 Appearance of boggy depressions and eroded ditches within boundaries of disturbance.	(2) Regulation of vehicle movement and reindeer grazing; recultivation.
		3 Appearance of small boggy depresssions and ground slumping, restricted to area disturbed.	(3) Recultivation.
II: Destruction of vegetation cover; felling and removal of trees.	Intensive movement of heavy vehicles, especially in summer; drilling and exploration of deep wells; preparing right-of-ways for "linear" construction; fires.	1 See I-1.	(1) See I(1).
		2 In taiga regions of central Yakutia thermokarst subsidence within boundaries of damage. Rock streams and solifluction development on slopes. Increased ground freezing, frost heaving and crack formation of soil without thermokarst.	(2) Insulation of cover; recultivation.
		3 Localized bog formation; soil slumping.	(3) Improvement of drainage; recultivation.
III: Destruction of plant and soil covers, including peat lands; removal of tree stumps; exposure of mineral soil.	Intensive construction; surface grading; clearing for agricultural use.	1 See I-1.	(1) See I(1); winter work preferable; main construction should take place in winter and early spring when clearing forest for agricultural purposes; avoidance of areas of ground ice occurrence; local thermal insulation; drainage; recultivation.
		2 Thermokarst-bog depressions and lakes within limits of destruction. In northern section of West Siberia appearance of "sand arenas." In taiga and forest-stepped regions of West Siberia see II-2.	(2) See II(3); rapid land improvement and recultivation.
		3 Bog formation; appearance and increased development of solifluction and rock streams on slopes.	(3) See II(3).
IV: Excavating and stockpiling of soil and sediment; placement of embankments and pads.	Intensive construction; surface grading; drainage and irrigation ditches; open-pit mining; dredging in rivers.	1 See I-1.	(1) See III(1); placement of fill over vegetation cover; installation of artificial thermo-insulation layer; drainage system for adjacent areas.

Table 4 (cont'd). Main types of human-induced terrain disturbances in permafrost regions of USSR, their causes and probable consequences, and general recommendations for environmental protection measures, depending on the surface sensitivity and type of disturbance (1, 2, 3) Based on N.A. Grave (in Gerasimov, in press).

Type of disturbance	*Causes of disturbance*	*Probable consequences of disturbance (according to region's sensitivity)*	*Recommended measures for environmental protection*
		2 See I-1.	(2) Drainage and recultivation.
		3 Bog formation between dredge piles on fine-grained soils.	(3) If possible, quick reclamation; covering with organic layer.
		In southern regions of permafrost increased freezing of walls and trench bottoms and ditches and permafrost forms if no water present. Development of heaving.	
V: Destruction of mineral rock masses with partial removal of ore, including pumping of water, oil, gas.	Underground mining of minerals; pumping of water and hydrocarbons.	1 See IV-1; subsidence; deep cave-ins of surface overlying mines.	(1) Use of shallow-mining systems with refilling of mined space.
		2 See IV-2; subsidence; cave-ins of surface.	(2) Special measures for reinforcing ceilings of mines and back-filling.
		3 See IV-3; in some cases possible cave-ins and subsidence due to thaw in mine ceiling; possible also to increase freezing of ceiling and walls of mine to increase stability strength.	(3) Under certain conditions induced or forced cold air in shaft; recultivation and surface and ground water drainage.

1 Region of extreme sensitivity:
Intensive processes of thermokarst; thermal erosion forming "sunken" lakes and gullies resulting from outside the limits of the slightest surface disturbance.
2 Region of average sensitivity:
Not so intensive; disturbances remaining within the boundaries of the slightest surface disturbances.
3 Region of low sensitivity:
Weak subsidence with formation of bogs and slope movement phenomena within the area of disturbance.

CONCLUSIONS AND RECOMMENDATIONS

A large number of observations on the response of permafrost terrain to human-related activities and natural processes have been reported. The majority of the North American investigations were undertaken in the Mackenzie Valley and a lesser number in the Arctic Islands and Alaska. Computer modeling of natural and impact processes and related field measurements are providing insight into the relationships of coupled moisture and heat flow. Approaches to terrain sensitivity analyses have been undertaken and partially evaluated.

Active, natural processes occur primarily in the summer and provide useful indicators of potential terrain hazards. These include thermokarst and thermal and hydraulic erosion processes on permafrost terrain containing large quantities of ground ice and river bank erosion and soil slumping and flows on steeper terrain. Fire as a natural agent of thermal disturbance generally results in thickening of the active layer over a number of years and greater incidence of slope failure.

Human-induced disturbances are limited to specific areas of construction or urban areas and linear transportation routes. The intensity and time of disturbance and terrain properties control the response of the terrain to disturbance. Disturbances resulting from summer activities have greater physical and visual impacts than activities occurring in the winter. Most disturbances caused by surface activities in the summer are no longer permitted due to restrictions of access. However, past disturbances are still active and provide useful information on questions of long-term stability and recovery. Off-road vehicle traffic on low pressure or air cushion tires in the summer produces some immediate visual impact and considerably less thermal or physical disturbance compared to more conventional tracked vehicles. Spillage of hydrocarbons on permafrost terrain seems not to cause major thermal disruption; however, the saturated soils and the underlying impermeable permafrost may facilitate movement of the oil downslope and thereby increase the area of impact.

Observations on natural and disturbed active layer thicknesses, thermokarst features, ice wedges, and mass movements are leading to a better understanding and predictive capability of the geographic consequences of disturbance. Response to disturbance by active layer thickening is greater in the warmer discontinuous permafrost zone compared to the colder conditions that exist, for instance, in the Arctic Islands. The use of terrain disturbance as an indicator of climatic change has much to offer. For instance, deterioration of the permafrost at its southern boundary is obvious from the appearance of thermokarst features. Activity and stratigraphy of ice wedges and other ground patterns provide more subtle indications of change.

Some recommendations for continued research are:

1. Continue observations on past disturbances in order to establish the time required to reach the maximum level of disturbance and rate of recovery.
2. Continue development and field testing of terrain sensitivity mapping at several scales and compare approaches and synthesize results between North America and the USSR.
3. Undertake comprehensive geomorphic and regional geothermal investigations for purposes of establishing the stability of permafrost conditions under natural climatic change.
4. Continue the development of computer modeling of coupled heat-moisture flow and field validation in order to anticipate the results of human and natural activities.
5. Establish long-term monitoring observations to confirm or invalidate prior environmental assessments and impact prediction of large engineering projects such as dams, pipelines, and highways (National Academy of Sciences 1975).
6. Continue research to develop improved methods and guidelines of environmental protection and restoration of permafrost terrain.

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APPENDIX I: SYNOPSIS OF TEMPERATURE LITERATURE ON LAND-BASED AND SUBSEA PERMAFROST, MICROCLIMATE AND ENERGY BALANCE, AND RELATED MODELING LITERATURE

Reference	*Location*	*Synopsis*
	Land-Based Permafrost (Non-alpine)	
Brown (1975)	Quebec and Newfoundland	Permafrost is patchy and restricted mostly to peaty areas between the −1.1°C and −3.9°C mean annual air temperature isotherms. Permafrost is widespread north of the −3.0°C isotherm.
Brown (1977)	Devon Island	An upland plateau site yielded the highest mean annual temperature (−14.6°C) and a limestone site near the coast the lowest (−16.8°C).
Brown (1978)	Manitoba and Keewatin	Reports are given on active layer and ground temperature data to depth of 15 m.
Decker and Bucher (1977)	Antarctica	Permafrost thickness is up to 970 m and the temperature in the upper 50 m is as low as −24°C.
Hollingshead et al. (1978)	Mackenzie Delta	Permafrost beneath the channels of the Mackenzie Delta is apparently aggrading in water depths of less than 85 cm.
Isaacs (1974)	Fort Good — Norman Wells	Mean annual temperatures in the upper several meters are generally warmer than at depth, suggesting a climatic warming trend.
Judge (1973)	Mackenzie Valley	Detailed information on the thermal regime is given and the role of snow in maintaining high ground temperature is identified as extremely significant.
Judge (1977)	Devon Island	Based on Brown (1977), the range of thickness of permafrost on Devon Island is 210 m in coastal areas and 659 m on adjacent uplands.
Mackay (1975)	Mackenzie Valley	Mean annual ground temperature increased 3°C from the late 1800s to the 1940s, with a possible 1°C decrease since. The warming has resulted in disappearance of permafrost in many areas of the upper Mackenzie Valley.
Taylor and Judge (1976a,b)	Arctic and Subarctic Canada	Based on temperature measurements, equilibrium conditions were estimated and thicknesses of permafrost are given: Arctic Islands over 700 m; Mackenzie Valley 300-600 m on east side, <150 m on younger west side.
	Land-Based Permafrost (Alpine)	
Barsch (1978) and Haeberli (1978)	Alps	Permafrost is continuous above 3500 m, which is equivalent to a mean annual temperature of −8.5°C; the lower limit of active rock glacier is −2°C MAT.
Fujii (1978)	Northern Hemisphere	Distribution of alpine permafrost is given and total area estimated at 2.3×10^6 km^2. This occurrence of alpine permafrost is related to the coldest and warmest months' mean temperature.
Fujii and Higuchi (1976)	Himalayas	Permafrost occurs above 4900-5000 m.

Reference	*Location*	*Synopsis*
Land-Based Permafrost (Alpine) (cont'd)		
Gorbunov (1978)	World-wide	Two types, oceanic and continental, and eight categories of geocryological belts are distinguished. Permafrost occurs above snowline in the oceanic type and below snowline in the continental type. Permafrost occupies an estimated 1,500,000 km^2 in mountains, excluding the uplands of eastern Siberia and the Far East.
Harris and Brown (1978)	Canadian Rocky Mountains	Temperatures of −1.0° to −1.5°C to depths of 15-30 m are reported, with thickness in excess of 100 m.
Ives (1974)	U.S. Rocky Mountains	Continuous permafrost exists above 4100-4400 m, which is equivalent to an extrapolated minimum mean annual temperature of −9°C.
Woodcock (1974)	Mauna Kea, Hawaii	Permafrost occurs to a depth of 10 m at an altitude of 4140 m.
Subsea Permafrost		
Chamberlain, et al. (1978)	Prudhoe Bay	The physical properties and temperature profiles of shallow subsea permafrost are reported including the occurrence of an overconsolidated marine clay.
Harrison and Osterkamp (1976)	Prudhoe Bay, Alaska	A coupled heat- and salt-transport model is proposed.
Hunter et al. (1976)	Canadian Beaufort Sea Shelf	Beyond the warming influence of the Mackenzie outflow, the maximum thickness of permafrost in equilibrium with the surface temperature ranges from 25 to 75 m.
Judge (1974)	Canadian Arctic	Equilibrium permafrost is widespread off the Arctic Islands. In water more than 100 m deep, areas which were unglaciated and which have undergone little isostatic movement probably contain thick remnants of subsea permafrost.
Lachenbruch and Marshall (1977)	Prudhoe Bay, Alaska	A simplified analysis of the near shore thermal conditions is presented in two cases. 1) Permafrost thaws progressively downward from the sea bed and eventually disappears. 2) Permafrost persists near the sea bed in shallow water that freezes to the bottom seasonally. It requires 1800 years for temperatures to become nearly uniform following inundation.
Lewellen (1977)	Barrow, Alaska	Temperature profiles from varying distances offshore range from −8°C to <0.5°C; the influence of a barrier island on temperatures is discussed.
National Academy of Sciences (1976)	North America	Problems and priorities for research in the offshore permafrost environment are reviewed, particularly for northwestern North America.
Osterkamp and Harrison (1977)	Prudhoe Bay, Alaska	Sea bed temperatures increase from −3.4°C 203 m offshore to <1°C several meters offshore.
Raj and Judge (1977)	Mackenzie-Beaufort Sea	A coupled two-dimensional, heat-mass flow model predicts relict permafrost is probably found in water depths of 60-90 m; in shallow water (<20 m) permafrost is degrading from both the top and bottom; in deeper water (>20 m) it is degrading at depth and may be aggrading near the surface.

Reference	*Location*	*Synopsis*
	Microclimate and Energy Balance	
Addison (1975)	Queen Elizabeth Island, Canada	Microenvironment, energy and water regimes of both natural and disturbed surfaces of two plant communities were determined.
Beattie et al. (1973)	Tununuk, Canada	Energy budgets over disturbed and undisturbed terrain and their relation to the Muskeg Research Institute terrain disturbance classification system are evaluated.
Courtin and Labine (1977)	Devon Island, Canada	The descriptive microclimatology and an evaluation of the energy inputs are given based on data from 12 sites on the Truelove Lowlands and adjacent plateau.
Gray et al. (1974)	Tuktoyaktuk, Canada	Methods to evaluate the energy budgets were developed and data are given for different levels of disturbance.
Guymon (1975, 1976)	Barrow and Fairbanks, Alaska	Field measurements of soil moisture, pressure and temperature were made and seasonal patterns of soil moisture regime are discussed.
Haag and Bliss (1974a)	Tuktoyaktuk, Canada	Energy components for undisturbed upland tundra and disturbed areas including winter roads, oil spills, fires and revegetated sites are analyzed.
Haag and Bliss (1974b)	Norman Wells, Canada	The influence of local forest cover and seismic line on energy exchange and depth of thaw are evaluated.
Haugen, et al. (1976)	Atkasook, Alaska	Air, surface and soil temperatures in tussocks, between tussocks, and in a pond were monitored for summer 1975 and multiple regression analyses performed to obtain relationships among temperature parameters.
LeDrew (1975)	Niwot Ridge, Colorado	The surface energy balance of alpine tundra is determined and an empirical formula for evapotranspiration is derived.
Luthin and Guymon (1974)	Fairbanks, Alaska	Summer soil moisture and temperature data under different vegetation were obtained and a conceptual model of drainage, vegetation cover, and thermal regime proposed.
Mackay and Mackay (1974)	Gary Island, Canada	Regression equations for influence of snow depth on ground temperature at 90 cm are estimated based on 1968-1973 data base; snow cover is probably a major determinant in permafrost depth.
Maykut and Church (1973)	Barrow, Alaska	Monthly and annual averages of incoming shortwave radiation, albedo, incoming longwave radiation and net total radiation are reported and analyzed for the period 1962-1966.
Nicholson (1976, 1978a)	Schefferville, Canada	Vegetation can be removed and snow accumulated by fences to modify ground thermal conditions; heat flux computations are given based on 5.5- and 16.5-m depths.
Ohmura and Muller (1976, 1977)	Axel Heiberg Island, Canada	Heat balance of tundra is given with emphasis on snow melt and active layer developments.
Rouse (1975)	Hudson Bay Lowlands, Canada	Present analyses of mid-summer radiation balance for a shallow tundra lake, wet ridge tundra, natural spruce-lichen woodland, freshly burned woodland, upland lichen heath, and 25-year-old burn.
Rydén (1978)	Abisko, Sweden	Water balance and energy exchange for a tundra mire are presented and results compared with Barrow, Alaska, and several other sites.

Microclimate and Energy Balance (cont'd)

Reference	*Location*	*Synopsis*
Skartveit et al. (1975)	Fennoscandia	Energy flow, microclimatic and climatic components at three arctic and subarctic sites are summarized.
Smith (1975)	Canada	Significant differences in thermal regime exist under various vegetation types; mean annual ground temperature decreases with increasing vegetation.
Weller and Holmgren (1974)	Barrow, Alaska	The microclimate is described and daily heat components computed and summarized by periods throughout the year.

Modeling

Excludes pipeline and other construction-related modeling.

Reference	*Location*	*Synopsis*
Abbey et al. (1978)	Tuktoyaktuk, Canada	Two index models for predicting ground heat flux during the thawing period are presented and verified; one is based on cumulative heat radiation and the other on cumulative air temperatures.
Arnold (1978)	Non-site-specific	A model is described for estimating ground surface temperatures based on relative humidity and point temperature.
Atwater and Pandolfo (1975)	Barrow, Alaska	The relative magnitude of thermal modification and moisture changes due to towns in tundra are simulated.
Goodrich (1978)	Non-site-specific	Non-linear effects associated with temperature-dependent soil thermal conductivity and soil latent heat can significantly affect the snow-ground temperature interaction.
Goodwin (1976)	Barrow, Alaska	Summer soil temperatures on several microrelief elements were obtained and the sensitivity of diurnal near-surface thermal regimes to spatial variability in surface conditions is explored through development and use of models of the surface energy balance.
Goodwin and Outcalt (1974)	Canada	The effect of organic layer removal and drying of the soil surface upon active layer thicknes is simulated; wetness is more sensitive than peat removal in the model.
Goodwin and Outcalt (1975)	Barrow, Alaska	A digital computer model simulates the annual evolution of the thermal regime in the snow cover and active layer.
Guymon and Luthin (1974)	Non-site-specific	A one-dimensional coupled heat and moisture transport is developed.
Lord et al. (1974)	Barrow, Alaska	Interactions of thaw lakes and surrounding tundra are simulated by one- and three-dimensional models.
Lunardini (1978)	Non-site-specific	A theoretical equation for N-factor as a function of air index, seasonal surface heat transfer exclusive of convection, surface coefficient of convection, and soil thermal properties is developed.
McGaw et al. (1978)	Barrow, Alaska	Precise soil temperatures and measured thermal conductivity data for wet organic-rich soils are combined to calculate summer heat fluxes to a depth of 1 m.
McRoberts (1975)	Non-site-specific	Thawing under the natural active layer occurs according to the equation $X = \alpha\sqrt{t}$ (X = depth of thaw, t is time, and α is a constant expressed as cm/s$^{1/2}$).

Reference	*Location*	*Synopsis*
		Modeling (cont'd)
Miller (1975)	Non-site-specific	A surface heat balance simulator is described which can be used to predict permafrost temperatures due to disturbance and to permafrost protective schemes.
Ng and Miller (1975)	Barrow, Alaska	Model structure and initial validation of a tundra canopy soil temperature-thaw model are presented.
Ng and Miller (1977)	Barrow, Alaska	Calculated air and soil temperature agree within 1°C of measured profiles and thaw is generally predicted within 1 cm for an improved canopy-soil temperature model.
Outcalt et al. (1975)	Barrow, Alaska	Snow ripening, melt, and accumulation and active layer temperatures are simulated in conjunction with a snow fence modification experiment.
Outcalt and Brown (1977)	Fairbanks, Alaska	The thermal modifications of forest clearing, snow removal and accumulation and pavements are simulated.
Outcalt and Carlson (1975)	Non-site-specific	A simple surface climate simulator is described which can be used to simulate the surface energy budget and soil thermal evolution.
Sheppard, et al. (1978)	Non-site-specific	Verification of coupled flow model using detailed laboratory and field experiments.
Smith (1977)	Eureka, Canada	A model which simulates microclimatic and ground thermal regimes is evaluated using field data for a dry and wet site, and the computer program and user's manual are presented.

GEOPHYSICS IN THE STUDY OF PERMAFROST

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Review Paper: Third International Conference
on Permafrost, Edmonton, July 1978

I. INTRODUCTION

A. Scope

In this review of permafrost geophysical techniques emphasis is placed on methods that penetrate into the earth to depths great enough to provide information on permafrost properties or distribution. The emphasis is also on the North American literature and experience, because of the origin of the authors. A brief summary of current Soviet experience has been prepared by Akimov et. al., (1979). The review covers the period since the Second International Conference held in the Soviet Union in 1973, although in a few cases the period was extended to establish historial perspective. The discussion includes investigations made on land and off shore, based on surface and airborne observations.

The reason for interest in geophysical exploration techniques in permafrost regions is obvious. As northern regions are developed we are continually reminded of the unpredictable nature of ground ice and permafrost distribution, the consequence of inadequate subsurface data, and the high cost of drilling even at large interhole spacings.

As a result of the need for methods to supplement drilling observations and to provide less expensive means of rapidly obtaining subsurface data, geophysical methods have seen increased application in research and problem-solving studies in permafrost regions. This has included studies associated with the large pipeline programs in both Alaska and Canada. A new emphasis in commercial geophysical equipment development is also apparent, directed at acquiring shallow subsurface data to fill the needs of geologists and engineers.

Two processes are involved in the interpretation of data from geophysical measurements in permafrost terrain. The first is the derivation of the geophysical character of the ground (for example, distribution of resistivity or velocity values) from the raw data. The second is the determination of the relationship between these geophysical properties and the permafrost conditions which prevail. Some of the geophysical techniques considered in this paper have relatively well developed interpretation schemes and therefore their utility rests on the relationship between the observed geophysical parameters and the permafrost properties of interest. Other techniques are limited by interpretation procedures which are currently relatively undeveloped.

The application of almost all geophysical methods to problem-solving in permafrost regions is linked to the change in the physical properties of earth material associated with freezing of incorported water, and formation of varying amounts of incorporated ice. The degree of change in the physical properties depends on moisture content, pore size, pore water chemistry, ground temperature, and pressure on the material. Some of these variables can have a significant influence on the properties by controlling the temperature at which freezing can occur and the amount of ice associated with a material. This is true, for example, in marine sediments where pore water can have a high salt concentration, and in fine-grained soils such as clay that can have high unfrozen water contents due to the interfacial interaction that occurs between the mineral matrix and water (Anderson and Morgenstern, 1973). For this reason the parameters detected by most geophysical methods in permafrost distribution studies may not correlate exactly with permafrost distribution as indicated by temperature alone.

Therefore it is necessary to understand what properties are being measured during geophysical investigations in order to anticipate any differences that may exist between permafrost limits indicated by the various techniques. Fortunately, in most cases the significant changes in properties of the earth to which the various geophysical techniques are sensitive occur at temperatures only slightly lower than 0°C. The following section discusses the parameters determined by the geophysical methods covered in this review, and their dependence on freezing of incorporated water.

B. Relevant Geophysical Parameters

Observations made by electrical and electromagnetic techniques at excitation frequencies below 100 kHz are sensitive primarily to the resistivity of materials. Figure 1, based on Hoekstra and McNeill (1973) and Olhoeft (1978) shows the variation in resistivity with temperature for some materials and illustrates the general increase in resistivity that normally occurs with freezing. The techniques that operate at frequencies above 100 kHz are influenced by both resistivity and relative permittivity (dielectric constant) (Katsube et al., 1976). High-frequency laboratory measurements made by Annan and Davis (1978) illustrate the dependence of relative permittivity on temperature for a clay soil (Figure 2). Additional data showing changes in relative permittivity and loss tangent with freezing of the

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ground are available from studies reported on in the proceedings of this conference by Rossiter et al., (1978). Their data, obtained from field measurements, show a noticeable decrease in loss tangent and relative permittivity with seasonal freezing of the active layer.

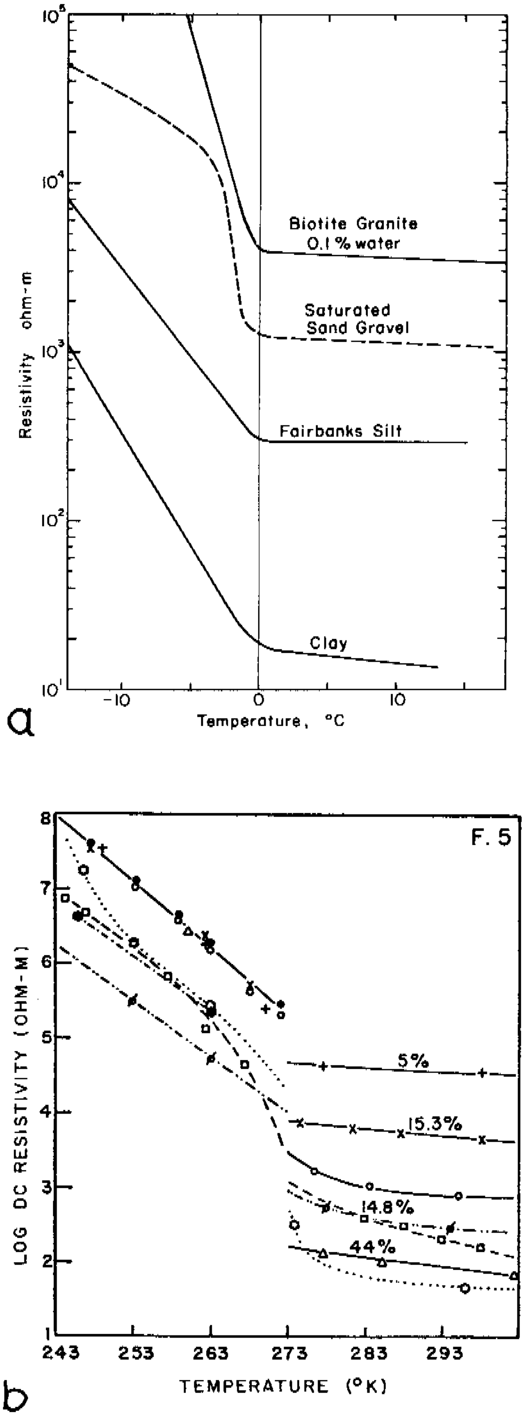

Figure 1. Variations in resistivity with temperature for some material types. (a) after Hoekstra and McNeill (1973), and (b) after Olhoeft (1978).

The seismo-acoustic techniques all rely on changes in the compressional and shear wave velocities of rocks and soils which normally occur with freezing. These changes can be as dramatic as those that occur in the electrical properties of most earth materials. This change in velocity with freezing is discussed by Pandit and King (1978), whose measurements were made at acoustic frequencies on rocks with varying pore-water salinity. Figure 3, which shows changes in velocity with temperature for several material types, is based on the studies done by Aptikaev (1964). Studies of compressional wave velocities conducted by Stevens (1973) and others indicate compressional velocities of around 3100 m/s for silt-sized material at around -4.0°C. The velocities were similar to field measurements obtained by Hunter (1973a) for ice wedges in permafrost at the same temperature. On the basis of these studies Stevens concluded that detection of massive ice in material of this type was not possible because of lack of velocity contrasts.

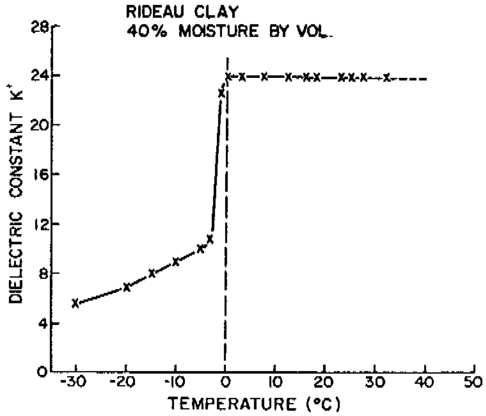

Figure 2. Dependence of relative permittivity (dielectric constant) on temperature, based on high-frequency measurements made by Annan and Davis (1978).

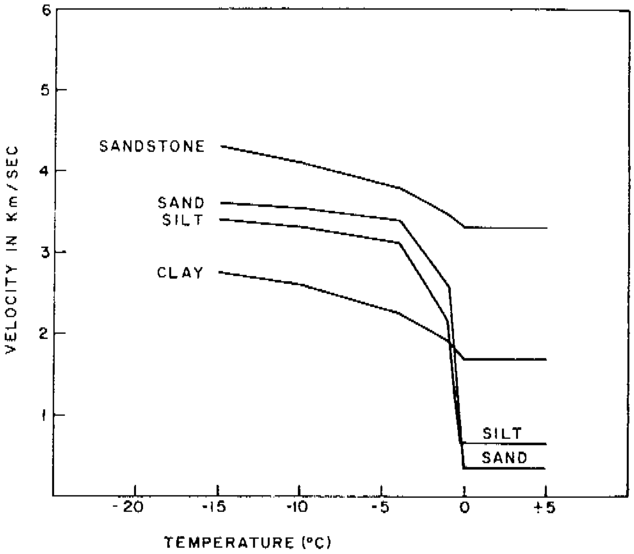

Figure 3. Dependence of velocity on temperature from observations made by Aptikaev (1964).

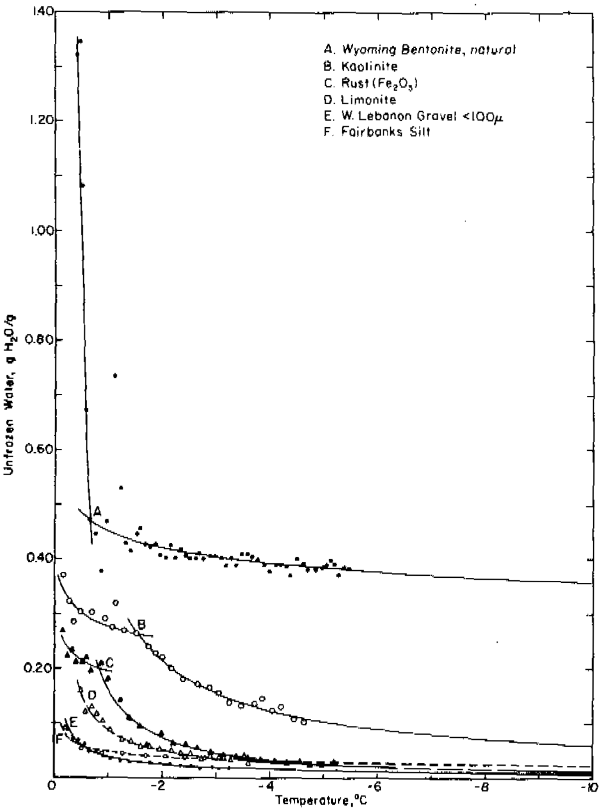

Figure 4. Influence of temperature on unfrozen water content from Anderson and Morgenstern (1973).

In general, then, resistivity and velocity increase and relative permittivity and loss tangent decrease as temperature decreases through 0°C. It is important to note that these temperature-dependent changes are the result of the formation of ice in the material under study, and thus need not occur exactly at 0°C. If the pore water is saline, for example, ice may not form until the temperature drops significantly below zero. Thus the position of a freezing front determined by geophysical techniques may differ considerably from the position of the 0°C isotherm. (Kurfurst et al., 1974).

In addition to the initial change in the parameters caused by ice formation, the progressive change in properties with decreasing temperature can be related to the amount of unfrozen water that can remain in some materials (Tice et al., 1978). The illustration from Anderson and Morgenstern (1973) (Figure 4) helps to indicate the large quantity of unfrozen water that can occur at temperatures as low as -5.0°C in some material.

The density of earth materials is an additional parameter to which some geophysical techniques are linked. The density of some soils can be greatly reduced when they are subjected to freezing. This degree of change can vary with soil grain size, availability of water, and freezing history, the same parameters that influence the frost heaving characteristics of a soil. Ice lenses forming in fine-grained soils (silt and clay) can reduce the soil density to a value approaching that of ice, with the reduction continuing during freezing until water is no longer available or the freezing rate is no longer appropriate. Coarse-grained materials undergo little density change through ice lens formation but can contain ice masses formed by other mechanisms such as ice wedge development. The density and ice content of earth materials have been examined by radiometric techniques. Density has also been used as the critical parameter in determining distribution of large ground ice features by gravity techniques.

Most geophysical techniques used in permafrost studies respond to changes in acoustic velocity, electrical resistivity, relative permittivity, loss tangent and density or to changes in combinations of these parameters. Interpretation of the results obtained from the geophysical measurements yields only values and distribution of values of these parameters. An additional step is required to correlate the interpreted parameter values with permafrost conditions.

C. Problems Amenable to Solution by Geophysical Techniques

To help structure this paper and to provide an indication of the many geophysical systems and their unique characteristics, two tables were prepared. The first introduces the techniques and associated methods. The techniques are grouped in four general classes: electrical, electromagnetic, seismo-acoustic and miscellaneous. Methods in the first two classes are referred to the frequency range of the excitation used in the measurement (Table I). The methods listed under these techniques are all treated independently in the followingdiscussion. This is done with the aid of Table II, which indicates how the varous geophysical techniques have been applied to problem solving in permafrost regions. This table includes all the geophysical techniques and specific methods that have recently been utilized in permafrost studies in North America. Characteristics of the methods covered include the energy or excitation source and its frequency. A general discussion of the type of equipment used includes a description, its stage of

Table I. Geophysical Techniques and Associated Methods.

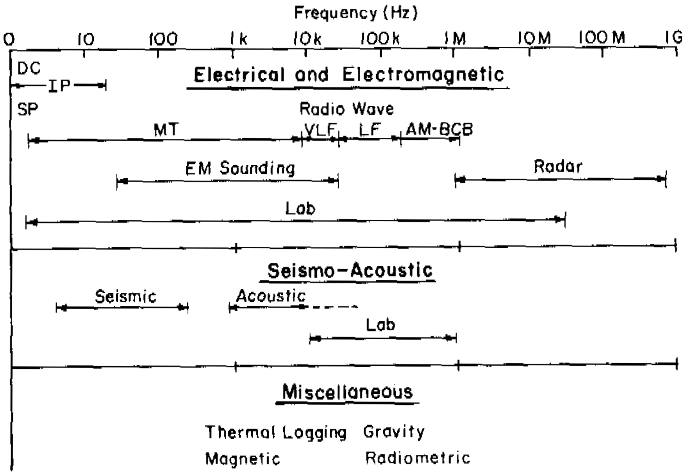

Table II Geophysical Techniques and their application to problem solving in permafrost regions.

						APPLICATIONS				
						PERMAFROST DISTRIBUTION		PROPERTIES		
Technique	**Method**	**Excitation**	**Freq.**	**Example**	**Deployment**	**Horizontal**	**Vertical**	Ground ice **1. Pore 2. Lens 3. Massive**	**Material Type**	**Section**
ELECTRICAL	"DC" Resistivity	Galvanic (electrodes)	DC-15hz	Commercial and research equipment with electrodes commonly placed in Wenner, Schlumberger or other array	Surface (land)	Wide application	Wide application	Some application (2&3)	Some application	II.A
					Surface (water)	Limited application	Limited application	unknown	unknown	II.A
					Borehole	Some application	Some application	Some application	Some application	II.A
	SP	Electro-chemical differences	DC	Commercial equipment	Surface (land)	Limited application	Not applicable	unknown	Limited application (metallic sulphides)	II.B
					Borehole	Not applicable	Some application (dynamic freezing fronts)	unknown	unknown	II.B
	IP	Galvanic (electrodes)	DC-15Hz	Commercial equipment	Surface (land)	Limited application	Limited application	unknown	Some application (especially metallic sulphides)	II.C
ELECTRO-MAGNETIC	MT Natural	Natural Fields-Solar Storm	<1Hz	Long period MT Commercial and research equip.	Surface	Limited application (thick permafrost)	Limited application (thick permafrost)	Not applicable	Not applicable	III.A
		Atmospheric Discharge	>1Hz	Short-period AMT research equip.		Limited application	Limited application	unknown	unknown	III.A
	MT Artificial	Remote Transmitter		Radiowave methods						
		Naval	VLF 3-30 kHz	Surface impedance (radiohm)	Surface	Some application (especially thick permafrost)	Limited application	Limited application	Some application	III.B
				wave tilt	Airborne	Limited application (large features)	Limited application (large thicknesses)	Not applicable	Some application (large features)	III.B

Technique	Method	Excitation	Freq.	Example	Deployment	Horizontal	Vertical	1. Pore 2. Lens 3. Massive	Material Type	Section
ELECTRO-MAGNETIC	MT Artificial	Aircraft Navigation Aid	LF 200-400 kHz	Surface impedance (radiohm)	Surface	Some application	Limited application	Limited application	Some application	III.B
				Wave tilt	Airborne	Limited application (large features)	Not applicable	Not applicable	Limited application	III.B
		AM Broadcast transmitters	AM-BCB 500-3000 kHz	Wave tilt	Airborne	Limtied application	Not applicable	Not applicable	Limited application	III.B
	Inductive sounding and profiling	Inductive	40Hz-45kHz	Coils on rigid boom	Surface	Wide application (especially thin permafrost)	Some application (thin permafrost)	Limited application	Some application	III.C
				Helicopter EM	Airborne	Limited application (large features)	Limited application (thin permafrost)	Not applicable	Some application (metallic sulphides)	III.C
				Large Coils variable spacing and frequency	Surface	Limited application	Some application (thick permafrost)	Not applicable	Limited application	III.C
				Small Coils variable spacing	Surface	Some application	Some application	Limited application (3)	Some application (including metallic sulphides)	III.C
				Induction Logging	Borehole	Not applicable	Some application	unknown	Some application	III.C
	Radar	Local transmitter (antenna)	1 MHz-100 mHz	Commercial and research equipment (Impulse)	Surface (land)	Limited application (limited by fine-grained materials)	Some application	Some application	Limited application (inference from structure)	III.D
					Surface (ice)	Wide application for ice-thicknesses studies				III.D
			1 MHz-1000 MHz	Altimeter and radio echo sounder	Surface and airborne	Wide application for glacier ice studies				III.D
	TDR	Transmission line	1 MHz-1000 MHz	Commercially available (cable tester)	Surface	Not applicable	Some application (active layer studies)	Limited application (1 & 2) (freezing front studies)	Not applicable	III.E
	Radio-Freq. Interferometry	Local transmitter	1-32 MHz	Research equipment	Surface	Not applicable	Unknown (probably not applicable)	Not applicable	Not applicable	III.F

Technique	Method	Excitation	Freq.	Example	Deployment	Horizontal	Vertical	1. Pore 2. Lens 3. Massive	Material Type	Section
SEISMIC	Refraction	Explosives	5-500 Hz	Single ended and reverse multichannel array-single detector moving source array	Surface (land & water)	Wide application	Wide application (top of permafrost)	Some application	Wide application	IV.A
		Vibrator			Surface (land & water)	"	"	"	"	"
		Weight drop			Surface (land)	"	"	"	"	"
		Gas Exploder			Surface (land & water)	"	"	"	"	"
		Air Gun			Surface (land & water)	"	"	"	"	"
		Sparker			Surface (water)	"	"	"	"	"
	Reflection	Explosives	5-500 Hz	Split Spread shooting	Surface (land & water)	Some application (feature size equal array length)	Some application (with velocity stocking)	Limited application (3)	Some application	IV.B
		Vibrator		Single ended array	Surface (land & water)					
		Weight drop		Common depth point	Surface					
		Gas Exploder			Surface (land & water)					
		Air Gun			Surface (water)					

Technique	Method	Excitation	Freq.	Example	Deployment	Horizontal	Vertical	1. Pore 2. Lens 3. Massive	Material Type	Section
SEISMIC	Borehole	Explosives	5-500 Hz	Crystal cable (multi-channel hydrophone array)	Borehole	Not applicable	Wide application	Some application (1&2)	Wide application	IV.D
		Vibrator								
		Weight Drop		Three component wall lock geophone (single & multi-channel array)						
		Air Gun								
	Surface Wave	Explosives	5-500 Hz	Rayleigh Wave	Surface (land)	Limited application	Some application (top of permafrost)	Not applicable	Limited application (with refraction)	IV.F
		Vibrator								
		Weight Drop								
		Air Gun								
ACOUSTIC	Reflection	Air Gun	1-10 kHz	Both single and multi-channel detector arrays	Surface (water)	Some application (shallow permafrost)	Some application (top of permafrost)	Not applicable	Limited application	IV.C
		Sparker			Surface (water)					
		Various electro-mech devices (Boomer)			Surface (water)					
		Transducers			Surface (land & water)					
	Borehole	Transducers	10-100 kHz	Single source-multi detector array	Borehole	Not applicable	Limited application (incased holes, to find base of permafrost)	Not applicable	Not applicable	IV.E

Technique	Method	Excitation	Freq.	Example	Deployment	Horizontal	Vertical	1. Pore 2. Lens 3. Massive	Material Type	Section
MISCELLANEOUS	Gravity	Natural Gravitational Fields	N/A	Gravity profiling	Surface	Not applicable	Not applicable	Limited application (2&3) (total excess ice only)	Not applicable	V.B
	Magnetic	Natural Magnetic Fields	N/A	Magnetometer profiling	Surface	Not applicable	Not applicable	Limited application (3, when contrast exists)	Not applicable (except for prospecting in permafrost region)	V.A
	Thermal Logging	Natural ground temp.	N/A	Thermal profiling (vertical)	Surface (land & water) Borehole	Wide application	Wide application	Not applicable	Not applicable	V.D
	Radio-metric	Gamma Radiation	N/A	Density Logging	Borehole	Not applicable	Not applicable	Some application (2&3)	Some application	V.C
		Neutron	N/A	Porosity	Borehole	Not applicable	Not applicable	Some application (2&3)	Some application	V.C

development, and terms or trade names commonly used for identification. Discussion indicates the applicability of existing equipment for ground or airborne studies, and more specifically for land, marine or borehole investigations.

Permafrost problems amenable to solution by geophysical means fall into two major groups: defining distribution and determining properties. The problem of defining permafrost distribution is subdivided into definition of horizontal limits (mapping) and vertical limits (sounding). Mapping of the horizontal limits of permafrost is, for many engineering projects, most critical in the southern, more discontinuous permafrost zone (Brown, 1967), because of the frequent transitions from frozen to thawed materials. In such cases thawed material surrounds local frozon zones. In contrast, in the more continuous zone, permafrost mapping problems are related to determining the shape and the size of taliks.

The study of vertical limits or distribution of permafrost involves determining its upper and lower boundaries, as well as the position of thaw zones within the permafrost section. The great variation in permafrost thickness from several meters at its southern boundary to several hundred meters in the far north (Brown 1970) imposes a wide variety of equipment requirements. The various methods all have characteristic effective depths of penetration, with some methods suited only for qualitative determination of one of the vertical limits.

Interpretation of most of the data acquired by the methods to be discussed is based on simple models. The model for horizontal distribution of permafrost (Figure 5a) assumes lateral variation in temperature from values above 0°C to values below 0°C. In geophysical terms this model has high relative permittivity, high loss tangent, low resistivity, low velocity and normal density in the region with temperatures above 0°C, and low relative permittivity, low loss tangent, high resistivity, high velocity and slightly lower density in the region with temperatures below 0°C. The contact between frozen and unfrozen zones is considered to be well defined by relatively sharp changes in the electrical properties.

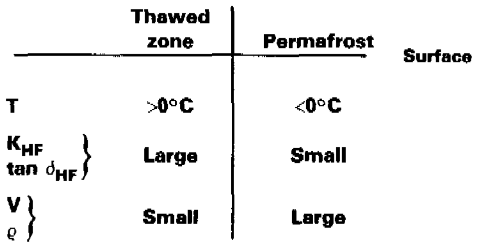

Figure 5a. Simple Model for Horizontal permafrost distribution.

The model for vertical permafrost distribution (Figure 5b) assumes a situation in which geophysical properties depend only on depth and are laterally invariant. The simplest model assumes two homogeneous layers: a frozen layer representing permafrost, and an underlying unfrozen layer. In the unfrozen layer relative permittivity and loss tangent are high, resistivity and velocity are low. In the frozen layer relative permittivity and loss tangent are comparitively low and resistivity and velocity are high. If the model is for summer conditions, it is necessary to add an upper unfrozen layer.

	T	K_{HF}, tan δ_{HF}	ρ, V	Surface (summer)
Active layer	**>0°C**	**Large**	**Small**	
Permafrost	**<0°C**	**Small**	**Large**	
Thawed zone	**>0°C**	**Large**	**Small**	

Figure 5b. Simple Model for Vertical permafrost distribution.

The most common and successful application of permafrost geophysics has been for permafrost distribution studies. Some of the earliest permafrost geophysics efforts in Alaska were directed toward providing information on the horizontal extent of permafrost. Limits of permafrost were determined by resistivity methods in early studies by Joesting (1941) and Barnes and McCarthy (1964). The latter study employed shallow seismic refraction, and DC resistivity. Past work and more recent investigations supported with new equipment and procedures continue to demonstrate that data can be acquired on permafrost limits in geological settings where adequate geophysical contrast exists between the frozen and thawed materials (Arcone et al., 1978; Hoekstra et al., 1975; Seguin, 1978; Scott and Hunter, 1977; Annan and Davis 1978; Rennie et al., 1978, Rogers and Morack, 1978).

Geophysical studies in permafrost regions have been directed more recently to characterising permafrost properties. The properties amenable to geophysical determination are ice content and material type. The property unique to permafrost and to which most practical problems can be related is ground ice content. For this reason part of the applications section of Table II is devoted to ground ice. The ground ice types have been grouped into three classes for comment: pore ice, lens ice, and large massive ice features. This is a simplified grouping compared to the classification schemes discussed by Péwé (1963). These classes were selected because they can have distinctly different physical properties to which some of the methods can be sensitive.

Pore ice occurs in the natural voids in earth materials. The volume may vary from saturation of the voids to films of ice on void surfaces or grain contact points. Formation of pore ice is primarily responsible for initial changes in properties of most material types.

Ice lenses are small ice masses that form when water moves to a freezing front. This process forms lenticular ice (excess ice) which upon melting results in moisture contents in excess of saturation and void ratios in frozen soils that commonly exceed unity. These features are unique to materials that are fine grained such as silts and clays. An arbitrary limit of several centimeters in thickness was selected for the upper size of the lenses in this category, with all larger lenses placed in the massive ice class.

The massive ice class is extremely general and includes all large ice masses found incorporated in perennially frozen, usually ice-rich materials. The ice features include pingo ice, wedge ice, large lenses and ice layers and bands.

Acquiring information on ground ice continues to be a significant challenge even though adequate geophysical contrast exists between ice and some material types. The best opportunity for success exists in geological settings where subsurface conditions are very homogeneous and variation in geophysical parameters can be related to a single variable such as changing ice volume. Even under these ideal conditions the results can be adversely influenced by such variables as ground temperature and material type (Arcone et al., 1979). In some materials low ground temperatures reduce the unfrozen water content of the sediment to the point where contrast in physical properties of frozen ice-rich sediment and massive ground ice is significantly reduced.

Several recent investigations based on observations made with electromagnetic and gravity techniques have illustrated that under some ground conditions data can be acquired on distribution of ground ice masses (Delaney et al., 1977; Kovacs and Morey, 1979; Bertram et al., 1972; Arcone et al., 1978, Arcone et al., 1979; Osterkamp and Jurick, 1979; Rampton and Walcott, 1974, Hunter et al., 1975, Scott and Hunter, 1977). In most of the cases cited the investigations provided information on the large ground ice masses such as wedges and lenses. Obviously the detection and characterization of permafrost are dependent in most geological situations on the contrasts between ice-free ground and ground containing ice. Until recently few attempts to characterize ground ice distribution were made or were even possible because of the limited capability of most techniques to resolve local variability in ground conditions, and small contrasts between some ground ice types and adjacent material.

Table II also indicates which methods have been used to provide information on subsurface material types. Natural variations in the properties of earth materials can significantly influence the parameters to which geophysical methods respond. Aspects such as grain size of sediments, distinction between sediment and rock, and presence of metallic minerals can be determined. Many geophysical methods have historically been used in nonpermafrost settings to determine differences in material types and properties. For example, well established relationships exist for resistivity as a function of grain size of material (Jackson et al, 1978). Many of these relationships still apply even in permafrost regions where a general increase in values is associated with incorporated ice (Sellmann et al., 1977).

II: ELECTRICAL TECHNIQUES

A. DC Resistivity Method

The DC resistivity method is one of the most commonly used for permafrost studies. It involves passing current through the ground between electrodes and measuring the resulting potential distribution through other electrodes. The exciting current commonly is either DC or at an extremely low frequency, 15 hz or less, and the penetration depth controlled by electrode geometry. Since the method has been in use for more than 50 years techniques for interpretation are well developed, particularly for layered models. Recent advances in applying inversion techniques to the interpretation of DC resistivity data (Inman, 1975; Pelton et al., 1978); Rijo et al., 1977; Zohdy, 1975) allow the determination of both lateral and vertical variation of resistivity together with some estimate of the reliability of the interpretation. Since penetration is a function of the size of the exciting array, increased penetration causes a loss in lateral resolution. If the vertical resistivity distribution contains large contrasts in resistivity, the sounding technique may not be able to resolve small thicknesses of highly resistive permafrost (Scott and Mackay, 1977). In general, however, the resistivity technique on land has proven extremely useful for studying both horizontal and vertical distribution of permafrost and has gained wide acceptance. (Wyder et al., 1973; Scott and Hunter, 1977; Ghosh and Halloff, 1974; Cooper, 1974; Seguin, 1977 and 1978; Haeberli, 1978).

Estimating the concentration of ground ice in a permafrost section by correlation with the interpreted resistivity distribution is not always simple. In fine grained sediments small variations of temperature can produce large variations in resistivity which could be mistaken for variations in pore ice content. (Olhoeft, 1975; Hoekstra et al., 1974, Seguin, 1978). However, as the concentration of ice increases and as ice occurs more in lenses and in massive form, a combination of interpreted resistivity and geometry becomes increasingly useful. With experience in a given area, one can identify the type of material present in a permafrost section with some reliability. (Hoekstra et al., 1975).

In recent years attempts have been made to employ the DC resistivity method in shallow waters having low salinity for mapping the distribution of sub-bottom permafrost (Scott, 1975a; Scott and Hunter, 1977). While present experience is extremely limited the concept shows considerable promise both for mapping permafrost distribution and possibly for determining the ice content and material type within sub-bottom permafrost regions.

DC resistivity measurements have been made in boreholes to locate interfaces between frozen and thawed zones in complicated permafrost conditions. Such measurements have been used along with other geophysical data to assist iron-ore mining operations in permafrost regions. (Seguin, 1978).

Since there is in general a large contrast in resistivity between frozen and unfrozen material of the same type, and since DC resistivity methods can be readily interpreted to yield subsurface resistivity distributions, the DC resistivity method continues to be used to study a number of permafrost problems. The major disadvantage of DC resistivity techniques is the slow rate at which data are taken. Each measurement requires ground contact at a minimum of four points, and as a result the time required for a large survey is great. With the development of non-contact methods for resistivity measurement, the DC technique is receiving less emphasis, but it will likely continue to provide a useful approach for solving some permafrost problems.

B. Spontaneous Polarization Methods

The Spontaneous Polarization, self potential or SP method involves the determination of the regional static potential distribution which arises because of electrochemical differences in the subsurface. The SP method is well known in mineral prospecting and consequently commercial equipment is readily available (Telford et al., 1976). The SP method has, however, not been widely applied in permafrost studies.

In laboratory studies significant potential differences have been observed across the interface between ice and water during freezing. The observed potential differences are a function of the rate of freezing and of the ionic content of the water (Petera, 1973; Yarkin, 1973). Large potential differences have also been observed in the field across the interface between frozen and thawed portions of the active layer (Mackay, 1978) and in drill holes across frozen zones in discontinuous permafrost (Seguin, 1977).

Since the magnitude of the freezing potential depends on movement of the freezing front it is unlikely that the SP technique will be useful in mapping the horizontal distribution of permafrost when that distribution is stable. However, in situations where permafrost is aggrading or where an active layer is freezing the method shows some promise of yielding an indication of the rate at which freezing is progressing. Since interpretation techniques for SP methods are not well developed even in non-permafrost applications, (Telford et al., 1976, p. 468) it appears unlikely that SP methods will be useful in determining the properties of permafrost sections, except where measurements are made in boreholes.

C. Induced Polarization (IP) Methods

The Induced Polarization method is a special case of the DC resistivity method in which the measurement of resistivity is extended to include determination of the low-frequency relative permittivity of the earth. Significant values of relative permittivity arise from the perturbation of electrical polarization on the surface of particles when current is applied to the ground. The IP technique is commonly used for prospecting for metallic sulphides, which exhibit strong surface polarization (Telford et al., p. 702 et seq). In the absence of sulphides, the degree of polarization of frozen ground varies with temperature and ice content (Olhoeft, 1975). Field measurements have proven the utility of the technique for permafrost studies but it is still not widely used in North America, although it has been employed in the USSR (Melnikov and Snegirev, 1973).

D. Summary

Among the electrical techniques DC resistivity has achieved widespread acceptance for use in studies of permafrost distribution and analysis of properties in the permafrost section. Other methods such as SP and IP may have relevance to particular problems but have not achieved widespread acceptance in permafrost work in North America.

III: ELECTROMAGNETIC TECHNIQUES

A. Natural Field Magnetotelluric Methods

Magnetotelluric (MT) methods utilise naturally occuring electromagnetic fields within the earth. The long period, low frequency part of these fields is caused by the interaction of solar storms with the earth's magnetic field while the short period, high frequency part is caused by atmospheric discharge of electricity. In both cases the fields in the earth are horizontally-polarized plane waves propagating vertically downwards.

In the MT method, observation depth or penetration is a function of the frequency of the signal being measured. Use of the MT method involves measuring both the electric field and the orthogonal magnetic field at or near the surface. From the ratio of these two quantities an apparent resistivity can be calculated. Measurement at many frequencies provides information on the variation of resistivity with depth. Inversion techniques for interpretation of MT data are nearly as well developed as for DC resistivity (Nabetani and Rankin, 1969; Rankin et al., 1974). Some success has been achieved with short period MT (audiofrequency MT or AMT) in measuring both the thickness and the horizontal distribution of permafrost (Koziar and Strangway, 1975 and 1978; Rossiter et al., 1978). The interpretation of the presence of ground ice or of material type appears to be beyond the limits of accuracy of the technique. The MT method has an advantage over DC resistivity in determining the thickness of very thick permafrost sections since the exciting field occurs naturally and consequently does not require elaborate high-powered generators for its utilization. Natural field MT has not, however, achieved great acceptance in the study of permafrost conditions.

B. Artificial Field Magnetotelluric (Radiowave) Methods

Artificial field MT or radiowave methods are similar to natural field MT methods with the exception that the electrical and magnetic fields being used are generated by transmitters at distances of several wave lengths or more for the study area (Collett and Becker, 1967). Measurements are made in the VLF (3-30 kHz), LF (200-400 kHz) and AM broadcast (500-1500 kHz) frequency ranges. Observation depth or penetration is a function of frequency (Figure 6) and is generally limited by the high frequency of the signals utilized, although this limitation is less significant in high-resistivity permafrost. Commercially available equipment can be utilized to measure surface impedence at VLF and LF and thus to determine resistivity in the same manner as for natural field magnetotelluric methods. Radiowave methods have not been used in a marine environment because of the shielding effect of conductive seawater. Commercially available equipment can be used to obtain resistivity by measurement of wave tilt.

Radiowave techniques have been used with considerable success to map lateral variations in surface impedance and consequently to determine horizontal distribution of permafrost (Hoekstra and McNeill, 1973; Hoekstra et al., 1977; Scott and Hunter, 1977; Arcone et al., 1978, Sellmann et al., 1977). Making measurements at several frequencies in the available range permits the determination of vertical variation of resistivity and consequently of permafrost distribution. Measurements at VLF can be made virtually anywhere in North America, but measurements at LF and in the broadcast band are limited by the short range of useful transmitters in permafrost regions in northern North America (Sellmann et al., 1974 and 1977, Arcone et al., 1979).

Interpretation techniques for the radiowave methods are relatively undeveloped, although curves for interpretation based on a two-layer model are available (Geonics, 1971) as are suites of model results (Madden and Vozoff, 1971). Advances have been made in the interpretation of VLF wave-impedance measurements in thin permafrost by considering both the magnitude of the wave impedance and the phase difference between the electric and magnetic components of the field (Powell, 1978).

With experience in a given region, some estimates of the ice content of a permafrost section can be made on the basis of apparent resistivities, determined from surface impedance measurements (Scott and Hunter, 1977; Arcone et al., 1979). With experience in a given region it is also possible to make some estimate of material type if there is good correlations between geological variation and resistivity (Scott, 1975b).

Radiowave techniques or measurement of surface impedance have achieved considerable acceptance in North America because they are simpler to use than DC resistivity and because the results are useful in studying permafrost. Surface impedance measurements still require contacts to be made with the earth. Consequently, although they are faster to make than conventional DC resistivity, they are not so fast as the non-contact electromagnetic methods.

Non-contact radiowave measurements (wave tilt) have been made on an experimental basis on McNeill and Hoekstra (1973). This approach has been applied in a routine manner only from the air. Since in an airborne survey it is difficult to achieve detailed lateral resolution (Arcone 1977 and 1979), the airborne

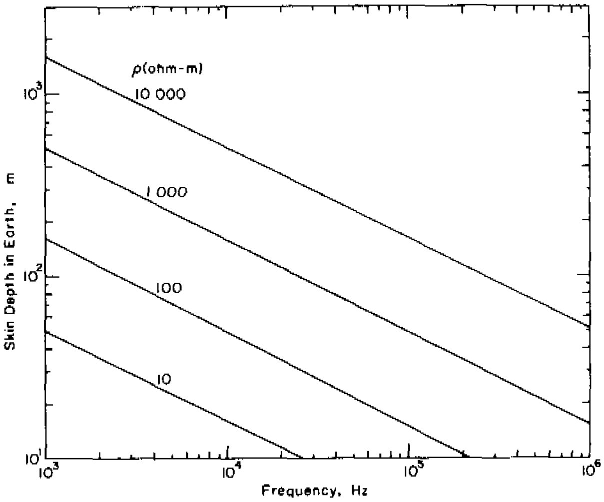

Figure 6. The skin depth of electromagnetic radiation as a function of frequency at several values of ground resistivity.

wave tilt or E-phase* technique is most useful to obtain a generalized picture of resistivity distrubution and consequently of permafrost distribution. The airborne wave tilt technique is more useful in areas where permafrost is thicker than 100 metres (Scott and Hunter, 1978).

C. Inductive Electromagnetic Methods

Inductive Electromagnetic (EM) methods use a local electromagnetic transmitter to generate a field which induces eddy currents in the earth. These eddy currents produce a secondary field which is detected by an electromagnetic receiver. The eddy current magnitude is related to the conductivity of the earth. EM sounding techniques can increase penetration either by increasing the separation of the transmitter and reciever or more commonly by decreasing the frequency of excitation and keeping the spacing of transmitter and reciever fixed. Equipment is commercially available to perform soundings by either approach.

Experience in Alaska and in northern Canada has shown that variable frequency sounding can give reasonable estimates of permafrost thickness in areas where the thickness is of the orders of the 100 metres or larger (Daniels et al., 1976; Ghosh & Hallof, 1974). Rigorous interpretation techniques for electromagnetic sounding are at the present time limited to simple layered situations in which the number of layers is small. The use of variable frequency electromagnetic soundings to study complex permafrost sections is still very difficult. Since the technique can give estimates of the resistivity of various layers these estimates can be correlated with ice content in a known soil type.

Small portable EM units have been built with fixed spacings between transmitter and reciever coils (McNeill, 1976; Delaney et al., 1977; Henderson and Hoekstra, 1977; Rennie and Henderson, 1979). The operating frequencies of these instruments are chosen low enough that, for all resistivities within the range of calibration, penetration is limited by the transmitter-reciever spacing rather than by skin depth effects. These instruments have been used with considerable success to determine near-surface lateral distribution of electrical resistivity and consequently to map the horizontal distribution of permafrost. Within a known soil type in a known geological setting the results of such surveys can also be used to infer ice content and massive ice distribution and, to a limited extent, to estimate the thickness in areas where it is comparable to the penetration of the system (Hoekstra, 1978). Measurements at a number of transmitter-reciever spacings can give a good estimate of the vertical distribution of permafrost (Sellmann et al., 1979). As a result of the success experienced with this method in studies in Alaska and northern Canada, the method has achieved considerable acceptance in North America for mapping the distribution of shallow permafrost in the discontinuous zone.

An electromagnetic induction system carried by a helicopter has been used to map permafrost distribution in the discontinuous zone in the Mackenzie Valley, N.W.T. (fraser, 1978). The technique proved useful for identifying large permafrost features and for determining material types on a large scale. The resolution limits inherent in an airborne system prevented mapping permafrost distribution in the same detail that can be achieved by ground measurements. Such systems are, however, frequently used to prospect for metallic sulphides in permafrost regions.

Induction techniques are commonly used to log wells drilled for petroleum exploration or production in permafrost regions (Hnatiuk and Randall, 1977). The estimated resistivities are used in combination with other geophysical parameters to determine the position of the base of permafrost intersected in the particular hole. Interpretation techniques for induction logging are well developed, and consequently the resistivities so determined can be used with some confidence.

In the last five years electromagnetic sounding and profiling methods have gained considerable popularity in North America in mapping permafrost distribution because they are self-contained and do not rely as signals from distant transmitters. A growing acceptance of electromagnetic techniques is probably the most significant development in permafrost geophysics in North America since the last permafrost conference in Yakutsk.

D. Radar Methods

Radar methods use local antennas to radiate signals and to receive echos or returns from reflecting interfaces. The frequency range for ground-probing radar techniques is from 1 Megahertz to 1000 Megahertz. Penetration is limited primarily by attenuation of the radar signal by the material penetrated. Attenuation is highest in low-resistivity materials, and particularly in fine-grained sediments such as clays and silts. Even when frozen, clays and silts tend to have high attenuation (Davis et al., 1976).

Ground-probing radar systems utilise wideband antennas and impulse signals. Sometimes narrow band antennas radiating pulsed, single frequency signals are used (Annan and Davis, 1977a).

Commercially available impulse radars have been used on land with considerable success (Scott et al., 1974; Annan and Davis, 1978; Kovacs and Morey, 1979). They can be used in coarse-grained sediments at depths up to 30 meters to study permafrost distribution and structure within the permafrost section. Unterberger (1978) has described a non-commercial system for which considerably greater penetration is claimed. Determining the presence of ground ice in a permafrost section by measuring high frequency electrical properties alone is difficult. There is only a slight difference between the relative permittivities of pure ice and well-frozen clean sand with some excess ice. However the high receiver sensitivity, and spatial resolution of radar techniques permit the determination of the geometry of lens and massive ice within a permafrost section and consequently facilitate the detection of ice if suitable control is available. Radar techniques can be used to indicate changes of material type in permafrost sections and with adequate control can be used to identify material types, although penetration is greatly restricted in fine-grained materials (Annan and Davis, 1976).

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* "E-Phase" is a patented name of Barringer Research Ltd, Rexdale, Canada.

Commercially available impulse radar equipment has been used to map the thickness of both fresh-water ice and sea ice, and to study the electrical properties of sea ice (Bertram et al., 1972; Campbell and Orange, 1974a and 1974b; Kovacs and Morey, 1978; Kovacs, 1978a and b). In the fresh-water environment radar has mapped bottom topography at water depths of up to several tens of meters from the ice surface (Annan and Davis, 1978). An impulse radar has also been used in an airborne configuration to measure ice thickness and lake-bottom configuration (Kovacs, 1978b).

Pulsed radar systems are commercially available in the form of altimeters and radioecho sounders. Such equipment has been used with success on the ground surface and from the air to measure ice thickness in glacial studies and to outline glacial bottom topography (Gudmansen, 1970, Cambridge, 1975). Continuous-wave radar techniques are useful for determining the properties of ice within a glacier (Kovacs and Gow, 1977a and b). Pulsed radar has been used in boreholes to identify the base of permafrost in solid rock (Lytle et al., 1976).

Radar techniques have for some time been used with success in glacier studies and are generally accepted for that purpose. Recent developments in the use of impulse radar in shallow studies of permafrost have demonstrated the potential of such techniques in detailed studies for engineering purposes in areas of coarse-grained materials. Use of ground-probing radar for permafrost studies is another significant development since the permafrost conference in Yakutsk.

E. Time-domain Reflectometry

Time-domain reflectometry (TDR) techniques (Davis and Chudobiak, 1975) have been used to study sea ice (Bogorodskii and Tripol'nikov, 1973) and near-surface active layer characteristics (Pilon et al., 1979). The method involves emplacing two parallel probes in the ice or ground several centimeters apart. The probes form a transmission line along which it is possible to transmit an electromagnetic signal. Discontinuities in the material penetrated by the probes generate reflections which can be identified at the ground surface. Commercially available TDR equipment can be used for this purpose. The technique is primarily limited by the practically attainable length of transmission line. Present experience indicates a maximum penetration of the order of 2 meters.

The TDR method is useful in very detailed studies of variations in electrical properties of the upper two meters, associated, for example, with the position of the freezing front and ice formation in the active layer (Pilon et al., 1979). It is, however, less suitable for large-scale engineering studies, because of the required probe installation and limited depth of penetration.

F. Radio-frequency Interfeometry

The radio-frequency interferometry method (RFI) has been described by Rossiter et al., (1978). This method uses a horizontal electric or magnetic dipole as a transmitter, emitting signals at six frequencies from 1 MHz to 32 MHZ. Direct and subsurface reflected waves interface at the ground surface. The interference pattern observed with increasing distance from the transmitter can be interpreted in terms of a layered model. This method is largely experimental, and is not commonly used in permafrost studies in North America.

G. Summary

Electromagnetic techniques commonly used in permafrost studies in North America use low and high frequency radiowaves, magnetic induction and ground-probing radar. The most significant development since 1973 is the increased use of inductive resistivity methods, which have largely replaced DC resistivity methods for permafrost studies particularly in the discontinuous zone. Ground-probing radar has also gained acceptance in this period particularly for uses in coarse-grained soils and on sea- and fresh-water ice.

IV: SEISMIC TECHNIQUES

A. The Seismic Refraction Method

The seismic refraction method involves measuring the velocities of refracted compressional waves travelling through media which, for most applications, are considered to be layered. In most field situations, successful applications require that compressional wave velocities increase with depth; often, however, when this condition is satisfied, "hidden layers" or thin zones where large velocity-depth gradients occur can be a problem (Telford et al., 1976, p. 417). In general, refraction field methods require long source-detector offsets; hence hydrophones and geophones used must display good low frequency responses. Since refracted events are generally of lower amplitude than reflected energy, high-energy sources are necessary and explosives continue to be commonly used. Weight drops and marine air guns and sparker units have been successful in some cases.

Refraction methods were developed early in the history of geophysics and a large number of interpretation techniques have been developed to interpret velocity-depth structure (Musgrave, 1967). Since refraction methods can measure velocity accurately, in permafrost they can provide estimates of ice-content, ground temperature and material tyoe and strength. Several laboratory measurements have been made in recent years on rocks and soils involving comparison of shear and compression wave velocities at acoustic frequencies with variables such as temperature, moisture content, pore-water salinity and sample composition (Dzhurik and Leshchikov, 1973; Frolov and Zykov, 1971; King and Bamford, 1971; King, 1977; Kohnen, 1974; Kurfurst and Hunter, 1976b; Nakano et al., 1971; Nakano et al., 1972; Nakano and Froula, 1973; Nakano and Arnold, 1973; Ogilvy, 1970; Stoll, 1974; Zykov and Baulin, 1973). From these studies some general conclusions can be drawn:

1) Compressional velocities increase with decreasing permafrost temperatures for water saturated samples; the effect is most pronounced in soils and is a function of the water content.

2) For moisture-saturated low-salinity soils, most of the pore water is frozen at temperatures close to 0°C in coarse-grained samples; as grain size decreases, the velocity increases at a much lower rate with decreasing temperature.

Hence in the field situation, if additional information is available on the composition of subsurface soils or rock, a temperature-moisture content-salinity range can be established from velocity measurements.

The refraction method has been used to measure active-layer thickness in soils and rock glaciers (Garg and Stacey, 1973; Green, 1970; Hunter and Good, 1971; Kurfurst et al., 1974; Carson et al., 1975; Gagné and Hunter, 1975; Barsch, 1978). Good velocity contrasts exist between the active layer and ice-bonded permafrost. The method is particularly applicable to problems of active layer thickness variations in areas of thermal disturbance such as on road, railway or pipeline construction sites as well as in river-bank and lake-shore studies (Carson et al., 1975; Good and Hunter, 1974; Hunter et al., 1976; Kurfurst et al., 1974; Kurfurst and Hunter, 1976a).

Seismic velocity measurements have been made to determine ice-bonded permafrost distribution and soil type along construction routes (Kurfurst and Hunter, 1976a). The most successful applications involve combined seismic and electrical surveys (Scott and Hunter, 1977). Measurement of compressional and shear wave velocities and amplitude attenuation rates has led to the description of these parameters in the form of the "generalized acoustic parameter" which varies as the ice content, soil type and temperature of the material (Akimov, 1973). In mining applications, seismic compressional and shear wave velocity measurements have been used to determine the depth of overburden for stripping estimates, the quantity of frozen ore and the relative strength and blasting characteristics of ice-bonded ore zones (Gary and Stacey, 1973; Garg, 1973; Garg, 1976).

Ice bodies at depth in permafrost soils have been examined by the seismic refraction method and successful attempts to measure the distribution of ice-bonded permafrost and large ice masses have been made (Hunter, 1973a; Scott and Hunter, 1976; Voronkov, 1973).

Marine refraction methods have been employed to map the depth to ice-bonded permafrost beneath the sea floor and to obtain estimates of the degree of ice-bonding (Carson et al., 1975; Hobson et al., 1976; Hunter, 1973b; Hunter and Hobson, 1974; Hunter et al., 1974; Hunter et al., 1978a and b; Rogers, 1976). The most definitive results have been obtained with hydrophone arrays designed specificially for shallow water refraction surveys, but refraction events picked from the early portions of records obtained from reflection arrays used for hydrocarbon exploration can yield useful information (Hobson et al., 1976; Hunter et al., 1975; Hunter et al., 1976; Hunter and Judge, 1975). Most refraction measurements made to data are of the "single-ended" type, in which the source is at one end of the array only; hence only approximate estimates of velocity and depth are possible unless overlapping record coverage is made (Telford et al., 1976). Reversed or "double ended" refraction profiling is possible through the use of telemetering sonobuoys. A sea-bottom hydrophone array with reversed profiling has been employed in the ice-covered ocean using available leads or cracks through which to deploy the array (McLaren et al., 1975).

B. Seismic Reflection Methods

Seismic reflection methods have been utilized throughout the world as one of the primary geophysical exploration techniques for hydrocarbons. The techniques involve digital magnetic recording of seismic waves from a source (explosives, air gun, weight drop, or vibrator) reflected from layered structure at depth. Computer-assisted velocity analysis methods are now available for processing multichannel reflection data. With these techniques, velocity-depth functions can be established in permafrost areas, and permafrost thicknesses and velocities can often be obtained. Corrections for permafrost thickness variations are important for most sedimentary hydrocarbon trap mapping; costly dry holes can result from incorrect assumption about permafrost conditions.

In thick permafrost areas where fine-grained materials predominate, the base of permafrost is often gradational in temperature and consequently in velocity, and therefore is not a reflector of seismic energy (Hunter, 1972). If reflectors are not present within the permafrost section, its thickness and average velocity can only be determined by indirect methods utilizing marker horizons beneath the base (Agofonov et al., 1973; Card, 1977; Muzychensko and Kozyrev, 1970). Computer modelling techniques are available to obtain best-fitting velocity-depth curves by this method (Card and McCallum, 1979).

The character of seismic reflection records is often an indicator of the presence of ice-bonded permafrost (Hunter et al., 1976; Kanereikin et al., 1971). In marine reflection profiling in areas where submarine permafrost is suspected, poor record quality (large amplitude reverberations) is often associated with the presence of a large velocity contrast at the top of ice bonding beneath the sea-floor.

C. Acoustic Reflection Methods

Acoustic reflection methods applied to permafrost problems are mainly confined to the marine mode; however, experiments with high frequency (7 kHz) transmitters and receivers have been attempted (Nelson et al., 1970). The sources commonly used in the marine mode are air guns, boomers (large plates which are displaced electromagnetically while submerged to generate a seismic signal), sparkers (which discharge electrical energy across a spark gap to generate a seismic signal), and high frequency electrodynamic transducers. These sources allow variation of the frequency and energy content of the signal. The source and receivers are closely spaced inorder to obtain nearly verticalincidence reflection recordings. High frequency content and consequent short-wavelength energy allow good resolution of small features. Reflections are obtained from layering with large velocity contrasts at depth beneath the sea bottom. Since no velocity information can be obtained, interpreting the top of ice-bonded permafrost can be subjective in some areas, as well as qualitative, often requiring control in the form of drill holes or refraction velocities. If such control is available, the acoustic reflection technique can map detailed topography on the top of ice-bonded permafrost; the seismic refraction method can not.

Pingo-like structures have been successfully mapped on the sea bottom (Shearer et al., 1971). High resolution (7 kHz) methods have also been used to delineate the variation in the upper boundary of permafrost in river channels and along potential offshore pipeline corridors (O'Connor, 1979).

To obtain maximum efficiency in mapping the upper boundary of ice-bonded permafrost, the acoustic reflection technique should be applied in conjunction with the marine seismic refraction method; both velocity variations (ice content changes) and detailed topography of this boundary can thus be obtained.

D. Borehole Seismic Methods

Borehole seismic methods involve the measurement of first arrival compressional wave travel times between a surface source and a hydrophone (or wall-lock geophone) array at depth in cased or uncased holes.

For measurement of thickenss and velocity distribution of permafrost in oil and gas exploration holes, a 12-channel array of hydrophones is used (commonly called a "crystal cable array"). Spacing between individual hydrophones is usually 15 m and the array is repositioned in the hole after each surface shot. Usually a small quantity of explosives is used, but air guns have also been successfully tried. The resultant travel-time-depth curve from the recorded first arrivals is interpreted to extract velocity information.

A "crystal cable" survey is commonly run as one of a series of standard borehole logs in wells drilled in permafrost areas. Velocity measurements often show the gradational nature of the lower boundary of permafrost as well as indicating the presence of low velocity zones within the permafrost section (Baird, 1976; Card, 1977; Hnatiuk and Randall, 1977; Hunter et al., 1976). Velocity correlations have been made with changes in lithology, porosity, water content and temperature (Walker and Stuart, 1976). In some cases surface shots are displaced from the borehole to obtain lateral velocity changes in the vicinity of the hole (Baird, 1976; Card, 1977).

An array of shots or geophones on the surface with an array of hydrophones or shots at depth can yield wave-front diagrams which may be interpreted to obtain lateral variations of seismic velocities (Gal'perin, 1971; Meissner, 1961). This method has been utilized to obtain variations in permafrost structure in mining (Hunter, 1974), and in mapping ground ice occurrence (Scott and Hunter, 1977) in shallow boreholes.

E. Borehole Acoustic Methods

Sonic logging tools measure the transit time of the first arrival compressional wave over a known distance, usually about 30 cm, in a borehole. Unfrozen, unconsolidated material near the surface has travel times in the order of 500-700 microseconds/meter, whereas similar frozen materials are in the range of 250-350 microseconds/meter (Hnatiuk and Randall, 1977). Since the range of the acoustic wave is small, thermal degradation of the permafrost resulting in oversized holes can often lead to erroneous results. This method should be used in conjunction with other borehole tools (i.e. dual-induction laterallog and the crystal cable).

Most sonic tools have been manufactured for use in large diameter holes drilled for hydrocarbon exploration. There are sonic tools under development which are designed for 3-10 cm holes with direct transducer coupling to the wall rock. Such tools will no doubt be useful for future applications in shallow drill holes (King et al., 1978; Tiutiunnik and Konovalikhin, 1973; Zykov and Baulin, 1973).

F. Other Seismic Methods

Surface waves, known in the seismic industry as "ground roll", display low velocity, low frequency and high amplitude, and have been considered as noise in most refraction and reflection surveying. Attempts have been made to minimize such interference in designing arrays and in subsequent data processing. However, with proper equipment and array design, such waves could be used to measure the thickness of near-surface layering (i.e. the active layer) and to obtain estimates of shear wave velocities in permafrost. By accurately measuring both compressional and shear wave velocities of permafrost materials *in situ*, estimates of dynamic elastic properties of the material can be made.

Other types of waves often considered to be seismic "noise" result from trapping of seismic energy in a high speed layer (Hobson et al., 1976). Analyses of the modes of propagation of this energy, and its amplitude decay, can yield estimates of permafrost thicknesses for areas where ice-bonded permafrost thicknesses are in the order of 100 m or less, and where estimates of the shear and compressional wave velocities of the surrounding non-ice-bonded material can be made.

The amplitude attenuation of first arrival refractions can be measured to obtain estimates of thickness of an ice-bonded permafrost layer (Donato, 1965; Rosenbaum, 1965) for a simple model of a thin high-velocity layer embedded in a low-velocity medium. The maximum thickness measurable with the technique is frequency dependent, and for most conventional seismic arrays the upper limit of thickness resolution is less than 100 m.

V: MISCELLANEOUS TECHNIQUES

This section covers several geophysical methods that do not fall into the first two main categories previously covered (Table 1).

A. Magnetic method

A very limited amount of permafrost geophysics has been done employing the magnetic technique. Volodko et al., 1973, describe an investigation which relied upon the magnetic contrast between ice and frozen mineral material for determining the distribution of ice wedges based on ground measurement. The method is applicable only when there is an uniform distribution of magnetic material in the soil surrounding the wedges, so that the wedges show as weak negative anomalies.

A field survey was conducted in an area of alluvial soils that had magnetic susceptibility values that apparently ranged from 20×10^{-6} to 200×10^{-6} CGSu, depending on ground ice volume and local mineralogy. Drilling of 29 holes in the study area confirmed that a correlation existed between negative anomalies and ice wedges. Some exceptions to this appear to be correlated with areas of high ice content in the adjacent mineral material.

It is unlikely that the magnetic method will ever become widely used for permafrost studies.

B. Gravity methods

Only limited use has been made of gravity methods in permafrost studies, even though they have been applied to ice thickness measurements in glaciological studies (Barnet et al., 1956; Bentley, 1964).

From glacier studies Ostenso et al., (1965) it has been determined a 1-mgal anomaly is equal to between 13.5 meters and 20 meters of ice, depending on the relationship used. The 13.5 meters was determined from flat plate theory while the 20 meters was determined from empirical relationships from glaciers with irregular bottom topography. If field measurements can be made to an accuracy of ± 0.1 to 0.2 mgal and other factors are ideal this suggests that variations in excess ice in the order of a few meters in thickness could be detected.

Gravity studies have been conducted for the purpose of studying permafrost in northern Canada by Rampton and Walcott (1974), who investigated three sites for which some ground control was available. Excess ice thickness was determined by calculating Bouger densities for the topography after removing linear trends in the data. The amount of ice required to produce these densities was proportioned, and variations from the average thickness of ice in the topography were calculated by applying the infinite slab formula to the residual anomalies. The technique worked well in the area studied and provided close agreement with control data.

Osterkamp and Jurick (1979) examined a site near Fairbanks, Alaska, to correlate gravity observations of ground ice distribution with control available from both drill holes and exposures formed during highway construction. Preliminary interpretation indicated a correlation between gravity anomalies and areas of massive ice.

The gravity method does not provide the exact depth of an ice mass. It does, however, provide an estimate of the amount of excess ice, when some control is available and when the study area has uniform geology, with ice volume being the major variable. Rampton and Walcott noted that linear trends in thickness of excess ice were difficult to detect. Uniform ice slabs under the entire study area were also difficult to detect unless a section of the profile crossed an ice-free zone. In their study the technique helped to establish some relationships between surface relief and ground ice distribution.

C. Radiometric techniques

The most commonly employed radiometric techniques for shallow engineering borehole studies in permafrost are active gamma (gamma-gamma) and neutron (gamma-neutron) methods.

The gamma-gamma logging methods are more versatile than the original natural gamma method, which only measures natural radiation. Natural gamma methods were used initially by the oil industry for distinguishing between various lithologic units with different concentrations of radioactive elements. An advantage of the gamma technique is that it can be used in cased drill holes.

The gamma-gamma logging method uses a borehole package that contains a gamma-ray source as well as the counter. The source and the scintillometer are positioned at a constant spacing and are held against the hole wall. A collimated beam of gamma radiation is directed into the earth material where scattering and absorption take place on the path to the sensor. The intensity of the detected gamma rays is a function of rock density (Telford et al., 1976). The large differences in bulk density and electron density between ice and most soil and rock make this technique well suited for ground ice detection and density determinations. Obtaining quantitative values for these parameters would require local calibration in material of known properties (McKay and O'Connell, 1975; Scott and Hunter, 1977).

The neutron method can utilize a gamma-ray source and a neutron detector. The neutron intensity detected is related to the amount of hydrogen in the earth material and, therefore, can be used to determine water content (frozen or unfrozen). Used in a dry hole, the tool can give additional information on the presence of high ice-content zones.

A logging system employing both gamma-gamma and neutron probes was developed for use during construction of the Alyeska Pipeline in Alaska. The equipment was designed for rapid logging in low-density material such as ice-rich permafrost. Both denisty and moisture-content data were routinely obtained with the system in holes drilled for placement of vertical support members for the pipe (Metz, 1976).

Investigations using gamma-gamma and neutron logging to provide information on density and ground-ice content have been described by Scott and Hunter (1977) and McKay and O'Connell (1978).

D. Temperature measurements

Temperature measurements represent the most fundamental geophysical approach to obtaining information on permafrost distribution and zones where properties may change significantly due to freezing. These measurements are usually made with thermistors or thermocouples, depending on the application, with the thermistors being more sensitive.

Subsurface temperatures are obtained either by installing strings of sensors, in some cases on a permanent basis, in an access hole, or by logging of an access hole with single or multiple sensors. Both approaches have advantages. Permanent installations eliminate the need for an open access hole, reduce the problems of convection that may occur in large access holes (Seguin, 1978) and permit rapid logging of temperatures at depths which do not change with time. Logging with a moving sensor allows the same equipment to be used at many sites and allows frequent recalibration.

Jessop and Judge (1974) have described temperature measurement methods and interpretation techniques. A common problem in thermal measurements is correction for drilling disturbances.

Thermal profiles in the marine permafrost environment have been described by Chamberlain et al (1978), Osterkamp and Harrison (1978), Hunter and Judge (1975) and Hunter et al., (1976).

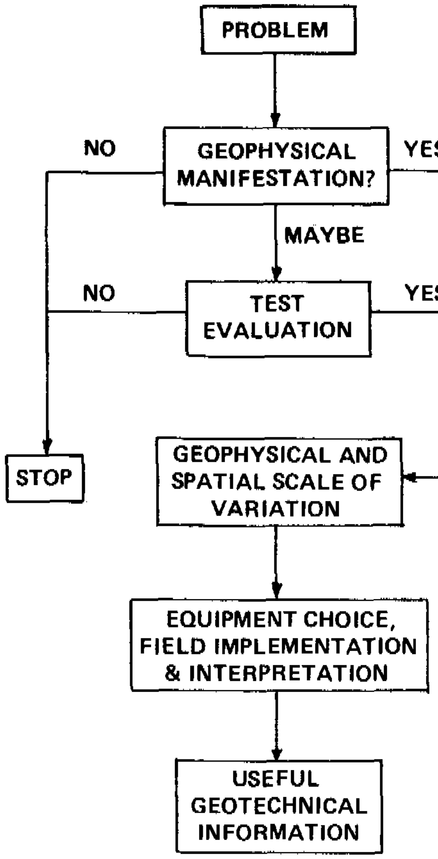

Figure 7. An approach to the selection of Geophysical methods for solving geotechnical problems, (modified from Annan and Davis, 1977b).

VI: SUMMARY AND CONCLUSIONS

The appropriate selection and application of a geophysical method or combination of methods for permafrost studies or problem-solving can be difficult even with some knowledge of the many systems. The selection process is extremely important since it can determine the utility of the geophysics program, the type of results that can be anticipated, and the most efficient approach. The importance of complete assessment of the geophysical methods and their capabilities cannot be understated. Discussion in this summary section is based on a flow chart modified from Annan and Davis (1977b), shown in Figure 7.

The first step is a detailed definition of the problem to assure all project requirements and objectives are understood. The problem definition should include a compilation of all available background data from the site or region that is to be studied. Some of the important information that should be considered to indicate whether geophysics can be usefully employed and to guide the choice of appropriate technique or techniques is listed below:

1. Size of area to be studied.
2. Size of feature to be observed.
3. Anticipated depth to feature to be observed.
4. Accessibility of the area.
5. All available information on material properties and subsurface characteristics, including seasonal variation.
6. Proximity and energy level of excitation source required by some passive systems.
7. Proximity to potential natural or cultural disturbance.
8. Comparison of projected cost and advantages for geophysical and non-geophysical alternatives.

Once the problem has been defined and all variables have been described, the next step is to establish if adequate geophysical manifestation of the desired feature exists. At this point, the determination may be based on the preliminary data acquired during the problem definition. This usually means attempting to establish if a contrast in properties is likely between the feature of interest and the adjacent material. A contrast is required in electrical, seismic, or any other physical parameters that might be detected by one of the various methods. The significance of contrasting properties at depth can be established for some methods by theoretical modelling, using procedures similar to those used for evaluating and analysing the data.

Lack of geophysical contrast or manifestation would suggest that a geophysical approach to the study is not justified. An indication of a geophysical manifestation wuld support the need for field testing or evaluation. This field evaluation could be approached in several ways. The most ideal approach would be to visit the intended study area and conduct a small pilot field survey. In many instances only a few hours are required to obtain enough information upon which to base judgments. If this is not feasible, measurements could be made in a region where the subsurface is anticipated to be similar or in some situations even laboratory observations can be helpful.

If the test evaluation provides promising results then more detailed aspects of the program should be considered as indicated in the next block of the flow chart. In this step the information from the problem definition and the field study will help determine the thickness and horizontal spacing of the parameter of interest. These conditions can then be compared with system characteristics such as skin depth or horizontal resolution of the measurement. This comparison will help to determine if features can be individually detected or will appear as a single larger feature or layer. These considerations are essential for linking data needs and subsurface characteristics with field procedure such as spacing of observations.

If satisfactory methods and procedures for obtaining the required data are available then the final step on the flow chart is appropriate. The final selection of equipment and development of a field plan may result in use of more than one method. The multiple use of methods is important since it helps establish confidence, and can contribute an extra dimension to the observations. Equipment choice, including data analysis procedures, will require joint consideration in terms of the original objectives of the program. Some techniques require considerable data processing while others provide results that can be treated directly in a useful qualitative manner. When this much consideration is given to the program design, the end result is a geophysical program which properly meets the geotechnical requirements which were originally identified.

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ВЗАИМОДЕЙСТВИЕ ВЕЧНОМЕРЗЛЫХ ГРУНТОВ И СООРУЖЕНИЙ

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Аннотация

Основной задачей теории строительства на вечномерзлых грунтах является изучение закономерностей взаимодействия вечномерзлых грунтов с инженерными сооружениями и разработка способов направленного управления этим взаимодействием. Практические приемы использования вечномерзлых грунтов в качестве оснований сооружений, получаемые в результате таких разработок, проверенных опытом строительства, реализуются в СССР в виде Строительных Норм и Правил (СНиП) . С 1.1.1978 г. введена в действие новая редакция главы СНиП на проектирование оснований и фундаментов на вечномерзлых грунтах, отображающая достижения теории и практики фундаментостроения на вечномерзлых грунтах, накопленные за текущее время (предшествующая глава СНиП была выпущена в 1966 г.).

Взаимодействие вечномерзлых грунтов и сооружений заключается, с одной стороны, в тепловом и механическом воздействии сооружения на мерзлые грунты основания, а, с другой, в воздействии деформирующегося под нагрузкой основания на устойчивость и деформации конструкций сооружения. Исходя из положений термодинамики, можно установить связь между работой деформаций основания, вызванной нагрузкой от сооружения, потоком тепла от сооружения и приращением внутренней энергии и энтропии. Дополняя соотношение уравнением теплопроводности и реологическим уравнением состояния, можно получить зависимости, определяющие деформацию и длительную прочность основания с учетом переменного во времени температурного режима грунтов основания, вызванного тепловым влиянием сооружения и переменной нагрузки от сооружения, а затем рассмотреть совместную работу основания и сооружения. Такие представления должны стать общетеоретической базой для решения проблемы взаимодействия вечномерзлых грунтов и сооружений при последующем развитии этой проблемы. Однако некоторые из указанных представлений используются уже и в настоящее время, в частности, в новой главе СНиП. Положения этой главы и рассматриваются в настоящем докладе.

По-прежнему в качестве основных принципов использования вечномерзлых грунтов оснований принимаются два принципа - с сохранением мерзлого состояния грунтов основания (принцип I) и с допущением оттаивания этих грунтов в процессе эксплуатации сооружения или предварительно, до его возведения (принцип II). Однако способы расчета оснований значительно усовершенствованы. Эти расчеты производятся по двум предельным состояниям - по прочности (для принципа I)и по деформациям (для принципа II и для принципа I при наличии пластичномерзлых или сильнольдистых грунтов), причем в расчетах учитываются реологические свойства грунтов. Расчетные значения прочностных характеристик мерзлых грунтов существенно повышены. Регламентированы конструкции и способы расчета фундаментов под большие нагрузки.

Для расчета осадок оттаявшего основания принята новая расчетная схема, учитывающая наличие вечномерзлой толщи, рассматриваемой как жесткое основание, постилающее сжимаемый, оттаявший слой грунта. Предложен метод определения реактивных давлений оттаявшего грунта на фундамент и рассмотрен вопрос об учете совместной работы оттаявшего оснований и надземных конструкций сооружения.

Особое внимание уделено направленным способам управления тепловым режимом и механическими свойствами вечномерзлых грунтов оснований - путем их предварительного охлаждения при наличии "высокотемпературных" мерзлых грунтов, прерывистой мерзлоты и пр. или, наоборот, путем предварительного оттаивания основания в случае наличия льдонасыщенных грунтов, дающих большие осадки при оттаивании, и невозможности по каким-либо соображениям применить принцип I.

При применении принципа I использования грунтов основания принимается положение о том, что в качестве расчетной температуры мерзлого грунта основания должно быть принято не ее естественное, а некоторое заданное значение. Эта расчетная температура может быть ниже естественной, если грунты пластичномерзлые и должны быть согласно требованиям СНиП охлаждены, или выше естественной, если грунты основания разнотемпературные. Предложены мероприятия,обеспечивающие поддержание расчетной температуры грунтов основания,и способы совместного теплотехнического расчета этих устройств и теплового режима основания, в частности, способа расчета вентилируемых подполий, холодных первых этажей, охлаждающих труб и каналов.

Значительно расширена область применения Норм. Новый СНиП распространяется теперь и на неблагоприятные для строительства мерзлые грунты - засоленные, заторфованные, сильнольдистые, включая подземные льды, а также на вечномерзлые грунты в районах с повышенной сейсмичностью. Разработаны специальные мероприятия и методы расчета, обеспечивающие устойчивость сооружений, возводимых в этих мерзлотно-грунтовых условиях. Приведены расчетные характеристики (теплофизические и механические) для указанных грунтов.

Постановка задачи

Изучение закономерностей взаимодействия вечномерзлых грунтов и инженерных сооружений и разработка методов направленного управления этим взаимодействием является основной задачей при решении проблем строительства на вечномерзлых грунтах. Теоретические разработки этой проблемы и практические решения вопросов использования вечномерзлых грунтов в качестве оснований сооружений, проверенные опытом строительства, реализуются в СССР в виде нормативных документов - Строительных Норм и Правил /СНиП/. Недавно была разработана и выпущена в свет новая редакция главы СНиП на проектирование оснований и фундаментов на вечномерзлых грунтах /СНиП, 1976/. В настоящем докладе будут освещены те положения, которые заложены в эту новую главу СНиП и которые отображают достижения фундаментостроения на вечномерзлых грунтах за истекшее время.

Термодинамический подход

Прежде чем переходить к изложению указанных выше вопросов, остановлюсь на некоторых общетеоретических представлениях, еще полностью не реализованных в практике строительства на вечномерзлых грунтах, но являющихся, с моей точки зрения, теоретической базой для дальнейшего решения этой проблемы.

Основами теории строительства на вечномерзлых грунтах являются, как известно, теплофизика, физико-химия и механика мерзлых грунтов и льда. Но сложилось так, что все эти три направления развивались автономно. И хотя каждое из них имеет на своем счету большие достижения, в целом проблема из-за такой разобщенности проигрывает.

Взаимодействие сооружения с мерзлыми грунтами проявляется, с одной стороны, в виде теплового и механического /силового/ воздействия сооружения на грунты основания, в результате чего в грунте создается температурное поле и поле напряжений, отличное от естественных. Изменение температуры влечет за собой изменение физико-механических свойств грунта, а дополнительные/к природным/ напряжения вызывают деформации основания, особенно большие при переходе температуры через точку плавления. Деформации основания в свою очередь влекут за собой деформации конструкций здания, в чем сказывается воздействие грунта оснований на сооружение. Таким образом, тепловое и механическое воздействия являются взаимосвязанными. Следовательно, наиболее правильным было бы совместное рассмотрение тепловых, механических и физических процессов и получение уравнений, связывающих эти процессы. Такое рассмотрение возможно на основе положений термодинамики, поскольку именно эта наука изучает взаимные связи между теплом и другими видами энергии, в частности, механической. Так, из 1-го и 2-го начал термодинамики вытекает соотношение, связывающее тепловые и деформационные процессы

$$\theta dS \geqslant dE + \delta A. \qquad /1/$$

где θ - абсолютная температура/К/, dS -приращение энтропии, dE - приращение внутренней энергии, $\delta A = \sigma_{ij}\delta\varepsilon_{ij}$ - приращение работы деформации, σ_{ij} и ε_{ij} - компоненты тензоров напряжений и деформаций / ij = 1, 2, 3/. Отметим, что в свою очередь работа деформаций $A = A^e + A^p$ складывается из упругой работы $A^e = \sigma_{ij}\delta\varepsilon^e_{ij}$ и необратимой, диссипированной работы $A^p = \sigma_{ij}\delta\varepsilon^p_{ij}$, где ε^e_{ij} и ε^p_{ij} - компоненты тензоров обратимой/упругой/ и необратимой/пластичной, вязкой/ деформаций. Соответственно приращение энтропии можно рассматривать как сумму $dS = d\varepsilon^e + dS^p$, где $dS^e = \frac{dQ}{\theta}$ - прирост энтропии извне за счет внешнего теплового потока Q, а dS^p - прирост энтропии внутри тела за счет рассеивания/диссипации/ энергии, т.е. за счет перехода кинетической энергии необратимого деформирования в тепловую, а также за счет изменений микроструктуры тела в результате его деформирования.

Для написания полной системы уравнений к закону сохранения надо добавить определяющие уравнения, т.е. уравнения состояния. К ним относится закон Фурье, связывающий поток тепла q с градиентом температуры

$$q = \lambda \operatorname{grad}\theta, \qquad /2/$$

где λ - коэффициент теплопроводности, и реологическое уравнение состояния, связывающее компоненты тензоров напряжений, деформаций и их скоростей, а также время и температуру

$$\Phi(\sigma_{ij}, \dot{\sigma}_{ij}, \varepsilon_{ij}, \dot{\varepsilon}_{ij}, t, \theta) = 0. \qquad /3/$$

Уравнения теплопроводности

Из соотношения /2/ выводится, как известно, уравнение конвективной теплопроводности, позволяющее определить распределение температуры в грунте, при этом учет фазовых превращений воды, содержащейся в грунте можно осуществить, как это показал Н.А.Бучко /см. доклад В.И.Макарова и др. в трудах 7-ой секции настоящей конференции (Доклады, 1978)/, введением в это уравнение удельного теплосодержания/энтальпии/ $H_э$

$$\frac{\partial H_э}{\partial t} = \operatorname{div}(\lambda \operatorname{grad}\theta), \qquad /4/$$

где

$$H_э = \int_{\theta_1}^{\theta_2} C_{эф}(\theta)\,d\theta \qquad /5/$$

Здесь $C_{эф}(\theta)$ - эффективная теплоемкость, учитывающая как теплоемкость грунта, так и теплоту фазовых переходов грунтовой влаги.

Реологическое уравнение состояния

Чтобы раскрыть соотношение /3/ необходимо знать законы, связывающие компоненты напряжений и деформаций или их скоростей. Обычно такие законы устанавливают эмпирическим путем и тогда уравнение состояния носит феноменологический характер, являясь справедливым лишь для определенных условий и в определенных пределах. Более общим уравнение состояния будет только в случае, если исходные связи между компонентами напряжений и деформаций /и температурой / будут выведены из рассмотрения физической сущности процесса, например, на основании кинетической теории деформирования и длительного разрушения/Вялов, 1978/.

Согласно этой теории грунт можно рассматривать как хаотическое сочетание элементарных частиц - минеральных зерен и их агрегатов, связанных льдом-цементом и пленками незамерзшей воды. Для смещения таких элементов им надо сообщить энергию активизации U , большую энергии межчастичных связей. Поскольку размеры частиц всегда во много раз меньше любого рассматриваемого объема грунта, к ним можно применить положение статистической физики и считать, что вероятность получения частицами энергии U подчиняется закону распределения энергии Больцмана $N = N_0 \exp(-U/k\theta)$. Отсюда средняя скорость смещения частиц, т.е. скорость течения грунта определится соотношениями

$$\dot{\gamma} = \frac{d\gamma}{dt} = \frac{\tau}{\eta(\tau,t)}; \quad \eta(\tau,t) = B\exp\left[U(\tau,t)/k\theta\right] \qquad /7/$$

где $\eta(\tau,t)$ - переменная вязкость.

Формула /7/ учитывает изменение энергии активации, а соответственно и вязкости в зависимости от нагрузки τ и во времени t , что связано с изменениями микроструктуры мерзлого грунта в процессе деформирования. Для выявления таких изменений были проведены специальные микроструктурные исследования. Полученные на основании этих исследований закономерности описаны в статье автора в трудах настоящей конференции. Здесь же только отметим, что процесс деформирования является следствием двух взаимопротивоположных процессов - расслабления структуры грунта в результате нарушения межчастичных связей и развития дефектов структуры и упрочнения, обусловленного возникновением новых связей и "залечиванием" дефектов. Упрочнение приводит к затуханию деформаций ползучести, расслабление - к развитию незатухающей, прогрессирующей ползучести, заканчивающейся разрушением грунта. Эти процессы описываются единым уравнением, которое и определяет закономерность деформирования мерзлого грунта во времени

$$\dot{\gamma} = \frac{d\gamma}{dt} = \left(\frac{\tau}{\tau^*}\right)^{1/m}\left(\frac{t+t^*}{t^*}\right)^{-n(\tau)}, \qquad /8/$$

где τ^* - параметр, зависящий от физических свойств мерзлого грунта и его температуры, а $t^* = 1$.

В такой записи уравнение справедливо для изотермического процесса. Если же необходимо учитывать поступление теплопотока извне $N\dot{\theta}(t)$ и изменение температуры грунта во времени $\theta(t)$, то следует привлечь соотношение термодинамики /1/ и, представляя термодинамические силы в виде линейной комбинации потоков, получим, следуя работам Ленинградского университета/А.И.Чудновский/, следующее уравнение деформирования

$$\gamma(t) = \left[\frac{\tau(t)}{\tau^*(\theta)}\right]^{1/m} + \alpha\left[\theta(t) - \theta_0\right] + \int_0^t \left\{\left[\frac{\tau(\nu)}{\tau^*(\theta)}\right]^{1/m} - N\dot{\theta}(\nu)\right\}\left[k(\theta_0, t-\nu)\right]d\nu. \qquad /9/$$

Из термодинамических же соображений можно вывести уравнение длительной прочности мерзлого грунта с учетом поступающих в него теплопотоков и вызываемых ими изменений во времени температуры. Для этого надо решить уравнение /9/ относительно напряжения, введя в это решение условие длительного разрушения. В качестве такого условия можно принять достижение приращения энтропии ΔS в процессе деформирования некоторого критического значения ΔS_r, соответствующего моменту разрушения t_r

$$\Delta S_r = \int_0^{t_r} \dot{S}(t)\,dt, \qquad /10/$$

где $\dot{S}(t)$ - скорость приращения плотности энтропии, которую можно выразить в виде суммы $\dot{S} = \dot{S}_e + \dot{S}_i$, где $\dot{S}_e = \frac{dQ}{dt}\frac{1}{\theta}$ - внешний поток энтропии, обусловленный тепломассообменом с окружающей средой, а $\dot{S}_i = \dot{S}_i(\tau, \gamma^p, \theta, F)$ - внутренний источник энтропии, обусловленной работой диссипации A^p и свободной энергией F . Принимая, что работа диссипации затрачивается на изменение структуры грунта и рост плотности дефектов, а также используя соотношение /8/, можно получить уравнение длительного разрушения, как было показано автором ранее /Доклады, 1975/ в форме

$$\frac{1}{B}\int_0^{t_r} \exp\left[-\frac{\beta\theta(t)}{\tau(t)}\right]dt = 1 \qquad /11/$$

Это уравнение связывает время до разрушения t_r , переменное во времени напряжение $\tau(t)$ и переменную во времени температуру $\theta(t)$.

Таким образом, используя положения термодинамики, мы можем получить уравнение, описывающее тепловое и механическое взаимодействие мерзлого грунта и возведенного на нем сооружения. Решение конкретных задач может быть получено с помощью ЭВМ, а в простейших случаях и аналитическим путем. Некоторые такие задачи рассмотрены в докладе автора на настоящей конференции.

Основные положения СНиП П-18-76

В новой главе СНиП П-18-76 "Основания и фундаменты на вечномерзлых грунтах" можно выделить следующие основные положения, отличающие ее от ранее действующего СНиП'а :

усовершенствование способа расчета оснований и существенное повышение расчетных значений прочностных характеристик мерзлых грунтов;

регламентирование типов фундаментов и методов их расчета при больших нагрузках;

направленное управление тепловым режимом и механическими свойствами вечномерзлых грунтов оснований /путем предварительного охлаждения или, наоборот, оттаивания/;

разработка мероприятий и методов теплотехнических расчетов, обеспечивающих заданный температурный режим мерзлых грунтов оснований, в том числе с помощью вентиляционных каналов;

разработка рекомендаций, обеспечивающих возможность строительства на неблагоприятных вечномерзлых грунтах - засоленных, заторфованных и сильнольдистых, включая подземные льды;

разработка рекомендаций по устройству фундаментов на вечномерзлых грунтах в сейсмических районах .

Усовершенствование способов расчета оснований

Как и в старой редакции Строительных Норм и Правил в новом СНиП'е приняты два принципа использования вечномерзлых грунтов оснований: принцип I - с сохранением мерзлого состояния грунтов и принцип II- с допущением их оттаивания.

Расчеты оснований производятся по двум предельным состояниям - по прочности /несущей способности/ и по деформациям. Расчет по прочности исходит из условия

$$N = \Phi/K_{н} \ , \qquad /12/$$

где N - расчетная нагрузка, Φ - несущая способность основания, $K_{н}$ - коэффициент надежности.

Расчет по деформации исходит из условия

$$S \leq S_{пр} \ , \qquad /13/$$

где S - деформация основания, определяемая расчетом, а $S_{пр}$-предельнодопустимая величина деформации сооружения, зависящая от его конструктивных особенностей.

Вечномерзлые грунты, используемые по принципу I , рассчитываются, как правило, по несущей способности, поскольку такие грунты малосжимаемы. Исключением являются пластичномерзлые и сильнольдистые грунты, которые могут развивать ощутимые осадки и их рассчитывают и по несущей способности и по деформациям. При оттаивании, как известно, мерзлые грунты дают большие осадки и поэтому при использовании вечномерзлых грунтов по принципуII основным расчетом является расчет по деформациям.

Мерзлые грунты, как известно, обладают явно выраженными реологическими свойствами-способностью развивать деформации ползучести и снижать свое сопротивление нагрузкам при их длительном воздействии. Указанные свойства должны обязательно учитываться при рассмотрении работы мерзлых грунтов в качестве оснований и при их расчетах. При расчете по несущей способности следует исходить из понятия предела длительной прочности R_{∞} , т.е. такой нагрузки, при превышении которой возникает незатухающая ползучесть, приводящая к разрушению или к провальным осадкам /рис.1/.

Соответственно несущая способность основания Φ в формуле /12/ определяется как

$$\Phi = mR; \ R = R^{н}/K_{г} \qquad /14/$$

где R - расчетное сопротивление, $R^{н}$ - нормативное сопротивление, $m > 1$ - коэффициент условий работы, $K_{г} > 1$ - коэффициент безопасности. В свою очередь $R^{н} = \frac{1}{n}\sum_{i=1}^{n} R_{\infty,i}$, где $R_{\infty,i}$ - предельно-длительная прочность, полученная из данного определения, n - число определений.

Расчет мерзлых грунтов по деформации с учетом фактора времени осуществляется из условия, чтобы деформация основания за срок службы сооружения не превышала бы значений, оговоренных формулой /13/, причем значение S в этой формуле определяется как $S = S_0 + S(t)$, где S_0 - начальная деформация, а $S(t)$ - деформация, развивающаяся во времени t ; у мерзлых грунтов значение $S(t)$ обусловлено ползучестью, а у оттаивающих фильтрационной консолидацией и ползучестью.

Расчеты оснований, используемых по принципу I

Сохранение мерзлого состояния оснований обеспечивается согласно СНиП устройством вентилируемых подполий, охлаждающих каналов и труб, а также ограничением зоны оттаивания и заложением фундаментов ниже этой зоны /рис.2/.

С помощью вентилируемого подполья можно не только сохранить естественный температурный режим грунтов под сооружением, но и изменить его в нужную сторону, например, ужесточив его, как это и наблюдается в практике. Условием для этого должно быть по Г.В.Порхаеву соблюдение соотношения

$$M = \frac{F_{в}}{F_{с}} \ , \qquad /15/$$

где $F_{с}$ - площадь здания в плане, $F_{в}$ - площадь вентилирования, M - модуль вентилирования, вычисляемый в зависимости от температуры воздуха в помещении, среднегодовой температуры наружного воздуха, среднегодовой температуры воздуха в подполье, скорости ветра, наличия тепловых сетей в подполье и термического сопротивления пола 1-го этажа; способ определения величины M приведен в СНиП'е.

Основными типами фундаментов при строительстве по I -ому принципу являются сваи /включая сваи оболочки и сваи-столбы большого диаметра/ и столбчатые фундаменты.

Несущая способность оснований, используемых с сохранением их мерзлого состояния, определяется в соответствии с формулой /14/ следующим выражением, предложенным С.С.Вяловым еще в 1959 г. и включенным в СНиП/рис.3/

$$\Phi = m\left(RF + \sum_{i=1}^{n} R_{см.i} F_{см.i}\right). \qquad /16/$$

Эта формула справедлива как для всех видов свайных фундаментов, так и для фундаментов столбчатых, причем R есть расчетное давление на грунт под нижним концом сваи или под подошвой фундамента, $R_{см}$ - расчетное сопротивление сдвигу мерзлого грунта по боковой поверхности сваи или по боковой грани башмака столбчатого фундамента; F - площадь поперечного сечения сваи или подошвы фундамента, а $F_{см}$ - площадь смерзания грунта с боковой поверхностью фундамента. Знак суммирования ставится потому, что тип грунта и его температура по длине сваи может меняться, соответственно с чем будет различным и значение $R_{см.i}$ для каждого i-го слоя.

Значения R и $R_{см}$ должны, как правило, определяться из опытов – в полевых или лабораторных условиях. Одновременно в нормах приведены значения этих характеристик, которыми допускается пользоваться при отсутствии опытных данных. Эти значения даются в СНиП для разных типов грунтов и для различной их расчетной температуры θ[1] . Температура по глубине грунта в течение года, как известно, изменяется. Поскольку Нормы обычно исходят из худших условий, то в качестве расчетной принимается наиболее высокая среднемесячная температура $\theta_{max}(z)$ в году на данной глубине с тем, чтобы суммарная эпюра $R_{см}$ по всей длине сваи была наименьшей /см. рис.3/. Эти значения θ_{max} устанавливаются теплотехническим расчетом в зависимости от среднегодовой температуры грунта θ_o . На основании накопленного практического опыта и данных специальных исследований значения R и $R_{см}$, приведенные в СНиП П-18-76, значительно повышены по сравнению со значениями, которые рекомендовались ранее.

Для однородных грунтов формула /16/ упрощается, принимая вид $\Phi = m(RF + R_{см} F_{см})$, где R и $R_{см}$ определяются для некой эквивалентной температуры, исходящей из минимума площади эпюры $R_{см}$ по длине сваи и определяемой теплотехническим расчетом.

В случае определения несущей способности фундамента непосредственно по данным полевых испытаний мы получали суммарное значение предельно-длительной нагрузки $P_\infty = P^н$, откуда $\Phi = \frac{K}{K_г} P^н$, где $K_г$ – коэффициент запаса. Что же касается коэффициента K , то он учитывает то обстоятельство, что испытания могут проводиться при температуре грунта, отличной от ее расчетного значения. Поэтому принимают, что $K = \Phi_{пр} P_{он}$, где $\Phi_{пр}$ – несущая способность проектируемой сваи, определенная расчетом по формуле /16/ при табличных значениях R и $R_{см}$, соответствующих расчетной температуре θ_{max} , а $\Phi_{оп}$ – несущая способность опытной сваи, тоже подсчитанная по формуле /16/, но при значениях θ , которые имели место при опытах.

Погружение свай в вечномерзлый грунт может быть осуществлено различными способами – с пропариванием, с предварительным бурением скважин и с заливкой их грунтовым раствором или с забивкой в скважины свай /если диаметр скважин меньше диаметра сваи, что делается лишь в пластичномерзлых грунтах/ и т.д. Наиболее распространенным является погружение сваи в скважины/большого диаметра/ с заливкой скважин грунтовым раствором.

Если этот раствор изготовляется из выбуренного грунта, то сопротивление сдвигу $R_{см}$ принимается в зависимости от вида выбуренного грунта. Если же применяется заранее изготовленный песчано-глинистый или песчано-известковый раствор, то несущая способность сваи может быть повышена за счет более высоких значений $R_{см}$ для этих растворов. Такое повышение особенно эффективно в случаях, когда свая забивается в слабые грунты – глинистые, засоленные, заторфованные, сильнольдистые. Тогда расчет несущей способности следует производить из условия равнопрочности сопротивления сдвигу грунтового раствора по поверхности сваи R_{cg} и сопротивления сдвигу грунтового раствора по контакту с окружающим грунтом $R_{см}$, т.е. из условия $R_{cg} F_{cg} = R_{см} F_{см}$, где $F_{см}$ – поверхность смерзания со сваей, а F_{cg} – поверхность контакта раствора с окружающим грунтом, равная поверхности контура скважины /рис.4/.

Осадка столбчатых фундаментов, возводимых по принципу I, для их расчета из условия /13/ определяется по следующей формуле, обоснование и опытное подтверждение которой по данным 19-ти летних наблюдений приведено в докладе автора на настоящей конференции /Доклады III конференции, 1978/

$$S/d = 0{\cdot}8(1-\mu^2)\beta \int_0^t \left\{\frac{N(\nu)}{A[\theta(\nu)]}\right\}^{1/m} (t-\nu)^{\beta-1} d\nu, \quad /17/$$

где d – диаметр подошвы фундамента, μ коэффициент Пуассона мерзлого грунта, $A[\theta(\nu)] = a + B/\theta/^n$ – коэффициент деформирования, зависящий от температуры θ , в свою очередь изменяющейся во времени по некоторому закону $\theta(t)$, $N(t)$ – изменяющаяся во времени расчетная нагрузка, ν – переменная интегрирования, t – время.

Осадка сваи может быть определена по формуле

$$s/u = \left(\frac{1}{u\ell}\right)^{1/m} \beta \int_0^t \left\{\frac{N(t)}{\bar{A}[\theta(t)]}\right\}^{1/m} (t-\nu)^{\beta-1} d\nu, \quad /18/$$

где $\bar{A}[\theta(t)] = \bar{a} + \bar{B}/\theta(t)/^\lambda$ – коэффициент деформирования, зависящий от температуры, в общем случае переменной во времени, u – периметр сваи, ℓ –глубина заделки сваи в вечномерзлый грунт, остальные обозначения – те же, что и в формуле /18/.

Таким образом, формулы /17/ и /18/, являющиеся частными случаями уравнения /9/, определяют осадки столбчатого и свайного фундаментов, загруженных переменными нагрузками с учетом изменяющейся во времени температуры мерзлого грунта.

Расчеты оснований, используемых по принципу II

При принципе II допускается оттаивание грунтов основания как в процессе эксплуатации сооружения, так и предварительно, до его возведения. Первый случай имеет место тогда, когда мерзлые грунты оснований являются малопросадочными и при их оттаивании условие /13/ будет удовлетворено. Если же грунты дают большую осадку при оттаивании, то СНиП рекомендует принимать специальные меры, которые заключаются или в уменьшении деформаций основания при его оттаивании, или в приспособлении конструкций сооружения к восприятию повышенных деформаций.

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[1] В СНиП температура обозначена через t , а время – через τ .

Уменьшение деформаций основания может быть обеспечено регулированием глубины оттаивания путем устройства термоизоляции, замены льдонасыщенного грунта песчано-гравийными грунтами и т.д. Однако наиболее действенным способом является предварительное оттаивание грунтов основания /осуществляемое с помощью гидро- и электропрогрева/. Глубина оттаивания выбирается такой, чтобы последующая осадка нижележащего мерзлого грунта при его оттаивании находилась в пределах, удовлетворяющих условию /13/.

Уменьшение деформаций основания, исходя из условия /13/, является основным принципом фундаментостроения на вечномерзлых грунтах. Опыт строительства показывает, что, даже при самых усиленных конструкциях сооружений, осадки при оттаивании, особенно дисперсных льдонасыщенных грунтов, приводят к недопустимым деформациям зданий. Поэтому прежде всего необходимо тем или иным путем уменьшить величину осадки грунта, т.е. создать основание с заранее заданными свойствами. В то же время СНиП допускает в качестве дополнительного мероприятия приспособление сооружения к восприятию повышенных деформаций основания. Эти мероприятия заключаются или в повышении прочности и общей пространственной жесткости сооружения, или, наоборот, в увеличении податливости и гибкости сооружения. В первом случае мы стремимся к тому, чтобы дополнительные напряжения, вызванные деформациями основания, были безболезненно восприняты усиленными элементами конструкций сооружений. Во втором случае стремимся к тому, чтобы дополнительные напряжения вообще не появлялись, а возникающие деформации элементов конструкций могли быть выравнены. Соответственно при жесткой конструктивной схеме фундаменты принимаются в виде обычных или перекрестных лент, сплошных или коробчатых плит и т.п. При гибкой конструктивной схеме принимаются отдельно стоящие столбчатые фундаменты.

Расчет оснований, используемых по принципу , начинается с определения очертания зоны оттаивания мерзлого грунта под сооружением и ее развития во времени. Существует ряд приемов и формул такого расчета. Наиболее эффективным является метод численных решений - на приборе гидравлических аналогий или с помощью ЭВМ. Однако для повседневного пользования необходимы, кроме машинного, еще и аналитические методы расчета. Такой метод, разработанный Г.В.Порхаевым, приведен в СНиП П-18-76. Он позволяет определить глубину оттаивания за заданное время t под серединой здания H_c и под краями $H_к$ /рис.5/. Расчет сводится к следующим формулам

$$H_c = K_1(\xi_c - K_c)B,$$

$$H_к = K_1 \xi_к B \text{ или } H_к = (\xi_к - K_к - 0{,}1\beta\sqrt{J}), \qquad /19/$$

где параметры $K_1, \xi_c, K_c, \xi_к, K_к$ определяются по приведенным в СНиП номограммам и таблицам в зависимости от расчетной температуры воздуха внутри помещения и среднегодовой температуры вечномерзлого грунта, термического сопротивления пола 1-го этажа, коэффициентов теплопроводности мерзлого и оттаявшего грунта, суммарной влажности грунта, ширины B и длины L здания. Максимальная глубина оттаивания под серединой $H_{сп}$ и краем $H_{кп}$ здания, достигаемая при стационарном тепловом состоянии, вычисляется по формулам

$$H_{сп} = K_{II}\xi_{сп}B; \qquad H_{кп} = K_{II}\xi_{кп}B, \qquad /20/$$

где коэффициенты $K_{II}, \xi_{сп}, \xi_{кп}$ определяются по таблицам и номограммам.

Дальнейший расчет заключается в определении величины ожидаемой осадки.

Следует отметить, что для ориентировочной оценки осадки мерзлого грунта при его оттаивании существует ряд приближенных формул, исходящих из тех положений, что сжимаемость $\delta = \Delta h/h$ песчаных грунтов определяется относительной разностью объемного веса скелета оттаявшего и уплотненного грунта $\gamma_{ск.т}$ и объемного веса скелета мерзлого грунта в естественном состоянии $\gamma_{ск.м}$

$$\delta = \frac{\gamma_{ск.т} - \gamma_{ск.м}}{\gamma_{ск.т}}, \qquad /21/$$

а сжимаемость глинистых грунтов - изменением их пористости за счет вытаивания и отжатия льда - включений и частично льда-цемента в результате уплотнения под собственным весом и нагрузкой

$$\delta = 1 - \gamma_{ск.м}\left[\frac{1}{\gamma_s} - \frac{1}{\gamma_w}(W_p + K_g J_p)\right], \qquad /22/$$

где γ_s и γ_w удельные веса частиц грунта и воды, W_p - влажность на границе раскатывания, J_p - число пластичности, K_g - коэффициент, зависящий от величины давления на грунт p .

Однако эти формулы могут применяться лишь для оценки мерзлотно-грунтовых условий площадки, выборе принципа строительства и т.п. целей. Определение же осадок, необходимое для расчета основания, должно производиться по более точным формулам, учитывающим характер распределения напряжений по глубине грунта /рис.6/.

Хотя, строго говоря, зависимость между напряжением и деформацией нелинейна не только у мерзлых грунтов, но и у грунтов оттаивающих, для упрощения допускается определять осадку этих грунтов, исходя из закона линейного деформирования. Раньше исходили при этом из схемы упругого полупространства. Этот прием допускается и сейчас при большой глубине оттаивания. Но в качестве основного принимается расчетная схема в виде слоя слабого/оттаявшего/ грунта, подстилаемого жестким/мерзлым/ основанием с учетом концентрации напряжений на границе этого основания и соответствующим перераспределением напряжений. Формула для определения осадки ленточного фундамента получается суммированием осадок каждого i -ого слоя толщиной h_i , на которые разбивается зона оттаявшего грунта

$$s = b p_0 M_{om} \sum_{i=1}^{n} a_i (k_i - k_{i-1})(1 - \Lambda_{ci}) + \sum_{i=1}^{n}\left[(A_i + a_i p_{\delta i})(1 - \Lambda_{ci}) + K_{ni}\Lambda_{ci}\right] h_i, \qquad /23/$$

где P_o и $P_{\delta i}$ – соответственно давление на грунт под подошвой фундамента и давление от собственного веса грунта в i -ом слое, K_i и K_{i-1} – коэффициенты, учитывающие характер распределения вертикального напряжения от нагрузки по глубине грунта, $M_{\text{от}}$ – коэффициент, учитывающий влияние жесткого подстилающего основания и зависящий от отношения H/B , H – глубина залегания границы жесткого/мерзлого/ основания , a_i и A_i – соответственно коэффициенты сжимаемости и оттаивания грунта, $л_c$ – льдистость грунта до его оттаивания, B – ширина фундамента.

Таким образом, первое слагаемое правой части формулы /23/ учитывает осадку уплотнения оттаявшего грунта под воздействием внешней нагрузки, второе слагаемое – осадку уплотнения от воздействия собственного веса грунта и осадку оттаивания, а третье слагаемое – осадку от вытаивания ледяных включений и смыкания макропор, причем,т.к. это смыкание не бывает полным, то вводится коэффициент $K_\Lambda < 1$.

Параметры a и A определяются по данным полевых или лабораторных испытаний. Последние проводятся в одометре, т.е. в условиях компрессии с невозможностью бокового расширения. Опытные точки наносятся на график "сжимаемость δ – нагрузка P ", по которому и определяются параметры a и A . Испытания проводятся с образцами, не имеющими крупных ледяных включений – последние определяются отдельно /по керну, извлекаемому при проходке скважин или по измерениям на стенках шурфов/ и учитываются, как говорилось, введением в формулу /23/ специального слагаемого.

Более достоверные результаты по сравнению с лабораторными дают полевые испытания с помощью нагреваемых штампов,к которым после оттаивания небольшой зоны грунта прикладывается ступенчатая нагрузка. Значения a и A и в этом случае определяются по графику $\delta - P$, с тем, однако, отличием от лабораторных опытов, что полевые испытания определяют осадку всего массива грунта, включая и ледяные прослойки. Соответственно при определении осадки с использованием данных полевых опытов в формуле /23/ следует принять $л_{ci} = 0$.

При предварительном оттаивании происходит осадка /до возведения сооружения/ за счет собственного веса, определяемая формулой /23/ при $P_o = 0$. Осадка же после возведения сооружения будет равна

$$S = S_{\text{п}} + S_{\text{доп}} \qquad /24/$$

где $S_{\text{п}}$ – осадка слоя грунта, оттаявшего предварительно на глубину , обусловленная последующим /после возведения сооружения/ уплотнением грунта за счет внешней нагрузки; эта осадка,определяется .формулой /23/ при $A_i = 0$ и $\Lambda_{ci} = 0; P_\delta = 0$; $S_{\text{доп}}$ – дополнительная осадка слоя грунта, оттаивающего в процессе эксплуатации на глубину $H - h_{\text{от}}$ /где H – полная глубина оттаивания/; эта осадка определяется формулой /23/.

Развитие осадок во времени

Формулы /23/ и /24/ определяют величину конечной, стабилизованной осадки. Однако большое значение имеет характер протекания осадки во времени, что особенно важно при предварительном оттаивании. В этом случае важно знать, закончится ли осадка от собственного веса предварительно оттаявшего грунта до возведения сооружения или она будет продолжаться и в процессе эксплуатации сооружения, и ее надо в этом случае учитывать при расчете деформаций сооружения.

Развитие осадки во времени происходит за счет фильтрационной консолидации $S_ф$ и за счет ползучести $S_{плз}$, причем можно условно считать, что ползучесть возникает только после окончания фильтрационного процесса. Тогда полная осадка будет равна /Цытович, 1973/

$$S(t) = S_1 + S_2 + S_3 + S_4, \qquad /25/$$

где $S_1 = Ah(t)$ – осадка оттаивания, обусловленная вытаиванием льда-включений и льда-цемента и развивающаяся по мере увеличения глубины оттаивания, которая в свою очередь равна $h(t) = \beta\sqrt{t}$;
$S_2 = a[x_1 h(t) p + x_2 \gamma h^2(t)/2]$ – осадка уплотнения, протекающая одновременно с оттаиванием под действием внешней нагрузки P_o и собственного веса грунта $q = \gamma h(t)$ и зависящая от коэффициента фильтрации, функциями которого являются коэффициенты x_1 и x_2 ; $S_3 = S_\infty^p U^p + S_\infty^q U^q$ – осадка доуплотнения грунта, происходящая после его оттаивания под воздействием внешней нагрузки P_o и собственного веса грунта $q = \gamma H$ /$H = h_\infty$ – глубина оттаивания/, причем $S_\infty^p = a(1-x_1)HP_o$ и $S_\infty^q = 0{,}5a(1-x_2)\gamma H^2$ – стабилизованные осадки, а U^p и U^q – степень консолидации грунта, определяемая из решения задачи фильтрационной консолидации и зависящая от соотношения $\Lambda = \beta/2\sqrt{C}$, где $C = K_\varphi/\gamma_в a$ – коэффициент консолидации, K_φ – коэффициент фильтрации.

S_4 – осадка ползучести, определяемая из решения теории ползучести; во многих случаях это слагаемое можно не учитывать.

Осадка S_2 , протекающая одновременно с оттаиванием, также как и глубина оттаивания $h(t)$ пропорциональна корню квадратному из времени, поэтому $S(t)/h(t) = const$. Характер процесса консолидации зависит от параметра Λ , т.е. этот процесс определяется скоростью оттаивания, характеризуемой тепловым коэффициентом β и скоростью фильтрации, K_φ характеризуемой коэффициентом фильтрации .

Если скорость оттаивания велика , а коэффициент K_φ мал, то консолидация продолжается и после оттаивания. Если же оттаивание происходит медленно, а K_φ велик, то процесс консолидации происходит в период оттаивания и $S_3 \approx 0$. Такой случай характерен при оттаивании грунтов основания в процессе эксплуатации, когда оттаивание длится в течение ряда лет и закон развития осадки во времени определяется законом оттаивания $h(t) = \beta\sqrt{t}$. Иначе обстоит дело при предпостроечном оттаивании. Это оттаивание происходит относительно быстро, и если оттаивающие грунты глинистые с относительно небольшим значением коэффициента фильтрации, то консолидация будет продолжаться и после возведения сооружения. Кроме того, произойдет консолидация оттаявшего грунта за счет внешней нагрузки и, таким образом, величина осадки доуплотнения S_3 будет достаточно ощутима.

Совместная работа сооружения и основания

При расчете оснований по деформациям необходимо рассматривать совместную работу сооружения и основания, учитывая, что осадки основания зависят от конструкции сооружения, а, возникнув, они воздействуют на эти конструкции, вызывая в них деформации и приводя /при статически неопределенной схеме сооружения/ к перераспределению усилий.

Для массовых видов сооружений с наиболее распространенными конструктивными схемами значения предельных деформаций, которые эти сооружения могут безболезненно воспринять, регламентированы СНиП'ом. В этом случае в задачу расчета входит определение деформаций основания /средней осадки, ее разности, крена/ и их сопоставление, в соответствии с условием /13/, с величиной предельно допустимой деформации для данного вида сооружения. При этом рассмотрение совместной работы сооружения и основания ограничивается определением реактивных давлений грунта на подошву фундамента и расчетом фундамента на возникающие в нем усилия от этого давления.

В большей степени совместную работу сооружения и основания необходимо учитывать при проектировании сооружений, предельные деформации которых не задаются, а должны устанавливаться в результате расчета. В этом случае, как показано в статье В.Г.Позовской, Л.И.Неймарка и автора, представленной на настоящую конференцию, поступают следующим образом.

Рассматривают сооружение конечной жесткости и определяют изложенным выше способом деформацию оттаявшего/в процессе эксплуатации или предварительно/ основания, вызванную нагрузкой от сооружения и от собственного веса грунта. Далее решают контактную задачу взаимодействия основания и сооружения, и из этого решения определяют реакции основания, воздействующие на фундамент. При этом в целях упрощения расчета сооружение условно заменяют балкой или системой связанных между собой балок, эквивалентных сооружению по своей жесткости и статической работе.

Зная реакции основания, определяют дополнительные усилия, возникающие в конструкциях сооружений, включая фундамент, в результате неравномерной осадки, крена и т.д. Эта неравномерность обусловливается,с одной стороны, криволинейным очертанием зоны оттаивания грунта под сооружением, а, с другой - неоднородностью грунтов по площади. Расчет конструкций производится с учетом этих дополнительных усилий.

Решение контактной задачи выполняют, рассматривая фундамент как балку или плиту на упругом, винклировом основании. Реакции q в этом случае будут распределяться по длине X балки по закону

$$\bar{q}(x)=\bar{c}(x)\left[W(x)-Z_o(x)\right], \qquad /26/$$

где $\bar{c}(x)$ - коэффициент упругих местных деформаций грунта/коэффициент постели/, $W(x)$ - вертикальные перемещения балки, Z_o - просадки основания, обусловленные осадкой оттаивания $S=Ah(t)$.

Коэффициент $\bar{c}(x)$ определяется как функция осадки уплотнения и , поскольку эта осадка развивается во времени /в соответствии с изменением во времени глубины оттаивания и развитием консолидации/, то этот коэффициент также есть функция времени. Кроме того, коэффициент $\bar{c}(x)$ изменяется по длине фундамента X , поскольку очертание зоны оттаивания криволинейно, а следовательно осадки в каждой точке X различны.

Для простейших случаев рассмотренной задачи имеется аналитическое решение /рис.7/, изложенное в "Пособии по проектированию оснований и фундаментов зданий и сооружений на вечномерзлых грунтах" /Стройиздат, 1969/. Метод основан на том, что криволинейная эпюра реактивных давлений $\bar{q}(x)$ заменяется системой сосредоточенных сил , и расчетная схема сводится к упругой балке, к которой сверху приложена нагрузка, а снизу - реактивные сосредоточенные силы, заменяющие основание. Такая система рассчитывается методами строительной механики. Следует отметить, что увеличение жесткости основания в какой-либо точке X , например, под краями здания, где глубина протаивания мала и, следовательно, $\bar{c}(x)$ велико, приводит к возрастанию реакции основания $\bar{q}(x)$.Однако при достижении этой реакцией предельного значения $\bar{q}_{пр}$ происходит пластическое течение грунта, вызывающее перераспределение реакций, делая их более равномерными, что положительно сказывается на работе фундамента. Положительным фактором является и уменьшение величины просадки $Z=Ah(t)$, что лучше всего достигается предпостроечным оттаиванием.

Более эффективным является решение задачи с помощью ЭВМ, позволяющее учесть достаточно большое количество факторов, влияющих на совместную работу сооружения и основания.

Сваи - стойки

При наличии на достижимой глубине скальных грунтов в качестве фундаментов рекомендуется принимать сваи-стойки, заделываемые своим нижним концом в скале. Такой прием применяют для ответственных сооружений даже при глубоком /до 40 м/ залегании скалы. Сваи-стойки выполняют в виде составных свай сплошного сечения, свай-столбов, свай-оболочек и даже буронабивных свай с принятием специальных мер по обеспечению схватывания и твердения бетона в вечномерзлых грунтах. Строительство в этих случаях осуществляется по II принципу /с принятием мер против просадки пола/. В этом случае учитывается, что оттаивающий и оседающий грунт будет воздействовать на сваю в виде отрицательного трения, которое учитывается как дополнительная нагрузка. Несущая способность сваи определяется по формуле

$$\Phi = mRF - m_1 R_{\text{сд.н}} F_{\text{сд.н}}, \qquad /27/$$

где R – расчетное сопротивление грунта /скалы/ под нижним концом сваи; $R_{\text{сд.н}}$ – отрицательное трение; F и $F_{\text{сд.н}}$ – площадь поперечного сечения сваи и площадь ее боковой поверхности в пределах глубины оттаивания; m и m_1 – коэффициенты условий работы.

Свая-стойка должна также рассчитываться по прочности материала сваи с учетом ее продольного изгиба, величина которого зависит от длины сваи и условий ее защемления в верху и в низу.

Предпостроечное охлаждение грунтов

Один из приемов направленного управления свойствами мерзлых грунтов оснований – их предварительное оттаивание – был рассмотрен выше. Другой прием заключается, наоборот, в охлаждении грунтов оснований, что особенно целесообразно в районах неустойчивой вечной мерзлоты. Вечномерзлые грунты в таких районах имеют близкую к 0°C температуру и ее понижение,с одной стороны, существенно увеличивает несущую способность основания /понижение температуры, например, с -0,3 до -1°C увеличивает прочность грунта в 2,5 раза/, а, с другой, – повышает надежность фундаментов в случае непредвиденного отепления грунта. Исходя из этих соображений, СНиП позволяет осуществлять строительство по I принципу на пластичномерзлых грунтах только при условии их охлаждения и понижения температуры основания. Искусственное охлаждение применяется и при наличии прерывистой, несливающейся мерзлоты в целях промораживания участков талых грунтов и создания сплошного мерзлого массива.

Наиболее действенным является машинное охлаждение с помощью рассолов, которое широко применяется при искусственном замораживании грунтов при проходке различных горных выработок и котлованов в плывунных и т.п. грунтах. Однако этот метод самый дорогой, поэтому он используется только в крайних случаях. Более эффективным будет охлаждение с помощью естественного холода – наружным зимним воздухом, когда используется сама суровость северного климата. Возможность такого охлаждения обусловлена ощутимой разницей между среднегодовыми температурами наружного воздуха и вечномерзлого грунта, составляющей от 2 до 8°C и более /что вызвано защитным действием растительного и снегового покрова и пр./.

Наблюдением установлено, что наличие высокого вентилируемого подполья приводит, как правило, с течением времени к понижению температуры мерзлых грунтов под зданием. Однако такое понижение происходит не сразу, а со временем, тогда как в расчете мы должны исходить из свойств грунта, которыми он обладает к моменту окончания строительства. Поэтому охлаждение грунта должно быть завершено к этому сроку.Представляется целесообразным осуществлять разовое охлаждение до начала строительства с тем, чтобы впоследствии достигнутое понижение температуры грунта поддерживалось воздействием вентилируемого подполья. Такое охлаждение может быть достигнуто систематической расчисткой снега, промораживанием котлованов, продувкой скважин перед установкой в них свай холодным зимним воздухом и пр. Широко применяется и периодическое охлаждение грунта холодным воздухом, подаваемым в грунт в зимнее время по трубам с помощью вентилятора или даже путем естественной тяги. Однако наиболее эффективным является применение саморегулирующихся сезоннодействующих охлаждающих установок/термосвай/ с естественной конвекцией жидкостного/керосин/ или парожидкостного/аммиак, пропан, фреон/ хладоагента. Такие установки не требуют энергетических затрат и обслуживающего персонала, являясь относительно простыми в изготовлении. Термосваи широко применяются как в США и Канаде, так и в СССР, и используются для понижения температуры пластичномерзлых грунтов в целях повышения их несущей способности и надежности, для промораживания талых участков на площадках с прерывистым распространением вечной мерзлоты, для создания промороженных ядер в плотинах, для восстановления мерзлого состояния в основаниях, где произошло непредвиденное оттаивание мерзлых грунтов и пр. Установки устраиваются как самостоятельно действующие, так и монтируемые в тело железобетонных или стальных трубчатых свай /т.е. собственно термосваи/.

В летний период холод, аккумулированный вокруг установки в течение зимы, частично поглощается окружающим грунтом, но все же общее понижение температуры грунта происходит. Совместно с действием вентилируемого подполья это приводит к весьма ощутимому эффекту,и,даже в первый год, имеет место существенное охлаждение грунта основания.

Особенно эффективно применение термосвай для сооружений с сезоннодействующими нагрузками, вызываемыми колебаниями температуры воздуха, ветром, снегом,гололедом,сезонным пучением грунта. Такие нагрузки являются преимущественными для опор линий передачи, газонефтепроводов, эстакад и т.п. Появление этих нагрузок или их экстремальные значения обычно совпадают с наиболее холодным периодом года, т.е. с периодом наибольшего повышения несущей способности грунтов в результате их охлаждения термосваями, что и делает применение термосвай для указанных сооружений исключительно эффективным.
Расчет термосвай должен включать в себя две стадии: 1 – определение температурного поля грунта вокруг свай и его изменения во времени при периодической подаче холода, 2 – определение длительной прочности и развивающихся осадок с учетом переменной нагрузки и изменяющейся во времени температуры грунта.

Решение первой из перечисленных задач теплофизической – получено при определенных допущениях как с помощью математического моделирования по ЭВМ, так и аналитическим путем. При этом рассматриваются отдельно активный период зимнего охлаждения и летний, пассивный период, когда подача холода прекращается.

Вторая задача - расчет осадки длительной прочности основания с учетом переменной нагрузки и переменного температурного режима грунта решается с помощью уравнений /9/ и /11/.

Закон изменения температуры грунта около термосваи можно принять циклическим $\theta(t) = \theta_0 - (\theta_0 - \theta_{max}) \cos \frac{2\pi t}{t_1}$, где θ_{max} и θ_0 - максимальная и средняя температуры грунта, $t_1 = 1$ год . Зависимость прочностных и деформативных характеристик Γ грунта от температуры выразим эмпирической формулой $\Gamma(\theta) = a + B|\theta|^n$. Тогда уравнение длительной прочности /11/ будет иметь следующий вид

$$1 \leq \frac{1}{B} \int_0^{t_r} \exp\left\{ -\left[\frac{a + B\left[\theta_0 - (\theta_0 - \theta_{max}) \cos \frac{2\pi t}{t_1}\right]^n}{\tau(t)} \right] \right\} dt, \quad /28/$$

где $\tau(t)$ - расчетная нагрузка $N(t)$, отнесенная к единице площади F боковой поверхности сваи или к подошве столбчатого фундамента

$$\tau(t) = \frac{K_T K_H}{m F} N(t)$$

/K_T, K_H, m - коэффициенты безопасности, надежности и условий работы, регламентируемые СНиП'ом/, t_r - срок службы сооружения.

Уравнение /28/, решаемое численным путем, позволяет определить несущую способность грунта, охлажденного термосваей, с учетом циклического изменения его температуры и переменной во времени нагрузки.

Закономерность развития осадки во времени с учетом переменной температуры и изменяющейся во времени нагрузки получим из уравнения /9/, которое после некоторых допущений будет иметь следующий вид

$$s/B = \frac{\omega \tau_{max}}{a' + B'|\theta_{max}|^n} + \left\{ \int_0^{t_r} \frac{\omega \beta (t-\nu)^{\beta-1} \tau(\nu)}{a' + B'\left[\theta_0 - (\theta_0 - \theta_{max}) \cos \frac{2\pi \nu}{t_1}\right]^n} d\nu \right\}^{1/m}, \quad /29/$$

где B - ширина фундамента/сечения сваи/, ω - коэффициент, зависящий от размеров фундамента/сваи/, остальные обозначения те же, что и в формулах /28/ и /17/.

Строительство в особых мерзлотно-грунтовых условиях

Среди вечномерзлых грунтов можно выделить особые, неблагоприятные для строительства грунты. Это пластичномерзлые грунты с неустойчивым температурным режимом, заторфованные, засоленные и сильнольдистые вечномерзлые грунты. Условия строительства на пластичномерзлых грунтах рассмотрены выше. Здесь изложим особенности использования в качестве оснований заторфованных, засоленных и сильнольдистых вечномерзлых грунтов.

Засоленные, заторфованные и особенно сильнольдистые вечномерзлые грунты, а тем более подземные льды обладают рядом отрицательных с точки зрения строительства свойств, и их использование в качестве оснований сооружений связано с определенными трудностями. Поэтому до последнего времени площадки с такими грунтами старались по возможности обходить. Что же касается подземных льдов, то на них вообще не строили. Однако широко развернувшееся строительство на Севере заставило отказаться от такой выборочной застройки и использовать для строительства не только те площадки, которые благоприятны по своим мерзлотно-грунтовым условиям, но и те, застройка которых необходима из технологических и т.п. соображений, вне зависимости от свойств слагающих их грунтов. Поэтому потребовалось провести комплексные исследования указанных грунтов и разработать специальные приемы их использования в качестве оснований. Соответствующие рекомендации и изложены в новой главе СНиП П-18-76.

Особенностью заторфованных и засоленных мерзлых грунтов является то, что эти грунты в результате наличия растительных остатков в первых из них и солей во вторых - имеют температуру замерзания значительно более низкую, чем обычные грунты, и соответственно находятся в пластичномерзлом состоянии, даже при сравнительно низкой температуре. Поэтому расчет фундаментов на таких грунтах должен, в соответствии с требованиями СНиП'а , производиться как по несущей способности, исходя из условия /12/, так и по деформациям, исходя из условия /13/. Фундаменты могут быть как столбчатые, так и свайные, но в последнем случае, в целях повышения несущей способности свай, скважины должны быть заполнены песчано-известковым раствором/а не шламом из выбранного грунта/. Тогда расчет можно производить из условия равнопрочности сопротивления сдвигу этого раствора по поверхности смерзания со сваей и по контакту с окружающими слабыми /засоленными или заторфованными/ грунтами. Поскольку это последнее сопротивление существенно меньше сопротивления раствора по поверхности сваи, то для соблюдения условия равнопрочности диаметр скважины следует увеличить с тем, чтобы свая и окружающий раствор работали как единый столб большего диаметра /см. рис.4/. Расчетные значения указанных характеристик регламентированы Нормами, но окончательную величину предельной нагрузки рекомендуется определять из полевых испытаний. На основании этих испытаний следует также определять возможную осадку фундаментов.

Особенностью льда является, как известно, его способность вязко деформироваться и течь при любой, отличной от нуля, нагрузке. Это вызвало недоверие к возможности использования сильнольдистых грунтов, а тем более подземных льдов в качестве оснований сооружений. Считалось, что такие основания будут развивать неограниченно большие осадки. Однако детальные исследования льда /Вялов и др., 1976/ показали, что у льда есть два критических значения напряжений, резко различающих характер деформирования льда. Если напряжение не превышает величины $R_л$, то деформации развиваются столь медленно, что за время,соизмеримое со сроком службы сооружения /50-100 лет/, их значение не превзойдет допустимого предела. При напряжениях же, хотя и больших $R_л$, но не превышающих $\sigma_л$ течение льда происходит только с постоянной скоростью и не переходит в прогрессирующую стадию с возрастающей скоростью /рис.8/. Соответственно расчет оснований из льда проводится по прочности и по деформациям. Расчет по прочности заключается в том, чтобы давление на лед не превышало величины $R_л$, а сопротивление сдвигу по боковой поверхности фундамента - величины $R_{см.л}$. Эти величины и подставляются в формулу /16/, а их рекомендуемые значения приводятся в Нормах.

Фундаменты на подземных льдах могут быть как столбчатыми, так и свайными. Но обязательным условием является исключение непосредственного контакта фундамента и льда. Поэтому под подошвой фундамента устраивается песчаная подушка, а скважина для установки сваи заполняется песчано-известковым раствором и расчет сваи ведется из условия равнопрочности.

Расчет столбчатых фундаментов по деформациям проводится из условия/13/, причем значение S в этом условии принимается равным $S = S_y + S_n$, где S_y - осадка, обусловленная уплотнением льда/за счет отжатия пузырьков воздуха/, а S_n - осадка пластичновязкого течения льда, накапливающаяся за срок службы сооружения $t_л$ и равная $S_n = v t_л$, где v - скорость течения льда, зависящая от нагрузки и коэффициента вязкости, в свою очередь являющегося функцией температуры льда. При этом проверяется давление P_0, передаваемое на лед - оно должно удовлетворять условию $P_0 \leq K_\delta \frac{2}{3} \sigma_л$, где K_δ -коэффициент, зависящий от размеров фундамента.

Осадка свай определяется по данным полевых испытаний.

В настоящее время построен и нормально эксплуатируется ряд зданий на подземных льдах, засоленных и заторфованных грунтах.

Основания и фундаменты на вечномерзлых грунтах в сейсмических районах

В области распространения вечномерзлых грунтов встречаются регионы с повышенной /более 7 баллов/ сейсмичностью. Особенности проектирования оснований и фундаментов в таких условиях также рассматриваются в СНиП П-18-76.

Прежде всего отметим, что сейсмическая балльность площадки зависит от мерзлотных условий. Если площадка сложена мерзлыми грунтами с температурой до -2°С и эта температура будет сохранена после возведения сооружений, то мерзлое состояние грунтов на балльность не влияет. Если грунты будут иметь температуру ниже -2°С, то сейсмичность площадки понижается на 1 балл, а если предполагается оттаивание грунтов, то сейсмичность площадки повышается на 1 балл. Исходя из этих и некоторых других соображений, СНиП рекомендует осуществлять строительство на вечномерзлых грунтах в сейсмических районах, как правило, по принципу I , т.е. с сохранением их мерзлого состояния. При невозможности/по техническим или иным причинам/ использовать мерзлые грунты по принципу I допускается применение принципа II , но при условии опирания фундаментов на малосжимаемые грунты - скальные, крупнообломочные или предварительно оттаявшие и уплотненные. Расчет фундаментов должен производиться с учетом сейсмических воздействий, причем несущая способность фундамента определяется по формуле /16/, но с введением дополнительно коэффициента условий работы $m_c \leq 1$. Кроме того, производится проверка сечения свай на прочность с учетом горизонтальных сейсмических воздействий.

Воздействие горизонтальных нагрузок

Свайные фундаменты, кроме расчета на восприятие вертикальной нагрузки N, должны быть также рассчитаны на действие горизонтальных нагрузок, в том числе возникающих при сейсмических воздействиях. Этот расчет должен включать в себя :

проверку прочности самой сваи при изгибе от действия горизонтальной силы, приложенной к верхнему концу заделанной в грунт сваи;

проверку устойчивости сваи в грунте из условия сопротивления грунта давлению, оказываемому боковой поверхностью сваи;

проверку величины горизонтального смещения у верхнего конца сваи по условию

$$y = y_{пр}, \qquad /30/$$

где $y_{пр}$ - предельно допустимое смещение сваи, зависящее от конструкции сооружения и устанавливаемое при проектировании.

При расчете сваи на действие горизонтальной нагрузки исходят из расчетной схемы, в которой сваю рассматривают как упругую балку, лежащую на линейнодеформационном основании. При этом считается, что основание характеризуется коэффициентами постели C по Винклеру, т.е. коэффициентом пропорциональности между нагрузкой и деформацией, возникающей в месте приложения силы. При расчете надо исходить из наихудшего случая, который соответствует осеннему периоду, когда верхний слой грунта оттает и станет наиболее податливым, а нижняя часть сваи будет защемлена в вечномерзлой толще. Учет этих обстоятельств достигается введением переменного по глубине грунта коэффициента постели C. В качестве первого приближения принимается, что C увеличивается по глубине по линейному закону/рис. 7 , схема 1/. Допустимость такого приближения обосновывается тем, что в расчете используется не сам коэффициент постели C, а некоторый обобщенный коэффициент деформации α, учитывающий как деформационные свойства грунта, так и жесткость самой сваи. Этот коэффициент определяется из натурных испытаний свай на горизонтальную нагрузку и тем самым он отображает фактический характер изменения коэффициента постели по глубине грунта.

Одновременно должны учитываться и реологические свойства грунтов. При расчете на быстродействующие нагрузки/сейсмические, динамические и др./ значение α определяется из быстрых испытаний, при расчете же на статические, длительнодействующие нагрузки коэффициент α определяется из длительных испытаний с доведением каждой ступени нагрузки до стабилизации перемещений.

Для свай, устанавливаемых в твердомерзлые грунты /обладающие повышенной прочностью/, можно принять, что в этих грунтах свая является полностью защепленной. При этом, если глубина слоя оттаивания $H_т$ не велика $- H_т \leq 5 B$ /где B поперечный разрез сваи/, то сопротивлением этого слоя можно пренебречь и рассматривать сваю как свободную консоль, защемленную в вечномерзлом грунте на глубине 1,5 B от поверхности вечной мерзлоты /схема II , рис. 7 /.
Если же $H_т > 5 B$, то следует учитывать сопротивление оттаявшего слоя грунта и рассматривать сваю как балку на линейнодеформированном основании с переменным коэффициентом постели C ,защемленную на глубине 1,5 B от поверхности вечной мерзлоты /схема III , рис. 7 /.

Изгибающий момент М и перерезывающая сила Q для этих двух схем определяется следующими соотношениями :
для схемы

$$M = \pm 0{,}5 \ell \eta_1 T ; \quad Q = \eta_1 T \qquad /31/$$

для схемы

$$M = \pm a \eta_2 T ; \quad Q = \eta_2 T \, , \qquad /32/$$

где T - горизонтальная нагрузка,
$\ell = \ell_0 + 1{,}5 B$ - длина участка сваи от ростверка до поверхности вечной мерзлоты,
η_1 - коэффициент, зависящий от величины вертикальной нагрузки N , жесткости сваи EJ /E - модуль упругости сваи, J - момент инерции/и длины сваи L , а η_2 и a - коэффициенты, зависящие от этих же факторов и, кроме того, от коэффициента деформации α.

Дальнейший расчет свай проводится как обычный расчет на прочность железобетонных или металлических конструкций.

Прогноз изменения геокриологических условий площадки

Освоение территории с вечномерзлыми грунтами и ее застройка неизбежно вызовут изменение геокриологических условий, причем преимуществено эти изменения будут направлены в неблагоприятную сторону. Вырубка леса, уничтожение растительного покрова, тепловое воздействие сооружений, сброс вод и т.п. приводит к повышению температуры вечномерзлой толщи, увеличению глубины слоя сезонного протаивания, а иногда и к оттаиванию вечномерзлых грунтов, а отсюда к заболачиванию территории, развитию термокарста, эрозии почв и т.п. Поэтому Нормы требуют принятия мер, обеспечивающих наименьшее нарушение естественных условий застраиваемой территории - сохранение растительного покрова, устройство подсыпок и т.д. Особое внимание уделяется устройству инженерных коммуникаций и предохранению вечномерзлых грунтов от их теплового воздействия.

Однако при любых мероприятиях застройка территории неизбежно влечет за собой определенные изменения геокриологических условий. Одной из главных задач инженерных изысканий и проектирования является прогноз этих изменений с тем, чтобы они были учтены при проектировании. Методика таких прогнозов рассматривается в некоторых докладах на настоящей Конференции.

В заключение приведем несколько фотоиллюстраций, на которых представлены примеры зданий, возведенных на вечномерзлых грунтах.

На рис. 9 и 10 представлены комплексы жилых домов, построенных на вечномерзлых грунтах по принципу I , т.е. с сохранением мерзлого состояния этих грунтов.

На рис. 11-14 показаны фото жилых и административных зданий с открытыми вентиляционными подпольями, а на рис. 14 - здание с закрытым подпольем, вентилирование которого осуществляется с помощью отверстий /продухов/ в цоколе.

На рис. 15-16 представлены фото монтажа коробчатого ленточного фундамента и надземной части здания, возводимого на оттаивающем основании /по принципу II/ с частичным предварительным оттаиванием грунта.

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ПЕРЕЧЕНЬ ИЛЛЮСТРАЦИЙ

Рис.1. Кривые ползучести
a - затухающая ползучесть/ $P < P_\infty$ /
b - незатухающая ползучесть/ $P \geq P_\infty$ /

Рис.2. Сохранение мерзлого состояния оснований
a - вентилируемое подполье, b - ограничение зоны оттаивания с заложением фундамента ниже этой зоны,
c - вентилируемые каналы в подсыпке.

Рис.3. Схема расчета фундаментов
a - столбчатого, b - свайного.

Рис.4. К расчету несущей способности свай по условию равнопрочности.

Рис.5. Расчетная схема оттаивания грунта под зданием

Рис.6. Распределение давления в оттаявшем грунте

Рис.7. Расчетная схема фундаментов на оттаивающих грунтах
а - расчетная схема/1- оттаявший грунт, 2- мерзлый грунт, 3- фундаментная балка/, b - эпюра изгибающих моментов, с - эпюра перерезывающих сил.

Рис.8. Кривые деформирования льда
1 - медленное вековое течение/$\sigma < R_h$/
2 - вязкое течение с постоянной скоростью/$\sigma < \sigma_{\lambda}$ /
3 - прогрессирующее течение с возрастающей скоростью/$\sigma \geqslant \sigma_{\lambda}$ /.

Рис.9. Здания на вечномерзлом грунте, построенные с сохранением его мерзлого состояния. Улица заполярного города.

Рис.10. Комплекс жилых домов, построенных с сохранением вечномерзлого состояния грунтов.

Рис.11. Жилой дом с высоким вентилируемым подпольем.

Рис.12. Административное здание с открытым вентиляционным подпольем.

Рис.13. Здание телеграфа с открытым вентилируемым подпольем.

Рис.14. Административное здание с вентилируемым подпольем, закрытым цоколем с вентиляционными отверстиями/продухами/.

Рис.15. Жилой дом с закрытым цоколем и вентиляционной щелью/внизу/.

Рис.16. Дома с вентилируемыми подпольями, цоколь с продухами.

Рис.17. Возведение коробчатого фундамента под жилой дом, строящийся на оттаивающих грунтах/ с их частичным предварительным оттаиванием/.

Рис.18. Монтаж жилого дома, возводимого на коробчатом фундаменте на оттаивающих грунтах.

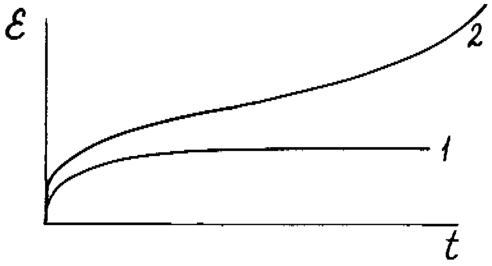

Figure 1

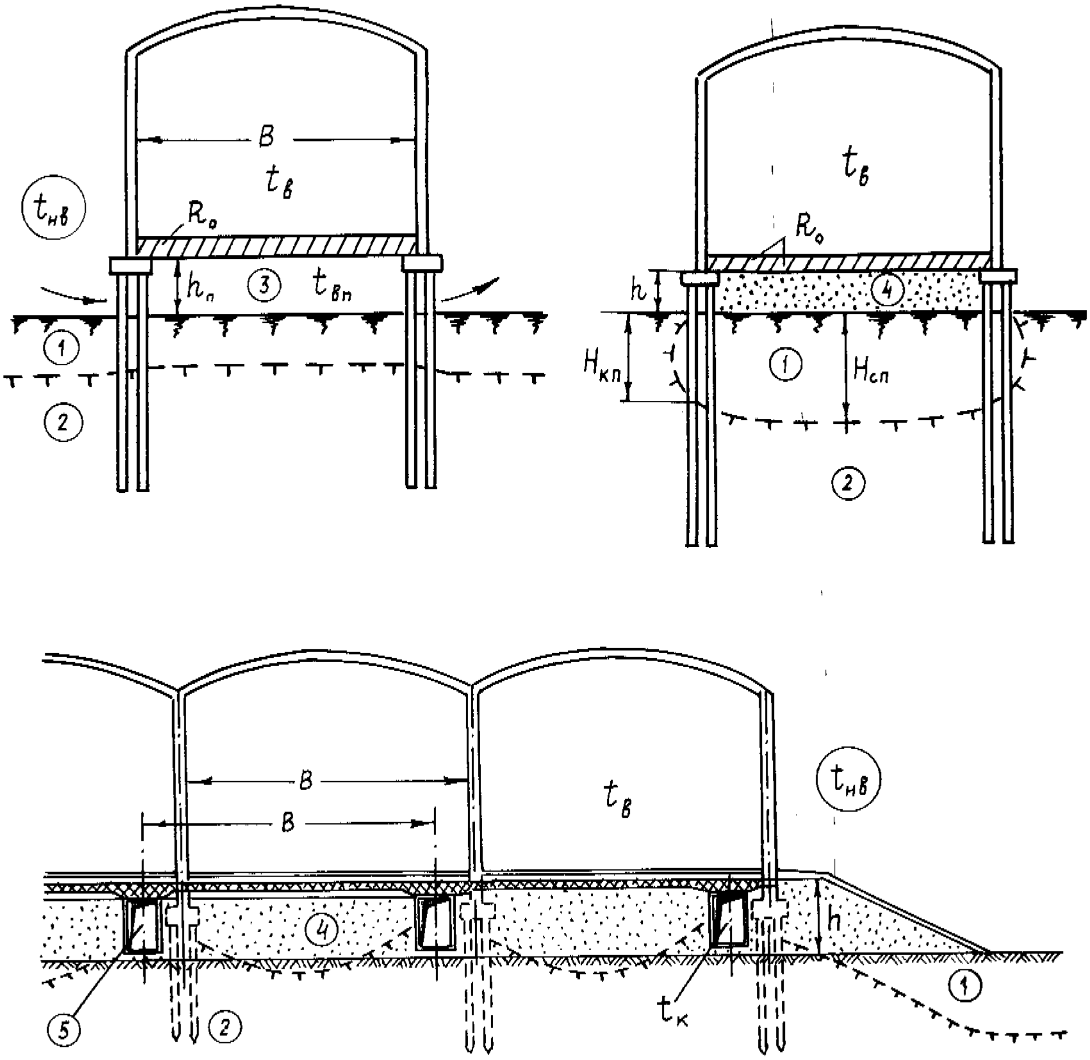

Figure 2

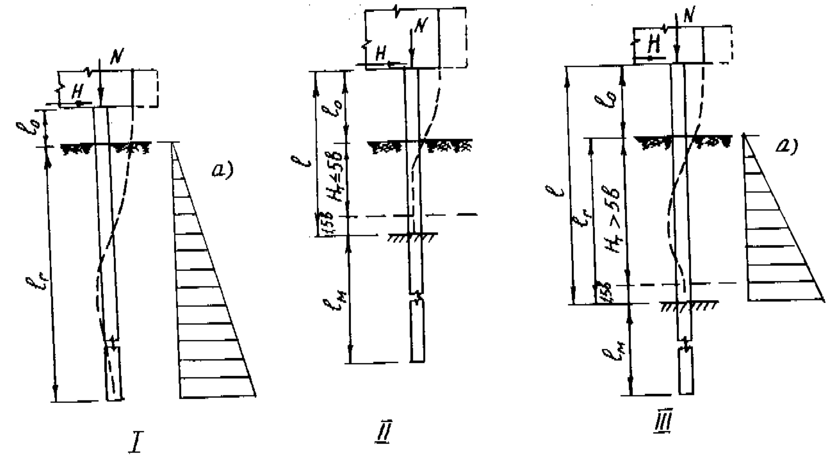

Figure 3

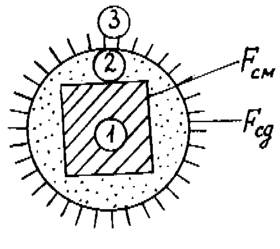

Figure 4

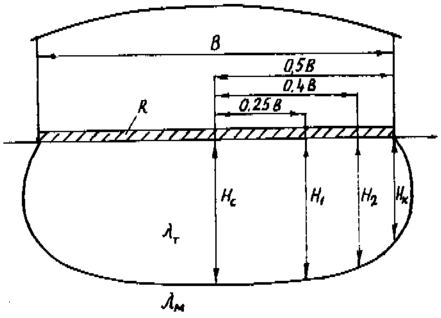

Figure 5

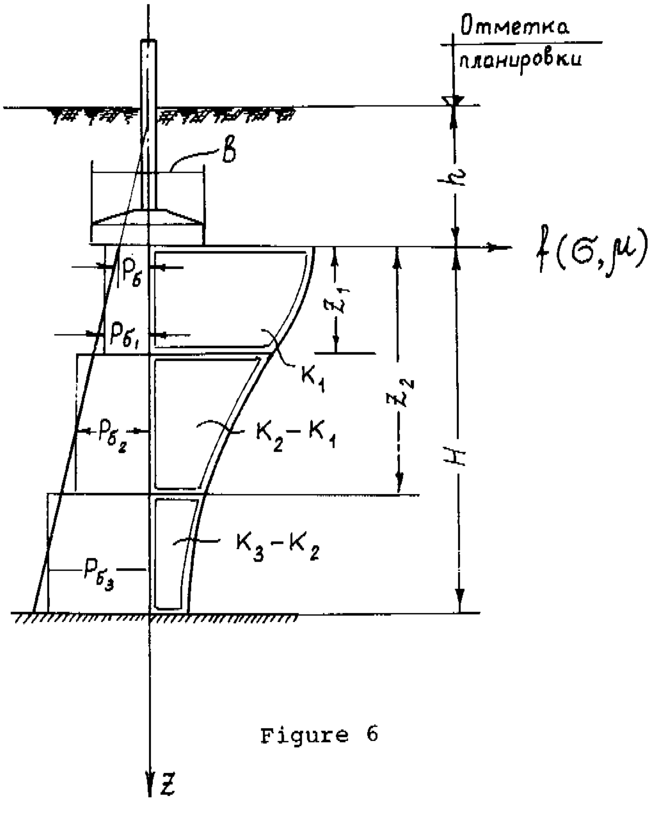

Figure 6

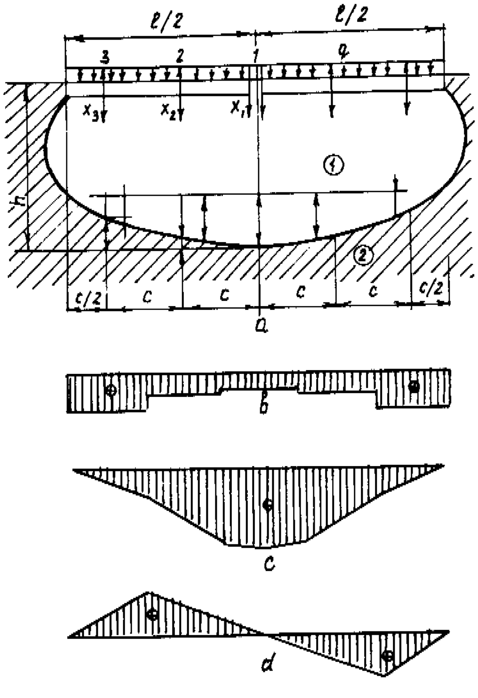

Figure 7

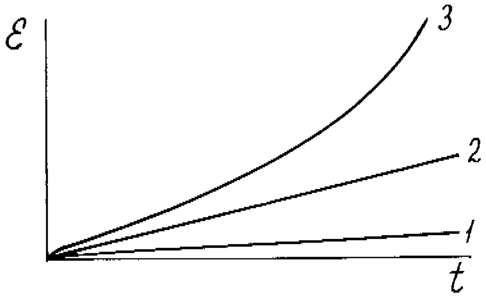

Figure 8

Figure 9

Figure 10

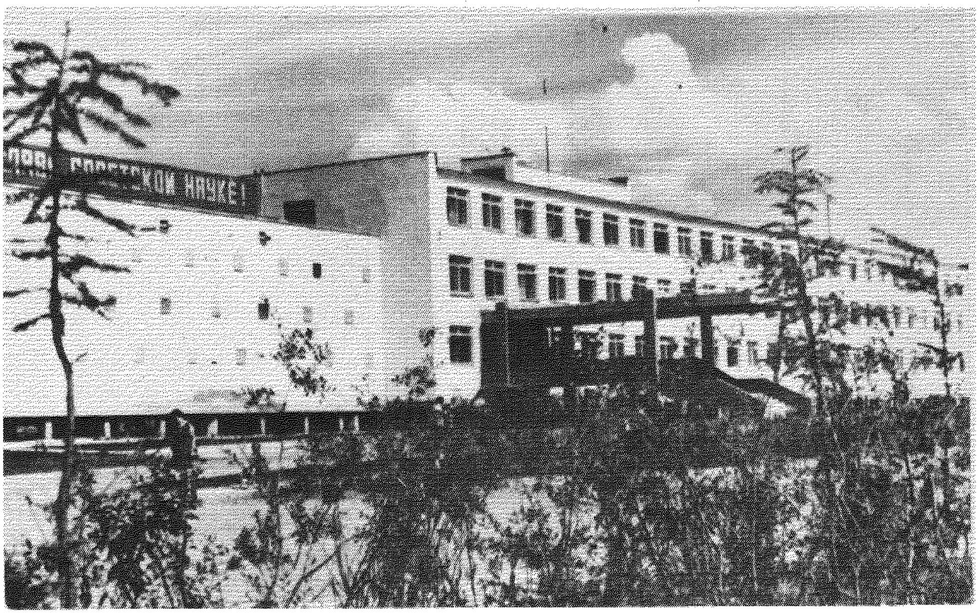

Figure 12

Figure 13

Figure 14

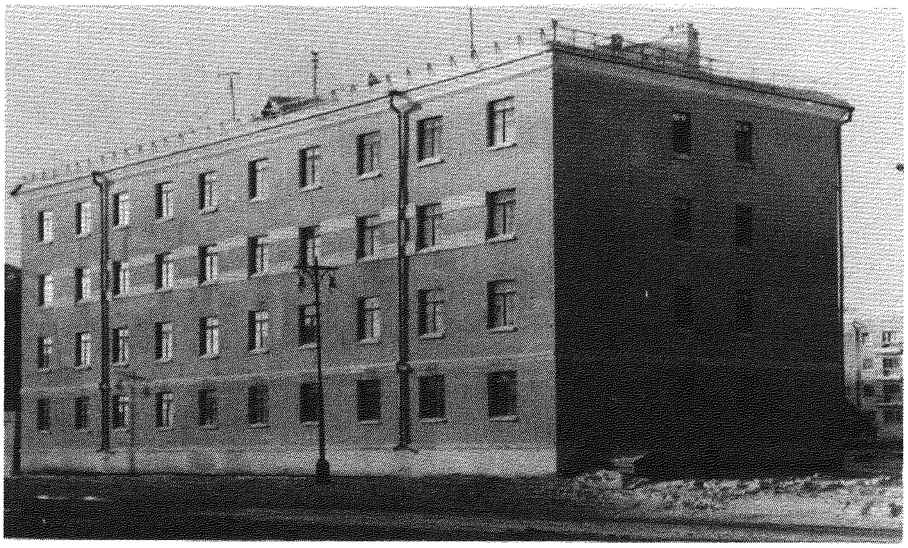

Figure 15

Figure 16

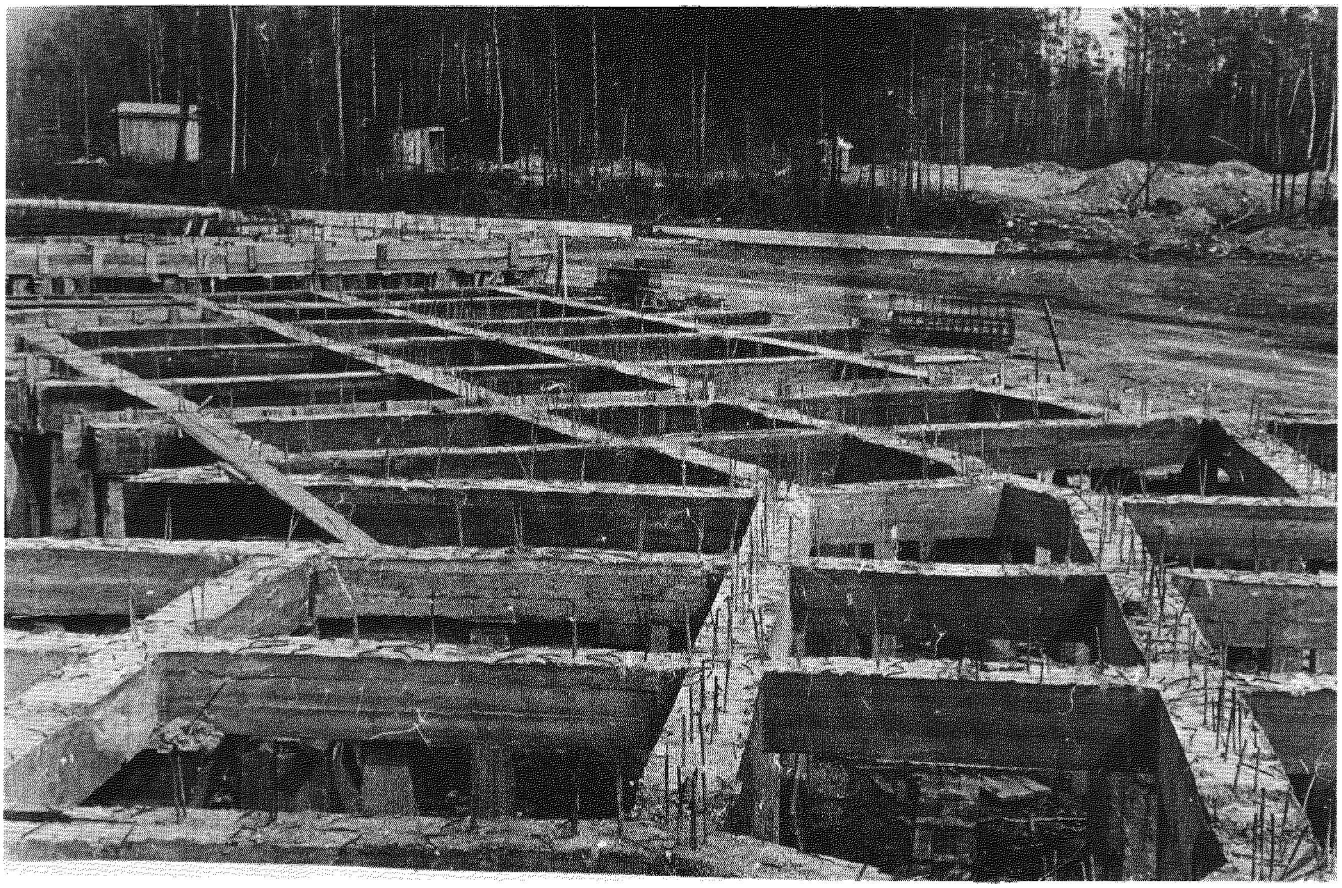

Figure 17

Figure 18

ПРОЕКТИРОВАНИЕ, СТРОИТЕЛЬСТВО И ЭКСПЛУАТАЦИЯ ГРУНТОВЫХ ПЛОТИН НА КРАЙНЕМ СЕВЕРЕ И В УСЛОВИЯХ ВЕЧНОМЕРЗЛЫХ ГРУНТОВ

Генеральный доклад на Ш Международную
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РЕЗЮМЕ

В докладе обобщаются опубликованные данные из опыта проектирования и строительства плотин из местных материалов в районах Крайнего Севера и вечномерзлых грунтов в СССР и за рубежом. Показана сложность и комплексность данной проблемы, решение которой требует комплексного подхода и строгого учета местных климатических, инженерно-геокриологических, технологических и экономических особенностей. Рассматриваются подробно основные особенности инженерно-геологических изысканий и геокриологических исследований для проектирования и строительства грунтовых плотин. Излагаются принципы проектирования и строительства плотин из местных материалов, а также основы расчета грунтовых плотин и их оснований. Описываются основные особенности организации строительства и технология возведения плотин мерзлого и талого типа, включая вопросы технологии зимней укладки связных грунтов в тело плотин, заготовки грунтов в карьерах, особенности строительства водосбросных сооружений и пропуска строительных расходов. Отмечается, что грунтовые плотины мерзлого и талого типа при достаточном обосновании и глубокой проработке проекта, качественном выполнении строительных работ и квалифицированной эксплуатации являются вполне надежными гидротехническими сооружениями.

ПРЕДИСЛОВИЕ

Проектирование и строительство грунтовых плотин для районов вечномерзлых грунтов и Крайнего Севера является весьма сложной проблемой и требует для своего рассмотрения комплексного подхода. Поэтому настоящий генеральный доклад составлен коллективом специалистов в составе: автора предисловия - доктора технических наук, работающего в области механики мерзлых грунтов и инженерного мерзлотоведения; кандидата технических наук Я.К.Кроника - специалиста по инженерному мерзлотоведению, исследованию криогенных процессов в грунтах и изучению поведения грунтовых плотин, возводимых в условиях вечномерзлых грунтов, и инженера Г.Ф.Биянова - опытнейшего строителя/главного инженера/ ряда грунтовых плотин на Крайнем Севере СССР.

Раздел I доклада /Из опыта строительства .../ и раздел 5 /Особенности производства работ.../ написан Г.Ф.Бияновым; раздел 2 /Инженерно-геологические исследования/ и раздел 4 /Основа расчетов грунтовых плотин/- Я.А.Кроником, а предисловие и раздел 3 /Принципы проектирования и строительства/ - Н.А.Цытовичем.

Настоящий доклад составлен исключительно по опубликованным литературным данным /см. список литературы в конце доклада/.

1. ИЗ ОПЫТА СТРОИТЕЛЬСТВА ПЛОТИН НА КРАЙНЕМ СЕВЕРЕ СССР

Проблемы водохозяйственного строительства на Крайнем Севере не менее остры, чем в любых других районах нашей страны. Здесь плотины могут возводиться для создания регулирующих водохранилищ гидроэлектростанций, хвостохранилищ горнообогатительных предприятий, прудов - охладителей тепловых и атомных эдектростанций, водоснабжения населенных пунктов и промышленных предприятий, затопления дражных полигонов, а также сельскохозяйственных нужд.

В Советском Союзе в связи с хозяйственным освоением районов Крайнего Севера, богатых цветными металлами и другими видами минерального сырья, ведется интенсивное строительство гидротехнических сооружений. Одной из первых плотин, построенных еще в конце XVIII века, является грунтовая плотина мерзлого типа на р.Мыкарт в г.Петровске-Забайкальском, успешно работавшая около 140 лет и разрушенная при ремонтных работах /1-3/. Ряд плотин был построен в самом начале, а также в 30-х и 40-х годах XX века. Особенностью этого периода строительства плотин является то, что они возводились еще без достаточного учета специфических геокриологических условий районов, вследствие чего сооружения часто приходили в аварийное состояние и эксплуатация их была связана с большими материальными затратами.

В конце 50-х и 60-х годов центр тяжести интенсивного строительства плотин на Севере переместился в Восточную Сибирь/1,3/. Был построен ряд низко- и средненапорных мерзлых и талых плотин. Среди них такие, как уникальная плотина Вилюйской гидроэлектростанции и Хантайская плотина.

Для этого периода северного плотиностроения характерен более уверенный выбор конструкций и методов строительства. В результате проведения научно-исследовательских работ и крупномасштабных производственных экспериментов разработана технология зимнего производства работ, позволяющая возведение плотин из грунтовых материалов практически в любых природно-климатических условиях круглогодично без сезонных перерывов. /1,3,23,27,29,30/.

2. ИНЖЕНЕРНО-ГЕОЛОГИЧЕСКИЕ ИЗЫСКАНИЯ И ГЕОКРИОЛОГИЧЕСКИЕ ИССЛЕДОВАНИЯ ДЛЯ ПРОЕКТИРОВАНИЯ И СТРОИТЕЛЬСТВА ГРУНТОВЫХ ПЛОТИН

Эффективное проектирование и строительство, обеспечивающие надежную и долговечную эксплуатацию грунтовых плотин в условиях Крайнего Севера и вечномерзлых грунтов, требуют проведения всесторонних и тщательных изыскательских работ для обоснования выбора створа плотины и размещения водохранилища, выявления месторождений местных строительных материалов и разработки прогноза влияния возведения водоподпорного сооружения на окружающую среду, в том числе в первую очередь оценки влияния плотины и водохранилища на вечномерзлое основание и переформирование берегов. Объемы и состав изысканий определяются целями проектирования, классом и ответственностью возводимого сооружения и зависят от инженерно-геологической, гидрогеологической и геокриологической изученности намечаемого района строительства.

Уже на самых первых стадиях составления схем использования водных ресурсов крупных рек и отдельных регионов проводится сбор и анализ климатических и гидрогеологических данных, и в случае их недостаточного объема организуются временные или постоянные гидрометеостанции и гидрологические посты для обеспечения получения достаточных для проектирования сроков и объемов данных натурных наблюдений.

Главное внимание на первых стадиях должно быть уделено сбору данных по инженерно-геологическим условиям и геокриологической изученности района, являющихся основой для рационального выбора створа гидросооружения и определения его типа, компоновки и основных характеристик.Основные принципы выбора створа и методики инженерно-геологических изысканий для гидротехнического строительства на Крайнем Севере наряду с общими чертами, аналогичными с изысканиями в районах с умеренным климатом и на талых основаниях/4/, отличаются также еще и специфическими особенностями, связанными с наличием вечной мерзлоты, важнейшие из которых следующие:

1. Производство комплексной мерзлотно-гидрогеологической и инженерно-геологической съемки/5/ для обоснования проектирования и разработки прогноза изменений в результате строительства инженерно-геологических, гидрогеологических и геокриологических условий. Особое внимание при производстве мерзлотной съемки следует уделять в районах со сложными мерзлото-грунтовыми(геокриологическими) условиями и островного распространения вечномерзлых грунтов, как например, на рис.1 , где приведен геологический разрез по створу правобережной плотины Усть-Хантайской ГЭС /3/.

2. Комплексное и всестороннее изучение строения, состава и свойств вечномерзлых пород основания сооружений. При этом особое внимание необходимо обратить на изучение криогенного строения вечномерзлых пород и изменения их физико-механических и фильтрационных свойств в процессе и в результате оттаивания, в том числе реологических свойств, учитывающих релаксацию напряжений и ползучесть мерзлых пород под нагрузкой.

Важно отметить, что советскими учеными и проектировщиками в последние годы на основе системного подхода и обобщения обширных материалов изысканий для северного гидротехнического строительства разработана методика комплексного изучения многолетнемерзлых скальных пород как оснований сооружений, установлены закономерности формирования криогенного строения скальных массивов и доказана главенствующая и определяющая роль криогенного строения в инженерно-геологической оценке и прогнозе изменения свойств мерзлых скальных оснований гидротехнических сооружений /6/.

Для высоких грунтовых плотин как правило выбираются наиболее надежные створы с прочными скальными основаниями, как например, для плотин Вилюйской, русловой Усть-Хантайской, Колымской ГЭС (в СССР), Кенни, Утард-4 (в Канаде)/3,7-9/. Для средне- и низконапорных плотин выбор створов с надежными скальными основаниями ограничен и поэтому такие грунтовые плотины возводятся практически на любых основаниях, при этом особое внимание при изысканиях следует уделить изучению просадочности мерзлых пород основания при оттаивании и конструкциям примыкания плотин к мерзлым бортам и основанию. При наличии сильнольдистых вечномерзлых грунтов в основании как правило выбирается мерзлый тип плотины с недопущением оттаивания основания и с промораживанием тела плотины, как например, Иереляхская плотина (рис.3)/3/. В случае отдельных островов вечномерзлых грунтов в основании зачастую проектируют талые плотины распластанного профиля на оттаивающем при эксплуатации основании, как например, правобережная плотина Усть-Хантайской ГЭС (рис.1 и 2) /3/, ограждающие дамбы водохранилища Келси /8,9/, правобережная плотина Кеттл /1/.

3. Изучение температурного режима, криогенного строения и криогенных процессов в мерзлых основаниях как основы для разработки методов расчета устойчивости и надежности вечномерзлых оснований и грунтовых плотин совместно с основанием и прогноза изменения инженерно-геокриологических условий после возведения плотины и создания водохранилища. При этом, одновременно с изучением терморежима и криогенного строения вечномерзлых пород, выполняемым при изысканиях, необходимо дополнительное привлечение специальных исследовательских организаций для тщательного изучения

криогенных процессов и явлений (криогенного пучения и трещинообразования, солифлюкции и термокарста, льдообразования и др.) с целью учета их при проектировании плотины и водохранилища и при разработке прогнозов изменения условий и переработки берегов/3,10,11/.

Особое внимание на последующих стадиях проектирования следует уделить разработке прогнозов температурно-влажностного режима основания плотины совместно с основанием, их напряженно-деформированного состояния, прочности и устойчивости при длительной эксплуатации плотин в суровых климатических условиях, а также весьма слабо разработанным в настоящее время вопросам прогноза переформирования берегов водохранилищ в области вечной мерзлоты/3,11/ и влияния гидростроительства на окружающую среду. Для решения этих проблем необходимо использовать не только накопленный опыт строительства и эксплуатации аналогичных проектируемой плотин, но и главным образом использовать данные натурных наблюдений на данном конкретном объекте строительства, которые необходимо организовать с самого начала изысканий, непрерывно вести в период проектирования и строительства и затем продолжить ведение их при эксплуатации; особенно это относится к натурным наблюдениям за температурным режимом вечномерзлых и оттаивающих оснований и устойчивостью к деформациям бортов каньона и основания.

4. Более тщательные и детальные изыскания месторождений местных строительных материалов для возведения грунтовых плотин и особенно поиски и выбор оптимального вида связных грунтов для противофильтрационных элементов и несвязных грунтов для фильтров и дренажей. При этом уже на первых стадиях изысканий необходимо точно оконтуривать месторождения и определять их запасы, чтобы не допускать возможности нехватки требуемых кондиционных материалов при строительстве, как это, например, обнаружилось в ходе возведения плотин Усть-Хантайской ГЭС, в результате чего были использованы искусственные грунтовые смеси и каменная мелочь.

При изыскании грунтовых материалов необходимо исходить из условий поиска их в максимальном приближении к створу строящегося гидроузла и с учетом возможности при соответствующих конструкциях плотин и мелиорациях грунтов использовать для укладки в тело плотины практически любые имеющиеся на месте грунты, включая вскрышные породы и материалы из полезных выемок. Однако предпочтительнее использовать грунты оптимального состава и с минимальной влажностью,близкой к оптимальной, месторождения (карьеры) которых должны специально оконтуриваться и детально исследоваться в процессе изысканий для уточнения конструкций плотины и технологии ее возведения. Опыт строительства грунтовых плотин Вилюйской, Усть-Хантайской и Колымской ГЭС и Магаданской ТЭЦ показал, что оптимальными грунтами для противофильтрационных элементов являются крупнообломочные грунты с супесчано-суглинистым заполнителем/12,13/, содержащие крупнообломочные частицы (более 2 мм) от 40% до 65% по весу, и аналогичные им искусственные грунтовые смеси, получаемые при перемешивании, например, супесей, суглинков или легких глин с моренными и крупнообломочными грунтами, с песчано-гравийной смесью или обломками полускальных пород. Такие грунты как правило приурочены к элювиально-делювиальным и моренным /12,13/ четвертичным отложениям и реже к флювиогляциальным и коллювиальным отложениям и зачастую слагают тела естественных осыпей, курумов.

Для материалов набросных упорных призм рекомендуются любые скальные и полускальные породы, отвечающие требованиям достаточной морозостойкости и прочности. При специальном зонировании тела плотины в зоны ее, не подверженные значительным температурным колебаниям, можно укладывать менее морозостойкие породы, однако для обоснования использования слабых скальных и полускальных пород в теле плотины необходимы специальные исследования.

5. Особенности буровых и горных разведочных работ в комплексе с геофизическими и другими изыскательскими работами и тщательное оформление всей документации. Специфической особенностью буровых и горных работ в области вечной мерзлоты является необходимость отработки методик проходки, позволяющих получать наиболее достоверную информацию об истинном температурном режиме и криогенном строении вечномерзлых пород и обеспечивающих возможность получения кернов или монолитов мерзлых грунтов ненарушенного сложения. В этой связи бурение следует вести колонковым способом на малых скоростях вращения, без подлива воды в скважину, с охлаждением скважин на забое и с максимально возможным диаметром. Так, хорошие результаты при изысканиях для проекта Колымской ГЭС дало бурение смотровых скважин диаметром до 1000 мм с отбором кернов по всей высоте, а также проходка штолен и выработок большого сечения, позволяющих получать наиболее достоверную информацию о геологическом и геокриологическом строении пород основания. Необходимо также учитывать, что в зонах возможных подземных вод и на границах талых и мерзлых зон подземные выработки в вечномерзлых породах довольно быстро заполняются льдом и зачастую не могут быть использованы для дальнейших длительных изыскательских и исследовательских работ, как это наблюдалось, например, в штольнях малого сечения в створе Колымской ГЭС.

Важнейшей необходимостью является также комплексирование непосредственных геологоразведочных работ и прямых геотехнических методов определения состава и свойств мерзлых пород и их криогенного строения с геофизическими работами и косвенными методами, позволяющими в комплексе проведение большого объема всесторонних изысканий в кратчайшие сроки при достаточно высокой степени достоверности и информативности.

По каждой скважине и выработке должна быть составлена тщательная документация с участием инженера-геокриолога (мерзлотоведа) с зарисовками криогенных текстур, вмещений льда и всех трещин, включая криогенную микротрещиноватость и выделяя фрагменты крупномасштабных зарисовок тектонических трещин, отличающихся чаще всего повышенной льдистостью и распученностью/6/. При этом обязательно указание на методику и сроки проходки скважины или выработки, на методику и сроки проведения температурных замеров, в том числе на сроки выдержки (выстойки) скважин после бурения до восстановления естественного температурного режима.

6. Необходимость проведения опытно-строительных и специальных научно-исследовательских работ. На последних стадиях изысканий, в начале строительства, точнее в подготовительном периоде до начала возведения основных сооружений гидроузла, а также в процессе строительства, когда ведется проходка подземных сооружений ГЭС, водоводов, туннелей, цементационных и смотровых галерей, подготовка основания и отсыпка тела плотины, необходимо проведение специальных исследований и опытно-строительных работ с целью уточнения инженерно-геологических свойств и геокриологического строения мерзлых пород основания, состава и свойств грунтовых материалов плотин, совершенствования конструкции и технологии возведения плотины и подземных сооружений гидроузла. При этом в ходе подготовки основания и проходки подземных сооружений вскрываются большие разрезы в основании и в карьерах месторождений, позволяющие существенно уточнить и скорректировать до мельчайших деталей геологическое и криогенное строение горных пород и внести соответствующие поправки и уточнения в проект и в технологию строительства гидроузла. При этом возможны непредвиденные обстоятельства и некоторые особенности мерзлых пород, не обнаруженные при изысканиях. Поэтому необходимо постоянное участие геокриологов и исследователей для оперативного решения совместно с пректировщиками и строителями всех возникающих в ходе строительства задач.

Важно также, чтобы до начала возведения плотины были изучены и отработаны в опытно-строительных работах все вопросы разработки карьеров и основания, оттаивания вечномерзлых грунтов и их технической мелиорации с получением оптимальных грунтов или грунтовых смесей, заготовки и складирования запасов талых грунтов, необходимых для обеспечения ведения зимних земляных работ, опытные укладки в противофильтрационные элементы связных грунтов (в летнее и зимнее время) с выбором оптимальных грунтов, технологий и уплотняющих механизмов и с обработкой и налаживанием тщательного геотехнического контроля качества ведения земляных и скальных работ и возведения грунтовой плотины.

Комплексные и тщательные изыскания и геокриологические исследования с последующими опытно-производственными и научно-исследовательскими работами перед началом и в ходе возведения грунтовых плотин позволяют разработать весьма эффективные проектные решения и рациональные технологические схемы, обеспечивающие в комплексе высокое качество строительства и надежную эксплуатацию грунтовых плотин в суровых климатических условиях Крайнего Севера и на вечномерзлых основаниях.

3. ПРИНЦИПЫ ПРОЕКТИРОВАНИЯ И СТРОИТЕЛЬСТВА ГРУНТОВЫХ ПЛОТИН В УСЛОВИЯХ ВЕЧНОМЕРЗЛЫХ ГРУНТОВ КРАЙНЕГО СЕВЕРА

В основу проектирования и строительства грунтовых плотин, возводимых на вечномерзлых грунтах Крайнего Севера, должны быть положены данные инженерно-геологических изысканий места постройки и результаты специальных геокриологических исследований. К последним в первую очередь относятся : мощность вечномерзлых грунтов, их температура на глубине 10 м , криогенное строение и объемная льдистость пород основания. Геологические изыскания должны в первую очередь определить условия залегания (глубину и пр.)коренных массивно-кристаллических пород и их инженерно-строительные свойства : залегают ли они сплошным слоем с незначительной трещиноватостью, или представляют собой типичные скальные породы, т.е. породы трещиновато-блочного строения, или же полускальные породы, рассланцованные многократными проявлениями криогенных процессов. Последние виды пород (рассланцованных-полускальных) весьма часто встречаются в районах распространения вечномерзлых пород и обуславливают наибольшие опасности для оснований гидротехнических сооружений, так как в мерзлом состоянии они представляют монолитные весьма прочные породы, а будучи подвержены оттаиванию часто превращаются в сильно сжимаемые породы, обуславливающие значительные их осадки и просадки.

В зависимости от наличия прочных массивно-кристаллических пород, или слабых (при оттаивании) грунтовых отложений, а также - устойчивости мерзлого температурного режима вечномерзлых пород места строительства,- выбирается принцип проектирования и строительства грунтовых плотин по талому или мерзлому их типу. Первый тип - талые плотины применяются при наличии лишь массивно-кристаллических не разрушенных коренных пород или слабосжимаемых талых и оттаивающих пород в основании, а второй - плотины мерзлые могут возводиться практически на любых вечномерзлых породах, при обязательном, однако, обеспечении вечномерзлого состояния как основания, так и большей части самого тела мерзлой грунтовой плотины, обеспечивающего водонепроницаемость плотины.

Первый тип - талые плотины- проектируется как правило с учетом полного оттаивания основания при длительной эксплуатации, причем водонепроницаемость самого тела грунтовой плотины достигается либо устройством противофильтрационного экрана (обычно из уплотненных глинистых грунтов) , как это было выполнено при строительстве русловой Вилюйской плотины высотой 75 м (рис.4, а /3/), либо устройством противофильтрационного водонепроницаемого ядра плотины, как это было выполнено при строительстве Хантайской, высотой 65 м, русловой плотины (рис.4 , б /3/).

При проектировании плотин по второму (мерзлому типу) могут применяться несколько решений : первое - устройство распластанного профиля (при углах откоса менее 1:5), при котором изотерма грунта в теле плотины под верховым откосом во все время, (и даже при установившемся температурном режиме) не доходила бы до середины профиля грунтовой плотины и низовой откос всегда оставался бы в мерзлом состоянии; второе решение- при менее распластанном профиле (с откосами 1:3; 1:4)применяется охлаждающее устройство(как, например, у Иреляхской плотины, рис.4 в /3/), состоящее из трубчатой завесы в центре профиля, холодный воздух в которой зимой или машинная циркуляция хладоносителя (обычно $CaCl_2$) поддерживает постоянно требуемую отрицательную температуру. В плотинах мерзлого типа нашла применение и такая система охлаждения, как, например, в плотине на озере Долгом (Фиг.4, г /3/), где с помощью автоматического проветривания зимой низового откоса, которое производится путем устройства специальной крытой галереи для циркуляции зимнего холодного воздуха, поддерживается уже более двадцати лет постоянно мерзлое состояние низового откоса.

Отметим, что при проектировании и строительстве грунтовых плотин в условиях вечномерзлых грунтов Крайнего Севера обязательны теплотехнические прогнозы глубин и областей оттаивания мерзлых пород с построением изотерм тела грунтовых плотин и их основания как для различных промежутков времени от начала заполнения водой водохранилища и эксплуатации плотины, так и для предельного стационарного состояния температурного поля грунтовой плотины и ее основания. При этом грунтовая плотина должна иметь такой профиль и такие дополнительные устройства, чтобы была гарантирована ее незыблемость и водонепроницаемость во все время эксплуатации плотины. Следует также обратить особое внимание на высококачественное устройство примыкания плотины к бортам водохранилища и особенно - устройств паводковых водоспусков, мерзлое состояние основания которых может поддерживаться периодическим применением искусственного охлаждения.

При эксплуатации грунтовых плотин на вечномерзлых основаниях обязательно должна быть предусмотрена закладка контрольно-измерительной аппаратуры (КИА) для периодического контроля состояния плотины и ее основания.

4. ОСНОВЫ РАСЧЕТА ГРУНТОВЫХ ПЛОТИН И ИХ ОСНОВАНИЙ ДЛЯ УСЛОВИЙ КРАЙНЕГО СЕВЕРА

Отличительной чертой проектирования грунтовых плотин на Крайнем Севере и вечномерзлых основаниях является необходимость проведения в первую очередь теплотехнических расчетов по прогнозу стационарного и нестационарного температурного режима плотин и их оснований, оттаивания бортов и ложа водохранилища, искусственного промораживания грунтов для создания мерзлотной завесы в мерзлой плотине и основании /14-17/. Бдагодаря успехам советских ученых, главным образом школ профессора П.А.Богословского /14,15/, члена-корреспондента АН СССР профессора Н.А.Цытовича /2,20/ и ВНИИГ им. Б.Е.Веденеева /16, 17, 18/, разработаны методы температурных расчетов земляных плотин и водохранилищ и решены аналитическими и численными методами (МКР) многие одномерные и плоские задачи, главным образом простейшие, для однородных земляных и каменно-набросных нефильтрующих и фильтрующих плотин. Однако многие практические задачи прогноза температурно-влажностного режима для плотин неоднородных, многосоставных, каменно-набросных, а также с учетом пространственного тепломассообмена и криогенных процессов в плотине и основании до сих пор не имеют своего решения,и потому проблема совершенствования и разработки новых методов расчета терморежима грунтовых плотин, особенно высоких, остается весьма актуальной. В этой связи представляется весьма перспективным для решения сложных пространственных задач прогноза температурного режима плотин и оснований использование численных методов, в том числе метода конечных элементов, широко применяемого в зарубежной практике и разработанного в последние годы в СССР для тепловых расчетов грунтовых плотин /21,22/.

По результатам теплотехнических расчетов для талых плотин назначаются конструкции и параметры из противофильтрационных элементов (ядер, экранов), фильтров, переходных зон, дренажных систем,балластной пригрузки на гребне и откосах; для мерзлых плотин определяются зоны мерзлых грунтов, являющихся водоупором, уточняются конструкции, а также устанавливаются схемы размещения холодильных колонок и выбираются замораживающие устройства, обеспечивающие мерзлое состояние тела плотины и основания.

Одновременно с температурными расчетами выполняются расчеты фильтрации в противофильтрационном элементе , и из условия недопущения суффозии грунтов ядра (экрана) подбираются обратные фильтры. Важно отметить, что в СССР во ВНИИГ им. Б.Е.Веденеева для высоких каменно-набросных плотин, возведенных с частично промороженными зонами ядра, разработаны методики экспериментального исследования и расчета тепловых и фильтрационных режимов и методики подбора суффозионно-устойчивых фильтров с учетом их частичного промораживания при строительстве и последующего оттаивания при эксплуатации под напором /23/. Однако еще нерешенной проблемой остается прогноз пространственного нестационарного температурного режима послойно промороженных ядер (экранов) и формирования фильтрации в процессе постепенного их оттаивания при эксплуатации.

Важнейшим этапом проектирования грунтовых плотин является расчет их напряженно-деформированного состояния, прочности и устойчивости при эксплуатации. Для талых высоких плотин методы этих расчетов аналогичны таким же расчетам талых плотин в умеренном климате. При проектировании высоких каменно-набросных плотин (например, для Колымской ГЭС) выполняются обширные исследования и детальные расчеты по устойчивости откосов плотин и прогнозу их напряженно-деформированного состояния на основе новейших достижений в области механики грунтов /20,21/ с учетом перекрестного влияния вида сложного напряженно-деформированного состояния НДС , среднего главного напряжения, траекторий нагружения, контракции, дилатации и других параметров и особенностей НДС, требующих своего специального учета для высоких (свыше 80-100 м) и особенно для сверхвысоких грунтовых плотин (свыше 150-200 м) . В то же время следует отметить, что для плотин мерзлого типа аналогичные детальные и сложные расчеты не выполняются, основные расчеты устойчивости откосов выполняются по известным в механике грунтов простейшим методам (типа круглоцилиндрических поверхностей скольжения и т.п.), но в недостаточной степени учитываются особенности мерзлых грунтов (их ползучесть, переменность прочностных и деформационных характеристик и т.п.). Кроме того, в механических расчетах грунтовых плотин на Крайнем Севере весьма недостаточно учитывается нестационарное сложнотемпературное состояние грунтов, предопределяющее в основном напряженно-деформированное состояние и надежность всей плотины в целом.

В этой связи представляется вполне оправданным и весьма перспективным использование в расчетах плотин теории термоупругости и термореологии /21/, а для сложных смешанных задач механики и термодинамики, учитывающих совместное влияние на НДС процессов механических, тепловых и массообменных (в том числе криогенных) /10/, теорий термомеханики сплошных сред и строительной термомеханики, разработка которых применительно к задачам северной гидротехники и инженерной геокриологии начата в СССР в самые последние годы /21, 25 и др./.

Важным достижением советских ученых является также установление основных видов и закономерностей развития криогенных процессов в грунтовых плотинах и их основаниях на основе многолетних комплексных аналитических, экспериментальных и, главным образом, натурных исследований для первых северных высоких каменно-набросных плотин Вилюйской и Усть-Хантайской ГЭС /3,10,20,23,26,27,28/, позволяющих разработать методы прогноза и управления ими с целью повышения долговечности плотин при эксплуатации в суровых климатических и сложных инженерно-геокриологических условиях Крайнего Севера. Необходимо отметить, что до последнего десятилетия криогенные процессы в грунтовых плотинах и их основаниях не учитывались и были недостаточно изучены, что способствовало недолговечной работе многих малых и низконапорных плотин /26/. При проектировании и строительстве первых высоких плотин Вилюйской и Усть-Хантайской ГЭС на основании специальных исследований, выполненных в МИСИ под общим руководством члена-корреспондента АН ССС Н.А.Цытовича /3,28,30/, уже были разработаны конструкции гребня и мелиоративные мероприятия, предотвращающие опасность криогенных процессов и деформации. Опыт эксплуатации этих плотин в течение 8-10 лет подтвердил эффективность рекомендованных МИСИ антикриогенных мероприятий (в том числе комплексного противопучинного засоления грунтов морозоопасных зон, утепления и пригрузки гребня, использования слабопучинистых оптимальных грунтовых смесей и др.) /3,27,25/, что позволяет рекомендовать их к более широкому использованию в отечественной и зарубежной практике строительства грунтовых плотин на Крайнем Севере.

Однако один из важнейших вопросов - разработка долгосрочного прогноза поведения плотин с учетом криогенных процессов и оценка влияния криогенных процессов на физико-механические свойства грунтовых материалов плотин, устойчивость откосов и долговечность плотины-в целом остается еще недостаточно изученной проблемой и требует своего дальнейшего исследования и решения. Особо следует указать на необходимость обязательного учета льдообразования в каменно-набросных упорных призмах плотин при проектировании и прогнозе их поведения при эксплуатации, без которого расчеты напряженно-деформированного состояния и устойчивости грунтовых плотин являются недостаточно корректными и надежными.

Для оценки морозоопасности грунтов, используемых для отсыпки плотин, при выборе оптимальных грунтов и проектировании плотин рекомендуется пользоваться критериями МИСИ, достаточно проверенными в практике северного плотиностроения за последнее десятилетие /13/.

Дальнейшие исследования в области совершенствования расчетов грунтовых плотин следует вести в направлении строгого учета температурно-влажностного и фильтрационного режимов и криогенных процессов в плотине и основании на основе данных натурных исследований грунтовых плотин при эксплуатации и с более широким использованием численных методов и ЭЦВМ, позволяющих решать практически любые сложные задачи теории и практики северной гидротехники и инженерной геокриологии.

5. ОСОБЕННОСТИ ОРГАНИЗАЦИИ СТРОИТЕЛЬНЫХ РАБОТ И ТЕХНОЛОГИЯ ВОЗВЕДЕНИЯ ГРУНТОВЫХ ПЛОТИН

5.1. Особенности организации строительства

Рассматриваемые районы строительства обычно характеризуются суровым климатом со среднегодовыми отрицательными температурами до - 12°С при внутригодовых амплитудах колебаний температур до 100°С и почти повсеместным распространением вечномерзлых грунтов. Гидрологический режим рек крайне неравномерен - основной объем стока приходится на весенне-летний период, зимой сток большинства малых и средних рек практически отсутствует, реки часто перемерзают.

Чрезвычайно сложные природные условия, малая заселенность и отдаленность от обжитых и промышленно развитых центральных и южных районов страны, слабое развитие путей сообщения крайне осложняют проблемы организации строительных работ в районах Крайнего Севера. При слабо развитой сети автомобильных и железных дорог главная роль в транспортной схеме принадлежит естественным водным путям, имеющим главным образом меридиональное направление, и автозимникам, но экономическое значение таких коммуникаций снижается сезонностью их действия, так как удлиняется время пребывания грузов в пути. Иллюстрацией к сказанному может явиться транспортная схема строительства Вилюйской ГЭС /1,29/. Строительные грузы для этой ГЭС доставлялись по железной дороге до порта Осетрово, далее по реке Лене до г.Ленска (990 км), затем до г.Мирного по автомобильной дороге (235 км) и по автозимнику (110 км) до строительной площадки.

Такая сложная транспортная схема с сезонностью и неравномерностью завоза материалов требует дополнительных складских помещений в пунктах перевалок, хранения почти годовых запасов материалов непосредственно на строительной площадке. При этом неизбежны значительные потери материалов при транспортировании и многочисленных перевалках, снижение качества их при длительном хранении. Все это ведет у значительному удорожанию стоимости строительства.

Изложенным определяется необходимость при строительстве гидротехнических сооружений на Крайнем Севере максимального использования местных грунтовых строительных материалов и максимального сокращения применения дальнепривозимых.

5.2 Особенности технологии возведения грунтовых плотин

Специфичность природно-климатических условий Крайнего Севера серьезно осложняет производство строительных работ. Интересы сокращения сроков строительства объектов диктуют необходимость продления строительного сезона за счет использования зимнего периода с низкими температурами наружного воздуха. В СССР проблемы зимнего ведения строительных работ в основном решены, и практически все строительные работы выполняются круглогодично. Гидротехническое строительство связано с выполнением массовых объемов земельно-скальных работ, выполнение которых в зимних условиях встречает определенные трудности. При этом наибольшие трудности связаны с зимним возведением качественных насыпей из связных грунтов, а также производством работ по подготовке оснований плотин.

5.2.1. Некоторые особенности технологии возведения мерзлых плотин

В состав строительных работ при возведении мерзлых плотин входит выполнение в определенной последовательности следующих видов работ: подготовка основания; проходка траншей и укладка суглинка в зуб ядра; возведение береговых частей плотины с сохранением прорана в русловой части для пропуска паводка; монтаж замораживающей системы и создание мерзлотной завесы в береговых частях плотины до перекрытия реки; перекрытие реки и отсыпка плотины в русловой части с последующим замораживанием подруслового талика и суглинистого ядра в этой наиболее ответственной части плотины.

Опыт строительства плотин показывает целесообразность отсыпки упорных призм в зимнее время. Такой способ строительства позволяет аккумулировать в теле плотины холод в максимально возможных количествах.

Технология и методы строительства мерзлых плотин мерзлого типа постоянно совершенствуются. Так, плотина на р.Сытыкан строилась в две очереди /1/. Причем технологическая схема строительства первой очереди существенных отличий от описанной выше не имеет. Представляет интерес смелое решение проекта, предусматривающее на втором этапе строительства сброс весенних паводковых вод через гребень недостроенной плотины. При этом через гребень плотины сброшено два паводка, один из которых вдвое превышал расчетный.

Замораживающие колонки в ядре плотины были установлены после окончания строительства первой очереди, поэтому достройка плотины до полного проектного профиля производилась с наращиванием колонок по мере отсыпки плотины. Практика показала техническую и экономическую целесообразность возведения плотины с опережающим монтажом замораживающей системы. Такая технология обеспечивает высокую надежность мерзлотной завесы, которая создается одновременно с отсыпкой плотины. Это обстоятельство позволяет изменить конструкцию плотины. Так, например, отпадает необходимость в устройстве зуба ядра, так как исключается возможность возникновения фильтрации через основание плотины; для укладки в ядро можно использовать любые грунты, в том числе и мерзлые комковатые при условии заполнения пор в отсыпке водой или грунтовыми растворами.

Технологические особенности строительства талых плотин в основном связаны с подготовкой основания и укладкой связных грунтов при отрицательных температурах. В Советском Союзе разработана технология зимней укладки в плотину связных грунтов /29/.

5.2.2. Технология зимней укладки связных грунтов

В практике гидротехнического строительства длительное время ведутся поиски способов зимнего возведения качественных насыпей из грунтовых материалов при низких температурах наружного воздуха. Особенно сложной становится эта проблема при строительстве в суровых климатических условиях на Крайнем Севере. Осложняются вопросы всего технологического комплекса от организации карьерного хозяйства в условиях вечной мерзлоты и малой мощности полезной толщи карьеров, разработки, доставки грунта с минимальными потерями температуры в нем до качественной его укладки с уплотнением и обеспечения необходимого качества контактов между отдельными слоями для получения однородной насыпи в условиях интенсивного промерзания грунта.

Советскими учеными и строителями выполнены исследования и внедрение в практику снижения смерзаемости грунтов солевой обработкой /20,28,30/, но при температурах наружного воздуха минус 30, минус 40^{0}С только одна солевая обработка грунтов недостаточна. Необходимо одновременное проведение других мероприятий, направленных на уменьшение потерь тепла по всей технологической цепи, сохранение грунта с положительной температурой до полного окончания уплотнения его. В дальнейшем, при открытом (без тепляков) ведении работ, несмотря на принимаемые меры, промерзание уложенного слоя до перекрытия его следующим слоем трудно предотвратить и последующий слой укладывается на уже промерзший слой.

В связи с этим, одновременно с применением метода химической защиты грунта от смерзаемости, требуется проведение еще и других мероприятий по сохранению грунта в талом состоянии с высокой положительной температурой, по подготовке карт, разработке, доставке грунта на карту и уплотнению его с обеспечением хорошего контакта между отдельными слоями.

В последние годы в нашей стране разработан и успешно осуществлен технологический комплекс укладки связных грунтов при крайне низких отрицательных температурах /29/, элементами которого являются следующие производственные операции от карьера до сооружения :

- организация карьерного хозяйства и заготовка грунта;
- зимнее хранение грунта в буртах;
- защита грунта засолением в буртах от промерзания;
- электропрогрев буртов зимнего хранения грунта;
- разработка буртов зимнего хранения грунта;
- транспортирование грунта к месту укладки;
- подготовка карты перед укладкой грунта;
- тепловая и солевая обработка поверхности ранее уложенной карты;
- прием грунта на карте и укрытие его от преждевременного охлаждения;
- разравнивание грунта;
- засоление поверхности слоя раствором соли;
- уплотнение грунта.

Четкое выполнение всех элементов этой технологической цепи при производстве работ обеспечивает сохранение укладываемого грунта в талом состоянии вплоть до окончания уплотнения на карте, получение плотных контактов между отдельными слоями отсыпки и высокое качество сооружения.

5.2.3. Некоторые особенности заготовки грунтов в карьерах

Мерзлое состояние грунта в карьерах и зачастую незначительная мощность полезной толщи, характерная для элювиально-делювиальных отложений, разнородный гранулометрический состав и влажность грунтов по глубине слоя, короткий благоприятный для производства строительных работ летний сезон при значительных объемах земляных работ определяют особенности организации карьерного хозяйства и технологии разработки грунтов. Экономичная разработка и заготовка связных грунтов в больших объемах практически возможна только в летнее время по мере оттаивания.

Работы по освоению карьеров начинают с уборки снега и сводки леса. Обычно эта работа производится бульдозерами, когда мерзлые деревья в начале весны сравнительно легко срезаются под корень и убираются вместе с кустарником и снегом. Освобожденная от снега и растительности поверхность карьера задолго до полного схода снежного покрова прогревается весенним солнцем, суммарная радиация которого в весенний период (апрель-май) в большинстве областей распространения вечномерзлых грунтов весьма высока. Своевременная уборка снежного покрова дает возможность более полного использования поступающего тепла для прогрева поверхностного слоя грунта за счет сокращения расхода того тепла, которое затрачивалось бы на таяние и испарение снега.

По мере оттаивания почвенно-растительного слоя на глубину не более 10-15 см приступают к его срезке. Дальнейшая разработка карьера и заготовка суглинка производится бульдозерами по мере оттаивания, интенсивность которого достигает обычно 10-15 см/сут. Собранный грунт находится в валках в течение 2-3 недель. За это время температура его значительно повышается, а влажность снижается. Затем грунт доставляется в бурты зимнего хранения или к месту укладки, если насыпь возводится летом /1,29/.

Обычные способы предохранения грунта от промерзания зимой в карьерах с сохранением естественных и устройством искусственных теплоизоляционных покрытий в суровых климатических условиях, при наличии мощной толщи вечной мерзлоты и залегании связных грунтов небольшой мощностью, неэффективны.

По этим же условиям весьма дороги и потому мало эффективны методы зимней разработки грунтов в карьерах с применением паро- и электрооттаивания или химических методов оттаивания.

Поскольку при зимней укладке грунта получить талый грунт в больших объемах и с малыми затратами при непосредственной разработке карьера практически невозможно, то его следует заготавливать в основном летом, складировать в бурты, где он хранился бы в течение нескольких месяцев до момента укладки в дело.

Исследованиями, проведенными на строительстве Вилюйской ГЭС, было установлено, что зимой теплопотери грунта в процессе его разработки, транспортирования, укладки и уплотнения в зависимости от совокупности ряда факторов составляют от 6 до 10^{0}С. Следовательно, для обеспечения на карте укладки грунта с температурой хотя бы +2 ÷ +3^{0}С минимальная температура его в бурте должна быть не ниже +10 ÷ +13^{0}С, что достигается созданием буртов зимнего хранения большого объема грунта. Имеется опыт создания буртов суглинка объемом 250 тыс.м^3, высотой 16-18 м и удельной поверхностью 0,12-0,13 м^2/м^3.

Но создание больших буртов зимнего хранения связных грунтов не исключает их промерзания; требуются дополнительные пассивные, активные, химические мероприятия, направленные на уменьшение глубины промерзания бурта с поверхности. При этом наиболее рациональным оказывается сочетание пассивного, активного и химического методов защиты грунта от промерзания. Такими мероприятиями явились:

- засоление грунта периферийных зон бурта;
- электропрогрев периферийных зон бурта и
- теплоизоляция бурта покрытием поверхности пенольдом.

В периферийные зоны бурта слоем 2-2,5 м грунта отсыпается с солевой обработкой из расчета 20-30 кг/м^2.

В качестве пассивных методов защиты грунта от промерзания может быть использовано укрытие откосов бурта пенольдом. При этом эффективность применения пенольда зависит от правильного выбора времени начала работ, предварительного подогрева воздуха, подаваемого в смеситель, что улучшает пенообразование, повышает устойчивость и кратность пены/29/.

5.3. Особенности строительства водосбросных сооружений

Анализ имеющегося опыта строительства показывает, что часто без должного обоснования основные сооружения гидроузла - плотина и водосброс - возводятся по разному температурному принципу. Отдельными специалистами высказывается мнение, что не обязательно все сооружения, входящие в состав гидроузла, строить по одному температурному принципу, но это,по нашему мнению, неверно.

Обычно водосбросные сооружения располагаются на одном из береговых склонов и примыкают к плотинам. В этих условиях неизбежно взаимное влияние их температурных полей и возникновение теплообмена. Причем процессы тепло- и массообмена в теле и основании водосбросного сооружения могут быть гораздо более интенсивными, чем в самой плотине. Поэтому при строительстве на вечномерзлых грунтах температурному режиму водосбросных сооружений и прогнозированию его динамики должно быть уделено особое внимание. Все сооружения гидроузла, как правило, должны быть возведены по одному температурному принципу.

5.4. Пропуск строительных расходов

Схема пропуска строительных расходов зависит от их величины,гидрологического режима реки, геологических и топографических условий створа и общей схемы возведения сооружений и сроков строительства. В то же время часто организация производства работ и технология возведения сооружений определяются гидрологическим режимом реки и принятой схемой пропуска строительных расходов. Наиболее целесообразной следует считать схему,при которой высокие паводковые расходы пропускаются по основному руслу реки или прорану в плотине (возможно также с переливом через гребень недостроенной плотины) , а пропуск расходов летней межени и зимних расходов - через водосбросные сооружения (туннель, канал, лоток, труба) . При этом в зависимости от этапа возведения сооружения схема пропуска расходов может меняться, например, на первом этапе- по прорану, на втором - по каналу или трубе и т.д.

Как уже отмечалось, гидрологический режим рек зоны распространения вечной мерзлоты своеобразен : до 85-90% их годового стока проходит в период весеннего паводка; летне-осенний период характерен в основном небольшими расходами и дождевыми паводками, а в зимний период расходы минимальные. В связи с этим в период малых расходов реки возможно возведение плотин с аккумулированием воды выше перемычек строительного котлована. Благоприятными факторами при этом, кроме небольших расходов реки, могут оказаться топографические условия будущего водохранилища, позволяющие аккумулировать сток реки на время возведения русловой части плотины на низких отметках, а также сравнительно небольшие объемы работ, которые могут быть выполнены в короткий срок с интенсивностью, опережающей подъем уровня воды в водохранилище. Отвод реки по обводному каналу или туннелю, с точки зрения производства работ, наиболее удобен. В этом случае возможна организация строительных работ одновременно по всему фронту, что существенно упрощает технологию возведения сооружений, но при строительстве на нескальных вечномерзлых грунтах этот способ не всегда применим (и особенно при строительстве мерзлых плотин) по условиям оттаивания основания.

При определении величины расчетных расходов летнего периода следует учитывать возможность совпадения пиков дождевых паводков с так называемыми "черными водами", поступающими за счет интенсивного таяния вечной мерзлоты.

В заключение следует отметить, что к настоящему времени накоплен определенный отечественный и зарубежный опыт успешного проектирования, строительства и эксплуатации грунтовых плотин в суровых климатических условиях Крайнего Севера и на вечномерзлых основаниях, требующий глубокого и всестороннего анализа и обобщения. Этот опыт показывает /3/, что "грунтовые плотины и мерзлого и талого типа при достаточном обосновании и глубокой проработке проекта, качественном выполнении строительных работ и квалифицированной эксплуатации являются вполне надежными гидротехническими сооружениями".

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ПОДПИСИ К РИСУНКАМ

Рис.1 Продольный и геологический разрез по оси правобережной плотины Усть-Хантайской ГЭС и ее основанию.
1- озерно-болотные отложения: торф, супеси,суглинки серые;
2- озерные отложения: суглинки пылеватые; 3- озерно-ледниковые отложения: супеси, суглинки темно-серые с прослоями песка, ленточные глины;
4- ледниковые отложения: суглинки коричневые с включениями гравия и щебня; 5- коренные породы: долериты, известняки; 6- граница островов вечномерзлых грунтов.

Рис.2 Поперечный разрез правобережной плотины Усть-Хантайской ГЭС.
1- гравийно-галечниковый грунт;
2- песчано-гравийная смесь;
3- каменная наброска долерита (зона крепления) ; 4- сортированный гравий фракции 10-80 мм ; 5- песок;
6- каменная наброска известняка;
7- ледниковые отложения; 8- коренные породы.

Рис.3 Продольный разрез по оси Иреляхской плотины и основания.

1- почвенно-растительный слой; 2- естественная поверхность земли; 3- границы максимального сезонного протаивания; 4- выемка торфа; 5- выемка илов; 6- суглинки иловатые, льдистость 60% ; 7- суглинки с дресвой и и щебнем коренных пород, льдистость 20-60% ; 8- глины плотные (коренные породы) ; 9- контур дна котлована под зуб плотины; 10- доломиты трещиноватые; 11- мергели трещиноватые; 12- известняки тонкоплитчатые; 13- старое русло реки, заполненное галечниками и гравием; 14- водосбросный канал; 15- гребень плотины; 16- подрусловый талик; 17- утонченная граница подруслового талика; 18- расчистка алювиальных отложений в русле реки; 19- границы подруслового талика по проекту; 20- мерзлотная завеса борта сбросного канала.

Рис.4 Поперечные разрезы и температурное состояние грунтовых плотин на Крайнем Севере: а и б - каменно-набросные плотины талого типа с экраном (Вилюйская) и ядром (Усть-Хантайская) русловая; в и г - грунтовые плотины мерзлого типа с воздушным двухтрубным охлаждением в центре ядра (Ирелякская) и воздушным охлаждением по галереям со стороны низкого откоса (на оз.Долгом).

\+ - 1-зона талого грунта;
\- - 2-зона многолетнемерзлого грунта;
± - 3-зона сезонного промерзания - оттаивания.

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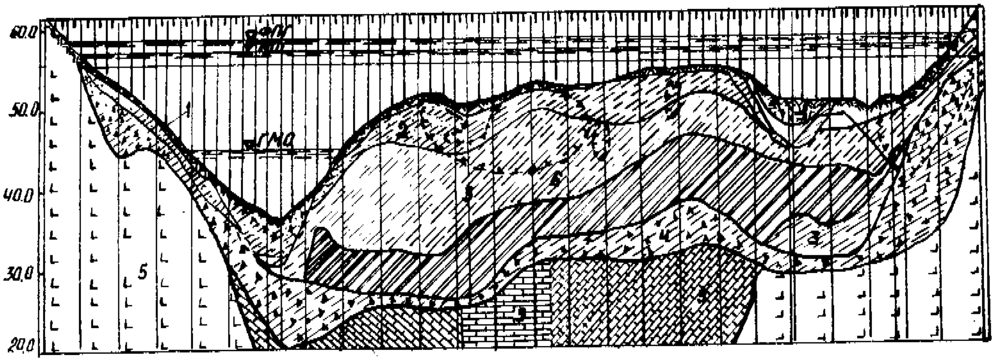

Figure 1

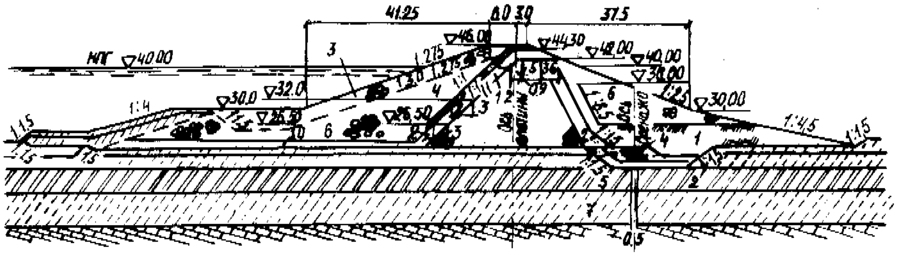

Figure 2

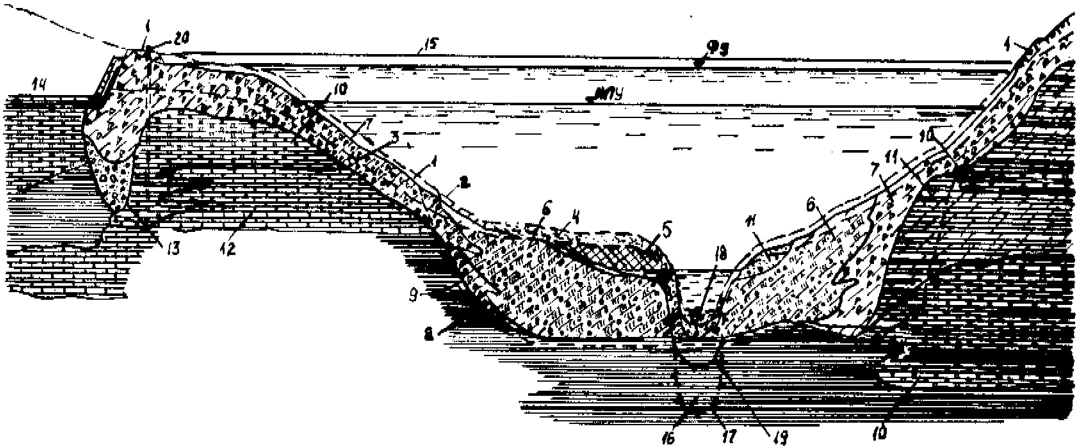

Figure 3

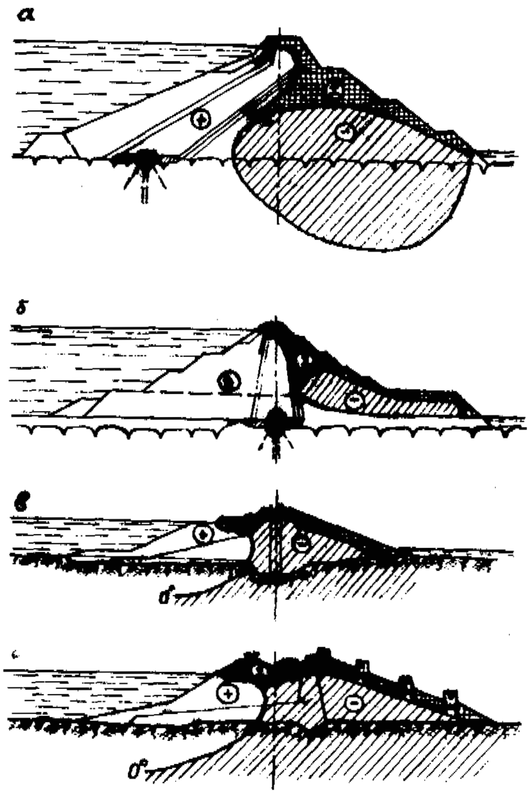

Figure 4

THE DESIGN AND CONSTRUCTION OF THE ALYESKA PIPELINE

A. Liguori, [1] J.A. Maple, [2] C.E. Heuer [3]

This presentation is dedicated by the authors to Dr. Hal Peyton who was involved originally on the pipeline as a private consultant and subsequently as a senior staff engineer and manager of staff engineering for the Alyeska Pipeline Service Company. Dr. Peyton was appointed to a delegation of permafrost experts representing the United States in a technical exchange program with the Soviet Union. As a part of this program, he assisted Soviet scientists who visited Alaska. During October 1976 as a member of an American delegation comprised of government and industry representatives, he toured the U.S.S.R. to visit research facilities, including the Permafrost Institute in Yakutsk and to inspect major oil and gas fields in the north central regions of that country. Had it not been for his untimely and tragic death, last year, he would be here today talking to you and it is in his memory that we dedicate this presentation.

This report will review some of the trans-Alaska Pipeline project highlights and detail major construction accomplishments. The pipeline was built by Alyeska Pipeline Service Company which is owned by 8 major oil companies or their subsidiaries. The 800 mile pipeline carries crude oil from Prudhoe Bay on Alaska's North Slope to Valdez, a year round ice-free port on the south coast of Alaska. From Valdez the oil is transported to market by marine tankers. These operators deliver the oil a short distance to pump Station 1 where the oil enters the pipeline, and is pumped south across the flat, treeless tundra of the north slope. About 160 miles south of Prudhoe Bay, the line crosses the Brooks Mountains through Atigun Pass. At 4800 feet this is the highest elevation along the route. The pipeline continues south over forested, rolling hills to the Yukon River, about 350 miles south of Prudhoe Bay. South of the Yukon River, about 450 miles south of Prudhoe Bay, it bypasses the city of Fairbanks, Alaska, the second largest community in the state. Further south, it crosses the Alaska Mountain Range through Isabel Pass at an elevation of 3575 feet. Nearing the southern end, the line crosses a third mountain range, the Chugach Mountain Range through Thompson Pass, elevation 2750 feet. In these mountains it also winds through the picturesque, but extremely rugged Keystone Canyon before dipping to sea level at Port Valdez.

The final pipeline route and sites for pump stations and terminal were selected after detailed studies of 8 possible routes and 4 possible terminal locations. The start of the line at Prudhoe Bay was fixed by the location of the North Slope Oil Fields. The choice of sites for the Southern Terminal was based on a variety of factors. They included a purchase to the Port, weather and water conditions, water depth, availability of land for a tank farm, access from the tank farm to docks and the relative merits of the location in terms of the pipeline length, and construction conditions. Once Valdez was selected as the Southern Terminal for the line the general route is further defined by the selection of major mountain and river crossings. An Atigun Pass crossing was chosen in place of Anituvik Pass in the Brooks Range largely because of soil conditions and route length, although Atigun Pass is higher than Anituvik, 60 miles to the east. The pipeline route at the Yukon River crossing was determined by the existence of a suitable bridge site.

There was no road north of the Yukon River to Prudhoe Bay so in early 1974,

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1. Formerly: Alyeska Pipeline Service Company, Anchorage, Alaska

   Now: Exxon Research and Engineering Company, Florham Park, New Jersey

2. Alyeska Pipeline Service Company, Anchorage, Alaska

3. Exxon Production Research Company Houston, Texas

convoys of construction equipment and supplies began moving north across the frozen Yukon River and over trails of snow and ice to build one. The State of Alaska obtained a right-of-way permit from the U.S. Department of the Interior, allowing Alyeska to build a 361 mile road roughly parallel to the pipeline from the Yukon River to Prudhoe Bay. Construction of the road was the first major undertaking of the pipeline project. Work on the road was begun April 29, 1974 and five months, 3 million man-hours, and 25 million cubic yards of gravel later, the road was finished.

In early 1974 the State of Alaska with Alyeska sharing the cost started construction of Alaska's first bridge across the Yukon. The bridge was completed in October 1975. A year later the pipeline was installed on a pipe floatway alongside the bridge. The bridge which towers 17 stories over the river, is supported by 5 piers. The structure is designed to withstand ice forces during spring breakup of the river, winds up to 80 miles an hour, temperatures ranging from -60°F to 100°F, earthquake stresses slightly more than 5 times higher than excepted engineering levels for that location, and the effects of a 50-year level flood.

The overall construction project has three basic components: the 800 mile pipeline itself, the pump stations, and the Valdez Terminal. Let us consider the pipeline first. The pipe was specifically engineered and fabricated for the Alaska Pipeline. Although it will not generally be subjected to unusual forces, the pipeline was designed to sustain all expected hydraulic pressures, thermal forces, and stresses induced by settlement, compaction, earthquakes and weight between supports of the elevated line, including snow and wind loads. Particular emphasis was placed on providing a high degree of assurance that the line will not leak oil although deformed well beyond the limit at which it can successfully transport oil. The pipe, manufactured in three grades and two wall thicknesses, .462 inches and .562 inches was alloyed slightly with vanadium and manufactured in a carefully controlled rolling process. The pipe has specified minimum yield strengths of 60, 64, and 70,000 lbs per square inch. Different grades of pipe were used in different locations depending upon the pressures and stresses encountered in each location. The pipe was specially coated and given cathodic protection to prevent bacteria-logical, chemical and electrolitic corrosion.

In stable soils, the pipe is buried in a conventional manner, much as it is in other parts of the world. Conventional burial was used in areas where soil is either bedrock, thaw stable sand and gravel or thawed soil, or the results of field exploration and analysis demonstrated that soil settlement or instability resulting from thawing would not cause unacceptable disruption of the terrain or damage to the pipeline. Slightly less than half of the pipeline is installed conventionally. Burial depths range from 3 foot minimum cover above the top of pipe, to occasional depths greater than 16 feet, depending on the pipe configuration, terrain and soil properties at each location. The pipe was bent conformed to the ditch bottom which was lined with at least 6 inches of crushed bedding material. The process of padding material was compacted around and on top of the pipe which was buried 8 to 16 feet below the surface. However, only about 380 miles of the pipeline could be buried in this way. More than one half of the route is underlain by ice rich permafrost that would be unstable if thawed. The pipeline is hot. The oil temperature as it comes out of the ground is approximately 180°F. Heat generated in pumping the oil and friction caused by its flow through the line keep it between 130°F and 140°F at a design rate of 2 million barrels per day.

In areas of ice rich permafrost, especially silts and clays, thawing would create difficult soil stability conditions. In these areas the pipe is elevated above-ground. Installation of the aboveground support system requiring approximately 78,000 vertical support members, called VSM's was completed in July of 1976. Holes for the VSM were drilled to average depths between 15 and 60 feet. For the majority of the supports, the space around the outside of each VSM was filled with sand slurry mixture which then froze to hold the support in place. Other VSM's were grouted in place and some were regular driven piles. The special thermal devices known as heat pipes were installed in about 80% of the VSM's to maintain the permafrost in a stable condition.

The aboveground pipe is supported on cross beams installed between vertical support members imbedded in the ground. To prevent thawing around the VSM's special thermal devices are installed inside them where required. These devices consist of metal tubes, filled with a refrigerant which vapourizes and condenses thereby chilling the ground whenever the ground temperature exceeds the temperature of the air. The devices are non-mechanical and self-operating.

The pipe is fastened to a special shoe, equipped with teflon slide plates that permit movement across the support beam and reduce heat transfer from the pipeline to the supports. In potentially more active seismic zones, extra large supports allow even greater movement. All aboveground pipe is insulated to prevent conduction of heat through the supports into the permafrost. Insulation also retards oil from thickening during emergency shutdowns, or periods of decreased flow in winter. Pipeline construction was conducted on a 50 foot wide gravel workpad. The workpad protected the permafrost and minimized other impacts. In the northernmost part of the route, where gravel is scarce, 98 million board feet of foam insulation were installed on the tundra beneath the gravel workpad. The insulation reduced the amount of gravel required.

There are 84 major river crossings on the pipeline. The one across the Tanana River is a 1200 foot long cable suspension bridge. At varied crossings the pipe is jacketed with a 5-inch layer of concrete of is weighted with concrete saddles, each weighing approximately 9 tons.

The second basic component in the overall construction project is the pumping system that keeps the oil flowing through the pipeline. Most of the stations are built on stable soils in a relatively conventional manner. However, at five station, 1,2,3,5, and 6, some structures are erected on refrigerated gravel atop permafrost. Hauls of pipe to circulate cold brine are buried in gravel beneath a plastic foam insulation mat under critical structures to keep the ice rich soils frozen and stable.

The third component of the project is the marine terminal at Valdez, where all ocean-going tankers call to pick up the oil and deliver it to market. The Terminal site covers about 1,000 acres and includes storage tanks, docks, a ballast water treatment facility, a power plant, a vapor control facility, office buildings, a warehouse and shop building and the pipeline's operational control centre. Eighteen crude oil storage tanks were built. Each tank is 250 feet in diameter, 62 feet high, and can hold 510,000 barrels of oil. The tanks have fixed cone shaped roofs to accomodate the heavy snowloads that are standard for the Valdez area. The tanks are sited in pairs within the containment dikes, with a capacity equal to 110% of the total volume of the tanks plus an additional 2 foot allowance for surface water which may be impounded within the area.

Communications for pipeline operations is performed via a microwave system utilizing 41 microwave stations. This network is backed up be a satellite communications system.

Dr. Maple will discuss some of the challenging design construction hurdles overcome by the Trans-Alaska Pipeline. The first and foremost problem was protection of the pipeline in areas where permafrost is not thaw stable. This was accomplished by elevating the pipeline on pile bents to avoid transfer of heat from the hot oil pipeline to the soil. A flexible system incorporating trapezoidal track expansion loops was selected over a fully restrained system as the flexible system provides greater operating reliability through relative insensitivity to settlement. The line is anchored at intervals of 800 to 1800 feet and is supported between at 60 foot intervals on sliding friction supports with low friction materials.

Sliding shoes also present a solution to the problem of ground motion due to earthquakes by decoupling the pipeline from the ground motion. The maximum ground motion experienced was par for an 8.5 Richter magnitude earthquake and associated with seismic activity along the route are three faults. On the Denali Fault the pipe was placed on beams to grade. The beams were 45 feet long and the pipe positioning was designed to account for a 20 foot right lateral by 5 foot dip fault movement. The pipe is positioned somewhat peculiarly on the beams, to take maximum advantage of the location of the fault and the length of the beams, so that the beam length could be minimized.

The McGinnis Glacier Fault Zone presented additional problems with up to 12 feet of scour and alluvial fans. Two alluvial fans, one on Castner and one on Lower North Creek were crossed. The scour depth plus the requirement for elevating the pipeline several feet aboveground due to icing conditions required an additional pile in each pile bed to accomodate the lateral loads, and fill in the system by friction when the pipe moves. To support this all three piles were tied together making a triangular trust work.

Terrain presented construction challenges at several locations along the pipeline. These challenges seemed almost insurmountable at three locations. Atigun Pass in the Brooks Range, Thompson Pass in the Chugach, and traversing the east wall at Keystone Canyon near Valdez. Atigun Pass has a critical stretch of pipeline about 165 miles south of Prudhoe

Bay. The currents of large, destructive slush flow avalanches in this area prevented aboveground construction making it necessary to place the pipe below ground. The design required burial in difficult ditching areas and resulted in a special thermal design utilizing new materials and procedures and requiring unusual construction techniques. The special thermal design required that the pipe be sealed and buried in an insulated box with wall thickness of 21 inches and supported on a 12 inch concrete slab to limit the 30 year thaw below the box to approximately 1 foot with no significant settlement. The pipe was placed in the box and a cement gravel grout was poured filling the space between the pipe and the insulation. The insulation and grout were required to seal around the pipe so that infiltration of groundwater could be eliminated which would then be welled to the pipe and could possibly cause additional thawing of the ground. This method was used on approximately 6,000 feet of pipe in the Atigun Pass area.

Keystone Canyon, 18 miles northeast of the Valdez Terminal was considered one of the more challenging sections of the pipeline route. The pipeline construction above the steep canyon was expected to be extremely difficult because of the rugged alpine terrain. Constructing the pipeline above the canyon, which seemed easier, would have required digging up an existing state highway which extends down the bottom of the canyon, caused lengthy road closures and public inconvenience. Alyeska decided to go above the high east wall of the canyon. The danger of rock and snow slides prevented anchoring the pipeline on the canyon walls. Small helicopters were used to ferry work crews to several points along the top of the canyon and the Sikorsky Skycrane was used to lift equipment. Where equipment was too heavy to be lifted in it was broken down and then reassembled on top of the canyon. A rock crushing plant was built at the tope of the canyon to manufacture backfill material to eliminate the need to truck gravel up the steep slopes at either end of the canyon where the pipeline drops about 800 feet on a 60% slope. If gravel had been trucked in, it would have had to be dragged up the steep slopes. Forty thousand yards of material were used to backfill the pipe in the canyon. The Keystone Canyon is 4 miles long with a 2,500 foot section at the north face which rises 840 feet and a 2,300 foot section which drops 820 feet on the south face.

In Thompson Pass which is located about 20 miles northeast of Valdez, it is 4,000 feet long and it plunges 1800 feet for that 4,000 feet. It has slopes of up to 125% and because of the severity of these slopes a special cableway was built to fly pipe up to the locations. Each section of pipe, which is 80 feet long, weighed about 10 tons. It was attached flat and lifted up the mountain,its position determined either by remote control or by coordinated control with radios and welded into place. Welding, X-raying, or just standing on the steep slopes themselves is a challenge and on such sessions welders harnessed themselves to a chain attached to the pipe and literally hung in midair as they worked. While some crews were rushing to complete pipe installation, backfill crews found themselves facing a race against worsening weather conditions including heavy snowfalls. To facilitate backfilling two numadic placing units were utilized. At three seperate locations in the upper portion of the pass where slopes were greater than 55%, a cement stabilized backfill was required to bind the pipe into the trench. Peter DeMay, former Vice President, Project Management for Alyeska referred to the building of the Thompson Pass section as one of the greatest challenges of the entire project. It represents one of the most significant construction accomplishments of the people building the pipeline.

Environmental protection presented its share of challenges to the design and construction of the pipeline too. Two notable examples were provision for caribou crossings and ice rich permafrost and a requirement to utilize approximately 5 miles of snow workpad to minimize the use of gravel on the north slope. In two locations where the pipeline intersects the migration route of the Nelchina herd, refrigerated burial was used for a total length of 4 miles in lieu of belowground pipeline.

At 23 locations along the route a 60 foot segment of pipe was buried in an insulated box with heat pipes installed for thermal protection and to limit thaw settlement to acceptable levels of approximately 2 feet. Because this section is located in aboveground pipe the flexibility of the line can accommodate settlement that is much greater than if that section had been buried.

Construction of the pipeline from a snow workpad was difficult because it required working during the winter season. Further difficulty was caused by the lack of available snow in the Arctic which required the manufacture of artificial snow to complete construction of the workpad. Construction on a snowpad is expensive but it can be accomplished without disturbing the tundra vegetation. Construction is slowest in the winter season and the time available is limited by the onset of breakup in the arctic.

Mr. Heuer will discuss in greater detail the utilization of heat pipes in pipeline construction. During construction and design of the pipeline many problems were encountered that involved the thermal protection of permafrost. Where possible these problems were avoided by route selection or mode selection, either buried or elevated. Where problems could not be avoided they were often solved using heat pipes. A heat pipe is a closed tube that transfers heat by natural conduction with change of phase and operates only during the winter when the air temperature is colder than the soil temperature. Because natural conduction is involved heat transfer is in only one direction, from the ground to the atmosphere, and since a change of phase is involved, heat transfer is efficient even at very low temperature differences. Properly designed heat pipes can provide enough cooling during the winter to more than offset warming during the summer. The Alyeska heat pipes have an internal diameter of 1½ inches and range in length from 28 to 75 feet. Ammonia is the worst fluid. Alyeska heat pipes were designed to transfer a minimum of 12 watts per foot of belowground embedment for a 3°F temperature difference across the heat pipe. Approximately 120,000 heat pipes were installed along the pipeline, most in VSM. All VSM receive two heat pipes although in many cases only one heat pipe was actually needed. This provided redundancy in case of a heat pipe failure and also a significant safety factor. Aluminum radiators were press fitted onto the upper portion of the heat pipe, the radiators were either 4 feet or 6 feet long, depending on the length of the heat pipe. It was important to size the radiators correctly to allow for efficient heat transfer. A conservative approach was taken in that still air conditions were assumed when determining the heat transfer coefficient, although it was known that low wind speeds even 1 or 2 miles per hour could more than double the heat transfer coefficient. The heat pipe extends about 6 inches above the top of the radiator. This provides a gas trap should non-condensing gas form inside the heat pipe. In this way it will collect in the gas trap rather than block the radiator. The VSM is filled with saturated sand slurry up to the ground level, the aboveground portion was not filled with the saturated slurry to avoid the potential of damage to the VSM when the slurry froze and possibly expanded. Heat pipes were placed as closely as possible to the VSM wall because the metal wall of the VSM acted as a belowground fin to improve heat transfer with the soil. The soil represented the major thermal resistance in the VSM soil system. The heat pipes had to extend within a minimum of 3 feet at the bottom of the VSM.

There were several reasons why heat pipes were installed in VSM. They were used to maintain initially frozen soil, frozen to cool frozen soil well below the freezing temperature, to freeze initially thawed soil, and to provide for the radial freezeback of the active layer. The specific reasons why heat pipes were installed in a particular VSM depended on the local soil conditions, in general heat pipes are less effective in coarse grained soils where there is less unfrozen moisture below the freezing temperature and there is a higher probability of groundwater flow problems. The use of heat pipes allowed cooler soil temperatures which permitted higher frozen strengths when calculating VSM load capacities. The heat pipes also reduced jacking and down drag to a negligible amount and could prevent soil liquefaction and slope instability problems. Installing heat pipes did significantly complicate construction, although they allowed much shorter VSM embedments than compared to conventional piles and therefore were cost effective. In some cases where the soils were especially poor, heat pipes provided the only design alternative.

Heat pipes were used in other situations other than VSM and direct support of the elevated pipeline. However, the same general geometry of the VSM was maintained. This allowed a uniform design and construction. An example is a bridge pier being protected by four free-standing VSM. The spacing is determined to provide thermal protection to all the load bearing piles for the bridge pier. Five different bridges are protected by free-standing VSM.

At a buried animal crossing free-standing VSM as well as insulation are used to prevent excessive thaw settlement. Fourteen different crossings were constructed in this manner. At a road crossing similar to a buried animal crossing, insulation and heat pipes were used to prevent excessive thaw settlement. The crossing is about 500 feet long.

At an aboveground valve site the valve building contains the power generation and communications equipment for the valve. In front of the building propane tanks were installed which are used as fuel for the power generation equipment. Heat pipes are used to support both the valve building and the buried propane tanks.

At a communications tower around the equipment building the heat pipes are installed in the external slurry of the piles supporting the building. To the left at the base of the tower leg are long piles which are similar in operation to heat pipes. The reason there are long piles there instead of heat pipes is because there was a different contractor; there were two different contractors at the site.

An unique installation resulted from a reevaluation by Alyeska of the soil conditions after the pipe had already been buried. Alyeska decided that to meet government stipulations remedial work was required. The pipe was buried between the two right-hand row of free-standing VSM. There are 22 free-standing VSM on a 100 foot section of pipe. The free-standing VSM and insulation were used to prevent excessive thaw settlement and slope instability.

The heat pipe and thermal VSM design were developed using extensive computer simulations, laboratory test, and field tests. Three different field tests were conducted using heat pipes. The first two used commercially available heat pipes but the third test used protype heat pipes. This slide shows the protype heat pipe test site outside Fairbanks. An actual 150 foot section of the pipeline was constructed. The soil conditions at the site are ice rich organic silt with the initial soil temperatures below the active layer ranging from 30 to 31°F. This is the type of soil conditions where good heat pipe performance is essential because if the soil does warm too close to 32°F or thaw there will be a drastic change in the mechanical properties of the soil. Thermistor strings were installed at the test site near 4 VSM, beneath the gravel pad and beneath the undisturbed tundra. Data collection began in October, 1974 when the heat pipes were installed and is still continuing but on a reduced basis. After one year of operation, at the end of summer, 1975, if the warmest VSM is considered and looking at the average temperature below the design active layer, that temperature is 1°F cooler than the corresponding temperature below the undisturbed tundra and 1½° cooler compared to beneath the gravel pad. By the summer of 1977, that is 3 complete years of operation, there had been an additional 8/10°F of a degree cooling, again looking at the warmest VSM compared to the undisturbed tundra. The temperatures at all the monitored VSM ranged from 27°F to 28°F. These are average temperatures below the design active layer taken at the end of summer so they are the warmest temperatures ever occurring along the VSM. Minimum temperatures during the winter could be as low as -10°F. For this site the data indicate that the standard VSM design is quite conservative in that the standard design assumes an average temperature over the entire life of the pipeline of 31.5°F.

Extra care was taken during design development to insure the long-term reliability of the heat pipes. A rigorous manufacture qualification program was conducted which included accelerated life testing of heat pipes to insure that excessive non-condensing gas would not be generated inside them. Despite the care taken, it was inevitable that at least a small percentage of heat pipes would fail and so a system had to be devised to detect and replace those failures. There are several different failure mechanisms. There could be only a leak of the working fluid, ammonia, generation of non-condensing gas, or poor thermal coupling between the pressed on radiator and the heat pipe. Regardless of the failure mechanism the result would be a decrease in radiator temperature during the winter and so it was chosen as the failure detection parameter and an air born infrared system was developed to measure temperatures during the winter.

Data were collected on standard black and white video tape. The advantage was that the data could be evaluated in the helicopter as they were being collected. It also provided for immediate data analysis once collection was completed. The data were taken during low temperatures when the heat pipes were operating near their peak and this had to be done during twilight or darkness because the sun shining on the radiators could provide anomalous temperature condition. Therefore, two men were sent in a helicopter in the middle of winter in the dark to monitor the heat pipes.

Heat pipes can become deficient when a heat pipe is slightly darkened, this means that it is slightly cooler. In the optical system of the infrared scanner were built in two black bodied references. The dark vertical strip represents the cold temperature reference, for example at -42°F. The white vertical strip on the other is the hot temperature reference, for example at -16°F. The intermediate temperatures are shown by various shades of grey. It could be determined quantitatively by linear interpolation on the output voltage from the system. The data were analyzed and the video tape was visually scanned looking for such anomalies. When one was spotted the temperature of the deficient radiator was compared to the temperatures of the other three VSM, the other three radiators in the bent. The average of these three radiators was considered to represent a properly functioning heat pipe and the temperature of the deficient heat pipe was also compared to a reference radiator. The reference radiator is a 2 foot section of heat pipe on a pipe stub at the same elevation as the standard radiators. The reference radiator is not attached to a working heat pipe, its temperature represents a completely failed heat pipe. If this comparison met certain criteria, then a heat pipe was replaced. A major problem in doing this was actually locating the VSM in the field and to do this a sophisticated ground marking system was developed. Deficient heat pipes are determined by counting anchors and then intermediate bents on the video tape after which the same thing is done in the field.

To replace a heat pipe the deficient one is simply cut off below the bottom of the radiator and a smaller replacement heat pipe can be slipped inside the standard one. The replacement heat pipe has an internal diameter of 1 inch compared to the standard heat pipe of 1-½ inches and is about 90% as efficient as a standard one. The annulus between the two heat pipes is filled with an ethyline, glycol and water mixture after which the two heat pipes are welded together. Two surveys, two infrared monitorings of the elevated line were conducted in the winter of 1976/77. As a result of that monitoring 120 heat pipes were replaced. A few additional failures were detected by 1977/78 monitoring. The number to be replaced has still not been finally decided, although it will be quite small, perhaps in the order of 10 to 15.

Approximately 150 thermistor strings have been installed near thermally sensitive pipeline structures, most of which are VSM. Data collection was started in 1976 and continues on a regular basis. Thus far the data indicate that the heat pipes are performing adequately. This is despite the unusually warm winter of 1976/77, immediately before pipeline startup. For example, in that winter the average January temperature in Fairbanks represented one warm winter out of 100.

During construction large diameter holes were drilled next to selected VSM. These VSM were installed in initially thawed soil but had one year of heat pipe operation. The inspection holes allow direct visual verification of the freeze bulb generated around the VSM. It was found that the freeze bulb radius was 3½ to 4½ feet from the VSM centerline which is consistent with computer calculations. Skin melting can occur which is the local depression of the active layer in the immediate vicinity of the VSM caused by heat conduction down the metal VSM wall. It may be as much as an additional 1½ ft below the local active layer near the VSM.

The development of natural resources has been greatly stimulated in recent years and this has led to increased interest in permafrost science and engineering. The Trans-Alaska Pipeline has played a major role and will undoubtedly continue to do so in the years ahead.

EXPERIMENTAL RESEARCH ON THE PRINCIPAL MECHANICAL PROPERTIES OF FREEZING AND FROZEN SOILS IN CHINA (A REVIEW)

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ABSTRACT

This is a review of the results of experimental research on the main mechanical properties of freezing and frozen soils relating to the following aspects: frost heaving in the active layer; various types of frost heaving forces and their effects; effect of ground temperature, water content and ice segregation on adfreezing forces; "in situ" method of measuring the bearing capacity of frozen ground and other factors that influence thaw consolidation characteristics of frozen ground and their relation to the basic physical properties of frozen soils.

INTRODUCTION

In the economic development of the extensive northeastern and northwestern regions of our country, the mechanical properties of frozen soils are becoming a significant factor in construction in areas of frozen ground.

As we know, most structures interact with the active layer, and while the ground is frozen they are both subjected to heaving and the accompanying pressure. When foundations such as piles or columns are buried in permafrost, the adfreezing strength between them and the soil not only provides bearing, but also offsets the heaving pressures in the active layer; with column foundations, and especially piers and strip foundations, the correct bearing capacity is the most necessary basic design data. Because the rheology of ice determines the creep properties of frozen ground under load and the relaxation effect deformation, investigations of the above problems must include those of observing the environment and changes in it.

If the foundation soil beneath a heated building on permafrost is allowed to thaw, the increase in depth of thaw due to the daily accumulation of heat, will result in thaw settlement and reconsolidation. Therefore anticipated settlement must be predicted at the design stage.

Since 1965, a series of systematic experiments and field observations on the basic mechanical properties of frozen ground have been successfully carried out in districts such as Chilien Mountains, the greater Khingan Mountain and along the Chinghai-Tibet Highway. Laboratory research was also done at the same time. Various agencies connected with the national railways, highways, construction, water conservancy and forestry have all made many investigations. In this paper, we will describe and analyze some of the results obtained from tests and observations on frost heaving, frost heave pressures, bearing capacity of soils and thaw settlement characteristics. The main results as mentioned in this article are the collective work of the group doing research on soil mechanics in the Cryopedology Research Division, Lanchow Institute of Glaciology and Cryopedology, Academia Sinica.

In order to obtain further knowledge on this subject, work is still being carried out.

FROST HEAVE AND FROST HEAVE PRESSURE

Frost Heave

The effect of the heaving of soil during freezing is the result, not only of the volumetrical swelling of water that freezes in the voids of the original ground, but also the continual migration and accumulation of water that becomes ice when frozen toward the freezing front in the unfrozen zone.

Tests show that when the water content in the soil reaches a critical value, the swelling of the soil undergoing freezing becomes noticeable; this critical limit is called the initial water content of frost heaving $W_o^{(1)}$. Table 1 shows W_o values for several types of soil under laboratorial testing.

Name	Clay, Clayey Loam	Loam	Clayey Soil Containing Gravel	Bouldery Soil Containing Silt and Clay	Bouldery Soil*	Sand
W_o%	12-17	10-14	9-11	8-10	6-8	7-9

* Weight of grain diameter < 0.005 mm less than 12% of overall weight

Table 1 Test Value W_o of Several Types of Soil

For clayey soil:

$$W_o \simeq 0.84\ W_p \qquad (1)$$

where W_p - water content at the plastic limit.

In a closed system and for the active layer in the permafrost region which is lacking in groundwater recharge, a linear equation can be used approximately to give the mean frost heave rate (Wu Tzu-wang, Chang Chia-yi, Wang Yan-qing and Shen Chong-yen, 1972; Tong Shang-chiang and Wang Yan qing, 1977).

$$\bar{\eta} = K(\bar{W} - W_o) \qquad (2)$$

in which $\bar{W}$ - mean water content in the active layer;

K - empirical coefficient relating to soil property.

It is particularly noteworthy that in the active layer in areas of seasonal freezing, as well as in permafrost regions, there exists a main zone of frost heave, as shown in Figure 1 (Chen Hsiao-pai, 1972). In the permafrost active layer (Figure 1a) the main frost heave zone is situated in 1/3 to 2/3 of the thickness of the active layer and the amount of frost heave exceeds 80-90% of the total; below this the frost heave is minimal; from there downward, near the permafrost table (still pertaining to the freezing front) is the subfrost heave zone. According to data from the Institute of Scientific Research on Low Temperature Construction, Heilungkiang Province, in areas of seasonal ground freezing, at one-third of the frost depth of the surface soil layer, the frost heave is about 65% of the total figure, and at 1/3 to 4/5 of the frost depth, it is about 30%; the main frost heave belt is located within the range of 2/3 of the total depth; and the zone with no heave usually lies at the base of the layer having the greatest seasonal frost activity.

In order to remove the effect of frost heave on buildings, clean dry sand (or sandy gravel) is used to replace frost susceptible soil. Sometimes, good results are achieved but, on other occasions, it proves to be the contrary. In 1974, a test by Chen Hsiao-pai, showed that the ideal result could only be obtained when a relatively permeable layer lies at the base of the exchange layer and surplus pore water has been removed under the influence of a freezing pressure gradient.

Frost Heave Pressure on a Foundation

When expansion due to frost heave is restricted, the freezing soil begins to exert an upward lifting force (sometimes it may be a compressive force) on the structure or foundation; it is simply called frost heaving compressive pressure (or frost heaving force). According to its relation to the foundation surface, it can be classified as follows (Chen Hsiao-pai, Tong Shang-chiang and She Qin-sheng, 1972; Chen Hsiao-pai and Tong Shang-chiang, 1977):

1. When the direction of heat flow Q is parallel to the foundation surface as shown in Figure 2a, there exists a lateral frost heaving pressure τ at the sides of the foundation and a frost heaving pressure σ_1 normal to the base of the foundation.

2. When the direction of heat flow Q is diagonal to the side of the foundation (Figure 2b), beside τ and σ_1, there is a lateral frost heaving pressure normal to the side of the foundation; it is also

called the lateral compressive thrust σ at the side of the foundation. It is this force that causes the concave deformation of building foundations (particularly strip foundations).

Tangential Frost Heaving Force

1. Process of development. Figure 3 shows the lines of tangential forces acting on a concrete pile, in relation to ground temperature in a permafrost region where the soil layer is frozen. On the whole, they can be divided into three stages (Chen Hsiao-pai, 1975; Chen Hsiao-pai and Tong Shang-chiang, 1977).

Stages of gradual change - Frozen penetration is about 30 cm; ground temperature gradient $d\theta/dh = 0.1\text{-}0.2^{\circ}C/cm$; overall frost heaving force gradually increases.

Stage of abrupt rise - Frozen depth from 30 cm down to the entire main frost heave zone. The peak value of the overall frost heave force often appears at the lower limit of the main frost heave zone. In this stage, the ground temperature gradient is comparatively small, generally $d\theta/dh = 0.06\text{-}0.01^{\circ}C/cm$. Large quantities of water accumulate in the soil layer, and the frost heave force rises abruptly. Because of the greater rheological potential of fine grained soils, where the increasing frost heave force is not strong enough to resist creep, phenomena of relaxation stress appear locally. In coarse grained soils, it is not so obvious.

Stage of relaxation - When the frost heave force increases, slowly or even stops, the rheological phenomenon becomes the dominant function. This shows that the relaxation process of frost heave force proceeds with time. In fine grained soil, especially ice rich soils, this stage is particularly conspicuous.

Observation of Chen Hsiao-pai in 1974 discovered that when the frost heave force developed to the stage of relaxation as shown by point N in Figure 3, the total frost heave force reached 7900 kg instantaneously. If the total force acting on a concrete pile were to be suddenly disengaged to 1150 kg (see Figure 4), a deformation of resilience S=13 mm appeared at the top of the pile, and the overall force increased continually afterwards; it reached 3190 kg in 8 hours and rose to 3670 kg in 36 hours; from then to 50 hours, the change slowed down and the line became smooth.

This phenomenon shows that: First, under the action of frost heave pressure, the frozen soil around the pile is under the field of influence of compressive stress. Once the stress is partially removed, that part of the elastic deformation of frozen soil can recover immediately.

Second, due to the increase of frost heave pressure around the pile, the freezing temperature of water drops correspondingly and the thickness of the water film decreases. When the stress is partially removed transiently, the freezing point rises, the unfrozen water in the soil will partially freeze. Simultaneously, the water of the unfrozen water film will migrate to where the film is thinner and freeze. This will cause the frost heaving force to recover partially.

2. Distribution with depth. Let the vertical coordinate h be the frost depth, and the horizontal coordinate represent the mean tangential frost heave force $\bar{\tau}$ corresponding to a certain depth of frost heave. Then we can obtain a statistical relationship of various observational data for permafrost regions as shown in Figure 5 (Chen Hsiao-pai and Tong Shang-chiang, 1977). Obviously, in the first stage of development of frost heave pressure, the mean pressure changes very little through the frozen layer. When it develops into the second stage, the corresponding mean frost heave pressure increases, abruptly with depth. After it reaches the peak value it enters the relaxation stage. At this time, the mean frost heaving pressure through the frozen layer rapidly declines. The statistics of many field observations show that the greatest depth of frost is between 120 cm to 150 cm. The highest mean tangential frost heaving forces appear to be between 50 and 100 cm and this depth corresponds to the main frost heave zone.

3. Influence of moisture. Tests show that when the water content of the soil exceeds W_o, the tangential frost heave force increases as the water content increases. Figure 6 shows the relationship between tangential frost heave force and water content (Shen Shong-yen, Chang Chia-yi, Wang Yan-qing, and Wu Tzu-wang, 1972). From Figure 6 we know that the tangential frost heave force would be greatest when the water content reaches a certain limit, but it decreases afterwards. Under laboratory conditions, a maximum tangential frost heave force exceeding 4 kg/cm^2 has been recorded.

In the active layer of permafrost regions where there is no stable recharge of groundwater, the greatest tangential frost heaving force of common clay usually ranges from 0.3 to 0.4 kg/cm^2 if the clay is very plastic. With increasing water content (W 100%), the tangential frost heave force reaches up to 1.2 kg/cm^2 (Chen Hsiao-pai, 1972; Chang Shang-qin et al, 1976).

We must point out that the values obtained from field measurements are always lower than those from the laboratory. The main reason is that in the former case, the freezing rate is relatively low, although it is conducive to moisture accumulation. However, in frozen soil the relaxation of stress is sufficiently developed. In the latter case, although less ice accumulates because the rheological process is rather short, the frost heave pressure is often much greater than that observed in the field. Because of laminations and numerous cracks in the natural undisturbed soil, part of the moisture freezes inside, and will cause the frost heave force to diminish.

Frost Heave Pressure Normal to Surface

1. As part of the test data, a concrete pile having a basal surface of 30.6 cm^2 in frozen loamy clay with moisture content of 30.4% is subjected to a recorded frost heave pressure normal to the surface reaching 35.6 kg/cm^2 against the pile base under laboratory conditions. The normal frost heave pressure decreases with an increase in area of the base (Shen Chong-yen, Wu Tzu-wang, Wang Yan-qing and Chang Chia-yi, 1972).

From field observations in the permafrost region the value obtained for unsaturated clayey soil generally was greater than that for coarse granular soil (Chen Hsiao-pai and Tong Shang-chiang, 1977). However, in the sand gravel layer of a valley bottom where the water table is shallow, groundwater under pressure after freezing at the ground surface forces moisture migration to the freezing plane. Furthermore, more moisture accumulates at the concrete pile than in the surrounding soil because of the former's higher thermal conductivity and cooling rate. Therefore, the frost heave pressure normal to the surface apparently increases. If the buried depth is 50 cm, the frost heave pressure normal to a concrete pile with a base of 400 cm^2 will exceed 20 kg/cm^2. Thus, in a region with high groundwater content (or supersaturated), the normal frost heave pressure is very large and great care must be taken.

According to data collected by the Institute of Scientific Research on Low Temperature Construction, Heilungkiang Province, where the ground surface is swampy, the water table being very shallow corresponds to the winter frost heave depth. Moreover, in highly plastic soil for a concrete pier with a bearing surface of 2500 cm^2, at a depth of 20 cm, a value of 11.6 kg/cm^2 for frost heave pressure normal to the surface has been recorded. When the buried depth is increased to 40 cm, it is 5.9 kg/cm^2.

2. Relation to depth of foundation burial. Figure 7 illustrates the relation between frost heave pressure normal to the surface and the depth of foundation burial (Chen Hsiao-pai and Tong Shang-chiang 1977). In this figure, curve I is the actual measured value for a pile of 20 cm x 20 cm cross section in a permafrost region; curve II shows the values with depth for a foundation having 50 cm x 50 cm cross section, recorded by the Institute of Scientific Research on Low Temperature Construction, Heilungkiang Province. Curve II converges more rapidly than curve I. Below the main frost heave zone (120 cm-140 cm) $\sigma_1 < 1$ kg/cm^2, which is a value that the foundation of an ordinary building could overcome.

3. Relation to bearing area. Every point in Figure 8 is the actual measured value of frost heave pressure normal to the surface of the foundation base at different depths in a permafrost region. Curve I in Figure 7 can be taken as a base to transform the measured value into the probable value at a depth equal to zero (i.e. the ground surface), and calculate the greatest probable value (Chen Hsiao-pai and Tong Shang-chiang, 1977). After analyzing the curve pattern, we get

$$\sigma_1^o = C + \frac{a}{F} + \frac{b}{F^2} \qquad (3)$$

in which σ_1^o - frost heave pressure normal to surface at foundation base when buried depth is zero (i.e. ground surface); (kg/cm^2);

$F \times 10^2$ - bearing area, (cm^2).

Under conditions of the curve in Figure 8, Formula (3) becomes:

$$\sigma_1^o = 3.85 + \frac{20.2}{F} + \frac{285.8}{F^2} \ (\text{kg/cm}^2)$$

As F increases, the value of σ_1^o decreases as a hyperbolic function. When the bearing area is very large, $\sigma_1^o \rightarrow 3.85$ kg/cm^2.

Test of Pressure Against A Structure

In order to determine the frost heave pressure on the back of a retaining structure when the ground is frozen, Shen Chong-yen, Wu Tzu-wang, Wang Ya-qing and Chang Chia-yi conducted an indoor model test on a soil sample 36 x 32 x 49 cm (long x wide x high). Only the top and retaining plane were directly exposed in the low temperature room; the remaining four sides were thermally insulated. The surrounding temperature generally was maintained at -15 ~ -20°C; the frost heave pressure was measured with a steel wire pressure transducer in the top, middle and bottom layers at the back of the retaining structure. Moisture contents at the liquid and plastic limits and grain size distribution of the samples are listed in Table 2.

The model test shows that the frost heave pressure on the retaining structure is closely related to the place where it is acting and to the soil moisture content. Figure 9 illustrates that the frost heave pressure increases as the moisture content increases in different types of soil with various positions of the retaining structure.

A field model test on a retaining wall was performed by the Scientific Research Institute, Ministry of Railways. The height of the wall was one metre, and it was divided into five equal sections (separated from each other). A pressure transducer was used to measure the total force on each section. In conditions of no deformation of the wall, the mean frost heave pressure at different sections was measured and listed in Table 3. The values were found to be in accordance with those observed at an actual construction site of the same Institute.

Observed Values at an Actual Construction Site. A steel wire pressure transducer was used to measure the frost heave pressure normal to the surface acting against the linings of a tunnel and vertical shaft while the surrounding soil was refreezing and also to measure the horizontal pressure against the sides of a building foundation when the local soil was frozen (Chen Hsaio-pai, 1972).

Tunnel and vertical shaft. The largest values of frost heave pressure normal to the surface of 4.1 and 1.4 kg/cm^2, were obtained respectively for the crown of the arch and side walls of a railway tunnel in a region of deep seasonal frost. In the permafrost region for saturated frozen sandy gravel the greatest frost heave pressure normal to the walls of a vertical shaft was found to be 1.7 kg/cm^2; for saturated refrozen loamy clay the frost heave pressure normal to the walls of a vertical shaft reached 2.8 kg/cm^2.

Sides of building foundations. Although the orientation of different sides is a critical factor, the moisture content exerts the greatest influence. When the ground surface is maintained in a fairly dry condition, the horizontal frost heave pressure normal to the foundation sides is between 0.1 to 0.3 kg/cm^2; when the ground surface is under water or swampy, the frost heave pressure reached $\sigma_{\_} > 1$ kg/cm^2, and occasionally exceeded 2^{-}kg/cm^2.

ADFREEZING STRENGTH BETWEEN SOIL AND FOUNDATION

When the pore water in the soil layer freezes, the force that cements the soil particles and foundation material together is termed the adfreezing strength between the soil and the foundation (simply, adfreezing force). It occurs only when shear deformation appears between the foundation and the soil. Thus, it is a sort of index for shear strength.

Long-term compressive and tensile pile tests were conducted in the laboratory and outside with controlled loading, the stable deformation standard was found to be 0.01-0.05 mm/hr for each load increment.

Practical experience indicates that the adfreezing force is determined by ground temperature θ, water content W, time of active loading τ and grain size d, that is:

$$\tau_{adf} = f(\theta, W, t, d, \ldots) \qquad (4)$$

The Influence of Ground Temperature

As shown in Figure 10 for each soil type, the unfrozen water content W_{unf} will decrease with an increase in negative temperature θ and the cementing ice content will increase, especially in the region of abrupt phase change (Hsu Hsieh-tzu, Tao Chao-xiang and Fu Su-lan, 1975). Furthermore, following a continuous temperature decrease, the strength of ice rises correspondingly as illustrated in Figures 11 and 12. When $\theta > -5 \sim -7$°C, the following formula can be used (Wu Tzu-wang and Wang Ya-qing, 1972; Chen Hsiao-pai, 1975; Chang Shang-qin, 1976):

$$\tau_{adf} = \tau_{adf-o} + C|\theta|^{\alpha} \qquad (5)$$

in which: τ_{adf-o} - Adfreezing strength when $\theta = \theta_o$ (freezing temperature) varying with soil property and water content;

Soil Type	W_p %	W_L %	I_p %	Grain Size Distribution									
				> 10 mm	10 | 5	5 | 2	2 | 0.5	0.5 | 0.25	0.25 | 0.03	0.05 | 0.01	0.01 | 0.005	0.005 | 0.001	< 0.001
Clayey Loam	17.8	25.7	7.9			36.20	6.69	6.77	46.52	20.62	1.72	7.35	6.70
Loam	13.9	18.9	5.0			11.84	21.80	7.57	44.91	3.36	1.11	6.17	3.34
Gravel				34.67	8.76	7.89	48.68						
Coarse Sand													

Table 2 Water Content at Liquid and Plastic Limits and Grain Size Distribution for Various Soil Samples

Backfilled Soil	Moisture Content before Freezing %	Pressure (kg/cm^2)				
		0-0.2m	0.2-0.4	0.4-0.6	0.6-0.8	0.8-1.0
Clayey Loam	15.7	0.09	0.30	0.39	1.10	1.42

Table 3 Actual Measured Value of Lateral Pressure on a Retaining Wall Model (1977)

C - coefficient varying with soil property and water content;

θ - negative temperature;

α - coefficient less than 1.

In practice (when $\theta > -3 \sim -4^{o}C$), we can state approximately $\alpha = 1$, that is:

$$\tau_{adf} = \tau_{adf-o} + C|\theta| \qquad (5')$$

When the temperature of loamy clay is below $-7 \sim -9^{o}C$, where the ice-water phase has reached the state of slow change, the adfreeze force will enlarge very little with an increase in negative temperature.

Influence in Moisture Content

Adfreeze strength between the soil and a foundation can occur only when ice forms in the pores. Therefore, when the moisture content is below the unfrozen water content, there is no adfreeze force - i.e. the soil is in the state of being "dry frozen".

Figure 13 illustrates changes in adfreeze strength at certain negative temperatures when moisture content increases. (Wu Tzu-wang and Wang Yu-qing, 1972; Chen Hsiao-pai, 1975; Chang Shang-qin, 1976). When the moisture content exceeds the unfrozen water content, the ice content cement in the soil particles and foundation materials also increases. The adfreeze force correspondingly increases until all the voids are saturated with ice. When the moisture content reaches W_c the soil particles have not been significantly separated from each other and the adfreeze force reaches its ultimate value. Within this range, the adfreeze force increases with ice content and displays a linear trend, that is:

$$\tau_{adf} = \tau_o + K(W-W_{unf}) \qquad (6)$$

in which: τ_o - frictional resistance when $W \leqslant W_{unf}$;

K - coefficient relating to negative temperature and soil property.

When $W > W_c$, the interfacing action between soil grains, ice and the foundation material gradually is displaced by an ice-foundation interface. As the moisture content continues to increase, the corresponding adfreeze force slowly attenuates and tends to become the adfreeze strength between the ice and the foundation material.

Effect of Relaxation

It is known, that ice under long-term load has a strong relaxation character, which determines that the adfreeze strength unquestionably becomes a function of load time.

Figure 14 shows the adfreeze strength between concrete and frozen sandy soil at -4.0 ~ -4.2°C. With a surface unit load on the test pile of 2.85 kg/cm^2, failure did not occur up to 75 hours (Wu Tzu-wang and Wang Yan-quin, 1972). Laboratory experiments show that long-term adfreeze strength is about 1/3 of the transient value. The results of many field experiments agree with the above result; the long-term value is about 0.3-0.4 that of the short-term value (reaches ultimate value in 3-8 minutes) (Chang Qin-sheng and Chang Shang-qin, 1977).

Effect of Ice Segregation

Other factors influencing the adfreeze force are the mechanical and mineral composition of the soil, soil salinity, properties of foundation materials, surface roughness, etc. It is necessary to indicate the ice segration effect around a foundation surface. Experiments prove that the moisture content near the soil above the foundation surface is different from that surrounding it, because the foundation material (concrete, steel) has a higher thermal conductivity than the soil. Therefore, when the soil around the foundation freezes back, horizontal heat flow occurs. Moisture accumulates and ice segregation occurs on the foundation surface which is at the frost front. From field observations there is an ice film of 2-12 mm which usually forms on the concrete foundation surface. Its thickness varys with moisture and freezeback conditions. Experiments show that when the thickness of the ice film exceeds 5 mm, the adfreeze strength between clayey soil and concrete decreases more than 30% over that of invisible ice films (Chang Qin-sheng and Chang Shang-gin, 1977). Therefore, the method of construction, backfill material and external freezing environment all influence greatly the adfreeze strength seriously.

Usually, the adfreeze strength of untreated metal foundations is expected to drop 30% more than that of concrete, but field data prove that this is not so (Chang Qin-sheng and Chang Shang-qin, 1977). Because of the good thermal conductivity of metal (especially pipe piles), the soil around a foundation surface freezes quickly and the moisture cannot migrate sufficiently. Thus, the effect of ice segregation is relatively weak and its adfreeze strength is slightly higher than that of concrete.

MEASUREMENT OF BEARING CAPACITY FOR FROZEN GROUND USING IN SITU METHOD

Method of Measurement

Up to now, various countries use different ways to measure the bearing capacity of frozen ground. Our experiment shows that the so called "in situ" method shown in Figure 15 gives the best result (Wu Tzu-wang, Ma Shi-min and Liu Yang-chi, 1977). The loading plate is buried in the frozen soil layer after which the top surface of the plate and the connecting rod are coated with grease. After the moisture and temperature revert to their natural state, the test is carried out. The stable deformation standard for each load increment is < 0.02 mm/hr. This method has the following favourable features:

1. It is similar to the actual foundation in situ method;
2. As the surface layer is almost thermally insulated under field conditions, it results in the ground temperature of the bearing layer being relatively stable. In 40 days the amplitude is 0.2°C;
3. It protects the surface of the soil samples from sublimation or other disturbances.

Theoretically and practically, both prove that the proportional limiting strength P_A obtained by the "in situ" method is almost equal to that obtained with the regular open method of bearing surface test. Moreover, it does not relate to the area of the bearing plate, and the ultimate strength Pj in the "in situ" method is obviously higher than in the open method.

P-S Curve

In the "in situ" static load test, in frozen bouldery soil, frozen fine sand, frozen clayey soil or soil ice and pure ice layers, the relative curve (P-S) of the load strength P and deformation S can obviously be divided into three stages (Wu Tzu-wang, Ma Shi-min and Liu Yung-chi, 1977). Figure 16 shows the P-S curve characteristic for ground ice containing soil layers. Figure 1 represents the linear deformation stage, in which elastic and irreversible deformation are the principal ones. However, the total deformation is not great. The soil (ice) is steadily compressed and the deformation ends with the greatest linear proportional limit of P_A.

When the load $P \geqslant P_A$, it enters the second stage. At this time, a plastic zone develops at the edge of the plate and continues to grow. Although the deformation under each load increment is great, it is still part of the attenuating stage. In view of the rheological property of ice, this process in frozen soil containing much ice is especially obvious.

After P > Pj, it enters into the third stage. The plastic zone penetrates under the load plate. If the load continues to increase, plastic flow occurs in the soil and the deformation is unattenuating.

Experiments show that the ultimate load Pj is about 1.7-2.3 times the proportional limit loading.

Relation of P_A to Soil Temperature

Like the other strength indexes of frozen soil, soil temperature is one of the most important factors. A number of field and laboratory experiments prove that when the soil temperature is below freezing, ice crystals occur; the cementing by the ice crystals causes the bearing capacity of frozen soil to increase and it rises as the negative temperature increases. As the temperature is higher than -3°C (this temperature range is usually found in practice), the relation between the proportional limiting load P_A and the negative temperature is linear as shown in Figure 17 (Wu Tzu-wang, Ma Shi-min, Xia Chin-ru and Liu Yang-chi, 1977). It can be expressed by the following formula:

in which: P_{Ao} - proportional limiting load when $\theta = \theta_o$ freezing temperature;

C - coefficient relating to soil property and moisture content;

θ - negative temperature.

Relation Between P_A and Moisture Content

When the moisture content exceeds the unfrozen water content (and $W_{unf} = f(\theta)$), the bearing capacity will increase with moisture content as shown in Figure 18 (Wu Tzu-wang, Ma Shi-min and Lui Yung-chi, 1977). The cause is quite clear when the soil pores are almost filled with ice. The bearing capacity reaches its highest value. If the moisture content increases, the soil particles enter into a suspended state, and the properties of the frozen soil approach that of ice. Thus, P_A will tend toward P_{Ai}.

Rheological Effect

Under load ice flows due to a drop in the freezing point which produces plastic flow imparting a rheological character to frozen soil.

Figure 19 shows the relation of soil with an ice layer of stable plastic velocity v = ds/dt under the condition of a constant temperature in the laboratory and an external load P (Wu Tzu-wang, et al, 1977). Following an increase in external load, the stable plastic flow velocity increase in the form of a parabolic curve, this is:

$$V = ap^2 + bp \qquad (8)$$

when $\theta = -1.0^oC$

$$V = 0.0059p^2 + 0.006p \qquad (8')$$

Figure 20 shows creep lines in clayey loam (W_p = 15.7%) under loads of 3, 5 and 8 kg/cm^2 respectively in with $\theta = 1.0^oC$ (± 0.1°C) and W = 29%. (Wu Tzu-wang et al, 1977). Obviously the greater the load, the more the deformation and the time required to stabilize the deformation will be much longer. If it is expressed in logarithmic coordinates as shown in Figure 21, its deformation before stabilization can be expressed by the following formula: (Wu Tzu-wang et al 1977).

$$\lg S = \lg S_o + C \lg t \qquad (9)$$

i.e. $$S = S_o t^C \qquad (9')$$

in which:

S - total amount of deformation;

S_o - instantaneous deformation under the effect of load;

C - coefficient relating to loading rate and soil property;

t - loading time.

Evidently, with different loading rates, the time required to stabilize the deformation t_s inevitably differs. Figure 22 illustrates the time t_s needed for stabilizing deformation for the samples mentioned above under P = 5, 8, 9.5 and 11 kg/cm^2 respectively (Wu Tzu-wang et al, 1977). Thus, within the range of experimental loading, it can be expressed by the following formula:

$$\lg t_s = K (\lg P - \lg P_o) \qquad (10)$$

in which:

t_s - time for stabilizing deformation under P;

K - coefficient relating to soil temperature and moisture content.

when $p \to P_o$, deformation of the soil is extremely small and the time needed to stabilize it is almost equal to zero.

CHARACTERISTIC INDICES OF THAW CONSOLIDATION OF FROZEN SOIL

It is well known that the thaw consolidation of frozen soil differs obviously from that of ordinary soil. The variation in void ratio of frozen ground are shown in Figure 23. When the pressure is low, the frozen soil thaws and afterwards under load, it consolidates and the variation in the void ratio Δe during thawing is:

$$\Delta e = \Delta e_o + \Delta e_p \qquad (11)$$

in which:

Δe_o - variation in void ratio when frozen soil thaws;

Δe_p - variation in void ratio under load P after the frozen soil thaws.

$$\Delta e_p = p \cdot tg\beta$$

if allow: $A = \Delta e_o$

$$\alpha = tg\beta$$

then $$\Delta e = A + \alpha p \qquad (12)$$

and amount of settlement when frozen soil thaws is:

$$S = H \frac{\Delta e}{1 + e_1} = H \frac{A}{1 + e_1} + H \frac{\alpha P}{1 + e_1} \qquad (13)$$

in which:

H - thaw depth of frozen soil layer;

e_1 - void ratio before frozen soil thaws;

let:

$A_o = \frac{A}{1 + e_1}$ - practical thaw settlement coefficient;

$\alpha_o = \frac{\alpha}{1 + e_1}$ - practical compression coefficient.

then: $$S = HA_o + H \alpha_o P \qquad (14)$$

It should be indicated that P in the formula is the additional stress of frozen soil after thawing, including the dead weight and external load pressure of the soil above (Chen Hsiao-pai and Tong Shang-chiang, 1977; Chu Yan-lin, 1977).

A_o and α_o are the characteristic indices in the thaw consolidation process of frozen soil. Here we will generalize and discuss them based on the large amount of experimental data from undisturbed soil samples.

Test Samples

Soil samples were taken from depths of 3.5 to 4 m, they include seasonally frozen and undisturbed permafrost soil samples. The latter contained some ice with soil layers. The soil samples were divided into: clean sandy gravel, gravel containing fines, fine sand, clayey loam and silty clay, heavy clay, etc. The representative grain size analysis curves are shown in Figure 24 (Chu Yan-lin, 1977). This work included both in situ testing and sampling.

In the testing, the area of the loading plates were 25 x 25 and 50 x 50 cm^2; the samples had a diameter of 7.5 cm and 4 cm in height. One dimensional thawing was maintained in the testing. The stable deformation standard chosen in the in situ testing, for all types of soil, did not exceed the following value within 2 hours: coarse-grain soil - 0.02 cm, fine-grain soil--0.05 cm, ice layer containing soil - 0.10 cm; in the small scale test, there was fine-grain soil with 0.05 mm, ice layers and 0.10 mm soil layers respectively (Chu Yan-lin, 1977).

Practical Thaw Settlement Coefficient A_o

A_o is the relative settlement caused by the volumetric shrinkage when ice becomes water which is drained out during the thaw of frozen soil. Therefore, it relates closely with its moisture content and dry density (degree of saturation of soil voids).

1. Water content W.

Figure 25 shows the relation between A_o and W for several types of soil. On the whole, the lines can be divided into straight line sections and curve sections. In the straight line portion, it can be indicated by:

$$A_o = K(W-W_o) \tag{15}$$

in which: K - coefficient relating to soil property;

W - moisture content of frozen soil;

W_o - moisture content when $A_o \to 0$ with clayey soil

$$W_o = 5 + Wp \tag{16}$$

with coarse-grain soil, W_o = 9-12%.

(Chen Hsiao-pai, 1972; Wu Tzu-wang, Chang Chia-yi, Wang Ya-qing and Shen Chong-yen, 1972; Chang Shang-qin, 1976; Chu Yan-lin, 1977).

In the curved portion section, it can be indicated by:

$$A_o' = K' \sqrt{W - W_c + A_{oc}} \tag{17}$$

in which: K' - coefficient relating to soil property;

W_c - moisture content at the boundary of the straight line and curved section;

A_{oc} - coefficient of thaw settlement when $W = W_c$

(Chu Yan-lin, 1977)

For the relationship of A_o for ground ice (ice layer containing soil) and W see Figure 26, the curved line A_o = 100% is taken as the asymptote.

2. Dry density. In fact, to a certain extent, there exists a close relation between moisture content and dry density. Thus, there is also a correlation between A_o and γd as shown in Figure 27;

let: γdc - dry density corresponding to W_c,

when $\gamma d \geqslant \gamma dc$, $A_o \sim \gamma d$ curve can be expressed by the following equation$^{(15)}$ (Chu Yan-lin, 1977):

$$A_o = K \frac{\gamma do - \gamma d}{\gamma d} \tag{18}$$

in which: K - coefficient relating to soil property;

γd - natural dry density of frozen soil;

γdo - initial thaw settlement dry density, i.e. when $\gamma d = \gamma do$, $A_o = 0$,

when $\gamma d < \gamma dc$, it can be shown approximately by linear equation (Chu Yan-lin, 1977):

$$A_o' = K\ (\gamma dc - \gamma d) + A_{oc} \tag{19}$$

Practical Compression Coefficient α

After the frozen soil thaws, under an external load, consolidation inevitably occurs. The practical compression coefficient α_o then becomes the characteristic index of that process. Like common thawed soil, α_o is determined by the state of consolidation of the soil which is the dry density.

Figure 28 shows that under the effect of P = 0-2 kg/cm^2, α_o varies with γd, after thawing of several types of frozen soil. Let: $\gamma d \geqslant \gamma do$, $x_o \to 0$. Thus, when $1.4\ g/cm^3 < \gamma d < \gamma do$, α_o almost follows the decrease of γd and shows a linear increase (Chen Hsiao-pai, 1972; Wu Tzu-wang, Chang Chia-yi, Wang Ya-qing and Shen Chong-yen, 1972; Chu Yan-lin, 1977).

that is: $\alpha_o = K\ (\gamma do - \gamma d)$ (20)

in which: K - coefficient relating to soil property and external load;

γdo - dry density when $x_o \to 0$;

γd - dry density.

When $\gamma d < 1.4\ g/cm^3$, the curve changes slowly and becomes irregular. The main reason is that, as the soil is supersaturated, the particles are in a state of suspension. When thawed, under the effect of the low stress of their dead weight, the suspended grains tend to come into contact, simultaneously. In view of the differentiation of the structure of frozen soil, the thaw settlement surely has a certain difference and all of these necessarily exert a strong influence on the compression coefficient.

Furthermore, the sod which grows in permafrost region, possesses great absorptivity and thermal insulative properties. In design and construction, the subgrade should be maintained in the frozen state. The sod must not only be kept in its original condition, but it should be covered. Therefore we also have to ascertain its thawed compressive behaviour.

Experiments show that the sod is spongy when thawed. The volumetric change of the frozen soil is not large, but under load (even if small), it shows very great compressiveness. Figure 29, illustrates the relation between the compressive coefficient and dry density (Chu Yan-lin, 1977).

CONCLUSION AND DISCUSSION

1. Frost heaving appears in soil only when the moisture content exceeds the initial requirements. The main zone of heaving is in the seasonally frozen layer. When sand and gravel are used to replace frost susceptible soil, heaving can only be achieved when there is a relatively permeable layer at the base.

2. The mean tangential frost heave force is distributed in the active layer similar to the frost heave zone. Tests show that the water-ice phase of frozen soil is in a state of dynamic balance.

3. In a closed system the tangential frost heave force increases with water moisture content, and gradually decreases when it reaches the ultimate value.

4. Frost heave pressure normal to a foundation base decreases with depth in the active layer. In the region of seasonally frozen soil, it attenuates rapidly. It still possesses a much larger value near the permafrost table.

5. The frost heave pressure normal to the surface rapidly decreases with an increase of bearing area and can be expressed by:

$$\sigma_1 = C + \frac{a}{F} + \frac{b}{F^2}$$

6. Adfreeze strength varies with negative temperature, and has $\tau_{adf} = \tau_{adf_o} + a|\theta|^{\alpha}$, when $\theta > -3 \sim -4^oC$, it is:

$$\tau_{adf} = C + a|\theta|$$

7. Adfreeze strength is related to moisture content and beyond the ultimate value, it gradually tends toward the adfreeze force of ice.

8. Since differences exist in foundation materials, conditions of burial and surrounding conditions, the state of ice segregation at the side of a foundation differs greatly, directly influencing the adfreeze strength.

9. The determination of the bearing capacity of frozen soil using the in situ method is similar to that using the buried method. The soil temperature is stable and sublimation and other disturbances are prevented. The "P-S" curve thus obtained corresponds with that of ordinary thawed soil.

10. Within the usual temperature range, the proportional limiting load P_A appears to have a linear relation with negative temperature, $P_A = P_{AO} + C|\theta|$. The relation of P_A to moisture content is similar to the adfreeze force.

11. Within the range of our experiments, the stable plastic yield velocity V of ice under load has a relation of $V = aP^2 + bP$.

12. The relation between frozen soil during compression before stable deformation and time can be indicated by $l_gS = l_gS_o + C\ l_g t$, and the stable deformation time t_s has a relation of $l_g t_s = K(l_gp - l_gP_o)$ with a load P.

13. The practical thaw settlement coefficient A_o has a close relation to moisture water content. The straight section of the curve is the range often used which can be expressed by the linear equation $A_o = K\ (W-W_o)$; the curved section can be indicated by:

$$A_o' = K' \sqrt{W-W_c} + A_{oc}$$

14. A_o has a close relation to dry density γd, when $\gamma d \geqslant \gamma do$, $A_o = K\ (\gamma do - \gamma d)/\gamma d$; when $\gamma d < \gamma dc$ it can be expressed approximately by the linear equation $A_o' = K(\gamma do - \gamma d) + A_{oc}$.

15. The practical compression coefficient α_o has a close relation to dry density, when $1.4\ g/cm^3 < \gamma d < \gamma do$. The linear equation $\alpha_o = K(\gamma do - \gamma d)$ can be used to express it. After $\gamma d < 1.4\ g/cm^3$ the curve changes slowly and there is no rule to which it can be referred.

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<u>Figure Captions</u>

Figure 1. The distribution of frost heave rate through the active layer.

Figure 2. Schematic diagram of different frost heave forces.

Figure 3. Lines of developing tangential frost heave force with time.

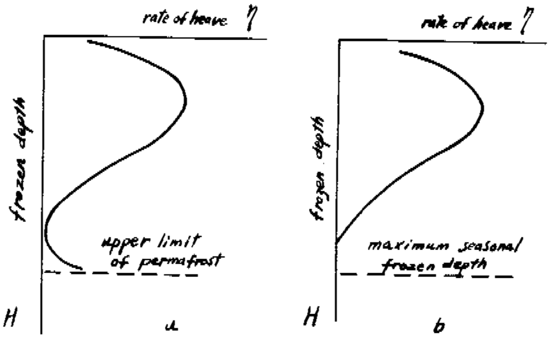
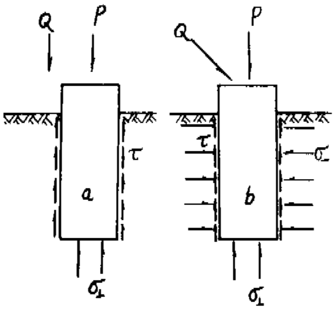


Figure 1



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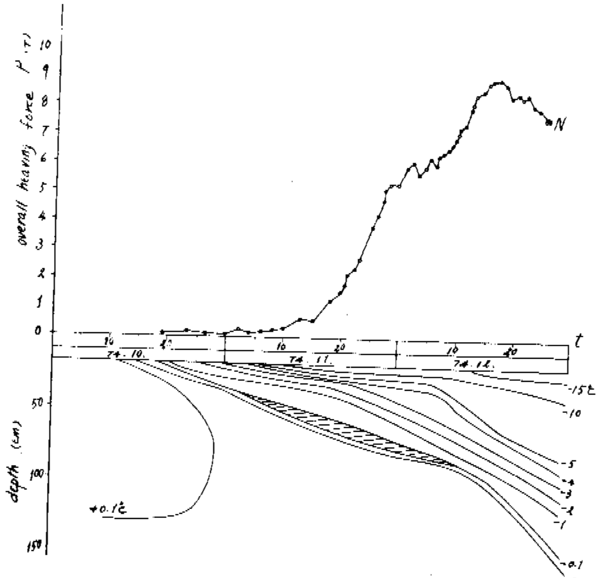

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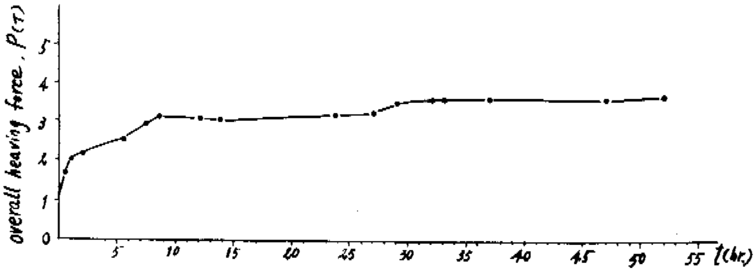

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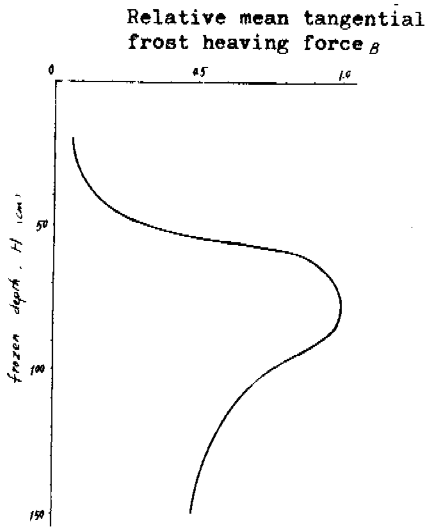

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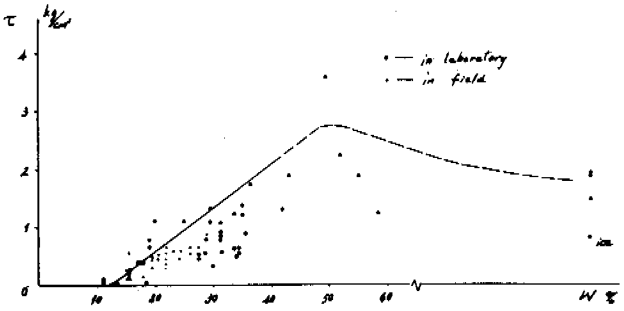

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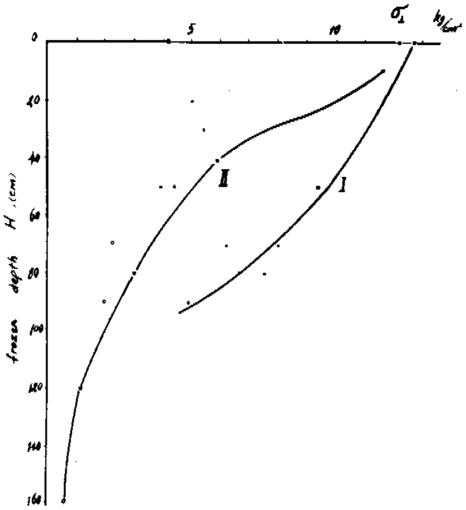

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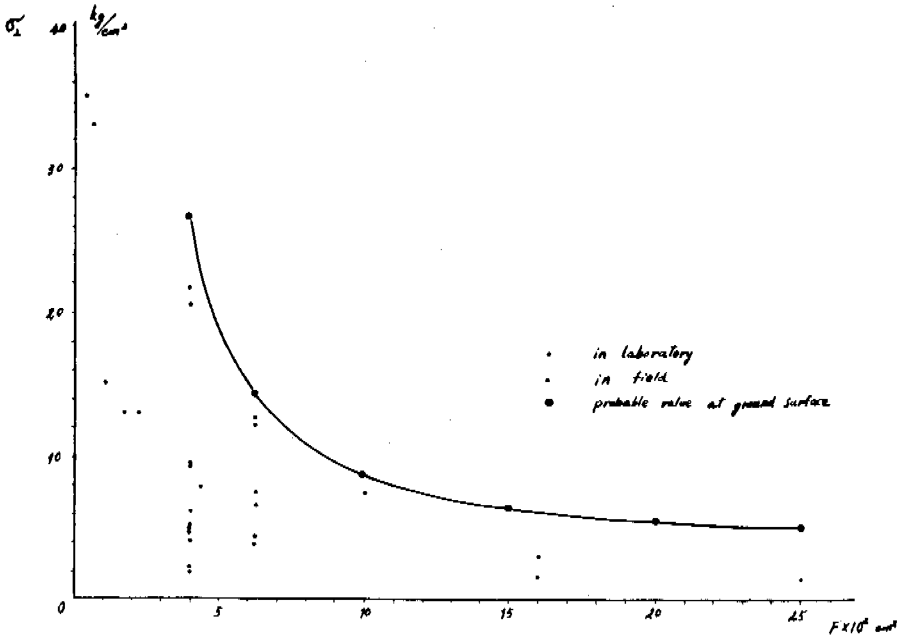

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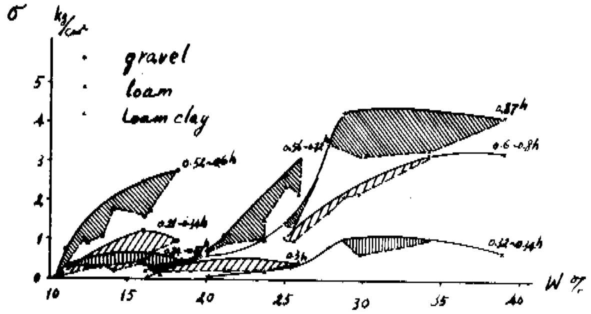

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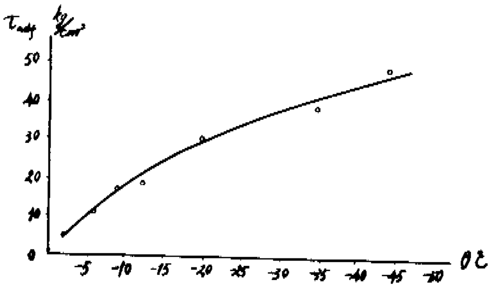

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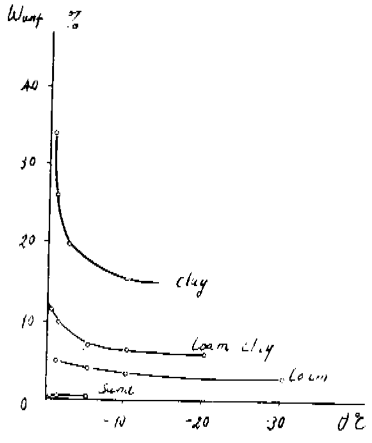

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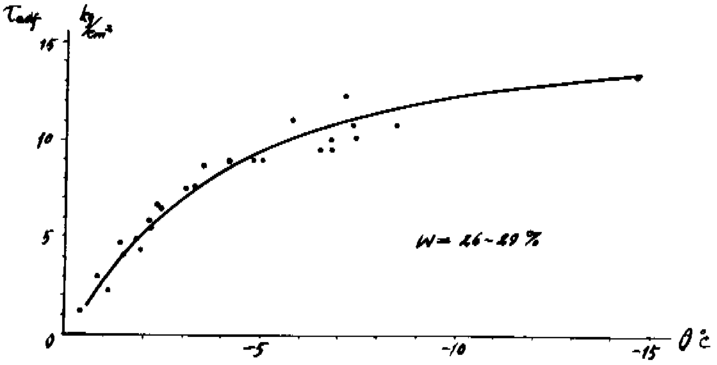

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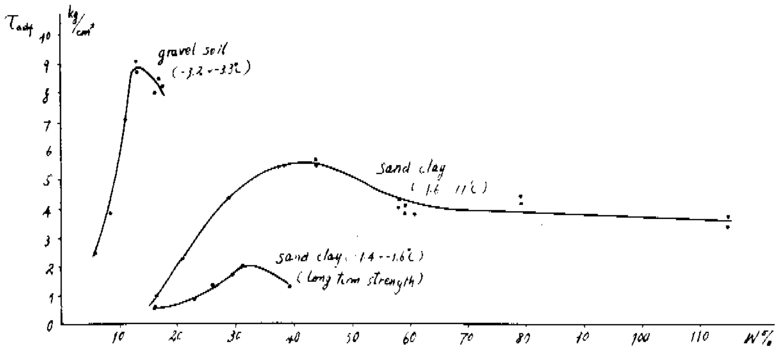

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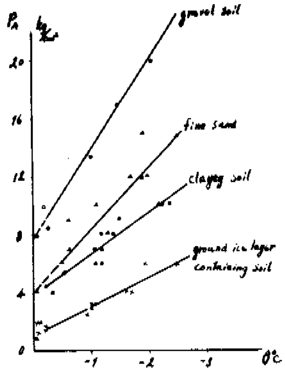

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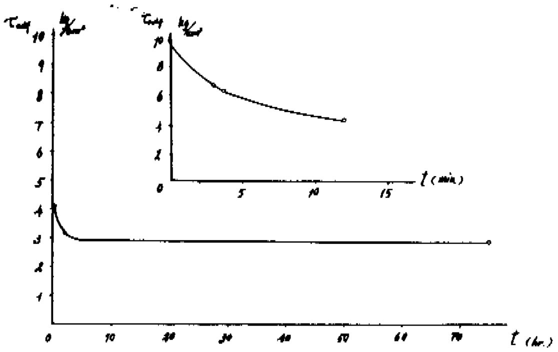

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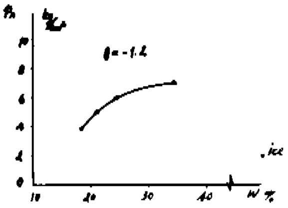

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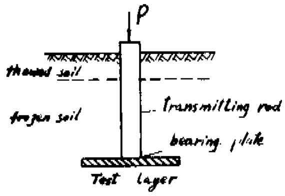

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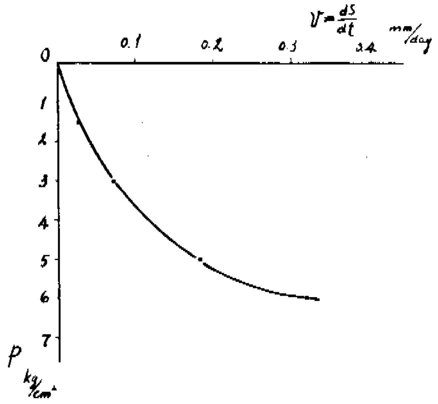

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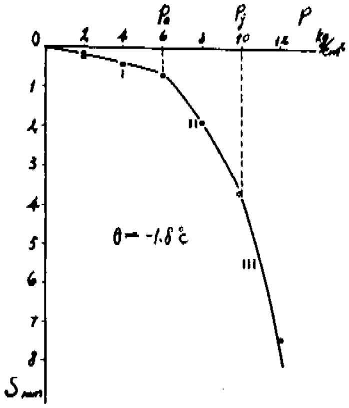

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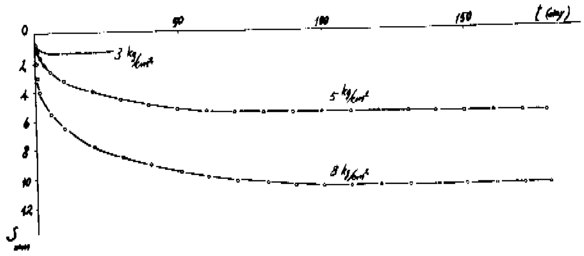

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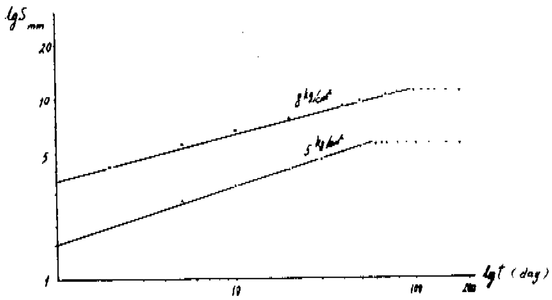

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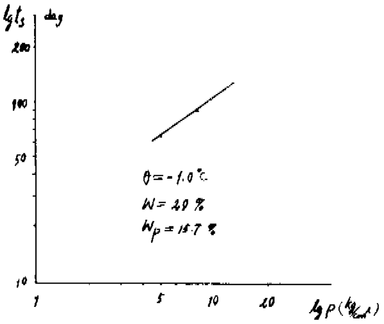

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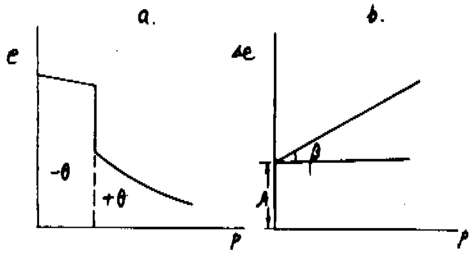

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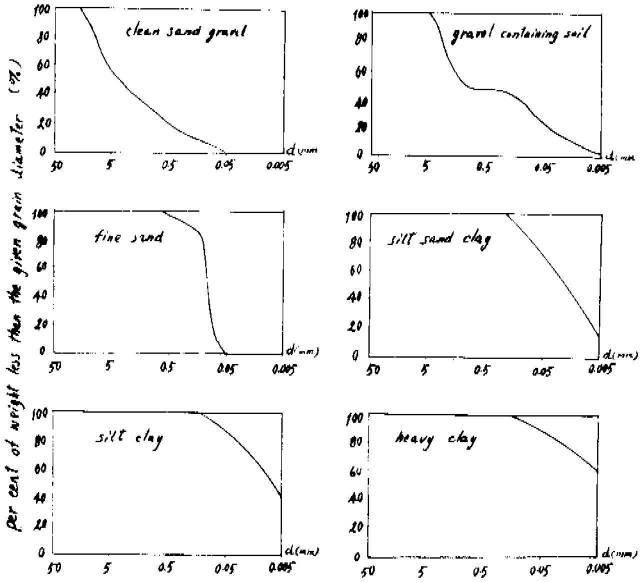

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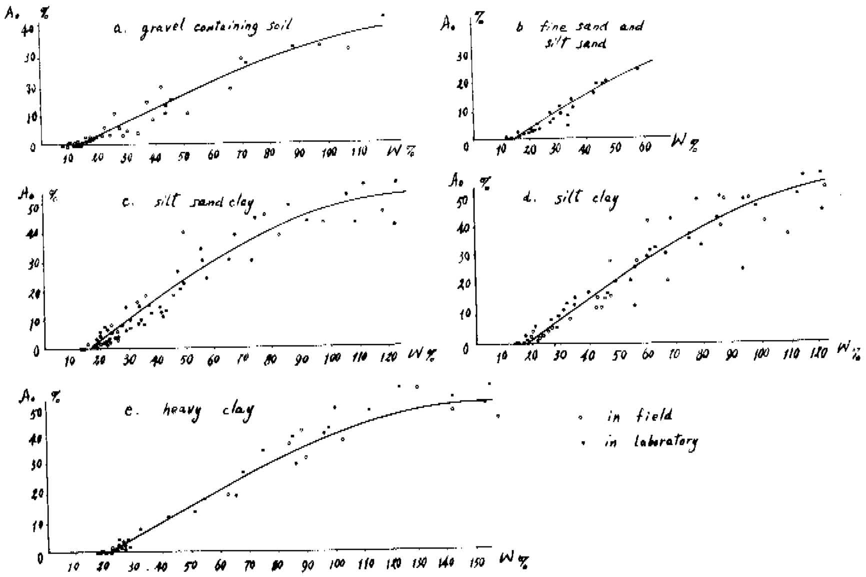

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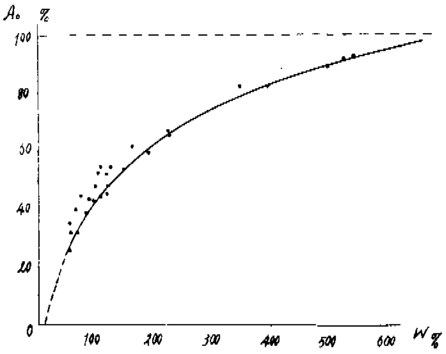

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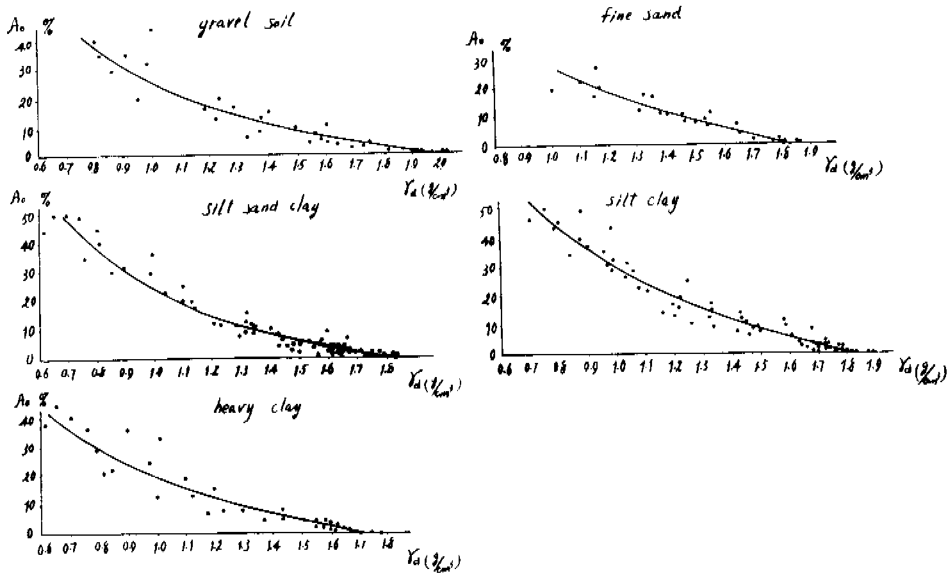

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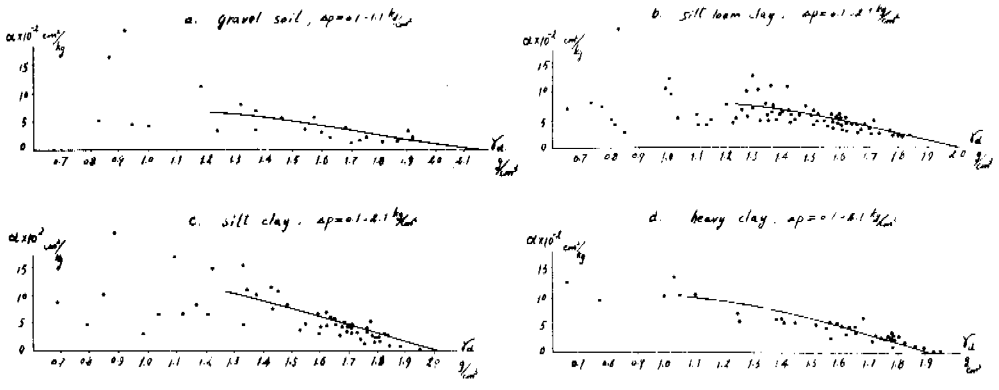

Figure 28

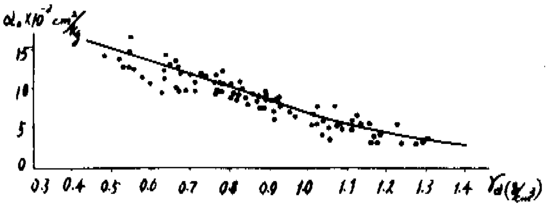

Figure 29

TESTING OF PILE FOUNDATIONS IN PERMAFROST AREAS

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ABSTRACT

This report presents the natural geographical and geological conditions of two permafrost pile test sites, one located in the Kukusili Mountains and the other near the Chumar River on the Chinghai-Tibet Plateau. The freezeback of the pile, the hardening of concrete at low temperature, durability and resistance to freezing and thawing of the cast-in-place reinforced concrete pile foundations, and results of static load tests are also described.

In comparison with other types of foundations in permafrost areas, piles have some advantages. Pile foundations have therefore been adopted recently in bridge and building construction in permafrost areas of China. The main types used here are drilled driven piles, drilled placement piles and drilled cast-in-place piles. All of them are of reinforced concrete. In order to develop design and construction criteria for the above-mentioned foundations, in addition to supporting laboratory experiments, two pile test sites, one in the Kukusili Mountains (Test Site K) and the other at the Chumar River (Test Site CH), were established for research purposes.

Test Sites K and CH are both located in continuous permafrost on the Chinghai-Tibet Plateau at altitudes of 4618 m and 4470 m with mean annual air temperatures of -5.7°C and -6.2°C respectively. The ground temperature at the depth of zero amplitude in both sites is -1.5°C at a depth of 10 m and -1.0°C at a depth of 8 m. The thickness of the seasonally thawed layer is 1.5 - 2.0 m and 2.0 - 2.5 m. The former site has dense soil with low ice content and well developed suprapermafrost water, while the latter has stratified soil with volumetric ice content of 40% to 70%.

The geological columns and curves of ground temperature are shown in Figure 1.

The plan and technical aspects of the test piles at the two sites are shown in Figure 2 and Table 1.

The main test results are as follows:

FREEZEBACK

The thermal equilibrium of the permafrost around the piles was disturbed due to installation, and the ground near the piles may even be thawed. After a period of some heat exchange, the thawed ground becomes refrozen so that a new state of thermal equilibrium is established. The time taken for freezeback depends on the amount of heat (heat due to drilling, heat from the drilling slurry, backfill material and concrete mixture, and heat of cement hydration) and the ground thermal regime around the piles.

As observed at the two test sites, the time of freezeback for drilled driven piles and drilled placement piles is quite short, and it is even not very long for cast-in-place piles.

Drilled Driven Piles

Because only a small amount of heat was introduced due to construction, the rise in ground temperature around the drilled driven piles was rather small. Freezeback was completed mainly in 7 to 11 days after placement (Figure 3). This demonstrates that natural freezeback may be used for drilled driven piles in these test areas.

Drilled Placement Piles

Because a comparatively large amount of heat was introduced in the backfill material around the piles, the time of freezeback required was 3 to 4 days longer than that for the drilled driven piles, i.e. 10 to 15 days were needed for the completion of freezeback after placement (Figure 4). This means that natural freezeback can also be used in drilled placement pile construction for the test sites.

Site	Type	Diameter (m)	Bored Hole Diameter (mm)	Method of Pile Placement	Placement Depth (m)	Quantity (pcs)
K	RC Tubular	400	350	Drilled driven	6.0	3
	RC Tubular	300	350	Drilled placement	6.5	3
CH	RC Tubular	550	500	Drilled driven	7.5	3
	RC Tubular	550	650	Drilled placement	8.1	3
	RC Circular	650	650	Drilled cast-in place	8.0	3

Table 1 Technical Characteristics of Test Piles

Drilled Cast-in-place Piles

For cast-in-place piles, due to the rather high temperature (10^{o}C - 20^{o}C) of the concrete mix and in addition, the cement hydration heat involved, there was a substantial rise of temperature around the piles. Hence the freezeback lasted approximately 30 days (Figure 5). A low temperature (around 0^{o}C) moisture will greatly reduce the volumetric heat content of the concrete and will also delay the hydration action of the cement. Thus, some reduction in thermal disturbance to the frozen soil around the pile will occur which leads to a shortening of the freezeback time.

Drilled Cast-in-place Concrete Piles

Drilled cast-in-place piles have the advantages of a large diameter and high bearing capacity. They are also suitable for various lithological conditions and for areas of active groundwater. Therefore, they are a superior type of foundation for structures carrying heavy loads. However, efforts must be made to minimize the thermal effect of the concrete, to accelerate its hardening at low temperatures and to improve its durability and resistance to freezing and thawing. For these purposes a series of tests was carried out both in the laboratory and at the site for which good results were achieved.

Efforts were made to modify and improve the technical properties of the concrete used for drilled cast-in-place piles, mainly through the use of chemical additives.

Three different preparations of additives were used in the tests:

(1) Air-entraining agent (AEA - alkyl sulfonate) + accelerating agent (AA - sodium chloride and sulphate);
(2) Water-reducing agent (WRA - naphthol sulfonate or naphthol sulfonic acid-formaldehyde dehydration product) + AA;
(3) WRA + AA + freezing resistance agent (FRA - nitrate).

The test materials were ordinary cement and early-strength cement, river sand, crushed stone and pebbles. The water-cement ratio was 0.30 - 0.60. The test specimen were cured at temperatures of 20^{o}C, 0^{o}C, -3^{o}C, -5^{o}C and -10^{o}C during hardening. Various tests for determining the physical mechanical properties and resistance to freezing and thawing were undertaken. Field tests included embedding thermocouples and thermistors in the pile to test the thermal effect of the concrete. Results proved that the specimen made of low water-cement ratio concrete and blended with chemical additives showed excellent workability. Compared to specimens without additives, the rate of hardening under low (or negative) temperature and the capability of resisting freezing and thawing showed appreciable increases. The strength values obtained from specimens cured in cryogenic containers (cold chambers) coincided approximately with those obtained in outdoors testpits in the frozen ground. All the values obtained were up to or above the designed value. The values for countermeasures freezing and thawing were also up to or over M-200 and met the designed durability criteria. During the first few days up to a dozen or more after placing of the concrete, the temperatures inside the concrete piles were above zero and then lowered gradually until a state of equilibrium in relation to the temperature of the frozen ground was attained. Generally this turned out to be during a 2-3 week period. Keeping down the initial tempature of the concrete mix was favourable to promoting thermal equilibrium between the piles and the surrounding frozen ground and the refreezing period of the latter was reduced. So, when casting the piles a temperature of approximately 0°C should be maintained in the concrete mix.

The key to successful results with cast-in-place piles lies in the concrete materials used and the procedure followed in their installation. Adding chemical admixtures into the concrete mix is a promising method.

Static Loading Tests

Vertical and lateral static loading tests were both carried out at Test Sites K and CH (Figure 6). Testing instruments and loading equipment are shown in Figure 7. Internal forces at different sections and reaction forces at the lower end of each pile were measured by resistance strain gauges and pressure sensors. Settlement and displacement were measured by micrometers.

Loading proceeded in several stages. For the vertical loading test, the load applied at the first stage accounted for 50% of the design value. In subsequent stages the load was applied in increments of 10% of the design load. Each load increment was applied when the previous loading reached a state of stability. The criterion of stability is: pile settlement less than 0.5 mm in 24 hours and observed for 3 consecutive days. Should the loading at any stage not reach stability within 10 days, the test should be stopped. For the lateral loading test, loads were applied in equal increments. A displacement of less than 0.02 mm per hour was taken as the criterion of stability. In case stability cannot be achieved during a certain loading stage which is sustained for 24 hours the test should be stopped.

The following points have emerged through the testing:

1. Under a vertical load in the permafrost a pile foundation will form an equilibrium force system consisting of the friction of the thawed soil, adfreezing bond of the permafrost, reaction force at the lower end of the piles and the external load. The magnitude and composition of the first three vary with the external load and the rate of loading. When the load is small, there will be no reaction force at the lower end of the pile. It appears apparently only when settlement occurs at a certain load causing relaxation of the adfreezing force in the upper part down to a certain depth. If the loading time is prolonged and the load increased, the relaxation phenomenon will develop continuously. Correspondently, the reaction force at the lower end will gradually increase at the same time, and reach up to 9% of the total reaction

Vertical Load		Settlement of Pile-Top (mm)	Reaction Force at Lower End	
Load Applied (t)	Sustained Application (24 hrs)		Magnitude (t)	Percentage of Ultimate Loading Capacity
15	1	0.09	0.036	0.24
30	1	0.46	1.450	4.83
38	5	4.14	2.156	5.65
45*	9	15.08	4.168	9.26

* Ultimate load

Table 2 Relationship between Reaction Force at Lower End of Drilled Placement Pile and Vertical Load at Test Site K

Ultimate Ad-Freezing Strength (t/m^2) / Type of Test Piles / Mean Temperature of Frozen Ground around Piles (C°)	Drilled Placement Pile	Drilled Driven Pile	Drilled Cast-in-place Pile
-1.0	6.0	8.7	---
-0.5	4.1	8.2	12.2

Table 3 Ultimate adfreezing strength around piles

force with ultimate loading (Figure 2). The results mentioned above indicate that there exists a problem of the optimum length of the piles for economic purposes in designing pile foundation. Further studies are required to determine the length.

2. The adfreezing force varies greatly with the type of pile foundation and construction method. The adfreezing force of a drilled placement pile is at a maximum while that of the drilled driven pile is at a minimum (Figure 3). But bored placement pile is convenient for construction. Its bearing capacity can also be greatly increased when applying special surface feature.

3. In making calculations for a pile foundation under horizontal load, the following equation can be applied to choose the foundation modulus along the pile length suitable for permafrost.

$$K = mZ^n$$

where K - foundation modulus
m - coefficient of foundation modulus varying with the depth
Z - length of pile beneath ground surface
n - power varies with lithological character

The bending moment of the pile can be tested and compared with the actual measured moment. The distribution of four foundation moduli along the depth in Figure 8 can be used for calculation. Results show that the maximum bending moment and maximum bending position calculated by means of (d) are near the actual measured value (Figure 9).

4. In permafrost areas, the foundation soil around the piles consists of thawed soil near the top, plastic high creep frozen soil in the middle and low creep frozen soil at the bottom. The reaction force coefficient at the top is very small, bigger at the bottom, and intermediate in the middle. The distribution of the foundation modulus is a concave parabola above the first elastic zero point. It is near the actual condition. The first elastic zero point is located below the freeze-thaw interface of the soil. The distance between the first elastic zero point and the freeze-thaw interface is related to the pile diameter and the characteristics of the permafrost.

5. It is unrealistic to use only the fixed displacement to work out the parameter m of the above formula. Two ultimate conditions should be considered, such as the splitting of the pile and the restraint effect of the foundation on the piles, and the smaller value taken. The value m obtained by this method and the foundation modulus K of the test pile obtained from (d) in Figure 8 are as follows:

(1) When mean ground temperature $t_1 = -0.5°C$, $K_1 = 130\ kg/cm^3$

(2) When mean ground temperature t_2 $t_2 = -1.0°C$, $K_2 = 200\ kg/cm^3$ $_2$

In practice, K should be deducted according to the loading characteristics, etc.

CONCLUSIONS

(1) The freezeback of soil around a pile foundation in permafrost areas depends not only on the ground temperature, but also on the type of pile foundation, method and season of construction, as well as heat introduced by backfilled material, etc. In the permafrost areas of the Chinghai-Tibet Plateau with mean annual ground temperature lower than -1.0°C, drilled driven piles, drilled placement piles and even cast-in-place piles can have rapid natural freezeback.

In construction with cast-in-place piles, the concrete mix should be near 0°C in order to reduce the natural freezeback process.

(2) Concrete with a low water-cement ratio can reach Mark 300 by applying chemical additives. Its index of resistance to freezing and thawing can reach or surpass M-200. It meets the design requirements and creates the possibility of a wide application of cast-in-place piles in permafrost areas.

(3) For pile foundations in permafrost, when settlement caused by a certain vertical load makes the relaxation of the adfreezing force at the top develop to a certain depth, a reaction force appears at the lower end. If the loading time is prolonged or the load increased, the relaxation phenomenon will develop continuously. Correspondently, the reaction force at the lower end will increase gradually at the same time. All these show that there exists a problem of economic pile length in designing pile foundations in permafrost. Further studies are needed to determine the length.

(4) For piles under a horizontal load in permafrost, although calculations common in soil mechanics do not entirely conform with reality, the foundation modulus can be determined through field experiments and can be used as a simplified calculating method for engineering design. The distribution of the foundation modulus is a concave parabola above the first elastic zero point of the pile and a rectangle below it. It conforms fairly well with the actual conditions. The first elastic zero point is located below the freeze-thaw interface and the distance between these two is related to the pile diameter and the characteristics of the frozen soil.

Figure 1. Geological column and ground temperature curves at the Test Site.

Figure 2. Lay out of Test Site CH.

Figure 3. Ground temperature curve during freezeback. (Prepared for driven pile No. 1 at Test Site CH)

Figure 4. Ground temperature curve during freezeback. (Prepared for placement pile No. 2 at Test Site CH)

Figure 5. Freezeback curve of No. 1 drilled cast-in-place pile at Test Site CH.

Notes:

1. Data taken
   20 hours before cast-in-place
   16 hours after cast-in-place
   3 days ditto
   7 days ditto
   11 days ditto
   52 days ditto
   98 days ditto

2. Date of cast-in-place: 17 hours, July 20, 1976.

Figure 6. View of Test Site CH.

Figure 7. Installation of static load test.

Figure 8. Distribution of foundation modulus along pile length

Notes:

(a) $n=0$ $K=K$

(b) $n=0.5$ $K=mZ^{0.5}$

(c) $n=1$ $K=mZ$

(d) Above the first point of zero displacement, $n>1$

Below ditto , $n=0$

Figure 9. Comparison between measured and computed bending moments.

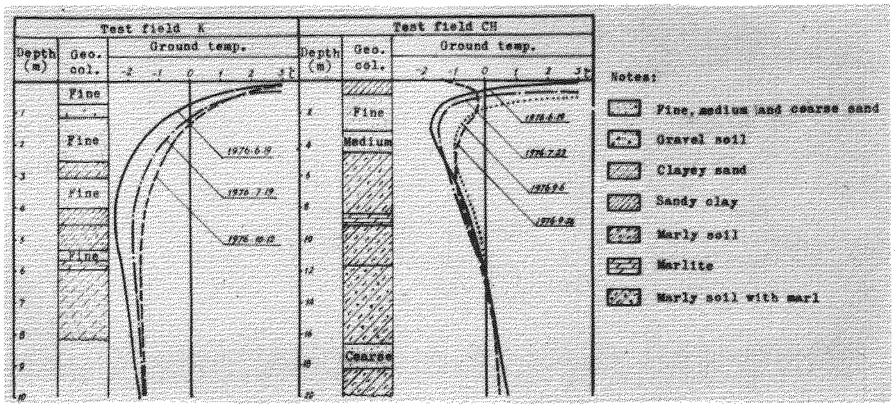

Figure 1

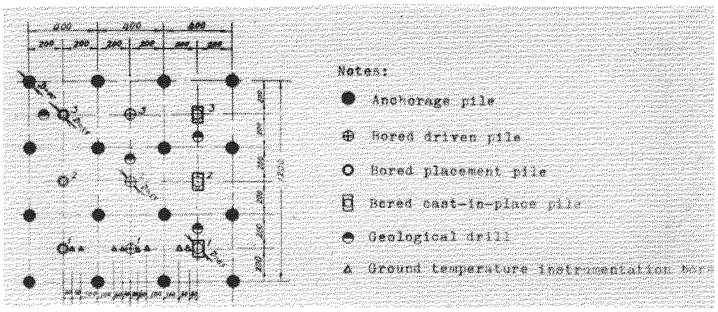

Figure 2

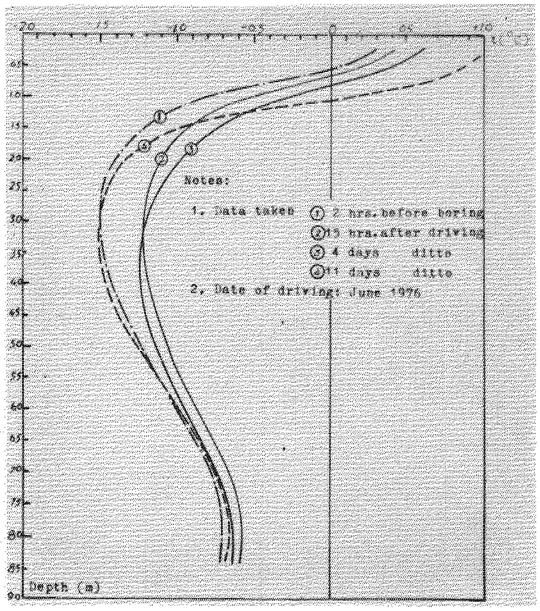

Figure 3

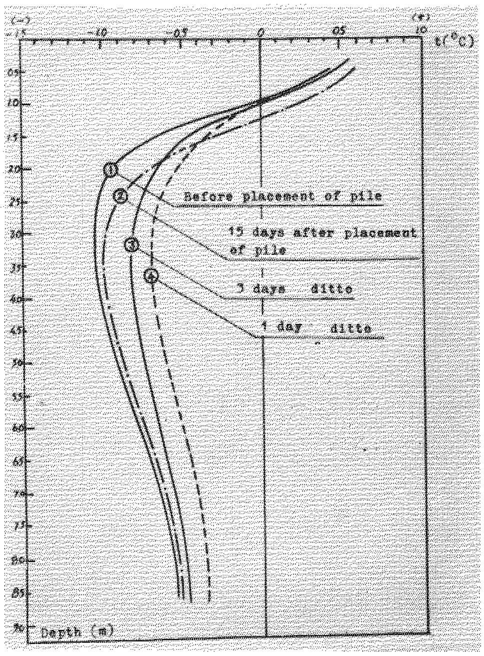

Figure 4

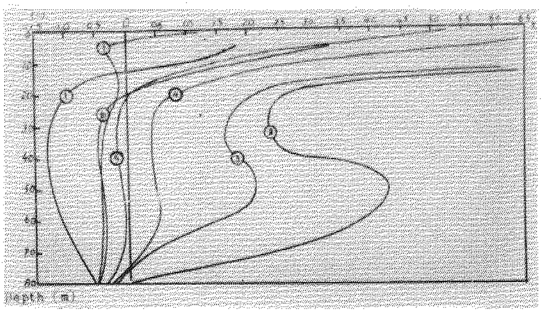

Figure 5

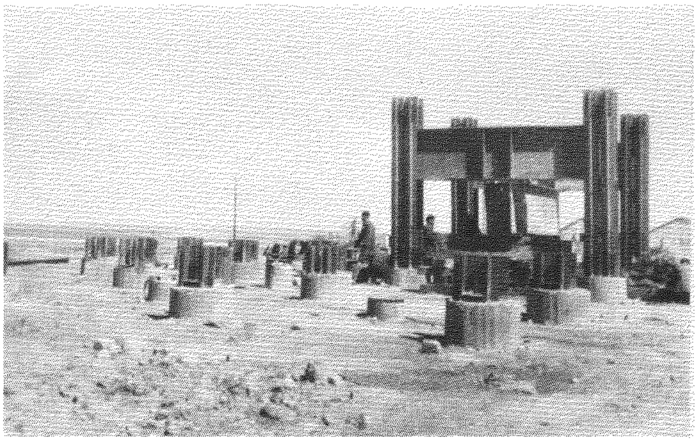

Figure 6

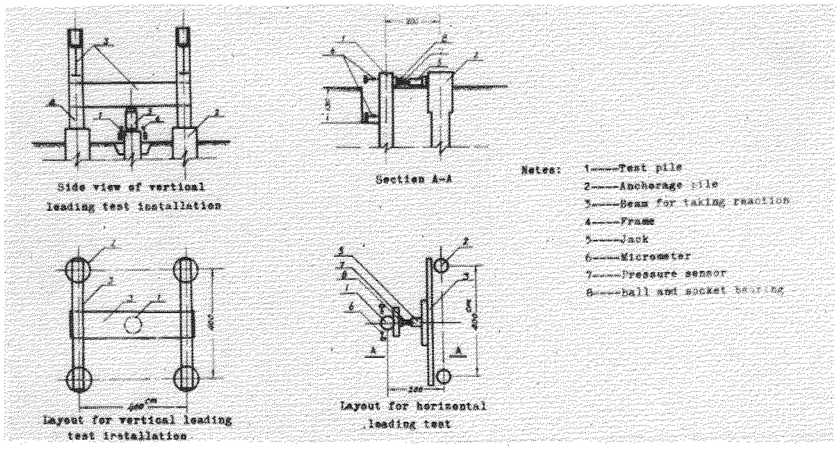

Figure 7

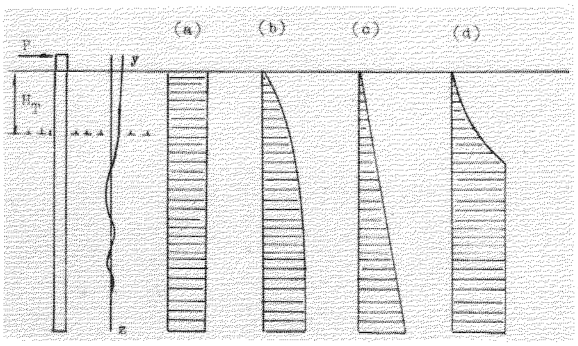

Figure 8

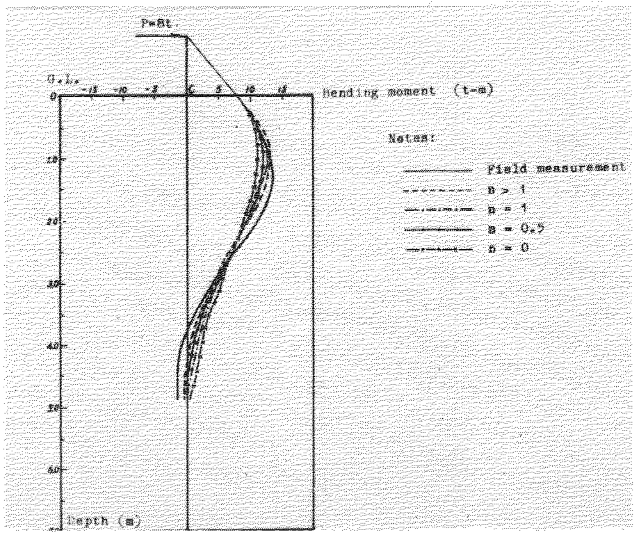

Figure 9

EXPERIMENTAL ROADBED IN AN AREA WITH A THICK LAYER OF GROUND ICE

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ABSTRACT

This paper describes results from an experimental roadbed at a section with a thick layer of ground ice in a permafrost area at Kukusili Mountain in the Chinghai-Tibet Plateau. The effects of using a small cross section in a cut and fill to preserve a thick layer of ground ice will be analysed. The regularity of variation of the permafrost table after the embankment is constructed, etc., will also be evaluated.

In China in the Chinghai-Tibet Plateau, there is extensive continuous permafrost with the highest altitude above sealevel in the world. Because of geological and climatic factors, the soil has its own special hydrothermal characteristics and thick layers of ground ice are present. In this section thermal sliding or thermal settlement will occur, due to natural causes or human activities, causing a great deal of troubles both to road construction and maintenance. Hence, research work has been carried out by constructing an experimental roadbed 480 m long in the Kukusili Mountain (Figure 1). This paper describes briefly the design principles of the experimental roadbed in this area with a thick layer of ground ice, treatment procedures and their effects.

GENERAL CONDITIONS OF EXPERIMENTAL SITE

The experimental site is 4780 m above sealevel where the permafrost is relatively stable. The geological and climatic characteristics are as follows:

1. The basic rock consists of purple red sandstone and mudstone interlayers of Tertiary age. Above it is Quaternary deluvium and alluvium of clayey sand and sandy clay, generally 3 - 5 m thick. The permafrost table is usually 1.3 - 1.6 m below the ground surface and increases to about 2 m beneath ditches with flowing water. An ice layer about 1 - 3 m thick is usually found just below the permafrost table. The thickness of the permafrost is about 80 - 120 m.

2. The mean annual air temperature is -4°C to -6°C and the mean annual ground temperature is -2.5°C (Figure 2). The period of negative temperature in 1976 was 255 days and of positive temperature was 110 days. The freezing index was 2640 degree (°C) days, the thawing index was 280 degree days and the ratio of freezing index to thawing index was 9.4. The natural ground surface freezing index was 2314 degree days, and the thawing index was 768 degree days (Figure 3). Capability of annual frost depth was much greater than that of annual thaw depth.

3. Precipitation is primarily in the form of snow, mostly in June, July, August and September. The annual precipitation is 300 - 400 mm, and annual evaporation is 1200 - 1400 mm.

4. Solar radiation is high, especially in the warm seasons. From April to October, the mean daily radiation exceeds 400 kcal/cm^2 day. The July radiation is 1.8 times that of December. The total radiation in 1976 was 141 kcal/cm^2, among of which direct radiation amounted to 88.1 kcal/cm^2 year and diffuse radiation to 52.7 kcal/cm^2.

Thus, the experimental site possesses natural characteristics of low air and ground temperature, larger quantity of heat dispersion than absorption at the ground surface, greater thickness permafrost, high water and ice content in the soil near and a few metres beneath the permafrost table, etc. For these reasons, the principle of experimental roadbed design in cuts is to protect the thick layer of ground ice and ice rich frozen soil and maintain them in a frozen state. An installed reinforced concrete L-shaped retaining wall and masonry retaining wall, as well as a drainage system were also constructed.

In order to investigate the construction technique of a roadbed in an area with ground ice during the thawing season, the experimental roadbeds were built during the period from May to September.

After the experimental roadbeds were completed, thermocouple cables, sensitive resistance thermometer units together with heat flow, heat conductance and moisture content measuring apparatus were installed. In addition, an automatic remote monitoring device was also provided for periodic observation.

TREATMENTS ON EXPERIMENTAL CUT AND ANALYSIS OF THEIR EFFECTS

Two types of cross section were adopted for the experimental cut: sideslopes and subgrade with insulation (Figures 4 and 5); sideslopes with revetment counterfort and subgrade with insulation (Figure 6).

1. Cross section of backfilled sideslope and subgrade with insulation.

For this type of cross section, the most important matter is to determine the thickness of the backfilled layer, which is worked out by the empirical formula:

$$h = 1.2K_1 \cdot K_2 \cdot K_3 \cdot H_{max} \ldots\ldots\ldots\ldots (1)$$

where h -- thickness of backfilled layer (m)
1.2 -- safety coefficient
K_1 -- backfilled material modifying coefficient
K_2 -- orientation modifying coefficient
K_3 -- surface feature modifying coefficient
H_{max} -- maximum depth of natural permafrost table in a typical site (good vegetation and open plain) for years, in metres.

Determination and selection of values H_{max}, K_1, K_2, and K_3 are briefly stated as follows:

1) Determination of H_{max}

(1) When it is determined by surveying, the natural depth of the permafrost table should be modified by adding the temperature fluctuation, i.e.,

$$H_{max} = H + \Delta H = H + A\ (T_p - T_H) \ldots (2)$$

where H -- depth of natural permafrost table obtained by surveying, in metres
ΔH -- increment of depth of natural permafrost table due to temperature fluctuation, in metres
A -- statistical coefficient determined by local geological conditions, in m/°C
T_p -- mean annual temperature of designed frequency, in °C
T_H -- mean annual temperature of the observing year in °C

(2) It may be calculated also by the following formula:

$$H_{max} = a\bar{t}_8 + b \ldots\ldots\ldots\ldots\ldots (3)$$

where $\bar{t}_8$ -- mean monthly temperature (°C) of the experimental section in August relating to designed frequency

It may be found in Table 1.

a -- empirical coefficient (m/°C) from statistical data $a = 0.1$ m/°C
b -- empirical coefficient (m), from statistical data $b = 0.85$ m

The actual data recorded over six years, verified that the maximum absolute deviation of calculated H_{max} by using Formula (3) is 9 cm and the maximum relative deviation is 70% (Table 2).

2) Determination of K_1

(1) For a slope surface covered with peat and subgrade with insulation

K_1 is obtained by the following formula:

$$K_1 = \frac{Z}{H_{max}} = \frac{d + (H_{max} - d)\sqrt{\frac{a}{a'}}}{H_{max}} \ldots\ldots (4)$$

where Z -- thickness of peat and soil layer converted into thickness of backfilled material above the natural permafrost table, in metres
d -- peat thickness at typical site (m)
a -- thermal conductivity of backfilled material in thawing state (m²/sec)
a' -- thermal conductivity of soil layer in thawing state (m²/sec)

(2) For the homogeneous insulation,

$$K = \frac{Z}{H_{max}} = \frac{(H_{max} + d\sqrt{\frac{a'}{a_o}} - d)\sqrt{\frac{a}{a'}}}{H_{max}} (5)$$

where a_o -- thermal conductivity of peat layer in thawing state (m²/sec)
others -- as above

Insurance (%)	0.1	1	2	5	10	20	50	90	95	99
Recurring Period (year)	1000	100	50	20	10	5	2	10	20	100
$\bar{t}_8$ (°C)	7.6	6.9	6.6	6.3	6.0	5.7	5.1	4.2	4.0	3.6

Table 1 Mean temperature of the experimental section in August according to designed frequency

Year	1966	1967	1969	1975	1976	1977
Actual measured (m)	1.49	1.38	1.30	1.41	1.30	1.34
Calculated (m)	1.41	1.38	1.33	1.46	1.21	1.31
Absolute deviation (cm)	8	0	3	5	9	3
Relative deviation (%)	6.1	0	2.3	3.5	6.9	2.2

Table 2 Deviation between actual data and calculated value of natural permafrost table

Orientation	Open Plain	Sunny Slope	Shaded Slope
Grade	0	1:1.5 - 1:1.75	1:1.5 - 1:1.75
K_2	1.00	1.10	0.85

Table 3 Orientation modifying coefficients

3) Selection of K_2

K_2 is related to insolation. It should be calculated by the thawing index at the ground surface of similar surface features and different orientation and slope. The orientation modifying coefficients which were obtained, are shown in Table 3.

4) Selection of K_3

K_3 is related to the surface heat absorption and reflection. It should be calculated by the thawing index at the ground surface of similar orientation, slope and different surface features. Surface feature modifying coefficients which were obtained are shown in Table 4.

In order to place the insulation in the warm season, the ice layer, exposed during construction, was covered by a light insulating curtain as a temporary protection; thus the thawing rate was reduced (Figure 7). The face of the slopes remained stable during the construction period and were preserved.

Coating Material	Peat	Polystyrene Foam Plate	Aerated Concrete Plate	Clayey Sand with Gravel	Bitumen Pearlite Plate
Colour	Yellowish green	White	Greyish white	Brown	Greyish black
Surface	Felt	Smooth	Rough	Coarse	Smooth
K_3	1.00	0.82	0.94	1.16	1.18

Table 4 Surface feature modifying coefficient

Construction practice and observed data for 2 - 3 years after completion of the cut show that such designing principles, calculating method and treatment can maintain the stability of a cut in an area with a thick layer of ground ice.

The initial conclusions are as follows:

1) After construction of the experimental roadbed, the maximum depth of seasonal thaw in various types of sideslope is 0.76 - 1.85 m, which meets the design needs. However, when industrial insulating material is used, its low thermal conductivity effectively reduces the thaw in the sideslope and subgrade. Among the six types of insulating materials used in the experimental roadbed, the insulating properties of the rigid foam plastic plate, plastic pearlite concrete plate and aerated concrete plate with water preserving treatment are most effective. Beneath the sideslope, the maximum depth of seasonal thaw is reduced by 0.7 - 1.1 m compared with that where clay is used as backfill material. For example, the depth of thaw in a sunny slope protected by a porous concrete plate is 0.98 m less than that by clay mixed with crushed stone. Its mean thaw rate is only 65% of that at a natural site. The mean monthly temperature difference between the upper and lower faces amounts to 11°C, which indicates good insulating values of the insulation material.

2) Because of its low thermal conductivity (only one-half that of the soil), peat has been used as an insulating material. Its amount of heat consumption is increased by photosynthesis and evaporation; its roots loosen the surrounding soil causing increased water absorption and latent heat of thawing. Therefore, when peat is used as backfill, the maximum depth of seasonal thaw in sideslopes is reduced by 14% (0.3 - 0.4 m) compared with that of local sandy clay mixed with crushed stone. During the warm season, the amount of rainfall is abundant in the Chinghai-Tibet Plateau, which is advantageous to the growth of the peat after transplanting. Two years after construction, the roots interweave into a single sheet and the sideslope is further stabilized.

2. Cross section of the sideslope with revetment structure and subgrade with insulation.

There are two types of revetment structure for this sort of cross section. One is a masonry retaining wall and the other is an installed (1 m wide per piece) L-shaped reinforced concrete thin plate revetment.

For the L-shaped reinforced concrete revetment structure, it should be filled with sand and gravel, the gravel containing clayey sandstone fragments and soil slurry. The foundation should be buried 0.2 - 0.4 m below the calculated permafrost table, or at sufficient depth to maintain the footing in a frozen state and utilizing the weight of the backfilled soil to overcome soil swelling and frost heave forces.

In order to investigate the force acting on the retaining wall and its deformation, nine force measuring units were installed behind the retaining wall along its height and the displacement was measured in front of the structure. At the same time in situ tests were also carried out on the model retaining wall and loading sensors were used to make observation.

From observations over two years, initial conclusions are as follows:-

Cross Section	Construction Period (month)	Height (m)	Mean Freezing Rate of Construction Year (cm/day)	Mean Thawing Rate in the following Year (cm/day)	Variation of Permafrost Table in the Construction Year (m)
0 + 215	June-July	7.3	5.1	1.75	Rise - 1.0
0 + 280	July-Sept.	5.4	3.0	1.53	Drop - 0.25

Table 5 Influence of construction season on permafrost under subgrade

1) The lateral normal frost heave force acting on the retaining wall is rather high and varies significantly with depth from 0.01 - 2.63 kg/cm^2. In comparison with the pressure of thawed soil at the same depth, the lateral normal frost heave force is generally 10 times or even up to a maximum of 35 times the soil pressure.

The lateral normal frost heave force acts mainly upon the middle and lower parts of the retaining structure.

2) The lateral normal frost heave force has a conspicuous characteristic of relaxation (Figure 10).

THERMAL ANALYSIS OF EXPERIMENTAL EMBANKMENT

Embankments of different height were constructed from 0 to 9 m and insulation tests were carried out at the experimental site to investigate the formation of a "frozen core" and the regularity of variation in the embankment. After construction was completed, thermal observations were carried out together with those on a neutron moisture meter water gauge, electric probe, etc. for monitoring the moisture migration and to measure surface deformation. From the construction and thermal analysis, the following conclusions were obtained:

1. Permafrost beneath the embankment subgrade is influenced by the construction season to a certain extent. When the embankment is constructed and completed during the latter part of the warm season, the permafrost beneath the subgrade may thaw locally resulting in an increase of embankment settlement. This is due to the depth of thaw in natural ground being comparatively great (70% - 80% of the seasonal depth of thaw by the end of July); the heat stored in the ground is considerable and heat brought into the embankment by the backfill is hard to dissipate. Moreover, the freezing rate in the same year is also affected. For an embankment less than 9 m high, the heat stored is entirely consumed after one or two years, and the thaw rate is basically proportional to the height of the embankment. However, the zone with zero degree temperature still remains in the middle and lower parts of the embankment and will gradually disappear after three years.

The technical data of embankment constructed in June and July (cross section 0 + 215) compared to that built from July to September (cross section 0 + 280) are given in Table 5, Figures 11 and 12.

2. The height of the embankment directly influences the depth of freezing and thawing. Based upon the observed data from twelve embankments of different heights filled with a clay gravel mixture, the following relationship is derived statistically:

1) The relation between embankment height H (≤8 m) and the rising σ of the permafrost table is

$$\sigma = 1.02H - 0.5 \quad \text{...........(6)}$$

The critical height of the embankment where the original permafrost table remains unchanged is 0.5 m. The minimum height of the embankment where the "frozen core" extends into the embankment is 1.8 - 2.6 m.

The above relationship does not agree with the σ - H obtained from thaw unstable soil embankments at various locations along the Chinghai-Tibet Highway.

Embankment Height (m)	Construction Period (month)	Amount of Stored Heat in Embankment per Linear Metre (kcal)	Mean Freezing Rate in Construction Year (cm/day)		Mean Thaw Rate in Following Year (cm/day)
			Freezing from above	Back freezing from below	
5.4	July - Sept.	3.85×10^5	3.0	1.6	1.53
4.6	" "	2.7×10^5	3.3	1.8	1.37
3.0	" "	1.4×10^5	4.3	-	1.24

Table 6 Influence of embankment height on freezing rate of the construction year and thawing rate of the following year

2) The relation between embankment height $H(0.5m \leq H \leq 8m)$ and maximum depth of seasonal thaw h_{max} at the centre of the embankment is

$$h_{max} = 0.15\ H + 1.8 \ \ldots\ldots\ldots (7)$$

3) The influence of embankment height on freezing rate in the construction year and thawing rate of the following year is given in Table 6.

3. H is due to the influence of sideslope orientation and subgrade surface unevenness; the artificial upper boundary in the embankment may be a curve inclined to both sides or a line inclined to one side. Both are detrimental to the stability of the sideslope. When the shoulder is facing the sun, its depth of thaw will be at a maximum (1.2 - 1.4 times that of the roadbed centre) because the heat conduction is a two-dimensional problem. Moreover, the upper boundary of the sideslope and subgrade surface is connected with a curve. On the other hand, the upper thaw depth of the shoulder at the shaded side is close to that of the roadbed centre (0.9 - 1.0 times that of the roadbed centre). Therefore, the freeze-thaw interface inclines gradually from the shoulder of the shaded slope toward that of the sunny side (or roadbed centre), forming an angle with the horizon greater than 6° (actual measured value is 8°). When ice accumulation at the upper boundary is sufficient and the side ditch cannot drain effectively, a split along the shoulder or even a sideslope slide will result. In this case, the stability of a steep sideslope and high embankment must be checked and local insulation or a berm should be provided if necessary.

4. Through an observation period of two to three years, the variation in moisture content in the embankment is not significant because the compacted density and moisture content have been controlled during construction. Furthermore, the type of cross section of the embankment is also conducive to dessication.

5. Insulation may reduce the depth of thaw and frost heave. In the experimental embankment with a rigid foam plastic plate, the curve of thawing beneath the insulation shows a significant turn. During the early part of the warm season, the thaw rate is faster than in the conventional embankment; however, as soon as the 0°C isotherm passes through the insulating layer, the thaw rate reduces quickly so that the maximum depth of seasonal thaw is 20 - 30% less than that of the conventional soil embankment and the thickness of the frost heave zone is reduced (Figures 13 and 14). At the same time, the freezing rate of the soil above the insulating layer is also increased in winter, reducing moisture migration above the insulation. Moisture migration beneath the insulation is intercepted. Correspondingly the amount of frost heave in the embankment is reduced.

SUBGRADE DRAINAGE SYSTEM AND ITS EFFECTS

According to the climate and characteristics of the permafrost at the working site, a side ditch in the subgrade, cut-off dike and intercepting ditch on the uphill side were incorporated to drain or intercept the water.

The cross section of the side ditch is generally 0.4 - 0.6 m wide (at the bottom), 0.4 m deep and its sideslope is 1:1. The bottom and side are covered with peat or sealed with clay. After two to three years of observation, it was found that deformation was not significant and the depth of thaw beneath the bottom of the ditch descended only 0.1 - 0.2 m compared with the permafrost table.

In the case of the deep cut, the cut-off dike obtained good results by utilizing the easy formation of a "frozen core" in this area to intercept and drain the water above the layer along the opposite frozen slope to prevent it from flowing into the sideslope. The dimensions of the cut-off dike are: centre height 0.8 - 1.0 m, width of upper surface 0.6 - 1.0 m and sideslope 1:1.5.

CONCLUSIONS

From the design, construction and actual observation of these experimental roadbeds, the main conclusions can be stated as follows:

1. The main principle of designing a roadbed in an area with a thick layer of ground ice and relatively stable permafrost, is to protect and maintain the ice and ice rich frozen soil in the frozen state. The following empirical formula may be used to determine the thickness of the backfilled layer:

$$h = 1.2K_1K_2K_3H_{max}$$

The calculation of the above formula is simple and the parameters involved in the calculation are easily obtained. However, for an important site such as a deep cut and high embankment, a two-dimensional mathematical analysis or an approximation of greater accuracy must be derived to determine the top boundary of the permafrost. This will lead to a reasonable selection of the cross section.

2. Industrial insulation has a more prominent effect on reducing the cut section and depth of thaw. If backfilled material is available locally, peat or coarse and fine grain soil may be also used.

3. In designing a retaining structure, full attention must be paid to lateral normal frost heave.

4. At the experimental site, after the 0.5 to 9 m high embankment was completed, the artificial upper boundary of the permafrost was rising. When the backfilled material is clayey soil, the relation between the rising height of the artificial upper boundary and the embankment height H is

$$\theta = 1.02H - 0.5$$

Namely, the minimum height of the embankment where the original permafrost table remains unchanged is 0.5 m; the critical height of the embankment where the "frozen core" extends into the embankment is about 1.8 m for clayey soil and about 2.6 m for coarse grained soil. But attention should be paid to the following conditions:

When the embankment is constructed and completed during the latter part of the warm season, as often as not the artificial upper boundary of the permafrost will drop during the construction year due to the potential heat of seasonally thawed layer and fill materials.

5. In this area, provided adequate protecting measures are being taken and attention paid to the organization and procedures of construction, both cuts and embankments in area with thick ground ice can be constructed during the warm season.

Figure 1.	Construction site of experimental roadbed.
Figure 2.	Monthly variations in ground temperature.
Figure 3.	Air and ground temperature processing curves.
Figure 4.	Cross section of experimental roadbed.
Figure 5.	" " " "
Figure 6.	Cross section of retaining structure.
Figure 7.	Temperature variation of sideslope with temporary insulating curtain

Notes
1. Temperature variation of natural ground surface in plain.
2. Temperature variation of sideslope surface facing sunshine with cover during day time and opened at night.
3. Temperature variation of sideslope surface facing sunshine with cover both during day time and at night.

Figure 7. (cont'd)

Notes 4. Temperature variation of sideslope surface facing sunshine without cover.

Figure 8. Mean monthly ground temperature

Notes 1. — protected by aerated concrete, sunny sideslope.
2. - - - typical natural site, open plain with good vegetation.

Figure 9. Thaw curves

Notes a ---- protected by aerated concrete, sunny sideslope.
b ---- typical natural site, open plain with good vegetation.

Figure 10. Relaxation curve of lateral normal frost heave.

Figure 11. Variations in ground temperature and moisture content with depth in section 0 + 215.

Figure 12. Variations in ground temperature and moisture content with depth in section 0 + 280.

Figure 13. Thaw curves.

Figure 1

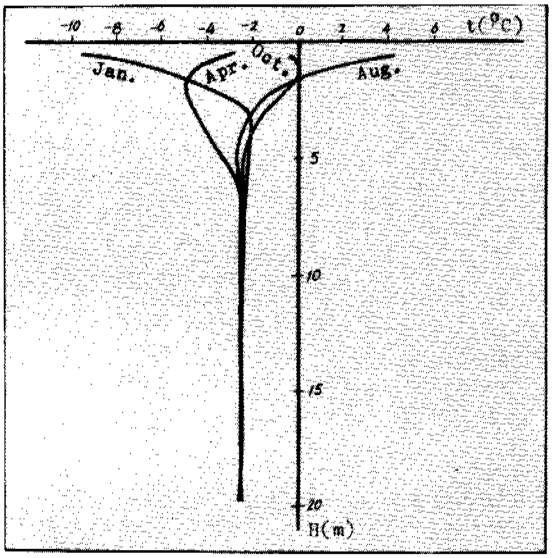
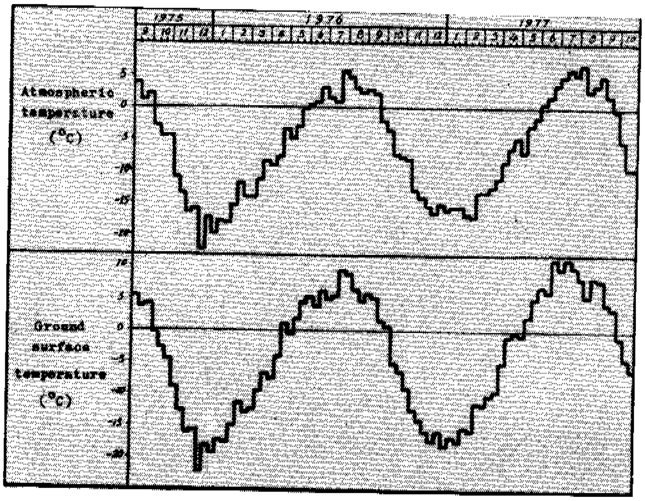


Figure 2



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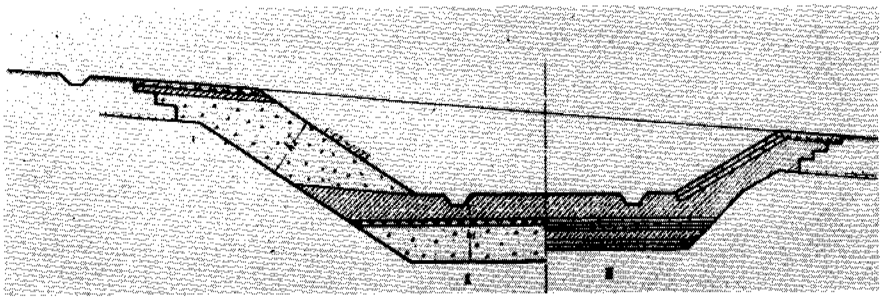

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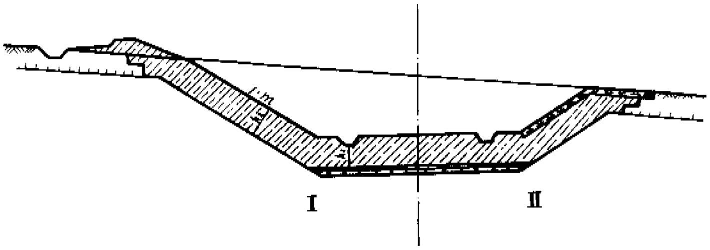

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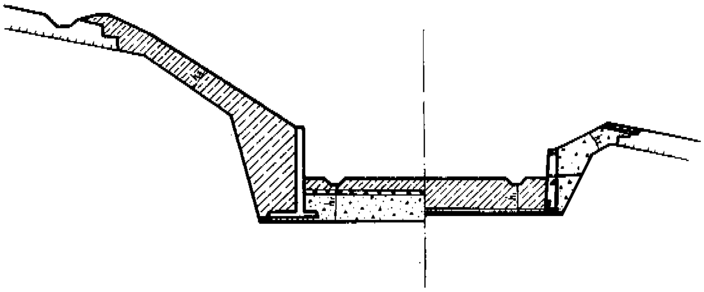

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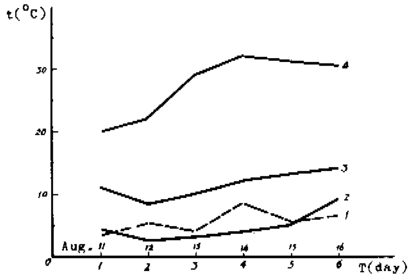

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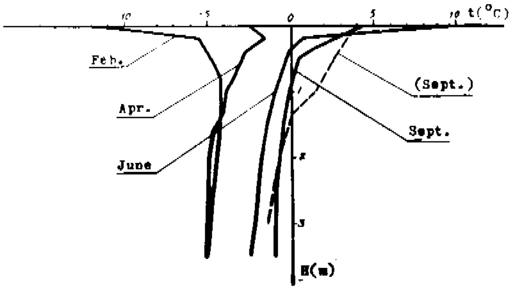

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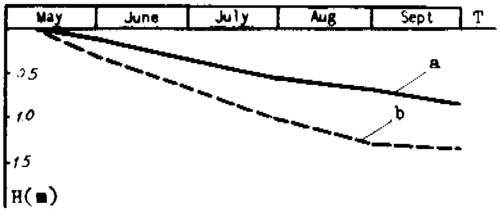

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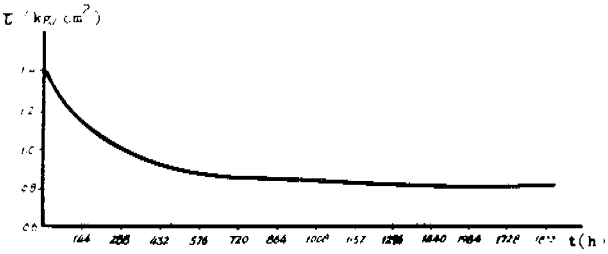

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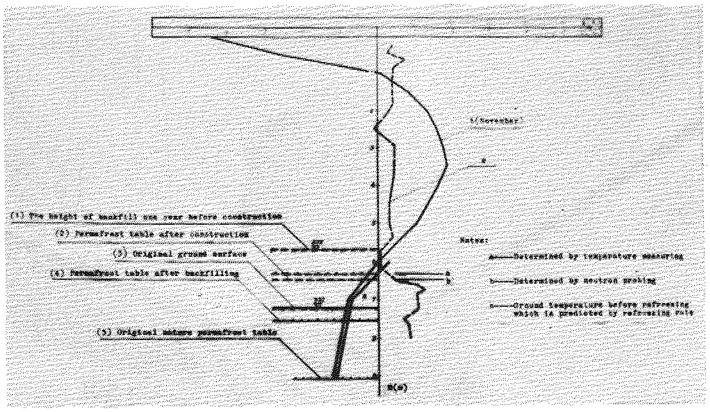

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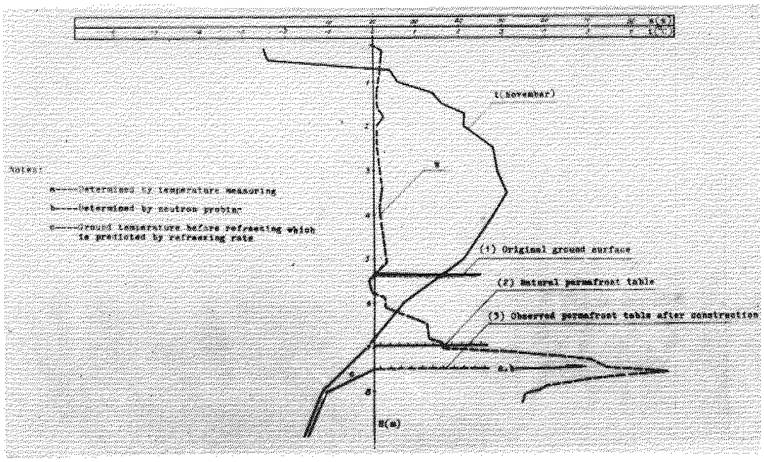

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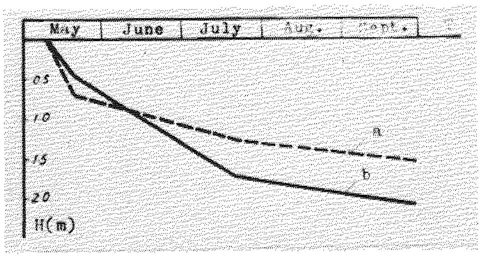

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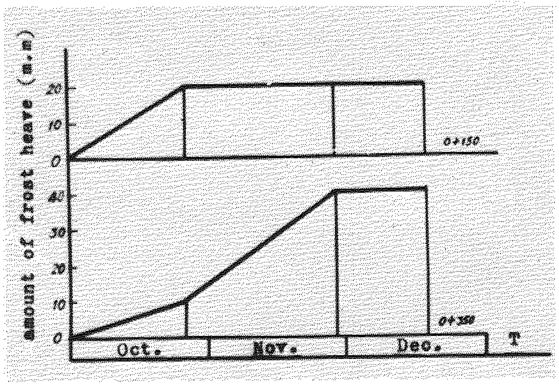

Figure 14

EXPERIMENTAL RESEARCH ON AN EMBANKMENT IN AN AREA WITH MASSIVE GROUND ICE AT THE LOWER LIMIT OF ALPINE PERMAFROST

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ABSTRACT

The Reshui experimental embankment is situated in an area with massive ground ice at the lower limit of the alpine permafrost situated at the southern foot of the Chilien Mountains. This paper summarizes the data obtained after a three-year observation programme on the experimental embankment and railway construction practice in the discontinuous permafrost region of the Greater Khingan Mountains. The influence of a number of factors, including materials and surface conditions of the embankment, compression of the soil layers in the base course, height and exposure of the embankment, construction seasons, water (including surface and groundwater), and long-term air temperature fluctuations on the permafrost table under the embankment are analyzed. According to these analyses, it appears that, under certain conditions it is possible to build embankments where massive ground ice occurs at the lower limit of the alpine permafrost based on the principle of protecting the permafrost. This paper points out problems to which attention must be paid in building embankments in this sort of terrain based on the above principle and proposes formulae suitable for calculating the position of the permafrost table.

In areas with massive ground ice in the discontinuous permafrost zone, the method of removing and replacing soil has always been adopted for building embankments. This method causes difficulties in construction and costs are high. On the contrary, if the principle of protecting the permafrost was used, it would be easy to work and the expense would be lower. However, if adopting the principle of protecting the permafrost in constructing embankments in regions where the ground temperature is near 0°C and the permafrost layer is thin, the question that has to be answered is whether it is possible to ensure the stability of the embankment. In order to explore the possibility of building an embankment in an area with massive ground ice in the discontinuous permafrost zone region using the principle of protecting the permafrost, an experimental structure was built in Reshui, Chinghai Province, in August, 1971. Observations were carried out there over three consecutive years to learn the relations between changes in the permafrost table under the embankment and the various factors which might influence it.

GENERAL INTRODUCTION

Reshui is located at the southern foot of the Chilien Mountains. The distribution of permafrost there has vertical zonation, i.e., from an elevation of 3,780 m upwards there is a zone of continuous permafrost, while from 3,480 m to 3,780 m a.s.l. there is a transitional zone with slopes in front of the mountains and ravines as well as valleys. The permafrost and seasonally frozen ground appear as islands or bands interwoven together. Below an elevation of 3,480 m there are areas of seasonally frozen ground.

The experimental site is in the discontinuous permafrost zone at an elevation of 3,700 m on a gentle slope. There is a spring at the upper foot of the mountain. Frost heaved peat hummocks are scattered throughout the site. According to data from the local weather station, the mean annual air temperature there was -3.7°C from 1973 to 1974. The ground begins to thaw in the middle of April, and reaches the maximum depth in the middle of September. The depth of thaw at the experimental site is generally 1.0-1.5 m. The annual precipitation is 500-600 mm, 90% of which occurs from June to September. The stratigraphy at the experiment site is shown in Borehole No.6 (Figure 1). From the surface to a depth of 1.05 m are layers of decayed vegetation, beneath which lies a layer of ground ice, about 5 m thick. A borehole, 100 m north of the experimental embankment shows that the thickness of permafrost is 30 m and the mean annual ground temperature is 0.5°C.

The experimental embankments were paved with crushed stoney-clayey loam. Their layout and borehole locations are shown in Figure 2. The orientation of the embankments is northwest. Each has a length of 10 m and heights of 1, 2 and 3 m, respectively. The tops are 6 m wide and the sideslopes are 1:1.5. Peat covered berms were built of clayey loam on both slopes of the 3 m high embankment. They are 1 m high and 2 m wide at the top. Above the embankment, an intercepting dike was built about 3-5 m from its foot to divert ground surface water and supra-permafrost water from the upper slope.

The ground surface temperature can be measured with a thermometer, while the ground temperature in the borehole can be measured with a slow-changing thermometer. It was verified by drilling that the position of the permafrost table corresponds to the 0°C isotherm.

The experimental embankment was in quite good condition three years after construction. The permafrost table is at different heights in the three embankments. The influence of various factors on the permafrost table in the embankments will be discussed in relation to the data obtained from observations on the experimental structure and on the embankment in the discontinuous permafrost zone in northeast China.

FACTORS, WHICH HAVE INFLUENCE ON THE PERMAFROST TABLE UNDER AN EMBANKMENT

Embankment Material and Surface Conditions

Under conditions of one-dimensional heat flow the existence and development of the permafrost can be expressed as follows:

$$|Q^-| - Q^+ \geqslant Q_g$$

where Q^- = heat released in winter half of year
Q^+ = heat absorbed in summer half of year
Q_g = annual heat flow from interior of earth a year

Latent heat is the main factor which controls the depth of thaw (freezing).

It will be more effective when the yearly situation is taken into consideration. Therefore, an approximate estimation can be made:

$$|Q^-| = h_M Q$$
$$Q^+ = h_T Q$$

where Q = latent heat of thawing (freezing) of a volumetric unit of soil

The superscript "-" and the subscript "M" denote the freezing state, while the superscript "+" and the subscript "T" denote the thawing state.

h_M = latent heat in the seasonally frozen layer

$$h = \sqrt{\frac{2\lambda}{Q}\int_0^T f(t)\,dt} = \sqrt{\frac{2\lambda\Omega}{Q}} \qquad (2)$$

in which -

λ = thermal conductivity of the soil
$f(t)$ = temperature function at ground surface
T = time when ground surface maintains a positive (negative) temperature
Ω = thawing (freezing) index of ground surface

The variation between Formula (2) and the computer result is less than 5% in sections with massive ground ice at the lower limit of alpine permafrost.

Therefore, we can obtain:

$$\sqrt{2Q}\,(\sqrt{\lambda^-\Omega} - \sqrt{\lambda^+\Omega^+}) \geqslant Q_g \qquad (3)$$

The rate and extent of the rise in the permafrost table in the embankment depends on $|Q^-| - Q^+ = Q_g$. The larger the value of Q_g the quicker the rate and extent in the rise of the permafrost table.

Formula (3) shows that, in order to make conditions favourable for the rise of the permafrost table beneath the embankment, the soil with a larger value of Q as well as of $\sqrt{\lambda^-\Omega_M} - \sqrt{\lambda^+\Omega_T}$ should be chosen for embankment material. Because fine-grained soil meets these conditions with regard to thermal conductivity, its use as embankment material is favourable to protecting the permafrost and to a rise in the permafrost table.

Compression of Soil Layers in the Base Course of the Embankment

The embankment load and traffic will cause settlement to occur for two reasons - compression of the embankment itself and the base course. This discussion will be concerned mainly with compression of the base course.

Observation at the Reshui experimental embankment (Table 1) show that the settlement of embankments constructed in summer is considerable. It becomes weaker and weaker as time passes on (Figure 3). The depth of thaw was greater during

No. of Embankment	Settlement during Construction (mm)	Settlement after completion (mm/year)			Total Settlement (mm)
		1st year	2nd year	3rd year	
No. 1	81.5	37.0-38.0	10.0-11.0	0- 5.5	128.5-136.0
No. 2	115.5-124.5	58.5-71.5	15.0-19.0	5.5- 7.5	194.5-222.5
No. 3	176.0	88.5-91.5	31.0-37.5	15.5-23.5	314.0-325.5

Table 1 Settlement of Experimental Embankment

construction. The entire layer of vegetation and the upper part of the ground ice thawed, resulting in large settlement up to 50% - 60% of the total during this period. In the third year after the embankment was constructed, the depth of thaw decreased and the thawing and compression of the vegetation layer gradually stabilized. The annual settlement was generally less than 3 cm.

The extent of settlement depends on the depth of thaw, lithological characters of the soil in the base course, water content, embankment height and materials. Generally speaking, the greater the depth of thaw, the higher the water content in the soil layers at the base course, and the greater the settlement of the embankment will be. Peat and other decomposed vegetation has especially high compression capacity. When all other conditions are similar, the higher the embankment, the more serious the settlement (Figure 4).

Generally the upper strata of an ice rich section is composed of peat and vegetation, which will be easily saturated after thawing. While under compression, the water content decreases and the dry volume weight increases. The thermal conductivity of the soil increases in response to an increase in its water content and the dry volume weight. A reduction in water content after the soil layers are compressed is conducive to a decrease in thermal conductivity and an increase in the dry volume weight will again cause an increase in thermal conductivity. Therefore, whether the heat conductivity can finally be increased or reduced after the soil layers are compressed depends on specific conditions. Results of investigations at Reshui show that after the vegetation layer beneath the embankment was compressed, its thermal conductivity increased slightly.

The thermal conductivity λ^- of the freezing soil and λ^+ of the thawing soil also increase in response to a rise of water content and dry volume weight. The rates of λ^- and λ^+ which rise together with an increase in dry volume weight, are similar, while the rate of increase in water content for λ^- is more rapid than that of λ^+. Therefore, after compression of the soil layers, the difference between λ^- and λ^+ will decrease, which is not conducive to protecting the permafrost.

In soil with high water content, the main factor, determining the depth of thaw, is the latent heat in a volumetric unit of soil. A decrease in water content after compression of the soil layers will certainly lead to a decrease of latent heat in a volumetric unit of soil. Compared with the original conditions, it can, of course, result in an increase in the depth of thaw. In the mean time, the decrease in thickness of the soil layers at the base course, due to compression, will be equivalent to the increase in depth of thaw.

It should also be pointed out that the coefficient of permeability will decrease after compression of the soil layers at the base course. When water permeates into the base course, the decrease in the coefficient of permeability will help to reduce the rate of convective heat exchange.

Height and Exposure of the Embankment

It is known from the above discussion that the compression of soil layers at the base course after construction of the embankment may possibly cause an increase in the depth of thaw. The values Q, λ and $\sqrt{\lambda^-} - \sqrt{\lambda^+}$ of the embankment material are also different from those of the soil layers in the seasonally thawed ground. The surface heat exchange conditions will also change after construction of the embankment. All these may cause the permafrost table to depress under certain conditions. However, the fact is that the existence of the embankment can develop thermal resistance which will be a factor conducive to a rising of the permafrost table. When the embankment is very low, the effect of disadvantageous factors, which can cause the permafrost table to depress, always exceeds the effect of the advantageous factors that make the permafrost table rise. Thus, the final result is that the permafrost table is depressed. With the gradual raising of the embankment, the effect of the advantageous factors will gradually increase. Once this effect increases to or exceeds the effect of the disadvantageous factors, the permafrost table will become stationary or rise in the embankment. In this way, under certain conditions, there is an optimum height of the embankment, such that when its actual height is greater than this height, the permafrost table will rise, and, when the actual height of the embankment is lower, the permafrost table will drop. This height is called the minimum embankment height, which causes the original permafrost table to be stationary. It is expressed as H_{min}, and can be calculated from the following formula:

$$H_{min} = \sqrt{\left(\frac{Q_2}{Q_1}\right)^2 \left(1 - \frac{21}{13}\frac{Q_1}{Q_2}\frac{\lambda_1}{\lambda_2}\right) h^2} + \frac{21}{13}\frac{2\lambda_1 T'}{Q} F - \frac{Q_1}{Q_1} h + S \qquad (4)$$

where λ_1, Q_1 = thermal conductivity and latent heat in a volumetric unit of embankment material

$\lambda_2 Q_2$ = thermal conductivity and latent heat in a volumetric unit of the base course after compression

h = natural permafrost table

F = average positive temperature of the embankment top surface in the thawing period

T' = length of time for positive temperature of the embankment surface

S = extent of settlement

When lack of data, $\left(\frac{2\lambda_1 T'}{Q_1} F\right)$ can be replaced approximately by the maximum depth of thaw of the embankment material (h_e) under natural conditions, i.e.,

$$h_e^2 = \frac{2\lambda_1 T'}{Q_1} F$$

Formula (4) is suitable for the minimum height of embankments in the ice rich sections near the lower limit of the alpine permafrost. Actually, H_{min} is the function of the mean annual ground temperature. When other conditions are similar, the lower the mean annual ground temperature, the smaller the minimum height of the embankment will be.

When it is necessary to cause the permafrost table in the embankment to rise to the ground surface, there also exists a critical height. When the actual height of an embankment is equal to or greater than this critical height, the permafrost table will rise to the ground surface or enter the embankment. This critical height can be shown as:

$$H_c = \sqrt{1 + \left(\frac{H}{2b + H\mathrm{ctg}\alpha}\right)^2}$$
$$\sqrt{\frac{2\lambda_1}{Q_1}\int_o^T F dt} = mh_2 \qquad (5)$$

H (m)	0	1	2	3	4	5	6	7	10	∞
m	1.00	1.01	1.02	1.04	1.05	1.07	1.08	1.09	1.11	1.30

Table 2 Value m of embankments for different heights

$2b = 6m, \qquad \mathrm{ctg}\alpha = \frac{3}{2}$

Embankment No.	Fill Material	Date of Construction	Natural Permafrost Table (M)	1971			1972			1973			1974		
				Embankment Height (M)	Depth to Permafrost Table (M)	Rise in Permafrost Table (M)	Embankment Height (M)	Depth of Permafrost Table (M)	Rise in Permafrost Table (M)	Embankment Height (M)	Depth to Permafrost Table (M)	Rise in Permafrost Table (M)	Embankment Height (M)	Depth of Permafrost Table (M)	Rise in Permafrost Table (M)
No. 1	Crushed Stone Clayey Loam	August - September 1971	1.20	0.90	2.33	-0.23	0.80	1.94	+0.06	0.76	1.92	+0.04	0.75	1.82	+0.13
No. 2			1.05	2.03	3.63	0	1.85	2.90	0	1.83	2.46	+0.42	1.82	2.84	+0.03
No. 3			1.20	2.96	4.00	0	2.75	3.67	+0.28	2.63	3.26	+0.57	2.61	1.72	+2.09
Intercepting Dike No. 4	Clayey Loam Covered with Peat	June 1973	1.05							1.65	2.30	+0.40	1.65	2.00	+0.70
Intercepting Dike No. 2		July 1972	1.15				1.20	2.00	+0.35	1.20	1.50	+0.85	1.20	1.60	+0.75
Old Dike		August 1971	1.05				0.50	1.33	+0.22	0.50	1.42	+0.13	0.50	1.44	+0.11

Table 3 Permafrost Table Elevation in Experimental Embankment and Intercepting Dikes in Reshui Region, 1971-1974

Fill Material	Embankment Height (M)	Lithological Character of Base Course		Accumulated Water at the Foot of Embankment (M)		Exposure		Value of Rise of Permafrost Table in Embankment (M)		Amount of Rise of Permafrost Table Under Foot of Embankment (M)	
		Thickness of Peat Layer (M)	Ice Content %	Left	Right	Left	Right	Left	Right	Left	Right
Sand-Gravel	7.7-7.8	0.4-1.4	<50%	0.1-0.2	No	Shady	Sunny	Descent >4.0	Descent >4.0	-1.7	-0.3
Sand-Gravel	7.8-8.0	0.5-0.9	<50%	Small ponds	Small ponds	Shady	Sunny	Descent >4.0	Descent >4.0	-	-1.5
Sand-Gravel	8.0	0.4-0.8	<50%	No	No	Dull	Dull	Descent >3.0	Descent >3.0	-1.9	-0.6
Sand-Loam Soil with Sand-Gravel	13.7	Peat-Clayey Loam 0.6-0.7	<50%	0.1-0.2	Small Ponds	Shady	Sunny	-1.0	-2.3	0	-
Upper Part: Sand-Gravel with soil base Clayey-loam	18.0	0.2-0.7	<50%	0.4	No	Dull	Dull	-1.5	-1.5	-	-0.4

Table 4 Permafrost Table under High Embankment in Discontinuous Permafrost Zone in Northeast China

Slope Exposure	Surface Material	Months												Annual Average
		1	2	3	4	5	6	7	8	9	10	11	12	
NE	Peat	-16.5	-12.3	-8.2	2.0	5.5	9.3	10.0	10.3	4.6	-0.6	-8.8	-15.6	-1.7
NE	Crushed Stone Clayey Loam	-15.4	-11.2	-7.3	2.8	6.9	10.1	10.8	11.0	4.8	0.0	-9.0	-15.4	-1.0
Embankment Top		-15.6	-10.9	-6.3	2.8	6.7	9.9	10.4	10.6	5.1	0.5	-8.0	-14.4	-0.8
SW		-13.4	- 9.9	-6.5	2.0	5.5	7.4	9.6	9.3	4.9	1.3	-6.3	-12.6	-0.7
SW	Peat	-13.7	-10.3	-6.9	1.3	5.3	7.8	9.8	9.3	5.4	1.1	-7.8	-14.7	-1.1

Table 5 Slope Surface Temperature of the 3-m Experimental Embankment
(Slope Angle 33°42')

Embankment No.	Borehole No.	Exposure	Ground Temperature below 3-m depth (°C)	Permafrost Table (M)	Borehole Location
1	2	NE	-0.9	1.32	Slope Centre
	4	SW	-0.3	2.00	
3	9	NE	-0.9	1.10	Slope at foot of berm
	13	SW	-0.4	1.29	
3	10	NE	-0.5	1.43	Boundary between slope and berm
	12	SW	0.0	2.00	Top of berm

Table 6 Ground Temperature and Permafrost Table Value under
Slope of Different Exposure (1974)

Fill	Embankment Height (M)	Lithology of base course		Accumulated Water at the foot of Embankment (M)		Slope Exposure		Rise in Permafrost Table under Embankment (M)		Rise in Permafrost Table under the Foot of Embankment (M)	
		Thickness of Peat Layer (M)	Ice Content %	Left	Right	Left	Right	Left	Right	Left	Right
Sand-Gravel	5.0	0.8	50	No	No	Shady	Sunny	0	-2.0	-2.0	-0.6
Sand-Gravel Crushed Stone with Soil	3.4	0.3	20-30	No	No	Shady	Sunny	+1.5	+0.2	0	+0.41
Sand-Gravel with Crushed Stone and Soil	2.6	0.1-0.2	20-30	No	No	Shady	Sunny	+0.7	-1.3	+0.16	+0.22
Upper Part: Sand Gravel-Pebbles Lower Part: Clayey Loam	1.5	1.3	10	No	No	Shady	Sunny	+0.3	0	0	0
Pebbles with Sand	2.0-2.2	0.3-0.4	50	No	No	Sunny	Shady	-0.35--0.6	+0.3	-0.6	-0.65
Upper Part: Clayey Loam Lower Part: Pebbles with Sand	2.2	1.37	50	No	No	Sunny	Shady	-0.5	0	0	0

Table 7 Permafrost Table in Slopes of Different Exposures in Railway Section from Jiagedaqi to Xintian in Northeast China

Height of Embank-ment (M)	Stratigraphy	Natural Permafrost Table (M)	Permafrost Table after Construction of the Embankment (M)	Drop in Permafrost Table (M)	Reference
3.94	Average thickness of peat 0.36m, with 15-25% pebbles. Clayey loam with pebbles, ice content about 40%, thickness is 1.3-2.2m. Below are pebbles with clayey loam and sand.	0.86	1.01	-0.15	Constructed in May; lower part filled with pebbly sand.
2.85	Average thickness of peat 0.17m. Below is clayey loam with ice content 10-40%, 1.6-2.6m thick.	1.17	1.37	-0.20	
2.45	Average thickness of peat 1.40m, clayey loam with ice content 50-60%, crushed stone about 30%.	0.71	0.65	-0.06	
3.60	Average thickness of peat 0.38m, average thickness of ice layers with clayey loam 1.41m. Below is clayey loam with ice.	0.38	0.63	-0.25	Constructed in June, filled with clayey soil.
3.90	Average thickness of peat 1.39m, clayey loam with ice > 1.3m, sometimes with thin layers of pebbles.	0.66	0.64	0.02	Constructed in May, filled with clayey soil.
4.45	Average thickness of peat 1.37m, pebbles with soil 0.3-2.1m. Below it is clayey loam with ice.	0.50	0.55	-0.05	Constructed in June, filled with clayey soil.
4.62	Average thickness of peat 1.11m with some clayey loam and pebbly soil.	0.60	0.65	-0.05	
3.45	Average thickness of peat 0.36m, ice layers with clayey loam 1.3-1.8m. Below it are pebbles with soil.	0.55	0.72	-0.17	
3.35	Average thickness of peat 0.97m, ice layers with clayey loam > 1.6m. Below it is pebbly soil.	0.55	0.57	-0.02	
3.10	Average thickness of peat 1.39m, clayey loam with ice > 1.1 m.	0.50	0.55	-0.05	

Table 8 Lowering of Permafrost Table during Construction of Experimental Embankments on the Huchung Branch Line

Borehole Locations	Embankment Height (M)	Mean Annual Ground Temperature at Different Depths																	
	Ground Temperature (°C) Depth (M)	0.5	1.0	1.5	2.0	2.5	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0	12.0	14.0	16.0	18.0	21.0
Centre of Ventilated Embankment	2.50	-2.0	-3.5	-3.7	-4.7	-3.7	-3.0	-2.1	-1.8	-1.4	-1.0	-1.1	-1.1	-0.9	-0.7	-0.6	-0.5	-0.4	-0.2
Centre of Embankment No. 3	2.61	-0.6	-0.3	-0.4	-0.3	-0.1	0.0	-0.1											
Centre of Embankment No. 2	1.82	-0.2	-0.4	-0.1	-0.1	0.0	-0.1	-0.2	-0.2	-0.3	-0.3	-0.3	-0.3	-0.4	-0.4				

Table 9 Mean Annual Ground Temperature of Various Embankments in 1974

			Permafrost Table (M)						
			In the year of construction			A year after construction			
Embankment	Date of Construction	Natural Permafrost Table (M)	Embankment Height (M)	Depth to Permafrost Table (M)	Rise in Permafrost Table (M)	Embankment Height (M)	Depth to Permafrost Table (M)	Rise in Permafrost Table (M)	Date of Maximum Depth of Thaw
Ventilated embankment	May to July, 1973	1.05	2.7	3.69	+0.06	2.5	2.85	+0.7	At the end of third week of August
No. 3	August to September 1971	1.20	2.96	4.0	Drop	2.75	2.67	+0.18	At the end of September
No. 2		1.05	2.03	3.63	Drop exceeding 0.55	1.85	2.9	0	At the end of September

Table 10 Position of Permafrost Table under Various Embankments

where H = height of embankment

2b = width of top of embankment

α = slope angle of embankment

F = function of embankment surface temperature

$m = \sqrt{1 + \left[\frac{H}{2b+mctg\alpha}\right]^2}$ -- influence coefficient which is related to the geometrical shapes of the embankments

When 2b = 6 m, the slopes are 1:1.5, the value m of different heights is shown in Table 2.

When the height of the embankment material exceeds the minimum height of the embankment, required to maintain the original elevation of the permafrost table, a rise of the permafrost table in the embankment will occur. Generally speaking, the higher the embankment, the greater the rise of the permafrost table. Data from the Reshui experimental embankment (Table 3) have proved this.

However, as the embankment continues to rise and its height reaches a certain value, the permafrost table in the embankment will begin to drop again. Data from the discontinuous permafrost zone regions in the Greater Khingan Mountains in northeast China have proved this (Table 4).

Usually, a high embankment imposes a high load which always causes settlement at the base course to a considerable extent forming a dish-shaped depression. When permeable coarse sand is used as fill for the lower part of the embankment, it always causes dish-shaped depressions with stagnant or permeating water, which adversely affects the descent of the permafrost table. Therefore, it is preferable to use clayey loam as fill for the lower part of a high embankment.

When the embankment is not so high, the top surface will be the main heat exchange surface. With increasing embankment height, the area of the slope surface will increase, too. For a high embankment, the slope is the main surface of heat exchange. As the slope has different exposures and gradients, the intensity and period of solar radiation are different too. Thus, it has its own special characteristics in radiation and heat balance. As a result, the temperature of different slopes, ground temperature below the slope and level of the permafrost table are all different.

The latitude of Reshui is 37°40'N and the orientation of the experimental embankment is southeast. Thus, the temperature difference between the top surface and the slope surface on both sides is not large. The surface temperature of the southwest slope is higher than that of the northeast slope. The difference between them depends on the various lithological characteristics (Table 5).

The difference in ground temperature at the 3 m depth beneath the slopes with different exposures is 0.5 - 0.6°C. The difference in the permafrost table depth is 0.2-0.7 m.

The latitude of the railway section from Jiagedaqi to Xintian in northeast China is 50°24'N, 51°10'W. Because of the higher latitude, the difference caused by exposure is comparatively large, especially when the route direction is east-west. The phenomenon often occurs where the permafrost table rises on the northern side and drops on the southern side (Table 7).

After construction of the embankment, the area of heat exchange increases, compared to the original ground surface, such that absorption of heat increases in summer and in heat loss increases in winter. Thus, if the freezing index of the embankment surface (including the top surface and the two slopes) exceeds the thawing index, the increase of this heat exchange surface will favour a rise in the permafrost table in the embankment, and vice versa. We can continue an approximate measuring of the mean annual temperature at the ground surface in accordance with the weighted means of the area and determine whether the freezing index of the embankment surface is larger than its thawing index. Suppose the width at the top of the embankment is 2b, the slope angle is α, the embankment height is H, the mean annual temperature at the top of the embankment is F_1 and the mean annual temperature on both slope surfaces are F_2 and F_3 respectively, then the mean annual temperature F on the surface of the embankment can be expressed by the weighted means of the area F_1, F_2, F_3,

$$F = \frac{2bF_1 + Hcsc\alpha F_2 + Hcsc\alpha F_3}{2b + 2Hcsc\alpha}$$

$$= \frac{6F_1 + Hcsc\alpha \frac{F_2 + F_3}{2}}{b + Hcsc\alpha}$$

suppose

$R = \frac{Hcsc\alpha}{b + Hcsc\alpha}$, the above formula can be rewritten as:

$$F = R\left[\frac{F_2 + F_3}{2}\right] + (1 - R)F_1 \qquad (6)$$

When H changes from 0, R will change from 0 to 1. Consequently, with a raise in height of the embankment, the surface temperature of both slopes will increase. Its influences will increase, too.

When F>0, it means that the freezing index of the embankment surface is less than its thawing index. The increase of the heat exchange surface by this time will be unfavourable to protecting the permafrost. If F<0, the increase of the heat exchange surface will be favourable to protection of the permafrost.

Here, we are going to discuss again how geometrical shapes of embankments influence the permafrost table. When the thawing is still progressing in the embankment, the depth of thaw (h) under the embankment can be expressed as follows:

$$h = \left\{ \left(\frac{H}{2b+Hctg\alpha}\right)^2 \int_o^T \frac{2\lambda}{Q}\left[\frac{F_2 + F_3}{2}\right]dt + \int_o^t \frac{2\lambda}{Q} F_1 dt \right\} \qquad (7)$$

It has been mentioned before that, under the conditions at the Reshui experimental embankment, one can consider approximately that, $(F_2 + F_3)/2 = F_1$. Thus Formula (7) can be rewritten as follows:

$$h = m. \sqrt{\frac{2\lambda}{Q}\int_o^T F_1 dt} \qquad (8)$$

where $\sqrt{\frac{2\lambda}{Q}\int_o^T F_1 dt}$ is the depth of thaw in the one-dimensional condition,

$m = \sqrt{1 + \left(\frac{H}{2b+Hctg\alpha}\right)^2}$ is the coefficient which only relates to the dimension of the embankment cross-section, and m can also be called the coefficient of influence of the geometrical shape of the embankments on the depth of thaw.

The top width 2b and the slope angles of the embankment are relatively stable. When 2b = 6 m and the slopes are 1:1.5, the value m can be listed in Table 2. From Table 2, one can see that when the embankment height increases, the influence coefficient value m will also increase. However, when the settlement is not too great, the value m will be very small.

When the one-dimensional formula is used instead of the two-dimensional formula (when thawing is continuing in the embankment), the expression of relative precision can be written as follows:

$$\delta = \frac{h - \frac{h}{m}}{h} = 1 - \frac{1}{m} \qquad (9)$$

When $\delta<5\%$ is required, m should be 1.05, and then, one can see that the height of the embankment is 4 m according to Table 2. Therefore, if the depth of thaw in an embankment with a height of less than 4 m is worked out with a one-dimensional formula, the relative precision will be less than 5%.

Construction Seasons

Because of the influence of the heat stored in the embankment, the original permafrost table in an embankment constructed in summer will usually drop. The problems in engineering, about which people are concerned are: whether the stored heat can disperse and at what rate. According to the one-dimensional formula, we are studying the effect of the heat stored by summer construction.

Suppose the depth of thaw is H_{n-1}, in the n-1 year after construction of the embankment; it will be H_n in the n year. According to data obtained from the Reshui experimental embankment, the ground temperature at the depth of zero annual amplitude 2 m beneath the embankment is not influenced by the construction. Thus, it can be assumed that the ground temperature (U_r) at the depth of zero annual amplitude (H_r) is a constant.

For an embankment with a thawed layer in the n-th year after construction, the heat gains and losses through the whole year can be written as follows:

$$q = q^- + q_n \qquad (10)$$

where q = heat absorbed due to extension of the thawed layer (when H_n H_n-1), or heat released due to construction of the thawed layer (when H_n H_n-1), in the n-th year, obviously $q = (H_n - H_n - 1)Q$

q^- = heat flow from the thawed layer to the underlying frozen strata in the n-th year.

$$q^- = \lambda_2^- \frac{U_r}{H_2} T = -\ell Q$$

in which, λ_2^- = heat conductivity of the underlying frozen strata

T = time (a year)

$\ell = \frac{\lambda_2^- T}{QH_1}|U_1|$ = value that can cause H_n to rise due to heat flow from the thawed layer to underlying frozen strata

q_n = algebraic quantity of heat that the thawed layer receives from outside through the ground surface during the thaw period and the heat that the thawed layer releases through the ground surface during the freezing period in the n-th year

$$q_n = \lambda^+ \frac{2f^+}{H_n + H_{n-1}} T'' + \lambda^- \frac{2f^-}{H_n + H_{n-1}} T'$$

$$= \frac{PQ}{2H_n}$$

in which T', T'' = continual period of negative and positive temperatures of the ground surface respectively

f^-, f^+ = mean surface temperature in winter and summer respectively

$$P = \frac{2\lambda^- T'}{Q} f^- + \frac{2\lambda^+ T'}{Q} f^+ = h_T^2 - h_m^1$$

In this way, $(H_n - H_{n-1}) = -\ell + \frac{P}{2H_n}$ (11)

This formula is going to be discussed as follows:

1) $P>0$

(a) When $H_n<\frac{P}{2\ell}$, $q_n>|q^-|$. Thus, $q>0$, and $H_n>H_n-1$, i.e., the depth of thaw increases and the thawed layer is extended. With an increase of H_n, $q_n = P/2H_n.Q$ will decrease. However, when H_n increases to a value equal to $p/2$, $q = 0$ and the thawed layer will be in a state of balance.

(b) When $H_n<p/2$, $q_n<|q\_|$. Thus, $q<0$, and $H_n<H_{n-1}$, i.e., when the depth of thaw diminishes, the thawed layer will contract. With a decrease of H_n, $q_n = p/2H_n.Q$ will increase. When H_n diminishes to a value equal to $p/2$, $q = 0$ and the thawed layer will be in a state of balance.

Thus, when $p>0 (h_T>h_M)$, the thawed layer will never disappear, and the depth of thaw will remain $H = p/2\ell$. From the above discussion we can see that the initial depth of thaw caused by construction in summer will directly influence the tendency in the change of the thawed layer.

In the above discussion, U_r is presumed to be unchangeable. This is only correct, when the height of the embankment constructed in summer is not great, the initial depth of thaw H_o is not large, and the existence of the thawed layer is short. When the existence of the thawed band is prolonged, the upper surface of the underlying frozen strata will continuously have a positive temperature, and the lower surface will be influenced by the heat flow from the interior of the earth. Therefore, the mean annual ground temperature will increase, resulting in $|q^-|$ diminishing, causing H_n to increase and the heat dispersing towards both sides will also increase. The result will be that two conditions appear: one is that the permafrost thaws completely, and the other is that a stable thaw basin forms.

2) $P<0$

Now that q_n is smaller than 0, q^- is also smaller than 0, resulting in $H_n<H_{n-1}$; i.e., the depth of thaw diminishes and the thawed layer will contract. With a decrease of H_n, $|q_n| = \frac{|P|Q}{2H_n}$ will increase. The result is that H_n diminishes more quickly, finally bringing about the disappearance of the thawed layer.

The number of year (n) when the thawed layer disappears can be obtained by the following formula:

$$n = \left(\frac{H_o^2 - h_M^2}{2\ell h_m - P}\right) - 1$$

where (A) indicates the integer part of A

H_o = H+h+s indicates the initial depth of thaw

in which H = height of the embankment

h = natural permafrost table

s = the drop in the permafrost table caused by construction in summer

The drop s of the permafrost table caused by the construction in summer is related to the height of the embankment, months of construction, duration of the construction period, ice content and thermal conductivity of the soil near the permafrost table. According to the observed data, the ice content and thermal conductivity of the soil near the permafrost table are the main factors. For example, according to observations on the construction of the experimental embankment at the Huchung Branch Line, where there was a thick peat layer with high ice content in the seasonally thawed layer, the maximum depth of thaw beneath the embankment constructed in summer approached that of the natural permafrost table, i.e., S=0 (Table 8). As for the experimental embankment at Reshui, it was also constructed in summer. Generally, in one or two months after construction, depth of thaw will be close to the natural permafrost table. Therefore, to measure the thickness of the peat layer and the high ice content, H_o = h+h can be adopted.

If the thawed layer is required to disappear in the n-th year after the construction, then

$$\frac{H_o^2-h_M^2}{2\ell h_m-P} \leqslant n$$

$$H \leqslant \sqrt{h_M^2 + n(2\ell h_m-h_T^2+h_M^2)}$$

In this way, in order to make the thawed layer disappear in n year, there is an optimum height H_n for the embankment. When the actual height of an embankment is greater than H_n, the thawed layer will not disappear within n years.

$$H_n = \sqrt{h_M + n(h_M+2\ h_M-h_T)} - h - s \quad (12)$$

Generally, the higher and the finer grained the embankment material, the longer the thawed layer will exist. Data from the experimental embankment at Reshui show that the thawed layer in the embankment lower than 3 m disappeared in the first and second winters. Observation at the Huchung Branch Line experimental embankment also shows that the 3-5 m high embankments are generally frozen throughout in the second or third winter. If the embankment constructed in summer is too high, the thawed layer will last longer. Therefore, the permafrost table will drop considerably. A 13 m high embankment constructed in summer on the railway section from Jiagedagi to Xintian can serve as an example, where the permafrost table dropped 1.0 - 2.3 m.

Embankments constructed in summer should not be built with insulated berms because heat stored in the fill will prolong the existence of the thawed layer. Thus, it is preferable to install the insulated berms after the disappearance of the thawed layer.

As mentioned above, embankments constructed in summer will always cause the original permafrost table to drop and the ground ice to melt. Observation on Reshui Embankment No. 3 also show that, three years after construction, between the depths of 2.5 and 4 m from the top, there was still a layer of warm permafrost with temperatures approaching zero. This was not favourable to the stability of the embankment. If construction had been carried out in winter, the working conditions would have been very difficult. Therefore in order to find a structural type of embankment suitable for construction in ice-rich sections near the lower limit of permafrost, an experiment with a ventilated embankment was carried out in the Reshui Region.

Construction of a ventilated embankment began in May 1973 and was completed in the last ten days of July. The base course of the embankments consists of a 0.5 m thick layer of clayey loam on the natural vegetated surface covered with 0.3 m diameter sandstone fragments. Above was a gravel layer 0.15 m thick. The ventilated embankment is 11 m long from east to west 7.5 m wide from north to south and 2.7 m high.

In comparing ground temperatures in the central borehole of the ventilated embankment constructed in 1974 with that of experimental embankments No. 3 and No. 2 of crushed stoney clayey loam, we can see that the ground temperature of the former is much lower than that of the latter, (Table 9).

During the year when the ventilated embankment was under construction, the permafrost table did not drop, but in the first year after construction, the permafrost table rose 0.7 m. As for embankment No. 3, which was built with crushed stoney clayey loam, the permafrost table under the embankment dropped considerably in the very year of construction. In the first year after construction the permafrost table rose only 0.18 m (Table 10). This clearly shows that the ventilated embankment is comparatively good.

When adopting the principle of protecting the permafrost, coarse grained soil is generally not used for construction of the embankment because it has higher heat conductivity properties. However, when the embankments are constructed by piling up stone blocks, conditions will be quite different. With the embankment body cutting off solar radiation, the main heat transfer will be in the form of convection. In winter, the high density cold air becomes heavier and can seep freely into the base course through the voids between the stones making the underlying soil extremely cold. However, once the air becomes warm, it will be pushed out by the colder air. In summer, on the other hand, the outside warm air will not enter the base course as freely as the cold air does in winter. The result is that it favours protection of the permafrost. According to experiments at Reshui, it appears that when the air freezing index exceeds the thawing index, and in regions where the summer rainfall is low, this type of ventilated embankments will be favourable for protecting the permafrost.

Effect of Water and Drainage Measures

After construction of the embankment, the movement of both the surface water and groundwater from the upper slope was interrupted. When drainage facilities are inadequate water often stagnates on both sides of the embankment and infiltrates into the subgrade.

Experience in the construction of embankments proves that, whenever there is stagnant water on both sides of the embankment and infiltration into subgrades, the permafrost table in most embankments will drop. The drop in the permafrost table is greater, especially when water percolates into the subgrade. The height of the intercepting dike at the Reshui Experimental Embankment No. 2 is only 0.5 m. It is not high enough to stop the stagnant surface water and suprapermafrost water outside the dike. Thus, the rise of the permafrost table under Embankment No. 2 is less. From Table 11, it is evident that the rise of the permafrost table is closely related to the amount of precipitation in the year of construction. The higher the annual precipitation, the more stagnant water and suprapermafrost water there will be outside the intercepting dike. Therefore, the rise of the permafrost table will be less too. Investigations on the permafrost table under the embankment in the discontinuous permafrost zone in the Greater Khingan Mountains in northeast China have also proved this (Table 12). In summer, the temperature in the northeast is higher than in the Reshui Region. The temperature of the stagnant water on the ground surface will be correspondingly high. Therefore, the influence caused by water on the permafrost table under the embankment in the northeast is greater than that in the Reshui Region.

When adopting the principle of protecting the permafrost to build embankments in the ice rich sections near the lower limit of permafrost, it is necessary to pay great attention to the drainage facilities.

In 1972 a drainage ditch, 15 m long, 0.6 m wide at the bottom, 1.8 m wide at the top and 0.6 m deep with 1:1 slopes was built at the Reshui experimental embankment. After one year's use, the permafrost table below the bottom of the ditch had dropped 0.54 m, but the permafrost table, one metre from the edge of the ditch, had changed very little. From data collected in the discontinuous permafrost zone in the Greater Khingan Mountains, it was found that the extent of horizontal influence of the ditch was only 1-3 m after 6 or 7 years. Therefore, a drainage ditch can generally be built 5 m upward from the foot of embankment. However, in a section where ground ice is well developed, especially at shallow depths, the installation of a drainage ditch will certainly cause melting of it. Furthermore, drainage ditches can only intercept and stop surface water flow. It cannot stop the suprapermafrost water. Therefore, when building embankments on ice-rich sections near the lower limit of permafrost, water should be drained with an intercepting dike. The dike should be built with impermeable material, to make the permafrost table rise to the ground surface. This will stop not only the surface water but also the groundwater. The minimum height of an intercepting dike, needed to make the permafrost table rise to the ground surface, can be calculated with Formula (5):

$$H_o = \sqrt{1 + \left(\frac{H_o}{2b+H_o \mathrm{ctg}\alpha}\right)^2} \cdot \sqrt{\frac{2\lambda}{Q}\int_o^T F dt}$$

Year Numerical Value Item	1972	1973	1974
Rise of Permafrost Table in Embankment No. 2 (M)	0	+0.42	+0.03
Annual Precipitation (mm)	580.0	390.5	509.2
Annual Temperature Mean (^oC)		-3.6	-3.7

Table 11 Permafrost Table under Embankment No. 2 and the Precipitation

$\sqrt{1+\left[\frac{H_o}{2b+H_o ctg\alpha}\right]^2}$ is only related to the cross-section of an intercepting dike and is expressed by m.

Thus, $H_o = mH$

When the width at the top is 1 m and the slope is 1:1 the value m at various values of H_o will be listed in the following (Table 13).

H_o can be calculated by trial and error.

Considering that the height of an intercepting dike is rarely more than 5 m and it has a certain safety coefficient, it can be presumed that,

$$H_o = 1.3\ H \qquad (14)$$

It is not suitable to build an intercepting dike far from the embankment. In order to rapidly drain away the stagnant water on the surface, a shallow ditch may be dug 1 m from the intercepting dike. Thus, part of the water flow may be led away. It enhances the thermal influence of the surface water on the intercepting dike and ensures the rise of the permafrost table under the dike.

Long-term Fluctuation of Air Temperature

The climate fluctuates in various ways at different periods of time. The longer the fluctuating cycle, the bigger the amplitude will be. In the past 10,000 years, the temperature in China has experienced the following four main fluctuating stages:

5-8°C in the past ten thousand years;
2°C in the past thousand years;
1°C in the past hundred years;
0.5-1.0°C in the past twenty years.

In regard to railway construction, it is necessary to consider the temperature fluctuation over a period of one hundred years, i.e. about 1°C.

Climatic variations over the past five hundred years from analysis of the annual rings of a pine 913 years old, still growing at the upper forest limit, 3,600 m a.s.l., in Tianjun county (37°24'N, 98°56'E) on the southern slope of the Chilian Mountains in Chinghai Province and reported by the Institute of the Central Bureau of Meteorology, basically coincides with the climatic variation summarized by Chu Ko-chen from the records of meteorology and phenology in the historical literature of ancient China. This confirms that climatic variations in western China reflected in tree-ring analysis coincides with that of the eastern part of our country to a considerable extent. The general tendency for climatic variation in the next 100 years in the region from Sidatan to Ando, according to the analysis of tree-rings coincides approximately with future climatic variations in eastern China and in other parts of the world. This is predicted by analyzing solar activity. This tendency can be summarized as follows:

The tendency of climatic variation in the coming 100 years in the Tangulha area (from Sidatan to Ando) is that it will be colder than at present except for a slight warming in the 1980s. The coldest period will be from 2,000 to 2,010 and before and after 2,050. It will be about 0.5° to 0.7°C lower than now. A relatively warm

Fill	Embankment Height (M)	Lithology of Base Course		Accumulated Water at Foot of Embankment (M)		Water Flow at Foot of Base Course	Rise of Permafrost Table Under Embankment (M)		Rise of Permafrost Table at Foot of Embankment (M)	
		Peat Thickness (M)	Ice Content %	Left	Right		Left	Right	Left	Right
Pebbles with Sandy Soil	3.0	0.5-0.6	Ground Ice	Thawed Pool	0.1	Moving Water	C	-0.5	0	0
Sandy Gravel-Crushed Stone Pebbles	4.0-4.1	0.2-0.45	20-30	0.1	Pond	Moving Water	-2.2	-3.0	0	-
Pebbles with Sand	2.7	0.8	Small	0.1	0.1	Moving Water	Descent exceeding 3.5m	Descent exceeding 3.5m	0	0
Clayey Loam with Crushed Stone	2.8	0.65	Ground Ice	0.1-0.2	No		-0.5	+0.4	-0.13	+0.3
Upper Part: Sandy Loam Soil Lower Part: Pebbles with Sand	3.6	0.4	Ground Ice	0.2	No		-0.55	+0.6	-0.20	-0.05
Sandy Loam Soil	3.3	0.5-0.6	Ground Ice	0.1-0.2	No		0	+0.35	-0.20	-0.40
Surface layer: Pebbles with Sand over Clayey Loam with Pebbles and Crushed Stone	2.3	0.3	>50%	0.1-0.3	No		-1.0- -1.3	0	-0.40	-0.20

Table 12 Permafrost Table Under Embankments in Discontinuous Permafrost Zone in Greater Khingan Mountains

H_o (m)	0	0.5	1.0	1.5	2.0	3.0	5.0	10.0	100.0	∞
m	1	1.05	1.12	1.17	1.20	1.25	1.30	1.35	1.41	1.41

Table 13 Value of m at various values of H_O

period will appear in the 2,030s and 2,050s. The air temperature then will be about 0.3°C higher than now. The maximum amplitude of the air temperature will be 1.0-1.5°C. In this general trend, there will be a small fluctuation which has an amplitude of about 0.5°C.

Thus, the most disadvantageous condition is that the mean annual air temperature will rise 2°C one hundred years from now. Under such conditions, is it still possible to construct embankments in ice rich sections near the lower limit on the principle of protecting the permafrost?

It has been known that the construction of embankments has little influence on the permafrost table in a horizontal direction, but the influence becomes very great when it is in a vertical direction. Relatively speaking, climatic variation gives a great influence when it is in a horizontal direction, but smaller in the vertical direction.

According to Formula (2), the maximum depth of thaw of the soil is $h = \sqrt{\frac{2\lambda}{Q}}\,\Omega$. It is assumed that, under the same climatic conditions, the maximum depth of seasonal thaw caused by the difference in water content and lithology $h_1 = \sqrt{\frac{2\lambda_1}{Q_1}}\,\Omega$. It is already known that, the ratio of the maximum depth of seasonal thaw caused by different lithology and water contents can reach $\frac{h}{h_1} = 3$. If lithology and water content do not change with climatic conditions, then, if we want $\frac{h}{h_1} = 3$, it is necessary to make $\frac{\Omega}{\Omega_1} = 9$. As mentioned above, the most disadvantageous condition in the next 100 years will be the rise of the mean annual air temperature by 2°C. This can hardly make $\frac{\Omega}{\Omega_1} = 9$. In other words, the difference of lithology and water content will produce a much greater difference in the permafrost table than that caused by the fluctuation of temperature within one hundred years. That is to say, within the context of a rise of air temperature and degradation of the permafrost, the choosing of ideal embankment material and design can still create conditions causing the permafrost table to rise.

It can also be seen that, after having constructed an embankment on the principle of protecting the permafrost, the ground ice at the original permafrost table will be farther from the surface. Thus, the difference in ground temperature at the original permafrost table and the heat arriving there will decrease. The embankment will be slow in reacting to the change of climate. The result will be advantageous to the preservation of ground ice.

Furthermore, some correlations exist between the temperature and the state of the permafrost. Generally, the lower the temperature of the permafrost, the greater its thickness will be. The temperature is sensitive to climatic change but the state of the permafrost has very great "thermal inertia". Thus, it reacts very slowly to climatic change. The higher the ice content in the permafrost, the greater the "thermal inertia" will be. Observation data from the experimental embankment at the Branch Line in northeast China indicated that, even if the embankment was constructed in summer and contained a large amount of stored heat, in the thick peat layers with high ice content, the permafrost table would not drop (Table 8). It is sufficient to note how large the "thermal inertia" is. Table (14) lists the relations between the change of air temperature and the permafrost table (there were ground ice layers at the permafrost table) in Reshui Region. It is evident from the table that, in spite of the gradual rise of air temperature from year to year, there is no change in the permafrost table. In fact, it is the coarse-grained soil that degrades rapidly. The soil has low ice content, although the mechanical properties are not so poor after thawing. On the contrary, in spite of the fine-grained soils with high ice content, it has poor mechanical properties after thawing. However, because of its large "thermal inertia", and the slow thawing, the annual amount of thawing caused by the long-term fluctuation in climate will be small, too. As long as a certain amount of settlement is allowed in the design and there is yearly maintanance, no great difficulties will occur.

Year Item	1970	1971	1972	1973
Mean Annual Temperature (°C)	-2.9	-2.6	-2.0	-2.2
Permafrost Table under Embankment No. 2 (m)	1.5	1.5	1.5	1.5

Table 14 Change of air temperature and permafrost table in Reshui Region

Practices in embankment construction also proved that, even if the embankment are constructed according to the principle of protecting the permafrost in the region where it is degrading, the permafrost table under the embankment will finally rise up as long as proper measures are taken.

Generally, we consider that the permafrost in the Reshui Region is going through a stage of degradation. Nevertheless, the permafrost table under the Reshui experimental embankment, including its intercepting dikes, is rising (Table 3). The result of anatomizing the banks at three locations in this region (some of them have existed for more than ten years) shows that the permafrost table under the embankments has risen by varying amounts (Table 15).

The railway section from Jiagedaqi to Xintian in northeast China belongs to the permafrost boundary region on the eastern slope of the Greater Khingan Mountains. The permafrost occurs in small scattered islands, with mean annual ground temperature of 0 to -1.0°C and the permafrost is 4-6 m thick. It is considered generally, that the permafrost there is in a stage of degradation. The air temperature in this region changes considerably each year. Despite that, the railway in the region from Jiagedaqi to Xintian was constructed on the principle of protecting the permafrost. Construction was completed in 1965. Investigations were made on the railway in 1971 and 1972. They proved that with the exception of those under the base course of the embankments with water percolation, those under the high embankments and those under the sunny slope of the embankments, there is a rise of the permafrost table to varying degrees under most of the embankment cross-section (Table 16).

In summary, we consider that near the lower limit and southern limit of the permafrost, even if the ground temperature is high and the permafrost is going through a stage of degradation, the construction of embankments on the principle of protecting the permafrost can cause the permafrost table to rise under certain conditions and ensure the stability of the embankments as long as the permafrost persists as a single body.

CONCLUSIONS

From the above discussion, we have come to the following conclusion:

1) Even if the climate becomes warmer and the permafrost degrades somewhat, reasonable construction of the embankments can still create favourable conditions for the preservation and development of permafrost, and for the rise of the permafrost table under embankment;

2) Surface water and groundwater are the main causes for the permafrost table to drop under embankments. Therefore, good drainage on the sides of embankments is an important measure to ensure their stability and careful attention must be given to this. An intercepting dike can keep not only surface water, but also groundwater from the upper slope and is strongly recommended;

3) From the viewpoint of heat conductivity, it is better to select a soil (such as clayey soil) for embankment material with greater differences between thermal conductivity in the frozen state and the thawed state;

4) When the freezing index in the region is greater than the thawing index, and the summer precipitation is low (or the summer air temperature is not very high), the use of ventilated embankments (piled up with stone blocks, ventilating pipes) will be favourable for protecting the permafrost;

5) The embankment height has to be greater than the minimum height that can

Experimental Pit No.	Thickness of Water Bank (M)	Size of Banks (M^2)	Water Content (%)	Distance between two Pits (M)	Depth to Permafrost Table (M)	Rise of Permafrost Table (M)	Lithology	Year of Construction
P1	0.0	7.1 x 6.0	8.09	25.0	1.20	1.10	Grass Mould-Clayey Loam	1960
P2	1.2		Medium Humidity		1.30		From 0.65m Upward is Clayey Loam with Crushed Stone, below it is Clayey Loam	
P3	0.0	5.2 x 8.5	54.7	27.0	1.42	1.22	Grass Mould-Clayey Loam	1960
P4	1.1		76.7		1.30		Clayey Loam with Crushed Stone	
M4	0.0	6.4 x 76.4	39.5	10.0	1.34	1.36	Grass Mould-Crushed Stone Loam	1970
M3	2.0		29.2		1.98		Clayey Loam with Sand Crushed Stone	
M6	0.0	20.0 x 8.0	14.7	11.0	2.15	1.59	Grass Mould Crushed Stone-Clayey Loam	1970
M5	1.2		35.6		1.76		Crushed Stone-Clayey Loam Grass Mould	
T5	0.0	15.0 x 15.0	72.9	17.0	1.30	1.10	Grass Mould-Clayey Loam	1959
T6	2.4		21.5		2.60		Crushed Stone-Clayey Loam-Grass Mould	
T9	0.0	7.1 x 10.0	56.6	25.0	1.30	1.24	Grass Mould-Clayey Loam	1959
T7	1.9		40.9		1.96		Crushed Stone-Clayey Loam-Grass Mould	

Notes: 1) Anatomizing time: October 1971
2) The water content denotes weighted means of all layers above permafrost table.

Table 15 Rise of Permafrost Table Under Artificial Embankments in Reshui

Embankment Material	Embankment Height (M)	Lithology of Base Course		Accumulated Water at foot of Embankment (M)		Slope Orientation		Rise of Permafrost Table under Embankment (M)		Rise of Permafrost Table under Foot of Embankment (M)		Remarks
		Thickness of Peat Layer (M)	Water Content (%)	Left	Right	Left	Right	Left	Right	Left	Right	
Sand-Gravel	5.9-6.0	0.4-0.7	Clayey loam with ice Content 52.3%	No	Accumulated in Rainy Season	Shady	Sunny	+2.60	0	-0.15	-0.65	Ground Water Permeates into Right Berm
Upper Part: Crushed Stones, Lower Part: Sand-Gravel	3.8	0.65-0.8	33%	0.1-0.2	No	Dull	Dull	+1.0	+1.0	-1.5	0	
Crushed Stones with Sand-Gravel	1.8	0.5-0.65	10.3-38.9%	No	No	Dull	Dull	+0.3-0.4	+0.3-+0.4	0	0	
Crushed Stones with Sand-Gravel	2.5	1.2-3.0	Ground ice	No	No	Dull	Dull	+0.3	+0.3	0	0	
Sand Gravel-Crushed Stones with soil	3.4	0.3	20-30%	No	No	Shady	Sunny	+1.5	+0.2	0	+0.41	
Upper Part: Sandy Loam Soil, Lower Part: Clayey Loam	3.0	0.7-1.0	50%	No	0.1-0.2	Shady	Sunny	+1.0	+0.8	+0.25	-0.45	
Filled with Clayey Loam and Sand-Gravel	3.4	0.2-0.45	Ground ice	No	No	Sunny	Shady	+0.7	+0.9	0	0	
Clayey Loam with Crushed Stones	3.8-4.0	0.6-1.0	50%	No	No	Sunny	Shady	+0.5	+0.9	0	0	

Table 16 Permafrost Table Under Embankment in Discontinuous Permafrost Zone of Northeast China

cause the original permafrost table to be unchanged. However, it should not be too high. It is not suitable to have an embankment higher than 6 m near the lower limit of permafrost. When it exceeds 6 m, proper measures must be taken - e.g. when construction is carried out in winter, the insulation should be increased.

6) The higher the latitude, the more evident the influence of slope orientation will be. On east-west sections of the line it is necessary to increase the insulation on sunny slopes when the embankment is too high;

7) An ice rich section near the lower limit of permafrost is not suitable for construction of embankments or insulating berms in summer;

8) Long-term air temperature fluctuations have some real significance to railway construction in the discontinuous permafrost zone where the mean annual ground temperature is near zero, and the mean annual ground surface temperature is above -2°C to -3°C.

9) The influence of urban building developments on discontinuous permafrost is so complex that more efforts should be made to study the problem in the future.

In conclusion, it is possible to construct embankments on the principle of protecting the permafrost in sections with ground ice near the lower limit of the alpine permafrost. However, because of the influences of long-term air temperature fluctuations and human activities, further study in this field must be carried out to develop regulations for applying this principle.

ACKNOWLEDGEMENT

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Figure 1. Borehole No. 6 in embankment No. 2.

2. Layout and borehole locations in experimental embankment.

3. Rate of settlement of the experimental embankment.

4. Relation between embankment height H and settlement.

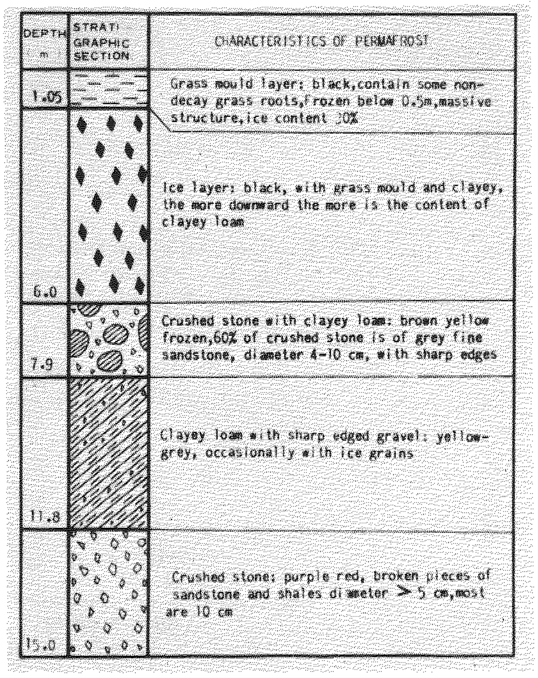

Figure 1

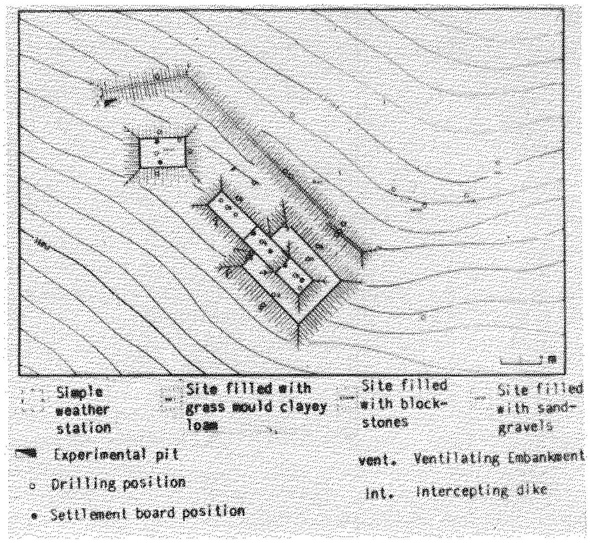

Figure 2

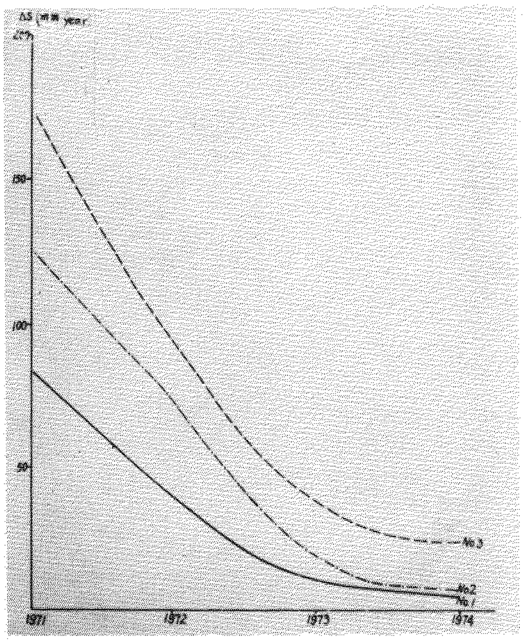

Figure 3

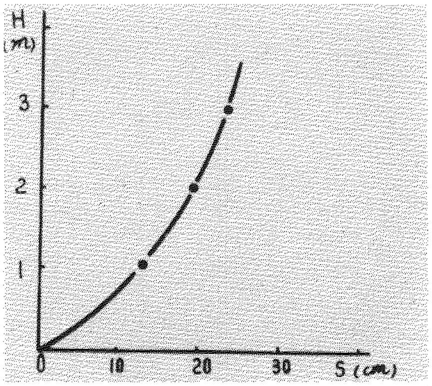

Figure 4

ADDRESS AT CONFERENCE DINNER

Robert F. Legget*

12 July, 1978

To many of us the happy days of fellowship at the First International Conference on Permafrost held at Purdue University in Lafayette, Indiana, will seem as if they were but yesterday. But almost fifteen years have passed since then, fifteen years of progress on many fronts, and of great progress in our own special field of interest, as the papers being presented at this, the Third Conference, make clear. Our host at that first Conference, Professor K. B. Woods, although rather seriously handicapped physically, retains his lively interest and will be glad to hear of the success of this continuation of that pioneer venture at Purdue.

To my very great regret, duties in Canada prevented me from attending the Second Conference in Yakutsk but many friends who were there have told me of the welcome they received and of their enjoyment of both meetings and visits. I was especially sorry not to have had the opportunity of meeting my good friends Dr. Melnikov and Dr. Vyalov on their own territory, after the pleasure of welcoming them to Canada; I might even have heard some of their Soviet fish stories, to set against their fishing prowess in this country. I would have been too early, however, to see one of the most remarkable of all Soviet permafrost discoveries, the baby mammoth only seven to eight months old that was found perfectly preserved just a few months ago in the Kolyma Berezovka permafrost area through the quick reaction of a bulldozer operator (Anon 1978). In Alaska a five to six year old mammoth has been found well-preserved in permafrost. But in Canada all we have so far found are a few mammoth bones.

Three days of this Conference have now been enjoyed; one is yet to come and then follow the field trips. We have therefore well passed the halfway mark of the formal deliberations. This most pleasant social occasion provides us, therefore, with a useful breathing spell, and a chance to sit back and take a more general look at our field of interest. You do not want from me another serious technical paper - and our charming ladies would not stand for any such antisocial act on my part. Yet our evening together should not pass into memory without some recognition of the fact that we are gathered here, from around the globe, because of our mutual interest in permafrost, that condition of the earth's crust when it is perennially frozen, and in all the consequences which result from the disturbance of that condition such as recent northern developments have made so clear.

Let us then take stock of what this Conference is considering. About 150 papers are being presented or summarized, authors coming from no less than fifteen countries, despite the general restriction of permafrost to northern terrains. Sixty-three per cent, or almost two thirds, of the papers describe permafrost phenomena in the field or practical experience involving its disturbance. Twenty-two per cent of the papers describe laboratory studies, and fourteen per cent present theoretical analyses. This judicious balance between the practical approach and necessary but complementary laboratory and analytical studies is greatly to be welcomed. It is a balance that is (alas!) sadly lacking in other branches of Geotechnique.

Your expertise in mental arithmetic will have shown you, I am sure, that there is still one per cent of the papers unaccounted for. There are just two papers that deal with fossil permafrost formations. This is passing strange, at first sight, in view of the extensive literature, especially in European journals, on this topic. Second thoughts, however, give a more rational appreciation. This Conference is being held in North America where current northern problems involving permafrost are vital and urgent - as they are also in the northern regions of the U.S.S.R. and of the People's Republic of China. The Organizing Committee therefore decided, very understandably if I may say so, to concentrate the attention of

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this Conference on these matters of current concern. So you will probably find more attention being paid to fossil permafrost features at future Conferences, not only as matters of great scientific and archaeological interest, but also from very practical points of view.

Serious trouble has already been experienced in Great Britain in the sinking of large shafts (for tunnel work) through the well-known Chalk of southern England, where the upper surface was found to be disintegrated (to a depth of almost sixty feet) in a manner that could only be explained as the result of permafrost (Haswell 1969). The fractured rock was still so "tight" that its true nature was not revealed by normal test drilling procedures. That this is no isolated phenomenon is perhaps indicated by the fact that I could take you to an island in eastern Canada and there show you an exposure of argillite that appears to be good, solid and competent rock but which is actually completely fractured into inch-long fragments. I suspect that some foundation problems in civil engineering practice are due to unsuspected fossil permafrost features, of which we may expect to hear more when the problems of the day permit.

But I am getting technical and this I must not do! Let me then observe that even more surprising than the few papers on fossil permafrost is the complete absence of any extended reference to the history of studies of permafrost. Some of my younger friends, in the manner of the day, may be tempted to regard this as perfectly natural and proper. They would like to say, perhaps, "So what?" - or at least to ask what relevance any record of work done years ago can have to their current studies of practical and urgent problems. Nothing directly, perhaps, one must admit; and yet as background to all the splendid work being done today, surely some general appreciation of the work of those who have gone before can have real validity. It has been well said that "History is as useless, but as important, as poetry and music." Poetry, despite occasional eulogies of the beauties of ice and snow (but never permafrost) has probably no place here tonight. In any case, I am no poet, as must by now be very obvious from my plodding pedestrian prose. But perhaps the equivalent of a minor musical interlude to your weighty deliberations may not be out of place. And we can all recall the remark of a very distinguished visitor to the August proceedings of the British House of Commons in Westminster, the "Mother of Parliaments" who, when asked what he thought of the debate to which he had listened, said that it would have sounded much better if there had been an orchestra.

If, sometime, you care to glance again at the volume of Proceedings of the First Conference, you will find that the two papers given at the opening session did touch upon the history of early permafrost investigations both in the U.S.S.R. and North America (Legget and Tsytovich, (1963). My good friend Academician Tsytovich, whose absence from this meeting we so greatly regret, gave some interesting details of early records in Russian literature, such as an early observation of 1662, and Middendorf's records of permafrost temperatures in 1848. He reminded us also of the publication in his country of a volume on permafrost as early as 1927. Nothing was said in these papers, quite naturally, about early Chinese records of permafrost studies. Now that we are hearing, for example, about some of the unique and remarkable Chinese records of earthquakes in that country, I venture to hope that our friends from the P.R.C. will be able to produce for us, one day, early records of Chinese permafrost studies that will put in the shade, so to speak, even the oldest records we have of observations in this part of the world.

Thinking of the small gap between our two continents across Bering Strait, I may also note that little was said in the Purdue papers about any early studies of permafrost in Alaska. Today, we are all familiar with the way in which permafrost problems have been tackled in that largest State of the Union, not only from the early work of the U.S. Crops of Engineers but also, and notably, from the construction of the Alyeska Pipeline, so graphically described at this meeting. Let me remind you, then, that it was a Danish sea captain, then in the employ of the Russian Government, Vitus Bering, who first sighted the land of Alaska (Bancroft 1886). This was on his second voyage of exploration in 1741 when he saw Mount St. Elias and landed some of his sailors on the coast on 17 July of that year; they were, therefore, the first white men to set foot upon this northwestern part of North America. (I have sometimes wondered if there was any hidden significance in the fact that on Bering's first voyage, of 1728, the coast of Alaska was shrouded in such thick fog that, although probably near to it, Bering did not then see it.) It is sad to think that this intrepid man died miserably on 8 December of that same year (1741).

Other explorers from Russia followed, the first permanent settlers locating near Kodiak in 1784. There is still in existence, I believe, the journal of Zaikov (of 1783) and in this are some observations of Nagariov, discoverer of the Copper River. One would expect to find here some reference to permafrost but I do not know if this reference has been studied from this point of view. This was an age of great and many explorations. The Spaniards, therefore, also saw the coast of Alaska in 1775 and some of their original journals from these voyages are said still to be extant. Spanish Archives might, therefore, yield information surprisingly germane to our common interest. So also might the records of a French navigator, Le Pérouse, who sailed along the Alaskan coast in 1786. Soon after this came the years of the Russian American Company (founded in 1799) but I feel sure that our Soviet friends have already dug deeply into the records of this singularly interesting pioneer commercial venture (Bancroft 1886).

Justly famous as was the Russian American Company, I trust that our Soviet guests will forgive me if I point out that we have in Canada an even older commercial company. I mention it only because some of its early record books have already yielded interesting information about early permafrost observations in this country. I refer, of course, to "The Governor and Company of Adventurers trading into Hudson's Bay", today more commonly known as the Hudson's Bay Company, the oldest commercial company in the world. Incorporated on 2 May 1670, one feature of its recent tercentenary was the transfer of its Head Office and its invaluable Archives from London, England, to Winnipeg. Eight years older than the Honorable Company is the Royal Society of London, the oldest scientific society of the western world. And of the eighteen original "Adventurers" named in the Charter of the Company, no less than six were (or became) Fellows of the Royal Society (Stearns 1945).

This link between commerce and science is still today, as we shall shortly see, a happy feature of our northern development. It was evidenced in the early days by the questionnaire which the Royal Society persuaded early travellers and explorers to answer. There is still in existence a manuscript copy of the twenty-two questions, with replies, addressed by Henry Oldenburg, Secretary of the Society, to Captain Zechariah Gillam after he had returned from a voyage into Hudson Bay in 1668-69. Employees of the Company who resided at one or other of the posts established on the shores of The Bay naturally included references to the terrain around them. In the Proceedings of the First Conference, you will find some extracts from the records compiled by James Robson and James Isham, first published in 1752 and 1760 respectively (Legget 1963). I have brought with me a photocopy of an even earlier record, exhibiting it now so that my more critical friends cannot write this off as just another of "Legget's Tall stories".

Captain Christopher Middleton was one of the most able of the Company's early servants. The Royal Society published in 1731 a table of his meteorological and magnetic observations made during nine voyages into Hudson Bay. He was elected a Fellow of the Society in 1737. In the Philosophical Transactions of the Society for 1742 there was published a report which he had prepared about his residence at Fort Prince of Wales during the winter of 1741-1742 (Middleton 1742). Here are a few extracts:

> "All the Water we use for Cooking, Brewing etc., is melted Snow and Ice; no Spring is yet found free from freezing, though dug never so deep down. All Waters in-land are frozen fast by the Beginning of October, and continue so till the Middle of May.
>
> The Walls of the House we live in are of Stone, Two Feet thick, the Windows very small, with thick wooden Shutters, which are close shut 18 Hours every Day in Winter. There are Cellars under the House, wherein we put our Wines, Brandy, strong Beer, Butter, Cheese, etc. Four large Fires are made in great Stoves, built on purpose, every Day; As soon as the Wood is burnt down to a Coal, the Tops of the Chimneys are close stopped with an Iron Cover: This keeps the Heat within the House (although at the same time the Smoke makes our Heads ake, and is very offensive and unwholsome); notwithstanding which, in Four or Five Hours after the Fire is out, the Inside of the Walls of our House and Bedplaces will be Two or Three Inches thick with Ice, which is every Morning cut away with a Hatchet. Three or Four times a Day we make Iron Shot of 24 Pounds Weight red-hot, and hang them up in the Windows of our Apartments. I have a good Fire in my Room the major part of the 24 Hours, yet all this will not preserve my Beer, Wine, Ink etc. from freezing."
>
> And again: "The Rocks which are split by the Frost, are heaved up in great Heaps, leaving large Cavities behind; which I take to be caused by the imprisoned watery Vapours, that require more Room, when frozen, than they occupy in their fluid state. Neither do I think it unaccoutable, that the Frost should be able to tear up Rocks and Trees,

> and split the Beams of our Houses, when I consider the great Force and Elasticity thereof."

And finally, although the temptation to go on quoting from this remarkable record is great:

> "The Frost is never out of the Ground, how deep we cannot be certain. We have dug down 10 or 12 Feet and found the Earth hard frozen in the Two Summer Months; and what Moisture we find Five or Six Feet down, is white like Ice."

(Capitalisation and punctuation are as in the original.)

Those of you who are taking part in Field Trip No. 4 will be visiting Churchill. I understand that you will be visiting the ruins of Fort Prince of Wales. You may then be moved to recall the fearsome winters spent there by Captain Middleton and other early servants of The Company. I urge you to visit also Sloop's Cove and there see, clearly chiselled into a smooth rock surface, the simple words "Samuel Hearne July 1767". Hearne was the first white man to reach the arctic coast of Canada by land. On his great journey to the Coppermine River he was also, although quite incidentally and without realizing it the first white man to set foot in the watershed of the Mackenzie River, seventh river of the world, and Canada's greatest waterway. Its discovery is linked strangely with Alaska, to the history of which we may now briefly return.

It is a strange but interesting coincidence that in the year 1867, only three and a half months after Canada achieved the status of a self-governing British Dominion (now an independent Dominion within the British Commonwealth of Nations), the flag of the United States of America should have been raised at Sitka, betokening the purchase of Alaska from the Russian Government by our neighbour country to the south. The purchase included that strange-looking pan-handle, reaching 300 miles into British Columbia, so peculiar a feature of the geography of western North America. (Parenthetically, I might perhaps be permitted to observe, purely personally, that the removal of the capital city of Alaska from the panhandle to "mainland" Alaska seems to leave the way open for a logical readjustment of this part of the map of North America).

In this thumbnail sketch of the history of the great state of Alaska, focus of so much permafrost work of the United States, one name has so far been omitted, that of Captain James Cook, R.N., one of the world's greatest nautical explorers. Canada is this year making the bicentenary of his landing in British Columbia, two most attractive postage stamps, still available, being part of the marking of the anniversary. Proceeding on his voyage northward, in search of the Northwest Passage, Captain Cook also sailed along the coast of Alaska, making his usual careful record of all that he saw. In one respect, however, he was wrong. When sailing across the mouth of what today is rightly called Cook Inlet, he thought that it was the mouth of a great river. James Cook was tragically murdered just a few months later (in Hawaii) but others reported on his discoveries and named the mythical river "Cook's Great River". This became known in eastern Canada and led another great explorer to attempt to find it.

This was Alexander Mackenzie, the young Scottish fur trader who not only discovered (in 1789) the river that now bears his name, but who, on an even more remarkable journey in 1793, reached the Pacific Ocean on 22 July, becoming the first white man - and in all probability, the first man, - to cross the North American continent from sea to sea. He was an astute observer and kept excellent records of his demanding journeys which we can read today in comfort (Mackenzie: Lamb 1970). He, too, remarked on the perennially frozen ground to be found in northern Canada. On Friday 31 July 1789, when returning up the great river after reaching the tidal waters of the Arctic Ocean in the delta, but having failed to find Cook's Great River, greatly to his regret, he recorded some miles upstream of the site of Norman Wells that "In other Places the Bank of the River is high of Black Earth and Sand continually tumbling, in some part shews a face of solid Ice, to within a foot of the Surface." Two days later, just after passing the mouth of the Bear River he recorded the existence of burning coal beds, buried continually by the summertime slumping of the frozen eastern bank of the River. Those of us who have had the privilege of sailing up or down the Mackenzie have seen these same features today- the "tumbling banks", "the Ice to within a foot of the Surface", and the burning coal beds, all just as Mackenzie saw them almost two hundred years ago. Participants in Field Trips No. 2 and No. 3 will see something of this remarkable river; they will see how little it has changed since Alexander Mackenzie first sailed down it in his canoe.

Until the discovery of oil in the 1920's at what is now Norman Wells, the entire northern part of the Mackenzie watershed (and the rest of northern Canada, apart only from the Yukon) was virtually untouched. A few Hudson's Bay Company posts, some independent traders, the first simple outposts of the Royal Canadian Mounted Police and a small military signal station in the Mackenzie Delta at what is now Aklavik were the only signs of the white man's intrusion into the domain of the northern Indians and Eskimo, or Inuit as they are now called. The Hudson Bay Railway had been started, to be completed to the port of Churchill in 1929, but this was all located in the province of Manitoba, even though passing over perennially frozen ground for much of its length, an indication of the vast extent of the Canadian North. Even the start of gold mining and the mining of uranium ore on Great Bear Lake in the late thirties were such local developments in the Mackenzie Valley that they had little effect on life in the valley beyond pointing the way to necessary improvements in transportation.

When I first came to know the great valley (in 1940), stern wheeler wood fired steamers were the principal vessels on both the upper and lower Mackenzie River, for the three month season of open navigation. The name "permafrost" had not yet been coined by Dr. Siemon Muller. But the phenomenon of perennially frozen ground was there, just the same. Courageous pioneer building techniques had been developed, notably at Norman Wells. It was the imperative of the Second World War that caused the first major intrusion of what we are pleased to call civilization into the Canadian North. First came the building of the Canol Pipeline across the mountains from Norman Wells to Whitehorse. Defence radar stations followed and the building of the series of joint Arctic weather stations whose continuing service benefits the whole world.

I give this thumbnail sketch of the opening up of the North of Canada for the benefit of our oversea visitors. It is a story familiar to most Canadians although, all too often in our public discussions, the fact that the so-called development of our North is something that started little more than thirty years ago is forgotten. Even after the alarms of war had disappeared, the North became once again a quiet and lonely land for some years longer, enlivened only by a few mining projects. So it was that, when in 1950 we started our research into permafrost and the problems it presents, many regarded us as crazy. Certainly none of us associated with that modest start could have foreseen what was to come in the next quarter century.

Canada's first northern research station was at Norman Wells, located at first in derelict buildings left over from the Canol project. We decided upon this location because of the existence of the small Imperial Oil refinery there, with the associated small workshops, the only such centre on the Mackenzie River. It is a special privilege tonight to pay public tribute, as we have often done privately, to the remarkable cooperation and assistance which we, in the National Research Council, received from "Imperial Oil" in starting our northern research work, as in all the years since then. It was this great Canadian corporation, with other leading oil companies, which pioneered the exploration for oil and natural gas throughout the lower Mackenzie Valley and adjacent arctic territory. This work led eventually to the grand concept of a Mackenzie Valley oil pipeline, to convey these products from both the Canadian and Alaskan arctic coasts to the markets of North America.

With subsequent political developments, surrounding these great projects we are not concerned tonight. Suffice to say that it is now improbable that either line down the Mackenzie Valley will be built in the immediate future. Rarely, however, have two such major engineering projects been planned on the basis of such extensive research work. The terrain along all possible routes for the pipelines was studied in detail, from the air and on the ground, this work extending along a corridor 1500 miles long. Our visitors may gain some idea of the extent of the Canadian North, from the fact that the distance from this most northern Canadian city of Edmonton, so truly known as the "Gateway to the North", to the arctic coast is just about the same as the distance from here across the prairies, past Winnipeg and the Lakehead and over Lake Superior to Sault Ste. Marie; or, if we went south, as far as the border of New Mexico. Three full scale test pipeline installations were built in this vast area, with a further one in Alaska at Prudoe Bay. The Canadian installations were at Inuvik (near the arctic coast), near the Sans Sault Rapids and at Norman Wells. All were fully operating oil or gas pipelines and they yielded invaluable and unique information.

Nor were the environment and the fish and wildlife of the North neglected. Extensive biological research was also carried out in all the areas through which the pipelines might be expected to run. I can recall so well that when, in 1972, this work was first described in public, it was remarked that this was probably the first time in history that over $3 million had been spent on fundamental field biological research for a great engineering project (Legget and MacFarlane 1972). Mention of this figure leads me to say that, although I have never seen any published estimate of the total expenditure on this tremendous research effort - almost all of it in "permafrost country" - such figures as have been published suggest that it must have been something like $50 million, if not indeed more than this.

From the start, and as is happily a common feature of the Canadian way of doing things, industry worked closely with interested Departments of the Government of Canada, with the National Research Council and with universities. That this is no idle statement was shown by the fact that, while this widespread research effort was underway, there was held in Ottawa a public conference at which excellent progress reports were presented on all major parts of the work then going on in the Mackenzie Valley. Organized by the Associate Committee on Geotechnical Research of the National Research Council of Canada, the Conference attracted well over 500 participants. In view of what has happened since, the Proceedings of the Conference have already assumed some historic value; a few copies are still available. Especially welcome was the presence of Mr. Shagen S. Dongaryan, Deputy Minister of the Ministry of the Oil Industry of the Soviet Union who shared with the meeting some of the experience of his Ministry, in keeping with the close liaison with the U.S.S.R. that has characterized Canadian permafrost research from its beginnings (Legget and McFarlane 1972).

Industry was responsible for the overall planning, direction and financing of the combined effort but it is good to think that all available knowledge in this country was marshalled to give the best possible results for the anticipated design and construction of the pipelines, consistent with due protection of the environment and of the fish and wildlife in all affected areas. Some research projects initiated at the time of the pipeline studies are continuing today; in due course, we may expect to see the results obtained published for public benefit. Much has already been published, with the ready agreement of the industrial sponsors. Some of the results obtained naturally have a proprietory value and must be retained as confidential to the sponsors until such time as their private value is minimal. Despite this very necessary and understandable limitation, I have a feeling that there still remains an appreciable amount of information resulting from this great cooperative effort of no special proprietory value but of great scientific importance that has not yet been published. I know well that excellent summary reports have been prepared with copies placed in key Canadian offices - but this is not publication. Some of the final reports have been placed in libraries for consultation - but, again, this is not publication.

The world-wide interest today in permafrost that is so well demonstrated by the attendance at this Conference suggests to me that, before memories of the Mackenzie Valley Pipeline Research enterprise begin to fade, those in industry responsible for the safekeeping of the records and the termination of this gigantic effort would perform another public service of great value if they would take another look at the records they have to see which might now be released and prepared for publication, with no loss or detriment to their respective companies. It would have the character of a salvage operation, admittedly, but if all the papers from the Mackenzie Valley permafrost research project, already published and yet to be published (I hope) were to be gathered together in a series of volumes, the world would be the beneficiary and the series would constitute a worthy record of enlightened industrial cooperative research that would be, in some respects, unique.

All of us know that publication is only "half the battle" of getting the results of even the best of research into use. Those who need the information for work in the North must be led to appreciate its existence in the first place, then to read it and then to put it into use. This is no easy task. I am sure that this transfer of research information into actual use is a worldwide problem. It is certainly an acute problem in Canada. We have had all too many examples of people going into Canadian North and "rediscovering the wheel" (as it is said), unfortunately often by making mistakes which in some cases were irremedial, so fragile is much of the permafrost terrain. That this is not just a dismal personal view is shown by this statement which came unanimously from a group of Canadian northern experts, meeting just five years ago:

> "The Group urges that prequalification of all designers of publicly financed buildings and structures for the North and of all contractors for publicly financed northern work, be mandatory." (Greenaway 1973).

This strong statement is in the public record; it should provide an absolute guideline for the conduct of all governmental work in our northern regions. I feel sure that similar limitations, to ensure the best possible work in northern regions, are followed in the U.S.S.R. and the P.R.C.

This desirable requirement surely places a very special responsibility upon all of us who know the northern regions of our countries - of Alaska, the U.S.S.R., China and Canada - to do all in our power to see that no work is done there except on the basis of the best information available. But I want to suggest to you, in conclusion, an even greater responsibility that rests upon our shoulders as professional men and women who know the problems caused by disturbance of surface vegetation and soils in regions underlain by permafrost.

Is it not our bounden duty to speak out against and actively oppose any disturbance of our fragile northern terrains which is not absolutely essential, so as to preserve for the future as much as possible of the wild lands of the North? Transportation, for example, should surely be by water to the extent that is possible and otherwise by air; railways should be constructed only when economics and northern welfare combine to make them essential; and roads only as a last resort, and when not only economics but demonstrated human needs make their building unavoidable. All who know the North know also that road construction and use can wreck more havoc to the northern environment than any other work of man.

We are, in a way, the Trustees of the North, with our special knowledge of permafrost and the hazards which its disturbance can cause. We must see to it that our northern territories - Canadian, Alaskan, Soviet and Chinese - are preserved in as natural a state as possible, consistent with controlled development of natural resources. I urge you to leave this fine Conference not only inspired by the new knowledge you have gained, not only enriched by new friendships, but firmly resolved never to forget your own personal responsibility as a conservator of our northern lands.

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OPENING PLENARY SESSION
Monday, 10 July, 1978

Dr. R.J.E. Brown: Ladies and Gentlemen. I should like to begin the Third International Conference On Permafrost by welcoming all delegates, accompanying persons and others connected with the Conference to the proceedings this morning. My name is Roger Brown. I am the Chairman of the Organizing Committee for the Conference. I will now introduce the other persons on the platform who will speak in this opening session. Dr. L.W. Gold, Assistant Director of the Division of Building Research, National Research Council of Canada, is the Chairman of the NRC Associate Committee on Geotechnical Research. This is the parent body of the Organizing Committee for this Conference. Dr. T.L. Péwé is the leader of the delegation from the United States. Professor P.I. Melnikov is the leader of the delegation from the Soviet Union.

As you know we will be in Edmonton for four days for the technical sessions including the presentations of the special review papers. At the end of these meetings on Thursday afternoon, there will be a closing plenary session at which some questions will be raised. One will be about the possibility of forming some sort of international permafrost association among the various interested countries. Another will concern the Fourth International Conference On Permafrost.

A principal task of the Chairman of the Conference is to acknowledge the assistance of the many people who are involved in its organization and arrangements. First, I wish to thank all of you for attending. In these days of high travel costs and conflicting commitments it is difficult to travel to the many conferences that are being held. The Conference organizers are gratified by the attendance which is nearly 500 from about 15 countries in North America, Europe and Asia.

I should like to mention various groups and individuals who contributed so much time and effort to the organization of the Conference. One of the most notable is the Local Arrangements Subcommittee of the Organizing Committee chaired by Dr. J.I. Clark. They organized all of the local arrangements and functions and we are grateful to him and his subcommittee for this valuable assistance. The very fine program for accompanying persons is chaired by Mrs. Morgenstern and we greatly appreciate her efforts. Dr. N.R. Morgenstern is chairman of the subcommittee which organized the technical program. The excellent Volume I of the Proceedings resulted from the work of his group and the subcommittee on publications chaired by Dr. W.O. Kupsch. I think you will agree that this is an excellent piece of work and we appreciate their efforts very much. The coordinator for organization of the field trips is Dr. D.E. Kerfoot whose assistance is gratefully noted. I should like to thank Dr. L.W. Gold for the very active support which he has given to the work of the Organizing Committee. I wish to make special mention of my colleague and close friend, Mr. G.H. Johnston, whom many of you know, and with whom I have worked for many years. He assisted me in more ways than I can recount to you and I should like to acknowledge publicly the great help which he gave me. I would be remiss if I did not mention the work of the staff in the Conference Services Office at the National Research Council of Canada, Ottawa, headed by Mr. K. Charbonneau. You saw his name and that office mentioned in the Bulletins of the Conference. They are working now at the registration desk where they spend long hours. This vital service now and the many months of effort prior to the Conference is gratefully acknowledged.

The Conference has been supported by quite a number of donations. The National Research Council of Canada itself being the sponsoring agency has given a great deal of help, both monetary and in other ways. Six Canadian federal departments gave financial contributions: Energy, Mines and Resources; Fisheries and Environment; Indian and Northern Affairs; National Defense; Public Works; and Transport. We also received donations from industrial firms, mostly in western Canada, to whom we are most grateful. The Province of Alberta has been very generous with its financial assistance. A representative of the provincial government will address our banquet Wednesday evening. The City of Edmonton has also contributed and the Mayor will speak to our luncheon tomorrow. We are very fortunate to be here in this fine City of Edmonton in the Province of Alberta, and we appreciate the hospitality and friendly atmosphere that exists here. With these comments I now declare the Third International Conference On Permafrost to be officially opened. I would like to call on Dr. Gold to say a few words. Thank you.

Dr. L.W. Gold: Mr. Chairman, Honourable Delegates, Ladies and Gentlemen. It is both an honour and a great pleasure for me to welcome you on behalf of Dr. Schneider, the President of the National Research Council of Canada, and to bring you his greetings and best wishes for a successful Conference. Dr. Schneider would have liked very much to bring these words to you personally, but he is the chairman of the organizing committee for another international conference that is being held in Toronto this week. I also want to welcome you on behalf of the Associate Committee On Geotechnical Research of the National Research Council of Canada. I would like to say a few words about this Committee. The Associate Committee is one of the Canadian national committees established by the National Research Council to consider problems of country-wide concern. It was formed in 1945 to coordinate and stimulate research on the engineering and physical aspects of the terrain of Canada. Because about one-half of our country is underlain by permafrost, it was natural that the Committee should pay particular attention to this subject. In 1958 it sponsored the first conference held in Canada devoted solely to the subject of permafrost. That conference clearly showed the growing interest and concern that was developing in Canada on those questions. In response to this the Associate Committee established in 1960 a Subcommittee on Permafrost. That particular Subcommittee has been very effective in stimulating research on basic aspects of permafrost and related engineering activities, and in developing communication among individuals in universities, industry and government that have an interest in this subject. It has played a leading role in the development of the knowledge and capability concerning this particularly challenging ground condition, primarily through the sponsoring of seminars covering a broad range of topics. The proceedings of these seminars have been made available through the publications series of the Associate Committee.

Not only has this Subcommittee been active within the country, but it has also played a strong role for Canada internationally. It acted as the coordinating committee for Canadian participation in the First International Conference On Permafrost held at Purdue University in the United States in 1963. It carried out the same task for the Second International Conference On Permafrost held at Yakutsk in the U.S.S.R. in 1973. The chairman at that time, Professor J.R. Mackay, headed the Canadian delegation to the Soviet Union and issued there the invitation for the next conference to be held here in Canada. Under its present chairman, Dr. W.O. Kupsch, the Subcommittee undertook for the Associate Committee the task of putting together the Organizing Committee for this Conference. I think it is very fitting that the guest speaker at the banquet Wednesday evening is Dr. R.F. Legget. He is the individual responsible for the establishment of the Associate Committee and guided it for more than 20 years. It was largely due to his foresight and initiative that the Associate Committee has had the opportunity of participating in contributing to the growth of permafrost research and engineering in Canada and the privilege of providing the focal point for the organization of this Conference. An impressive number of papers of high quality has been submitted to this meeting. I know the sessions are going to be of great interest and the information presented of lasting value. On behalf of the Associate Committee, I want to wish you every success in your deliberations. Thank you.

Dr. R.J.E. Brown: Thank you very much, Dr. Gold. I should like to call on Dr. Péwé to speak on behalf of the delegation from the United States.

Dr. T.L. Péwé: Mr. Chairman, Delegates, Ladies and Gentlemen. The members of the permafrost community in the United States of America are most pleased to participate in the deliberations here in Edmonton, and in the field excursions to be held later. We appreciate the hospitality and the excellent planning that is so evident in this meeting. We are very happy to be here in Canada, for it is in this country that we have the earliest known record of permafrost observations in North America - observations made by early explorers in the Arctic Islands more than 400 years ago. Today, Canada is one of the leading areas of permafrost research in the world. We are happy to have worked closely in permafrost with our northern neighbours for decades. Now, permafrost experts from the United States in academia, industry, state and local governments are here to meet with their international colleagues. We wish to thank Dr. Brown and his staff in providing the opportunity for scientists and engineers from various parts of the world to discuss and extend our knowledge of theoretical and practical problems of perennially and seasonally frozen ground. Thank you.

Dr. R.J.E. Brown: Thank you very much Dr. Péwé. I should like now to call upon Professor Melnikov to speak on behalf of the Soviet Union.

Professor P.I. Melnikov: (Text in Russian at end of this session)

Ladies and gentlemen, Mr. Chairman, members of the Organizating Committee!

Allow me to transmit to you the sincere greetings and best wishes of the Soviet delegation to this Conference and of all geocryologists of the Soviet Union.

Five years have passed since the successful second Internation Conference On Permafrost which was held in the central region of the cryolithic zone of the USSR in the territory of Yakutiya. The work of the plenary sessions, the interesting and, I dare say, fascinating field trips have left good impressions on the delegates of the previous Conference.

The resolution of the second International Conference On Permafrost expressed the foremost problems of further development in permafrost research. During the past five years we have worked on these problems and have achieved a certain success in fundamental as well as applied research. The main results of these investigations are presented to the Conference in 53 papers and special editions of compilations of articles on various aspects of permafrost research. Soviet permafrost research workers prepared a total of 132 papers and articles for this Conference. This constitutes a weighty contribution by Soviet scientists towards the work of this Conference. The large number of papers presented by the Soviet delegation is indicative of the high level of development of permafrost research in the Soviet Union and constitutes a great contribution to this developing and very important field of scientific knowledge.

Investigations of the composition, structure, formation conditions, and evolution of cryolithic zones were carried on and developed. Zonal and regional peculiarities of geographic occurrences of seasonally frozen ground and permafrost were identified, and their thicknesses, temperatures, and interaction with groundwater established. Particular attention was devoted to the study of "Alpine permafrost" in the high mountainous regions of southern USSR.

Much attention was given to the investigation of the thermo-physical basis of the processes of formation and development of cryolithic zones.

Great importance is devoted to the development of scientific foundations and control methods of cryogenic processes in the economic development of permafrost regions.

We have worked on the development of new effective methods of permafrost research using modern technological means.

Working out the physical and mathematical foundations of forecasting the progression of cryogenic processes in the arctic regions under development has become the most important problem. One of the crucial problems in permafrost regions under economic development is the protection of the environment.

Due to lack of time I cannot dwell on all the geocryologic research being carried out now. I should mention, however, that all the subjects, singled out in the resolutions of the second International Conference On Permafrost are being worked on by Soviet geocryologists.

The published papers and reports presented at this Conference may help to judge the results of these investigations. About 300 monographs, papers, compilations, articles, and other types of publications, totalling more than 1000 typed pages, have been published in our country during the past five years. Such a great volume of literature is a vivid indication of the attention devoted to the development of permafrost research in our country. The Soviet Union, the USA, and Canada have gigantic areas of permafrost formations. Occurrences of valuable ores are concentrated in such area, and they are being developed at an increasing pace. Economic development of permafrost regions can, however, be realized effectively only if the technological and geocryological changes, dependent on the adopted methods for the development of the territory, have been carried out, and methods for the regional exploitation of natural resources and for the reestablishment of the disturbed natural vegetation worked out.

Research in the field of environmental protection has increased significantly during the past five years. This is becoming a global problem and all nations are devoting particular significance to it. The approach which considers nature to be an extremely complex system in equilibrium, must be given its due importance in our research. The Construction of the Trans-Alaska pipeline is an exemplary case. It is there that the requirements of the environmental protection legislation of the USA are being realized for the first time on a large industrial project. The costs of these measures constitute a high sum, but it is difficult to estimate the material and social price that would have been incurred, had the environment protection measures not been given such a great importance.

Much attention was devoted to geocryological forecasting during the past few years. This is understood to mean a scientific prediction of the direction of development and of the degree of change of the geocryological conditions which will take place in the future as a result of natural evolution, or economic development of the territory. The forecasting is based on investigations which are aimed to discover the laws, of specific, general, or regional character, which govern the formation of permafrost conditions and to unveil the meaning of such laws.

The study of the thermal state of the permafrost, its dynamics, its relationship with the climate and deep seated processes, and the development of the theory of deep freezing of the earth's crust are some of the principal problems in this category. The unstable permafrost occurrences, which have the widest development in Western Siberia, arouse considerable interest. It has been actually confirmed that these are developments separated from the suface of deeply occurring permafrost, which is melting at the present time from above and from below. The unstable permafrost contains information on the past glacial period. The strictly quantitative nature of the extracted information makes it all the more valuable. These are the first quantitative data on the palaeoclimate which are obtained directly from an analysis of the present day permafrost. It is, so to speak, a window opened into the actual evolution of permafrost during an epoch of abrupt climatic changes. Future work in this area requires a theory of the stable and unstable temperature fields and of the processes of deep freezing of the earth's crust.

We consider the determination of the age of permafrost to be of great importance. Until recently this age was considered to be of the order of 40 to 50 thousands of years. As a result of our investigations the concept of an uninterrupted existence of permafrost was developed. Data of the permafrost facies analysis of deposits dated by means of palaeontological and thermoluminescent methods indicate that the permafrost of Central Yakutia has not thawed for a period longer than 300,000 years. This very important discovery permits us to reconstruct the palaeoclimate in a new way, and to reassess the formation conditions and the evolution of the earth's permafrost in a different light.

The study of the hydrology of permafrost has always attracted the attention of Soviet specialists, because the complex interaction between groundwater and permafrost is the key to the understanding of permafrost dynamics; while the groundwater itself, which is protected from pollution, is regarded to be a potential source of water supply. In recent years we have conducted investigations of kriopeg* brines, which have negative temperatures. Undoubtedly the mighty pressure horizon, discovered in the northern kriopeg regions, participates in the convective heat exchange may be the source of the deep cooling of rocks. Kriopegs may complicate mineral mining operations.

In the field of permafrost engineering the introduction of refrigerating devices using seasonally acting fluids attracts the greatest interest. They are based on natural circulation of the refrigerating fluid and are used for controlling the temperature regime of the ground in northern construction. Such devices are employed in the Soviet Union in construction of buildings, linear structures, and earth dams. Research in this direction is extremely promising because of such advantages as high economic efficiency, increased stability of structures, and better feasibility of construction under complex geocryological conditions

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* - The definition for kriopeg given in the Russian-English Glossary of Permafrost Terms prepared by V.N. Poppe and R.J.E. Brown, NRC Technical Memorandum No. 117, Ottawa, April 1976, is as follows: body of liquid saline water below 0°C associated with permafrost; may also imply ice free permafrost with saline pore water.

The tasks of this international conference on permafrost are to elucidate recent research results, to characterize the scientific and practical achievements of the past five years, and to indicate the direction for future developments in permafrost research.

In conclusion I want to thank the Organizing Committee for the invitation to the Conference and for the hospitality offered to our delegation.

Dr. R.J.E. Brown: Thank you very much, Professor Melinkov. This concludes the opening session of the Conference. We will now proceed directly to the presentation of the first review paper. Thank you.

ВЫСТУПЛЕНИЕ НА ОТКРЫТИИ III МЕЖДУНАРОДНОЙ КОНФЕРЕНЦИИ ПО МЕРЗЛОТОВЕДЕНИЮ В КАНАДЕ

/10 июля 1978 года/

П.И. Мельников

Леди и джентельмены, господин председатель, господа члены Оргкомитета !

Позвольте передать Вам сердечный привет и наилучшие пожелания от прибывшей на конференцию Советской делегации, а также от всех геокриологов Советского Союза.

Истекло пять лет после II МКМ, которая успешно прошла в центре области распространения криолитозоны СССР на территории Якутии. Содержательная работа пленарных заседаний, интересные и, я бы сказал, увлекательные полевые экскурсии оставили хорошее впечатление у делегатов прошлой конференции.

В решении, принятом на II МКМ, были сформулированы наиболее актуальные проблемы дальнейшего развития мерзлотоведения. За истекшие пять лет мы работали над этими проблемами и достигли определенных успехов как в фундаментальных исследованиях, так и в прикладных. Основные результаты этих исследований изложены в представленных на конференции 53 докладах и специально выпущенных сборниках статей по различным аспектам мерзлотоведения. Всего советские мерзлотоведы подготовили к конференции 132 доклада и статьи. Это солидный вклад советских ученых в труды конференции. Большое число докладов, представленных советской делегацией, свидетельствует о высоком уровне развития мерзлотоведения в Советском Союзе и большом научном вкладе в эту развивающуюся, очень важную область научных знаний.

Продолжались и развивались исследования состава, строения, условий формирования и истории развития криолитозоны. Выявлялись зональные и региональные особенности географического распространения сезонно-многолетнемерзлых горных пород, их мощности, температуры и взаимодействия с подземными водами. Особое внимание было обращено на изучение "альпийской вечной мерзлоты" в высокогорных регионах юга СССР.

Много внимания уделялось исследованиям теплофизических основ процессов формирования и развития криолитозоны.

Большое значение придается разработкам научных основ и методам управления криогенными процессами при хозяйственном освоении области многолетнемерзлых пород.

Мы занимались разработкой новых эффективных методов исследования мерзлых толщ с привлечением современных технических средств.

Важнейшей проблемой стала разработка физико-математических основ прогноза развития криогенных процессов в осваиваемых районах Крайнего Севера. Одной из центральных проблем является охрана окружающей среды в связи с хозяйственным освоением области распространения многолетнемерзлых пород.

Я не имею возможности остановиться на всех проводимых геокриологических исследованиях, но должен сообщить, что темы, рекомендованные II МКМ как наиболее актуальные, разрабатываются советскими геокриологами.

О результатах этих исследований можно судить по опубликованным трудам и докладам, представленным на настоящую конференцию. За истекшие пять лет в нашей стране опубликовано около 300 монографий, трудов, сборников, статей и других видов печатной продукции общим объемом более 1000 п.л. Эта огромная литература является ярким показателем, какое внимание уделяется в нашей стране развитию мерзлотоведения. Советский Союз, США и Канада имеют огромные площади с многолетнемерзлыми породами. На этих площадях сосредоточены месторождения ценных полезных ископаемых, которые с возрастающей интенсивностью осваиваются. Но хозяйственное освоение области с многолетнемерзлыми породами может осуществляться эффективно только в том случае, если проведены детальные инженерно-геокриологические исследования, сделана оценка для целей строительства, дан прогноз геокриологических изменений в связи с принятым методом освоения территории, разработаны методы регионального использования природных ресурсов и приемы рекультивации нарушенных земель.

За истекшие пять лет значительно расширились исследования в области охраны окружающей среды. Эта проблема приобретает планетарный характер, и все страны придают ей особое значение. Подход к природе как исключительно сложной сбалансированной системе должен занимать достойное место в наших исследованиях. Показательным примером является строительство Трансаляскинского нефтепровода, где впервые на крупном промышленном объекте осуществлены требования закона США об охране окружающей среды. Расходы на это мероприятие составили значительную сумму. Но трудно оценить потери материальные и моральные, которые бы имели место, если бы охране окружающей среды не придавалось такое большое значение.

За истекшие годы много внимания уделялось геокриологическому прогнозу. Под этим понимается научное предсказание о направлении развития и степени изменения геокриологических условий, которые произойдут в будущем либо в связи с естественно-историческим ходом развития природы, либо в связи с хозяйственным освоением территории. Основой прогнозирования являются такие исследования, которые позволяют вскрыть частные, общие и региональные закономерности формирования мерзлотных условий и раскрыть содержание этих понятий.

К числу основных проблем относится изучение теплового состояния мерзлой толщи ее динамика, связь с климатом и глубинными процессами, развитие теории глубокого промерзания земной коры. Значительный интерес вызывают нестационарные мерзлые толщи, получившие наибольшее развитие в Западной Сибири. Здесь фактически подтверждено развитие оторванных от поверхности глубоко залегающих мерзлых пород, оттаивающих в настоящее время и сверху и снизу. Нестационарные мерзлые породы несут информацию о прошлой холодной эпохе. Ценность извлекаемой информации состоит в том, что она имеет строго количественный характер. Это первые количественные данные о палеоклимате, полученные непосредственно из анализа современного состояния мерзлых пород. Это-окно в реальную историю развития мерзлых пород в эпоху резких климатических изменений. В дальнейшем развитии нуждается теория стационарных и нестационарных температурных полей и процессов глубокого промерзания земной коры.

Мы придаем большое значение определению возраста многолетнемерзлых пород. До последнего времени считалось, что возраст мерзлых толщ определяется в 40-50 тыс. лет . В результате наших исследований разработана концепция о непрерывном существовании мерзлых пород. Данные мерзлотно-фациального анализа отложений, датированных палеонтологическим и термолюминесцентным методом, свидетельствуют, что многолетнемерзлые толщи Центральной Якутии ни разу не оттаивали в течение более чем 300 000 лет. Это очень важное открытие позволяет по-новому производить реконструкцию палеоклимата, по-иному оценить условия формирования и историю развития мерзлой зоны земной коры.

Исследования подземных вод мерзлой зоны всегда привлекали внимание советских специалистов, так как их сложное взаимодействие с мерзлыми породами является ключом к познанию динамики мерзлых толщ, а сами подземные воды, защищенные от загрязнения, рассматриваются как источник водоснабжения. В последние годы мы занялись исследованиями криопэгов-рассолов, имеющих отрицательную температуру. Мощный напорный горизонт, обнаруженный в северных районах криопэгов, несомненно участвует в конвективном теплообмене и может служить источником глубокого охлаждения горных пород. Криопеги могут осложнять проходку выработок и разработку полезных ископаемых.

В области инженерного мерзлотоведения наибольший интерес представляет внедрение сезоннодействующих жидкостных замораживающих устройств с естественной циркуляцией теплоносителя для управления температурным режимом грунтов в северном строительстве. Эти устройства применяются в Советском Союзе при строительстве зданий, линейных сооружений и земляных плотин. Большая экономическая эффективность, повышение устойчивости сооружений, возможность строительства в сложных геокриологических условиях делают это направление исследований весьма перспективным.

Настоящая международная конференция по мерзлотоведению должна осветить результаты исследований и охарактеризовать научные и практические достижения за истекшие пять лет, наметить пути дальнейшего развития мерзлотоведения.

В заключение я хочу поблагодарить Оргкомитет за приглашение на конференцию и за гостеприимство, оказанное нашей делегации.

CLOSING PLENARY SESSION
Thursday, 13 July, 1978

Dr. R.J.E. Brown: Welcome to the final session of the Third International Conference On Permafrost. We have been meeting here in Edmonton for the past four days to listen to many excellent papers on all aspects of permafrost, and now we are gathered together for some items of business and a few closing remarks. I would like to thank all of you on behalf of the Organizing Committee for attending the Conference. I am sure you will agree, that we have had four days of very fruitful discussion with friends from many countries involved in permafrost work and I know that we look forward to continuing these contacts in the days ahead.

There are several items to be discussed in this session. The first is the possibility of forming some sort of international permafrost association similar to those in other fields of interest. In the past, there has been no such group in this particular field, partly because we have had only a few international conferences. Furthermore the field of permafrost is extremely varied and interdisciplinary and attempts to join with one or another international organization have proven difficult in terms of satisfying everyone's requirements and interests. Earlier this week the heads of the delegations of Canada, United States, Soviet Union and the People's Republic of China held an informal meeting at which we discussed this matter. It was agreed that it would be worthwhile to investigate what would be involved in forming an international association. It was discussed several months ago at the last meeting of the Organizing Committee for this Conference and we agreed that we would be willing in Canada to establish an *ad hoc* secretariat to look into the possibility of forming some sort of association. There are difficult problems to be faced such as deciding on the structure of an association, relations with other similar groups, relation of national committees to an international association, etc. Dr. Gold and I agreed to look into this matter on behalf of the other countries involved in permafrost. Hopefully in the near future we will be able to formulate some proposal which meets with your approval to proceed with the formation of an international association. If any of you wish to write to me at a later date to ask how these matters are proceeding, I will be pleased to inform you of our progress. We will circulate written communications about our deliberations.

The next item on this afternoon's program is that Professor Melinkov, the head of the Soviet Delegation, wishes to make a few remarks.

Professor P.I. Melinkov: Mr. Chairman, Ladies and Gentlemen, I and the entire Soviet delegation have been very pleased to participate in this Conference. I took part in the work of the First International Conference On Permafrost. I was the chief organizer of the Second Conference and now we are here at the Third Conference. I am glad to see that the number of participants is continuously growing, and I hope that there will be twice as many people at the Fourth International Conference. In the Soviet Union we have more than 1,000 scientists and technicians working in the field of permafrost science. Two departments at Moscow State University are training experts in permafrost. A new department is being established at the University of Yakutsk and will begin functioning later this year. As for permafrost engineering, quite a few departments across the country are giving lectures and courses on the subject. As you know, our permafrost region occupies roughly 50% of the total dry land of the Soviet Union. More and more effort is being put into the development of our northern regions, and the need for permafrost experts is continuously growing. I do not know how permafrost scientists are being trained in Canada and the United States, but I feel that this aspect is extremely important. I feel that the creation of a new international association is relevant to this and it is hoped that it will be able to have some influence in developing new methods for training permafrost scientists.

We fully support the idea of this new association. At the Second Conference I did have some discussions with Dr. Brown and Dr. Péwé about the possibility of publishing an international journal on permafrost. Somehow this was never mentioned again and it appears that nothing has been done. I think that when we begin discussions about organizing this new association, we should also mention this possibility of publishing a new journal on permafrost.

Now I would like to leave a souvenir with the Chairman of the Organizing Committee for the Third International Conference, my very good and old friend, Dr. Roger Brown. It is a very ancient Yakut vessel called a "sharom". We have a national holiday in the Yakut Republic and on this day the people drink kumiss (mare's milk) from this vessel. We tried to find the most ancient vessel available in the Yakut Republic. There are various designs on this particular vessel and a special one which indicates that it was made entirely by hand at least 150 years ago. There is some information concerning the fact that when the famous Shergin shaft was being sunk in Yakutsk, the renowned Russian geographer and scientist Middendorf was passing through the area and it is quite possible that he drank from this vessel. It is of course a museum piece of the greatest historical value and in order to bring this vessel to Canada we had to obtain special permission from our Ministry of Culture. It is with great pleasure that I am leaving this souvenir here with colleagues who work in this new and wonderful field of permafrost science.

Dr. R.J.E. Brown: Professor Melinkov, thank you very much for this very beautiful gift which you have given to us. It is a great privilege for me to be the trustee of this very beautiful vessel. I will take it to Ottawa and put it on display at the National Research Council of Canada. People will be able to see it, and learn of the generosity of you and your Soviet colleagues. I hope that some day in the not too distant future, perhaps at the first meeting of the new international permafrost association, we might in the Yakutian tradition, fill the vessel with kumiss and pass it around so that all may drink from it. I should like people here to have the opportunity of examining this beautiful object so I will leave it on the table. Again our sincere thanks to Professor Melnikov.

Now I would like to call on Dr. Péwé, the leader of the delegation from the United States for some remarks.

Dr. T.L. Péwé: Thank you, Mr. Chairman. It was in 1962 that a small group of scientists and engineers, spurred on by Dr. K.B. Woods, on behalf of the National Academy of Sciences of the United States organized a meeting that was held in 1963. We know now of this meeting as the First International Conference On Permafrost. It was the result in large part of the expansion of interest in permafrost during the Second World War and immediately afterwards. The Soviet Union which has a long record of systematic studies in permafrost, in large part associated with their national Academy of Sciences, moved this activity rapidly through the stage of what might have been called a group, to a committee, then a commission, and finally an institute. It is this Permafrost Institute under the direction of Professor Melnikov which planned the historic Second International Conference On Permafrost at Yakutsk in 1973. Continued and rapid expansion of permafrost investigations and the utilization of northern resources ensued. Now only five years later today permafrost has come of age with the Third International Conference On Permafrost hosted by Canada. On behalf of the United States delegation and all participants from my country, I want to thank you, Mr. Chairman, and your industrious staff, for the wonderful Conference that you and your group have organized. We have all profitted greatly from the opportunity to exchange information with workers from all parts of the world. Now with the importance of permafrost and the number of permafrost investigations increasing every day, it is appropriate that this international exchange be continued.

It gives me great pleasure to submit an invitation to host the Fourth International Conference On Permafrost on behalf of the National Academy of Sciences of the United States through the Polar Research Board of the Academy. I have been authorized to extend this invitation for the Fourth Conference in the United States perhaps in four or five years. Furthermore, I am happy to report that this generous invitation has come from the centre of the permafrost area of the United States and from my former institution. One of the centres of permafrost research in the United States is in Fairbanks, Alaska. From the days of the placer gold mining in 1902 until today, central Alaska has been an area of various permafrost investigations. Through the courtesy of Dr. Howard Cutler, Chancellor of the University of Alaska at Fairbanks, I am authorized to extend an invitation from that university to host the Fourth International Conference On Permafrost on its campus.

The United States welcomes all of you here and all permafrost workers throughout the world to this forthcoming Conference. Thank you very much.

Dr. R.J.E. Brown: Thank you very much, Dr. Péwé. On behalf of the Organizing Committee for the Third International Conference On Permafrost and the participants at this Conference, I am very pleased to accept your invitation and we look forward to receiving news of developing arrangements for the next Conference. It is very fitting indeed that we have received this opportunity to visit Alaska a few years from now, to see the permafrost region which lies between northern Canada and Siberia. In the course of about ten years, we will have met in virtually all of the permafrost regions in the northern hemisphere. Again we thank you very much, Dr. Péwé.

To continue this thought for a moment, during the meetings here, I am certain that you have all noticed a large banner hanging on the wall at one end of this room. The name of our international permafrost conference is on it in the three official languages. The logos or emblems of the Second and Third International Conferences On Permafrost are in the lower left-hand corner and a space for the one of the First Conference, if one exists. I should like to present this banner now to Dr. Péwé and I charge him with the responsibility of looking after it until the next Conference. Our American colleagues can place the emblem for the Fourth Conference on the banner and for the First, if they wish to invent one.

Dr. T.L. Péwé: Thank you Mr. Chairman and the workers, and the artist who created this wonderful piece of work. I hope that I can keep track of it over the next few years and when the time comes, it will be prominently displayed with two additional logos.

Dr. R.J.E. Brown: We have now reached the end of the formal program for this Third International Conference On Permafrost. Soon we will be going our separate ways, some of us on the field trips, which leave Edmonton tomorrow morning. Again I would like to say thank you very much for coming, and until we meet again, best wishes to everyone. I declare the Third International Conference On Permafrost to be officially closed. Thank you very much.

POSTER SESSIONS/SÉANCES DE PLANCHES EXPLICATIVES

1. CARD, J., Sun Oil Company Limited, Calgary, Alberta, Canada.

   RECOGNITION OF PERMAFROST EFFECTS IN REFLECTION SEISMIC DATA.

2. CRAMPTON, C.B., Department of Geography, Simon Fraser University, Burnaby, B.C. Canada.

   SYNERGISM AND MULTIPLE-RESOLUTION ANALYSIS FOR TERRAIN EVALUATION.

3. EVERETT, K.R., Institute of Polar Studies, Columbus, Ohio, U.S.A.

   WEBBER, P.J. and WALKER, D.A., Institute of Arctic and Alpine Research, Boulder, Colorado, U.S.A.

   BROWN, J., U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, N.H., U.S.A.

   GEOECOLOGICAL MAPPING IN ALASKAN COASTAL TANDRA.

4. GILL, D. and KERSHAW, G.P., Department of Geography, University of Alberta, Edmonton, Alberta, Canada.

   PALSA-PEAT PLATEAU STUDIES IN THE MACMILLAN PASS - TSICHU RIVER AREA, NORTHWEST TERRITORIES, CANADA.

5. GIMBARZEVSKY, P., Canadian Forestry Service, Environment Canada, Ottawa, Ontario, Canada.

   AIR PHOTO ANALYSIS OF PERMAFROST LANDSCAPES.

6. JESSBURGER, H.L., Department of Civil Engineering, Ruhr University, Bochum, Federal Republic of Germany.

   THE FIRST INTERNATIONAL SYMPOSIUM ON GROUND FREEZING.

7. KAY, B.D., GROENEVELT, P.H. and JACKMAN, J.A., Department of Land Resource Science, University of Guelph, Guelph, Ontario, Canada.

   THE UTILITY OF GAMMA RADIATION IN MEASURING WATER AND SOLUTE TRANSPORT IN SOILS FREEZING UNDER LABORATORY CONDITIONS.

8. KLOHN, E.J., Klohn Leonoff Consultants Limited, Vancouver, B.C., Canada.

   CONSTRUCTION IN PERMAFROST TERRAIN.

9. KLOHN, E.J., DAVISON, D.M., and EDGEWORTH, A.L., Klohn Leonoff Consultants Limited, Vancouver, B.C., Canada, and Calgary, Alberta, Canada.

   INSULATED FOUNDATIONS.

10. OLHOEFT, G.R., U.S. Geological Survey, Denver, Colorado, U.S.A.

    EFFECTS OF MAN MADE STRUCTURES ON PERMAFROST AS SEEN BY RADAR.

11. PILON, J.A. and PICHETTE, D.R., Defence Research Establishment, Department of National Defence, Ottawa, Ontario, Canada.

    THE D.R.E.O. SOIL TEMPERATURE PROBE.

12. REID, R.L., Department of Mechanical Engineering, University of Tennessee, Knoxville, Tennessee, U.S.A.

    GOLDSTEIN, M.E., NASA Lewis Research Center, Cleveland, Ohio, U.S.A.

    FREEZING AND THAWING OF PERMAFROST IN THE PRESENCE OF GROUNDWATER FLOW.

13. VAN EVERDINGEN, R.O., Hydrology Research Division, Environment Canada, Calgary, Alberta, Canada.

    FROST BLISTERS (HYDROLACCOLITHS) AT BEAR ROCK, N.W.T.

14. VAN EVERDINGEN, R.O.,Hydrology Research Division, Environment Canada, Calgary, Alberta, Canada.

    KARST IN PERMAFROST TERRAIN NEAR GREAT BEAR LAKE.

15. WILSON, M.D., Department of Geology and Geophysics, Boise State University, Boise, Idaho, U.S.A.

    PATTERNED GROUND OF EROSIONAL ORIGIN, SOUTHWESTERN IDAHO.

FILMS

Title: 1. THE JAMES BAY DEVELOPMENT (20 minutes)

Subject: Field investigations in connection with the James Bay Hydroelectric Project in Northern Quebec.

Address:
Mrs. Dextraze,
Société de Développement de la Baie James,
800 est, de Maisonneuve,
Montréal, Québec, Canada.

Title: 2. SUB ZERO POWER (20 minutes)

Address:
Mrs. Dextraze,
Société de Développement de la Baie James,
800 est, de Maisonneuve,
Montréal, Québec, Canada.

Title: 3. EDGE OF EVOLUTION (40 minutes)

Subject: Northern ecology, especially in connection with muskeg.

Address:
Imperial Oil Limited (Distributed by City Films),
Esso Building,
2 Place Ville Marie,
Montreal, Quebec, Canada.

Title: 4. THE MISSING LINK (20 minutes)

Subject: Construction of a landing strip in the Arctic.

Address:
Dr. G. Jacobsen,
The Tower Company Limited,
Suite 15,
1390 Sherbrooke Street West,
Montréal, Québec, Canada.

Title: 5. NORTH TO TUK (20 minutes)

Address:
Mrs. Anne Burnett,
Federal Commerce and Navigation Limited,
Stock Exchange Tower,
800 Victoria Square,
Montréal, Québec, Canada, H4Z 1C4.

Title: 6. TRIAL BY ICE (40 minutes)

Subject: Investigations for gas pipeline construction in the Arctic.

Address:
Ms. B. Underhill,
Publication Editor,
Polar Gas Project,
P.O. Box 90,
Commerce Court West,
Toronto, Ontario, Canada, M5L 1H3.

Title: 7. ICE ACTION ON BRIDGE PIERS (30 minutes)

Address:
Mr. S. Beltaos,
Research Officer,
Alberta Research Council,
303 Civil-Electrical Building,
University of Alberta,
Edmonton, Alberta, Canada, T6G 2G7.

Titles:
8. THE PERMAFROST FRONTIER (25 minutes)
9. PIPELINE (20 minutes)

Address:
Mr. John Ratterman,
Public Relations Department,
Alyeska Pipeline Service Company,
1825 South Bragaw Street,
Anchorage, Alaska, U.S.A. 99504.

Titles:
10. THE MANHATTEN ODYSSEY (10 minutes)
11. HOW TO BUILD AN IGLOO (10 minutes)
12. NORTHWEST PASSAGE (27 minutes)
13. SEARCH INTO WHITE SPACE (17 minutes)

Address:
Mrs. Juliette Bastien,
Film Librarian,
National Film Board,
10031 - 103 Avenue,
Edmonton, Alberta, Canada, T5J 0L9

EXHIBITORS/EXPOSANTS

1. ARCTIC FOUNDATIONS INCORPORATED

Products on Exhibit: Thermo-ring piles, rigid and flexible thermo-probes.

Mailing Address:
Arctic Foundations Inc.,
6613 Arctic Blvd.,
Anchorage, Alaska, 99502
U.S.A.

2. CROWLEY ALL TERRAIN CORPORATION

Products on Exhibit: CATCO RD-85 with RDT-45 trailer unit. Designed to carry large payloads in the Arctic over unprepared surfaces with minimum damage to surface and vegetation.

Mailing Address:
Crowley All Terrain Corp.,
Fourth & Battery Bldg.,
2401 Fourth Ave.,
Seattle, Washington, 98121
U.S.A.

3. DOW CHEMICAL OF CANADA LIMITED

Products on Exhibit: Styrofoam Hl brand extruded, expanded polystyrene foam insulation.

Mailing Address:
Dow Chemical of Canada Limited,
P.O. Box 1012,
Sarnia, Ontario, Canada,
N7T 7K7.

4. EBA ENGINEERING CONSULTANTS LIMITED

Products on Exhibit: In recent years EBA Engineering Consultants Limited have been involved in numerous, unique projects throughout the Canadian north. A general slide presentation and photographic display of some of these sites, projects and field activities will be shown including specialized laboratory and sampling equipment.

Mailing Address:
EBA Engineering Consultants Ltd.,
14535-118 Avenue,
Edmonton, Alberta, Canada.

5. FIBERLITE PRODUCTS COMPANY LIMITED

Products on Exhibit: Sections of U-Dor, self contained and self supporting insulated services for sewage and water lines, and demonstrations of service connections for Utilidets and hydrants.

Mailing Address:
Fiberlite Products Co. Ltd.,
4920-76 Avenue,
Edmonton, Alberta, Canada.

6. GEOLOGICAL SURVEY OF CANADA

Products on Exhibit: Light weight soil drilling and sampling equipment designed for frozen ground and remote areas. Designed by Terrain Sciences Division and Technical Field Support Services, Department of Energy Mines and Resources.

Mailing Address:
Geological Survey of Canada,
Dept. of Energy, Mines & Resources,
601 Booth Street,
Ottawa, Ontario, Canada
K1A 0E8.

7. GEONICS LIMITED

Products on Exhibit: Electromagnetic instrumentation for the remote measurement of terrain electrical conductivity from the surface or in the air.

Mailing Address:
Geonics Limited,
1745 Meyerside Drive,
Mississauga, Ontario, Canada
L5T 1C5.

8. R.M. HARDY AND ASSOCIATES LIMITED

Products on Exhibit: R.M. Hardy and Associates Ltd. will demonstrate its experience in singular and multi-disciplined technologies of geotechnical, materials and metallurgical engineering, environmental and chemical sciences related to construction and resource development in arctic and subarctic regions and display applications of analysis design and field and laboratory testing capabilities.

Mailing Address:
R.M. Hardy & Associates Ltd.,
P.O. Box 746, 4810-93 Street,
Edmonton, Alberta, Canada,
T5J 2L4.

9. SLOPE INDICATOR COMPANY

Products on Exhibit: Instruments for the geotechnical, geophysical, structural, mining, hydrological and rock mechanics fields.

Mailing Address:

Slope Indicator Company,
3668 Albion Place North,
Seattle, Washington, 98103
U.S.A.

10. U.S. ARMY COLD REGIONS RESEARCH AND ENGINEERING LABORATORY

Products on Exhibit: The U.S. Army Cold Regions Research and Engineering Laboratory seeks to discover and understand the natural phenomena of cold regions, especially winter conditions, and to devise and refine methods for building, travelling, living and working there. Studies pertain to characteristics and events unique to cold environments, and to design of facilities, structures, and equipment used in these environments.

Mailing Address:

U.S. Army Cold Regions Research and Engineering Laboratory,
Box 282, Lyme Road,
Hanover, New Hampshire, 03755
U.S.A.

11. WESTBAY INSTRUMENTS LIMITED

Products on exhibit: Groundwater instrumentation: multiple piezometers, multiple zone sampling systems. Geotechnical instrumentation: combined piezometer inclinometer system. Piezometric permeability profiles.

Mailing Address:

Westbay Instruments Ltd.
Suite 1B, 265-25th Street,
West Vancouver, B.C., Canada,
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