Stability of Dykes Embankments at Mining Sites in the Yellowknife Area
Stability of Dykes Embankments at Mining Sites in the Yellowknife Area

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Indian Affairs and Northern Development
LAND Publication No. QS-3037-000-EE-A1

This report was prepared under contract for
the Arctic Land Use Research Program,
Northern Natural Resources and Environment
Branch, Department of Indian Affairs and
Northern Development. The views, conclusions and recommendations expressed herein
are those of the author and not necessarily
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ALUR 72-73-31
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ACKNOWLEDGMENTS

The present study has been greatly facilitated by a score of people that it would be too long to name here. Nevertheless, we wish to acknowledge, in particular, the helpful guidance and assistance of officers from the departments of Northern Affairs and Energy, Mines and Resources, in Yellowknife, N.W.T. Their constant help in facilitating field trips and personal contacts is gratefully remembered. Authorities from the two mines operating in Yellowknife, Giant Yellowknife Mines and Cominco Con Mines, must also be thanked for their constant cooperation in allowing researchers on their premises and bearing with the inconveniences involved. We acknowledge also assistance from the department of Environment Canada, in planning the program and especially that of the Western Water Quality Station, in Calgary, Alta., in providing with reliable and indispensable analytical services. Finally we wish to recognize the assistance from researchers of the University of Alberta.
SUMMARY

In this study, the major engineering factors relied to the investigation, design and operation of tailings embankments in Arctic regions, are considered. Factors affecting stability of tailings embankments and the methods of design analysis as stability, settlement, seepage, drainage and water bodies, are discussed with the considerations to the Arctic condition. Two mining sites have been investigated to study the considerations on stability of dykes embankments. The field investigations are located in Yellowknife area, North of The Great Slave Lake in the Northwest Territories.

The following important points as tailings system, design of dykes, ground temperature observations, thermal regime and settlement, have shown that the design and construction of mine waste embankments in northern regions must be approached in terms of the problems peculiar to the extreme climatic conditions encountered in Arctic regions.
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I. INTRODUCTION

In order to establish mine regulations in the Northwest Territories, a general engineering survey was undertaken in 1970 by the "Centre de Recherches sur l'Eau" (CENTREAU) of Laval University on the existing tailings disposal system located in the area of Yellowknife.

A major part of the objectives of the program was to undertake studies for the design and operation of tailings disposal systems in extreme climatic and permafrost conditions, and to develop preliminary guidelines covering the design, construction and operation of tailings dams. These guidelines may be placed into two broad categories: guidelines concerning the safety of the dam and appurtenant structures, and guidelines concerning the prevention of pollution. Both types of guideline affect the design of the tailings embankment facilities.

A good tailings embankment design must satisfy the basic requirements of safety, pollution control, storage capacity and economy. To achieve this, the design must be based on a thorough understanding of both the geotechnical problems involved, and the requirements of the mining development.

The purpose of the present report is to outline the major engineering
factors that should be considered in the investigation, design and operation of tailings embankments in Arctic regions. The types of foundation, the stability of the dykes, the seepage and the temperature regime in the dykes will be discussed from the observations undertaken in the mines of Yellowknife.

It is not our intention in the present report to discuss at length the problems associated with the design of tailings embankments, which have already been treated in the "Mines Branch Technical Bulletin, TB 145" (1972), and by Klohn (1972). However, we propose to stress particular points related to the problems of construction and operation of tailings ponds in Northern areas.

General considerations will be given in chapter II concerning the problems of permafrost and of the freezing and thawing conditions in the soils met in Arctic regions.

Field data obtained from the mining sites of Yellowknife will be presented and discussed in chapters IV and V; these data concern mainly design, settlement, seepage and thermal regime through dykes under operation, at Giant Mine and Cominco Mine of Yellowknife.
II. GENERAL CONSIDERATIONS

2-1. Purpose of Mine Waste Embankments

The purpose of waste embankments is the storage of solids. However, tailings ponds usually must be used to store temporarily a certain minimum volume of water for clarification prior to reclaim for plant use or discharge to adjacent streams.

Usually, the reclaim of water from tailings ponds will require that a tailings embankment retain a certain minimum volume of liquid for sedimentation of the suspended solids. Where tailings pond effluent would be a serious pollutant, tailings embankments may have to be designed to retain as much water as practicable. If this is not possible, it may be necessary to treat the water prior to its release from the pond.

In the Northwest Territories, where the climate is subarctic in character with a long cold winter, a particular purpose of the waste embankments is to accumulate water and solids during the freezing period, or to operate all year round by an adequate decantation system which can be operated in cold regions.

When the purpose of a waste embankment is to store solids,
the tailings embankments must be made relatively pervious. However, the storage of solids and water requires the tailings embankment to be relatively impervious.

The study undertaken in Yellowknife area, for instance at Giant Mine and Cominco Mine, showed that the tailings embankments built on these sites are of the pervious type. During the winter, accumulation of ice and solids occurs in the ponds. In these conditions, the accumulation of ice and solids requires very large reservoirs to allow a continuous operation during the long period of winter (7 to 8 months).

2-2. Factors affecting Stability of Tailings Embankments

The resistance to sliding along potential failure surfaces within the embankment and its foundation is a prime factor affecting the stability of an embankment. Shear strength of the material, both cohesive and frictional, and the pore water pressures at the failure surface, control the resistance. Cracking of embankments, which is caused by differential settlements, reduces the shearing strength along potential failure surfaces.

In cold regions, where continuous and discontinuous permafrost zones exist, the strength properties of frozen soils are
greatly reduced following an increase in temperature and when the soil is thawed, the strength may be lost to such an extent that the foundation will not support even light loads. Following thawing, fine-grained soils, which have high moisture contents turn to a slurry with little or no strength, and settlements and perhaps failures in foundation and/or in the embankments may occur. Frost action in the active layer, which freezes and thaws seasonally, may also affect the stability of tailings embankments.

The following features of permafrost are significant in construction of tailings embankments in Arctic regions:

a- the delicate natural thermal equilibrium is particularly sensitive to the natural or man-made change in the surrounding conditions,

b- permafrost is relatively impermeable to moisture and,

c- the ice content of frozen ground is a most important consideration. Fine-grained materials and organic materials, which usually have extremely high ice contents and are susceptible to freezing action, present the most severe problems. As long as the water remains frozen in such soils, the ice binds the individual particles together to produce a material with considerable strength; when thawed, however, these soils may change to soft materials with low or no strength.
2-3. **Methods of Design Analysis**

The methods of design and analysis for tailings embankments including its foundation and abutments must meet the following criteria:

i) The embankment and abutment must be stable and must not develop objectionable deformation under all conditions of construction and operation.

ii) Seepage through the embankment, foundation and abutment must not result in piping, sloughing or solution of material.

The approach to design consists in arranging embankment materials in a tentative section with regard to strength, permeability and economy, and performing some form of analysis to estimate the stability of the proposed section under anticipated loading conditions.

2-3.1 **Stability**

The result of a stability analysis is usually expressed in terms of a safety factor, which is the ratio of the average shearing resistance mobilized along a
potential surface of failure to the shear stress acting along that surface and resulting mainly from the weight of the material over that surface. The results of the stability computations depend on the shear strength selected, on the pore water pressure acting along the surface and on different other factors influencing the method used for computing the factor of safety.

The current procedures used for determining the safety factors of tailings embankments are based on the following fundamental methods:

i) Method of circular arc.

ii) Method of planes or wedges.

iii) Method using combinations of arcs and planes.

As stability analysis is a procedure of successive trials, a potential failure surface is first chosen and the factor of safety against sliding along that surface is determined. Different potential failure surfaces are then selected and the analysis is repeated until the most critical failure surface corresponding to the lowest factor of safety is found. The factor of safety against sliding along the critical failure surface is the relevant factor of safety for the slope.
The construction of tailings embankments on terrain underlain by permafrost will often alter the thermal regime to such an extent that melting of permafrost may result. Some examples in which this phenomenon has occurred are impounding of reservoirs, stripping of vegetation and the effects of building foundations. At a low rate of melting, the ensuing water will flow from the soil at about the same rate as the ice is melting. No appreciable excess pore pressure will result and settlement will proceed concurrently with thawing. However, if thawing occurs at a faster rate, excess pore water pressures may be generated, and may endanger the stability of the embankment. Slopes may become unstable and tailings embankment foundations may fail.

Frozen slopes, of course, have a high degree of stability but the active layer, when thawed, may reach a delicate state of equilibrium. Of greater consequence, however, is the fact that if a surface disturbance results in a deeper active layer, the newly thawed permafrost may be less stable than the soil in the older active zone.

The stability of thawing soil is difficult to analyse.
In fine-grained soils where high ice content is being thawed rapidly, the shear strength may become negligible at different periods of thawing. As rapid thawing usually does not occur under practical conditions, it may be expected that some consolidation occurs as thawing progresses with some increase in soil strength.

McRoberts (1972) suggested that quantitative stability predictions may be made by investigating the effects of excess pore pressures that result on the thawing of frozen soils. The work of Morgenstern and Nixon (1971) shows that the factor of safety against the excess pore water pressures due to thawing consolidation and resulting parallel seepage, is given by the following expression:

\[
F = \frac{\gamma'}{\gamma} \left[ 1 - \frac{1}{1 + \frac{1}{2R^2}} \right] \tan \phi' \tan \theta
\]

where \( F \) = factor of safety
\( \gamma', \gamma \) = effective and total unit weight
\( \theta \) = slope angle
\( \phi' \) = effective strength parameter

with \( R = \frac{a}{2 \sqrt{Cv}} \) = thaw consolidation ratio
\( Cv \) = coefficient of consolidation, and
\( a \) = rate of thaw, a constant in the Newmann's solution.
This study indicates that any natural or artificial change that increases the rate of thaw will contribute to the slope instability and that the predominant variables which influence both the rate of thaw in frozen soil and the rate at which the water produced by thaw can be squeezed out of thawed soil, are of fundamental importance in thaw slope stability.

Excess pore pressures and the degree of consolidation in thawing soils are dependent principally on the thaw consolidation ratio $R$. This parameter is a measure of the relative rates of generation and expulsion of excess pore fluids. As a first approximation, a value of $R$ greater than unity would appear to predict the danger of sustaining substantial pore pressures at the thaw front and hence the possibility of instability.

This analysis is capable of extension to a variety of melting and loading conditions of practical interest. However, considerable laboratory and field data are needed to assess the practical limits to the application of this analysis.

2-3.2 Settlements

The weight of a tailings embankment, together with that
of the water reservoir overlying the upstream slope, causes settlements in the foundation, ranging from a few inches at sites with hard rock to many feet at tailings embankments underlain by thick deposits of compressible soils such as clay and muskeg.

The magnitude of the foundation settlement will depend on the height of the embankments, the depth and thickness of the compressible strata within the foundation and their compression indices. The rate at which the foundation settlements occur will depend on: the magnitude of the change in vertical stress, the permeability of the compressible material, the drainage characteristics of the foundation and the conditions prevailing in the foundation such as thawing of frozen ground. Where fine-grained soils with high ice content are encountered in the zone of continuous permafrost, every effort can be made to preserve the frozen conditions, and minimize settlements. In some cases, in either the continuous or discontinuous zone, it may not be possible to prevent thawing of the ground during the life of the embankment and settlement must therefore be anticipated and taken into account in the design.
As discussed in the previous section, the excess pore water pressures generated in tailings embankments by thawing will cause important settlements and differential settlements may be aggravated.

A recent study by Morgenstern and Nixon (1971) has shown that the excess pore pressures and the degree of consolidation in thawing soils are dependent principally on the thaw consolidation ratio $R$ defined by the following expression:

$$ R = \frac{\alpha}{2 V C_v} $$

where $R$ is the thaw consolidation ratio, $\alpha$ is a constant determined in the solution of the heat conduction problem, and $C_v$ denotes the coefficient of consolidation.

As a first approximation, a value of $R$ greater than unity would appear to predict the danger of sustaining substantial pore pressures and hence the possibility of instability.

To prevent settlements, foundations and engineering facilities in permafrost areas are usually designed to
preserve the frozen condition of the ground in order to prevent thawing with potential settlement and stability problems, and to utilize the relatively high strength of frozen material. Where thawing of the frozen ground cannot be prevented, the rate and extent of degradation are factors that must be taken into consideration in the design. The thermal interplay between the atmosphere, the structure and the ground are basic considerations in foundation design.

Preventing degradation and encouraging aggradation of permafrost is accomplished by insulating the ground surface, isolating the structure from the ground, or a combination of both methods. Fills or pads are widely used not only for foundations but also to protect the surface cover from disturbance due to construction operations.

Lachenbruch (1959) has shown that the ability of a fill to maintain the frozen condition in the foundation material depends on its diffusivity and thermal contact coefficient and the contact coefficients of all underlying layers which are sufficiently close to the surface to produce appreciable effects.
Because of the possible effects that thawing the permafrost may have on the integrity of structures and stability of the terrain, it is imperative that engineers acquire the capacity to predict the consequences of their activity on ground temperatures, and develop design and construction techniques that will be acceptable for permafrost areas.

2-3.3 **Seepage, Drainage and Water Bodies**

One of the most important considerations in the design of dykes and tailings embankments for a given site is the choice of a cross section in which the seepage forces will be located so as to cause no trouble, or will be controlled in a positive and efficient manner.

Cedergrin (1968) specified that most failures caused by ground water and seepage can be classified in one of the two following categories:

i) Those which take place when soil particles migrate to an escape exit, causing piping or erosional failures;

ii) Those which are caused by uncontrolled seepage pattern and lead to saturation, internal flooding, excessive uplift, or excessive seepage forces.
Provisions for seepage control have two independent functions: reduction of the loss of water to an amount compatible with the purpose of the project, and elimination of the possibility of a failure of the structure from piping.

Control of seepage pressures and resulting erosion are the important considerations for the stability of tailings embankments. Regardless of the rate of leakage, seepage pressures must be controlled so that quick conditions and piping do not develop.

Pollution control requirements may necessitate the use of special design features, such as impervious cores, cut-offs, blankets, etc... to maintain the rate of leakage from the tailings ponds within tolerable limits.

The position of the phreatic surface within an embankment has a marked influence on its stability. If the permeability of the bulk of the embankment fill is of the same order of magnitude or is less than the tailings adjacent to the embankment, drains should be provided beneath the downstream shell of the embankment to
lower the phreatic surface. The drainage system may consist of granular blankets or strip drains.

The use of such drainage systems may be of a good efficiency in most areas through Canada. However, in Arctic region, it is not guaranteed that the same systems may operate properly. Frost penetration below the downstream face may reduce considerably the effectiveness of drainage which may become blocked by ice. The formation of ice and surface sloughing with subsequent thawing may cause sink holes and sliding of slopes. Even worse, they may create voids in the embankment, which, if connected to the upstream face, may result in concentrated seepage flows and possibly lead to failures by piping.

The thawing effect of water is of particular importance to the engineer in the design and performance of structures that impound water, such as dams and dykes.

Due to the relatively high heat capacity and latent heat of water, a large amount of heat can be transferred from one area to another by seepage or stream flow, or by evaporation and condensation. Because of its
heat storage capacity, surface and subsurface water exerts an important influence on the ground thermal regime. Standing and moving bodies of water can inhibit the formation of permafrost. Flooding or ponding of water in areas underlain by permafrost imposes a new temperature on the ground surface. Thawing of the permafrost may occur as the ground thermal regime adjusts itself to the new conditions.

In permafrost areas a thawed zone is always found under lakes and streams that contain unfrozen water throughout the year. Although such water bodies have the greatest thermal effect on permafrost, small ponds that freeze to the bottom each winter also influence and modify the ground thermal regime. The thermal effect of a water body can be felt not only below but also to some distance beyond the waterland interface. Where a thawed basin exists beneath a lake or stream the boundary between the unfrozen and frozen materials is usually found at or immediately adjacent to the edge of the water. However, its location depends upon a number of factors including the water depth, soil type and thermal characteristics of the water and soil. Examples of changes in the ground thermal
regime under lakes and reservoirs in permafrost areas have been reported by Johnston and Brown, 1964 and Johnston 1969.

Interruption of the natural surface and subsurface movement of water may have serious consequences if drainage is not considered or inadequate drainage facilities are provided. The effects of even shallow ponds as observed in tailings ponds of mines of Yellowknife, which may or may not freeze to the bottom during the winter, must be recognized. Settlement and stability are major considerations but, in addition, the availability of moisture can introduce or increase the detrimental effects of frost action on structures and engineering facilities.
III. DESCRIPTION OF SITES STUDIED

3-1. Location

The mining sites studied in the field investigations described in the present report are located in the Yellowknife area, North of the Great Slave Lake, along the Yellowknife Bay in the Northwest Territories. The two mines are Giant Mine and Cominco Mine of Yellowknife.

The Giant Mine, property of Yellowknife Mines Limited, is on the north shore of Great Slave Lake (62° 30' N, 114° 21' W) adjacent to the mouth of the Yellowknife River, and approximately four miles north of the town of Yellowknife (fig. 1).

The Cominco Mine is located a few miles southwest of the town of Yellowknife (62° 27' N, 114° 28' W) as shown on fig. 1.

3-2. Topography and Geology

The topography of the Yellowknife District is typical of the Precambrian Shield. Viewed from Berry Hill which
is the highest topographic feature within the district, the country is a peneplain strongly lineated by many valleys and rocky hills. With the exception of the lakes, the rivers and the organic deposits, the district features a surface of a nearly continuous rock outcrop. Exceptional opportunities exist for the observation and the study of the complex geological features, due to the fact that large forest fires have destroyed the once existing moss, lichen, and tree growths.

The district was once severely glaciated during the Pleistocene and erratic "roches moutonnées", outwash sand gravel plains, eskers, glacial lacustrine clays, and other glacial features, are present in many areas. The town of Yellowknife is built on a sand plain east of Sand Lake, and the airport rests on the broad sand plain south of Long Lake. The sand plain offers excellent construction sites. Abandoned beaches are found locally throughout the area. These are located at least 240 feet above Great Slave Lake in places and probably represent glacial material that has been reworked by wave action.

Yellowknife is in a region of discontinuous permafrost. According to Bateman (1949), permafrost is absent beneath rock ridges or outcrop areas, but is generally present
beneath deep overburden. He states that the depth of permafrost, which in some areas goes to 280 feet or more, is directly related to the thickness of the overburden. The same author suggests that the permafrost may have originated in late glacial time and was preserved by the insulating cover of clay, sand and muskeg. He mentions also that ice veins, filling cavities in late faults and fractures, have been observed in the permafrost zone down to depths of at least 250 feet.

All the consolidated rocks within the district are Precambrian in age (Henderson, J.F. & Brown, I.C., 1966). The oldest rocks, division A of the Yellowknife group, are a succession of massive and pillowed andesite and basalt flows with interbedded dacite flows, tuffs and agglomerates. Some flows are pillowed and variolitic along strokes for several miles and afford excellent horizon markers. The rocks of division B comprise a thick series of sediments including greywacke, slate quartzite, arkose, argillite and phyllite. Near the base of the series, dacites, trachytes, agglomerates and tuffs are interbedded with some conglomerates and greywacke.

The regional climate, though naturally severe, is not unpleasant. The summers are short, but warm, and the days
pleasantly long; temperatures occasionally reach the high 80's; August is the warmest month with a mean temperature of 60°F. The converse is true of the winter months, with January averaging -20°F. The mean annual air temperature at Yellowknife over the past 22 years is 24°F. Annual precipitation is low at slightly less than 9 inches per year, of which approximately 5 inches is rain.
IV. RESEARCH PROJECT - GIANT MINE OF YELLOWKNIFE

4-1. Tailings System

The tailings disposal of Giant Mine is composed of a series of three ponds which are separated by dykes. Water outflows from pond 1 to pond 2 and from pond 2 to pond 3. The limits of the basin are well defined by rock outcrops and partly by the dyke No. 3 as shown in fig. 2. The drainage area of the tailings water shed is about 0.165 square mile.

The flow direction inside and outside the tailings ponds is shown in fig. 2. The water of the tailings is flowing into the Baker Creek and then to the Great Slave Lake.

Materials such as clay, sand and gravel, are the principal constituents of the surface deposits met in and around the tailings disposal system. The working of the system has been previously described in the annual report LURE 3 (1971).

4-2. Design of Dykes

A longitudinal profile of the actual ponds created by a
series of rockfill dykes are shown in Fig. 3. It can be observed that the dykes No. 1 and No. 2 have been built over rock foundation, whereas the dyke No. 3 has been built over an old tailings deposit.

These dykes have been built of crushed rock from the mine. The grain size distribution curve given in Fig. 4 gives an indication of the size of rock used to build the dykes. The dykes, constructed entirely of the same material, are homogeneous dykes. Very low dykes are almost made of homogeneous material, because their construction tends to become unduly complicated if they are zoned. However, the dyke may then have an internal drainage system.

The use of crushed rock dumped from trucks and leveled by bulldozers with no compaction, resulted in a non-homogeneous grain size distribution of the material. No drainage system, such as downstream or blanket drains, has been incorporated in the dykes.

Any homogeneous dyke with a height of more than about 20 to 25 feet should be provided with some type of drain constructed of material appreciably more pervious than the soil of the dyke. The purpose of such a drain is twofold:
a- to reduce the pore water pressures in the downstream portion of the dyke and hence to increase the stability of the downstream slope against sliding, and

b- to control any seepage water as it exists at the downstream portion of the dyke in such a way that the water does not carry away soil particles of the dyke.

The seepage through the deposited rockfill is dependent not only on the coefficient of permeability but also on local variations such as fissures and large void ratio in the structure of the crushed rock. Where potential seepage is important, such as with tailings embankments retaining water, the possible existence of such fissures and voids should be considered. They often occur in the foundation, at the contact surfaces between the embankment fill and the underlaying foundation and abutments; within the fill itself, in the form of segregated seams of stony material between layers and at contacts between pipes and walls incorporated in the fill. The photos shown in Fig. 5 and 6 illustrate this type of problems met in the operation of rockfill dykes of Giant Mine.

As no specific rules can be given for selecting the inclination of the outside slopes of the dykes, the general
procedure is to make a first estimate on the basis of experience. Homogeneous rockfill dyke on stable foundation is commonly designed with slope equal to the angle of repose of the material. The slopes of dykes observed at Giant Mine are approximately equal to the angle of repose of the material used, i.e. crushed rock. The behaviour of these dykes appears to have ample safety factor against shearing failure of the slope.

An examination of Fig. 7 shows that the dykes are built from the old upstream construction type of tailings dams. This type of tailings dams does not meet conventional requirements for slope stability, seepage control (internal drainage) and resistance to earthquake shocks.

4-3. **Ground Temperature Observations**

A complete description of instrumentation installed in the dyke No. 3, the tailings deposit and the ground downstream the dyke has been described in previous annual reports LURE 3, 1970, 1971. A summary of field installations is shown in Table I and Fig. 8 of the present report.

Variations of temperature with respect to depth and
time were observed for more than two years, and the configuration of isotherm curves in the ground and in the dyke are obtained from temperature readings. This provides the opportunity to present a general view of the total fluctuation during complete cycles. The temperatures confirm that below a certain depth the mean annual temperature is just above $32^\circ$F. During summer, the surface warms up between $60^\circ$ and $68^\circ$F, reaching its maximum temperature usually in July or August, while during the winter months the ground surface temperature decreases to a minimum occurring in January. From Fig. 9, 10 and 11, we can observe the variations of temperature registered by thermocouple cables GT, GT₁, GT₂ and GT₃ shown in Fig. 8. The shape of the curves indicates that there is a large difference in the temperature gradient of the ground during warm and cold seasons. Snow cover and frozen ground properties influence the rate of change in the temperature gradient.

Temperatures observed on this site indicate that the ground temperatures are oscillating with the air temperature but at a smaller amplitude as depth increases. Measurements made with thermocouple cable GT₂ shown in Fig. 10 indicate that the mean annual temperature in the ground (old tailings downstream of dyke) is about $32^\circ$F and is almost
maintained constant below a depth of 20 feet. This shows that below this depth, ground is permanently frozen. Also between 4 and 20 feet, the change in the temperature gradient is approximately zero under the effects of the cold period, while large change is observed under the effects of the warm period.

Thermocouple cable GT is recording the temperature in the waste deposits under water. The monthly variations of these temperatures are presented in Fig. 9. These results provide the opportunity to present a general view of the total fluctuation during an annual cycle. The temperatures indicate that under a depth of about 16 feet, the tailing is continuously in unfrozen condition. A small variation between 33 to 40°F has been observed above a depth of 22 feet, for an annual cycle. Between 0 - 6 feet, the temperature follows approximately the air temperature at the surface of water, while in the upper part of the tailing (between 6 to 16 feet) the temperature decreases below 32°F during the cold season and increases during the warm season. Ice cover formed on the complete depth of water and the frozen tailing underneath insulate and preserve the unfrozen state of the ground.
The thermocouple cable GT$_3$ installed in the dyke No. 3 up to a depth of 37 feet below the crest of the dyke has provided temperature data. Monthly temperatures throughout the dyke obtained from these observations are shown in Fig. 11. The results are similar to those previously described for the tailings zone. Generally, the temperature gradient decreases with respect to depth according to the season. Below 22 feet, the temperature is almost maintained constant with a time lag in the temperature fluctuation relatively to the surface temperature. It can be observed that during the cold season, the temperature in the upper part of the dyke decreases below 32°F without, however, reaching the air temperature. The non-uniform temperature is then influenced by the heat transfer in the rockfill mass.

These temperatures indicate that during winter, seepage flow may be active in the dyke below the depth of about 22 feet. However, from Fig. 9, it is observed that no more water is available under the ice cover in the pond so that no seepage flow is taking place. Temperature observations in the ground downstream of the dyke confirm this result. Seepage flow from the pond may be active only up to November or December. However, it should be
mentioned at this point that the same situation would not prevail if the depth of water in the pond would have been greater.

4-4. Thermal Regime

Monthly isotherms for the three thermocouple cables GT₁, GT₂ and GT₃ placed along cross section perpendicular to the dyke, have been interpreted from the temperature observations and are shown in Fig. 12, 13 and 14.

The temperature pattern across the section of the dyke varies with time according to heat losses and heat gains due to variation in air temperature and in seepage conditions.

The progression in the heat losses during the cold season is very well illustrated in the monthly isotherm curves. The formation of the ice cover is initiated during October in the pond and downstream of the dyke. In the meantime the permafrost may be observed to progress in the ground downstream of the dyke. A continuous ice blanket in the dyke is formed during January and a confined seepage flow may be maintained for a certain period under that blanket.
Later in the cold season, the permafrost surface rises in the ground and coalesces with the ice blanket which had been thickening since the beginning of the cold season. The isotherm curves of May 1972 (Fig. 11) show a frozen ground up to the surface. This implies that no seepage flow may be possible under that condition. However, it is difficult to assume that every year the conditions are the same and that seepage flow is impossible all year round. From the isotherm curves, one can observe that the ice cover increases downward in the pond so that towards the end of the cold season, no water is available between the surface of the ground and the ice cover. When this condition arises, it becomes evident that the confined seepage flow may not be maintained all year round.

All interesting that these results may be, they cannot be generalized to every winter and every dyke in the Northern area. The coalescence of the permafrost table with the ice blanket depends upon many factors which have to be fully appreciated when the design of a dyke is agreed upon. Obviously the presence or absence of seepage plays a major role in that phenomenon and is itself influenced by the depth of water in the pond and by the freezing index of the area. However, a proper use of heat transfer theories may lead to realistic forecast.
4-5. **Settlement**

Bench marks and gauges were installed during the summer 1970 in order to measure settlement of dyke No. 3. Details of the gauges have been reported in LURE 3, 1972. The presence of tailings deposits underneath the dyke should normally result in a large amount of settlements in the foundation. The fill which consists of crushed rock leveled by bulldozers does not contribute appreciably to the observed settlement which is mainly the result of the consolidation of the foundation material. In May 1972, two years after the installation was completed, level survey indicates a maximum settlement of about 8.5 inches. Comparatively to the settlement of about 6 inches reported in the 1972 report, the settlement observed during the last year is not very significant. Due to the fact that the dyke has been built during many years and that no observations of settlements were taken before 1970, it is very difficult to interpret that behaviour since large settlements may normally be expected to take place during construction and immediately after in the following years. There are two possible explanations to that behaviour. One being that the settlement of 2.5 inches observed during the last year corresponds to a
secondary consolidation which is bound to decrease during the coming years. However, it is also possible that, depending on the yearly average temperature, the permafrost table is more or less affected and will appreciably influence the observed settlements; if this so, the settlements might be erratic from one year to another.
V. RESEARCH PROJECT - COMINCO MINE

5-1. Tailings System

The tailings disposal system of the Cominco includes a series of lakes, the first of which, Pud Lake, is located just a few hundred feet from the mill (Fig. 15). This area presents the same geomorphological aspects as those found at Giant Mine with respect to the general shape of the sedimentation basins, i.e. the lakes are surrounded by rock outcrops. However, a slightly flatter topography has been observed with more frequent muskegs and blue grey clay deposits. Permafrost occurs generally in and underneath the muskeg.

Between Kam Lake and Pud Lake, there is groundwater exchange through a low muskeg valley. Cominco Mine Company has cut off the valley to prevent the mill and waste water from flowing to Kam Lake.

5-2. Design of Dyke

The actual ponds created by rock outcrops and dyke are shown in Fig. 15. The dyke is built of crushed rock from the mine. Due to the inaccessibility of the site
by heavy equipment during summer, the dyke has been
constructed during wintertime over the ice and snow.
The material was simply dumped by trucks on the site.
The rock material composing the dyke is non-homogeneous
and the size of crushed rock varies from 0.25 inch to
12 inches.

In the deeper part of the valley, a dyke of about 5 to 8
feet high above ground surface lies on weak foundations
and is about 70 feet large at the crest. Where the dyke
lies on permafrost foundations, the width at the crest
decreases to 10 feet. A plan view of the dyke No. 1
and of the permafrost and unfrozen ground areas is
given in Fig. 16; this figure illustrates also the
superficial geology around the site of the dyke.

Fig. 17 shows by photo a partial view of dyke No. 1
after the thawing period of last spring. The size of
crushed rock used to build the dyke is illustrated and
it can also be observed from that photo that the material
is non-homogeneous. That photo illustrates the failure
of the dyke by erosion during the thawing period. In
that period the pond size was too small to accumulate
water resulting from the thaw and erosion was initiated
on the crest of the dyke up to complete failure by a large breach.

Fig. 18 illustrates a dyke under construction on the site. No preparation of the site and no study were undertaken to investigate the soil conditions underneath before the construction started. As mentioned above, the crushed rocks were dumped by trucks over the ice and snow cover.

5-3. Ground Temperature Observations

Four thermocouple cables were installed at the Cominco Mine since summer 1970 in the drilled holes, as indicated in Fig. 16 and 19,

- the thermocouple cables CT₁ and CT₂ are located downstream of the dyke: CT₁ is placed in the zone of unfrozen muskeg and clay, and CT₂ close to CT₁ but in the permafrost,
- thermocouple cable CT₃ is located in the dyke, and
- the thermocouple CT₄ in the tailings disposal (Pud Lake).

Data on thermocouple lengths and respective positions are given in Table II and Fig. 20. Complete informations
on the instrumentation were presented in previous reports LURE 3, 1971 and 1972.

Observations on the variations of temperature in soil and water with respect to depth and time are quite similar to those discussed for Giant Mine and the interpretation is much the same.

The results obtained by thermocouple cable CT<sub>2</sub> located in the ground outside the pond indicate permanent permafrost in that area, the temperature is maintained just below 32°F all year round, as shown in Fig. 21.

Measurements by thermocouple cable CT<sub>1</sub> (Fig. 22) located in the ground downstream of the dyke indicate a uniform temperature of about 30 to 32°F during the cold period and an increase in the temperature in the first 10 feet during the summer period.

Fig. 23 shows the variations in temperature through the dyke. One can observe that the temperature varies with the air temperature with respect to depth and time. It is interesting to note that the temperature decreases below 32°F on the total depth of the dyke, which
indicates that no seepage takes place during a part of the cold season.

The temperatures registered in and below the pond is shown in Fig. 24. Below a depth of 8 feet, the temperature is maintained over 32°F all year round. It can be noted that at the end of the cold season, all water was frozen in the pond which implies that no water was flowing under the ice cover at that time and that seepage was thus impossible.

5-4. **Thermal Regime**

Monthly isotherms for the four thermocouple cable installations $CT_1$, $CT_2$, $CT_3$, $CT_4$, placed along a cross section more or less perpendicular to the dyke, have been plotted from temperature observations and are shown in cross sections in Fig. 25, 26 and 27.

As in the case of Giant Mine, the temperature pattern is varying with time and is fluctuating in response to the heat exchanges. It can be observed that in the muskeg, clay and permafrost, the heat transfer is slower, comparatively to that in the rockfill dyke.
On the other hand, the temperature fluctuations recorded in the dykes follow promptly the environmental air temperature and the seepage water temperature.

Under the pond and the dyke, no permafrost has been observed during the two years of observation. At the beginning of the cold season, the ice cover forms from the surface in the pond and in the upper part of the seepage flow through the dyke. Later a confined seepage flow may be maintained if water is still available in the pond, which is shown by the monthly isotherm curves of January and February 1972. However, the isotherm curves of March and April 1972 show the closing of the ice cover downstream from the dyke. This implies that the confined seepage flow may be maintained under the ice cover for a certain period or stopped by the formation of ice in the total depth of the pond. A complete cycle of the frozen and thawing period is illustrated in Fig. 25, 26 and 27.

5-5. Dyke Settlement

Observations of the movements of the dyke have been made by means of the bore holes and of a level survey
on three settlement gauges. These gauges are placed mainly on the centerline of the dyke built over the unfrozen muskeg at about 100 feet intervals.

Along the cross section I-I, the large settlement that has occurred in the unfrozen muskeg foundation may be noticed in Fig. 17. It is estimated that, before the dyke was built, the top elevation of the muskeg was 574 feet. Thus, the settlement at present is about 8 feet on the centerline of the dyke and it is not yet completed.

Measurements taken on each settlement gauge after two years and referenced to temporary bench marks established on rock outcrops indicate that a vertical movement varying from 0.65 feet to 0.94 feet depending on the location of each gauge has taken place during that time.

In fact, the volume of rock used to build the first dyke at the beginning of the mining operation has just compensated for the compression of the muskeg under the weight of the rock material which was transported during subsequent years to maintain the dyke crest at the elevation of 579 feet.
On the contrary, along cross section II-II (Fig. 26), the dyke built over muskeg and permafrost is still stable. No appreciable settlement was encountered and the permafrost table which has not been affected by the dyke still constitutes a solid base foundation. This may be explained by the absence of seepage through the foundations in this section of the dyke where the initial level of the surface is higher than in section I-I. This implies that permafrost may be preserved in the ground when no seepage takes place, or else that seepage plays a major role in the melting of permafrost under dykes.
VI. DISCUSSION AND CONCLUSION

The observations made during the present research project have shown that the design and construction of mine waste embankments in northern regions must be approached in terms of the problems peculiar to the extreme climatic conditions encountered in these areas. The construction of structures involving water bodies and seepage is bound to affect the ground thermal regime and produce variations in the elevation of the permafrost table. Although the precise behaviour of a dyke on permafrost is difficult to predict, it is possible to define the main factors which have to be taken into account in order to insure that the structure will be stable and will fulfill its purpose.

Hence, the design and analysis of the tailings embankments and of their foundations and abutments have been considered in the present report under the different aspects of stability, settlement and impermeability as they may be influenced by the presence of water bodies and by variations in the ground thermal regime.

Stability

The construction of tailings embankments or dykes on terrains underlain by permafrost will often alter the thermal regime to such an extent that conditions of instability may result in the slopes or in the
foundations. This occurrence will depend on the type of soil, its ice content and the rate of thaw of the permafrost.

The rapid thawing of a soil with a low permeability and a high ice content may temporarily cause a large increase of the water content resulting in a build up of pore water pressure and a significant decrease of the shear strength; such conditions may lead to failures in the slopes or foundations. However, if the rate of thaw, the permeability and the ice content of the soil are such that the water produced by melting ice drains rapidly enough, the decrease of shear strength may be prevented.

The dykes at Giant Mine and Cominco Mine of Yellowknife are built with crushed rock having a very high permeability; hence no instability conditions may develop in the slopes of the dykes due to pore pressure build up. As for the foundations, it has been observed that the permafrost table was affected by the seepage; however, no instability conditions developed since the dykes were built by stages over the years allowing sufficient consolidation to take place so that the shear strength was kept well over the critical stresses.

Hence, when building a dyke in the North, it is essential to insure that the pore water pressure build up following the thawing of the permafrost in the foundation or of the seasonal frost in the slopes will not result in instability conditions. This may be insured by
a proper choice of dyke material, by an efficient control of seepage in order to keep the permafrost thawing rate to a minimum, and by a rational choice of the geometry of the slopes so as to keep the stress level below the anticipated strength of the thawing soil in the slopes or in the foundations.

Settlements

The settlements which are expected to occur during and after construction of embankments depend usually on the compressibility of the soil in the foundation or in the embankments. In most cases, the compressibility of the fill material is fairly low so that the settlements observed may be attributed to the presence of compressible soils, especially clayey or organic deposits, in the foundations.

When such structures are built in northern areas, they usually rest on foundations of permanently frozen soils with compressibilities which are low and will remain so as long as the soil stays in a frozen state. However, if the permafrost table is affected by the structure resting on the surface in such a way that the soil thaws in the foundation, considerable settlements may result depending on the ice content of the soil; the settlements may be of such a magnitude that the tailings dykes may develop leaking problems which may lead to piping and destruction of the structure.
The dykes which have been observed in Yellowknife are built with crushed rock and it is estimated that the compressibility of the rock fill did not contribute appreciably to the over-all settlements measured. Whenever the permafrost was affected by the structure and especially by the seepage in the foundation, considerable settlements resulted where fine or organic soils were present in the foundation. The major part of these settlements usually takes place during the first year following the construction of the dykes. If no seepage is produced in the foundation the settlements are small or negligible.

Both these cases were observed in Cominco Mine: a certain length of the dyke where seepage was observed to take place in the foundation, has undergone very large settlements whereas in other parts of the dyke, where the permafrost foundation was not affected by seepage, no movement could be observed.

Hence, when tailings embankments are built in northern areas on permafrost foundations, large settlements may be expected to take place; the magnitude of the settlements must be estimated on the basis of the ice content and of the compressibility characteristics of the thawed soils if a proper design of the dykes is sought in order to insure that they will fulfill their role as water and tailings containers.
Seepage

A proper operation of a tailings pond requires the confinement of a body of water of sufficient volume so as to insure an efficient sedimentation of solid particles before the waste water exists from the pond. Both the surface of the pond and the depth of contained water is of importance. The dykes must then be built in such a fashion as to insure their impermeability to water under normal conditions of operation. There are many possible techniques available for achieving that purpose (see Mines Branch Technical Bulletin, TB 145, 1972). The design of tailings dykes for seepage control is pertinent not only to northern areas but to any other regions and follows from good engineering practice. Obviously, if the seepage through the dykes is not under control, neither is the pollution downstream of the dykes.

In Yellowknife, the dykes are built with crushed rock; the resulting porous material incorporates fairly large voids which allows important leaks to develop in many places. As a consequence it was found difficult and even impossible to build up a body of water of sufficient volume for a proper sedimentation of solid particles to take place.

The evaluation of the volume of water to be stored in the pond must take into account the fact that an ice cover forms rapidly at the
beginning of the cold season, thus hampering the exit of water from the pond and resulting in a cumulation of the effluent from the plant in the form of ice layers.

It has been observed in the dykes at Yellowknife that at the same time that the ice cover is forming in the pond, an ice blanket also forms in the downstream face of the dyke. The seepage will then be confined between the ice blanket and the permafrost table; that situation will prevail until the bottom of the ice blanket progressing down into the soil coalesces with the permafrost table, at which time any seepage will be prevented. From the isotherm curves obtained, it has been observed that the end of seepage coincides with the time when the ice cover reaches the bottom of the pond so that no more free water is available.

A situation is then reached when no more water is flowing out of the pond neither by seepage nor by surface flow, so that the mine effluent will have to be stored in the pond in the form of ice layers during few months. If the usable storing volume of the pond is not sufficiently large, the dykes may be overflown by layers of iced effluent with undesirable consequences at springtime when the ice is melting.

It has also been observed that, at springtime, the melting mine
effluent is streaming at the surface of the ice cover through the pervious dykes without having properly sedimented its solid particles; in this situation, the pond does not fulfill its purpose.

Hence, it seems quite obvious that in order to make an efficient sedimentation pond, it is necessary to build a reservoir of sufficient volume with dykes sufficiently impervious to contain the effluent of the mine plant during the cold season. In order to calculate the required volume, many factors have to be taken into account including problems of heat transfer as discussed in the present report. All the observations made during the research program tend to show that mine waste containment systems should be built with impervious dykes if efficient pollution control is required.

There are many techniques available for insuring imperviousness of dykes even if large settlements are to be expected. However, due to the special conditions met in northern climate, it might be worthwhile to study new methods which might have economic advantages over known techniques. One of them being the use of peat as impervious core or blankets in the dykes. Peat has the advantage of being a very common material in the north; it is fairly impervious when compressed and has thermal properties which might be used with profit in the geometry of dyke in cold climate. Some more research should be done on this aspect of the problem.
REFERENCES


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* Depth below original ground surface. Negative sign indicates above ground surface.

† Represents thermometer for comparison point.

GTT Represents the new thermocouples cable installed in summer 1971.

Table 1 - SUMMARY GROUND TEMPERATURE INSTALLATIONS AT GIANT MINE
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<td>20-09-70</td>
<td>CTT₃,20,18,16,17,12,10,9,8,7,6,5,4,3,2,1,0</td>
<td>578.97</td>
<td>554.97</td>
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<td>CTT₃</td>
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<td>17-07-71</td>
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<td>578.97</td>
<td>577.97</td>
<td>1</td>
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<tr>
<td>CT₄</td>
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<td>0,1,2,3,4,5,6,7,8,9,10,12,14,16,17,20,24,28,CTT₄</td>
<td>576.25</td>
<td>546.25</td>
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<td>17-07-71</td>
<td>0,1</td>
<td>576.25</td>
<td>575.25</td>
<td>1</td>
</tr>
</tbody>
</table>

* Depth below original ground surface. Negative sign indicates above ground surface.

☐ Represents thermometer for comparison point.

CTT Represents the new thermocouples cable installed in summer 1971.

Table 2 - SUMMARY GROUND TEMPERATURE INSTALLATIONS AT COMINCO MINE.
Fig. 1 - TAILING DISPOSAL SYSTEM OF GIANT & COMINCO MINES OF YELLOWKNIFE, N.W.T.
Note: The elevations are referred to the original plan of Giant mines.

Fig 2: GIANT MINE, GENERAL PLAN OF TAILING DISPOSAL SYSTEM
Fig. 3 - GIANT MINE, LONGITUDINAL PROFILE OF TAILING DISPOSAL SYSTEM. (See figure No. 9.)
Fig. 4 - GRAIN SIZE DISTRIBUTION OF MATERIAL IN DYKE NO. 3.
Fig. 5: Giant Mine - Erosion resulting from water seepage downstream of dyke No. 2.

Fig. 6: Giant Mine - Erosion resulting from water seepage around a pipe incorporated in dyke No. 2.
Fig. 7 - GIANT MINE, DYKE N° 3, CROSS SECTION AND INSTRUMENTATION
(See legend page no. x)
Fig. 8 - GIANT-MINE, DYKE NO. 3, YELLOWKNIFE, N.W.T.
LOCATION OF THERMOCOUPLE CABLES
(See page no. for legend)
Fig. 9
Giant Mine Temperatures Measured in the Pond (GT₁)

Temperature, °F

Depth, ft.
Fig. 10 - GIANT MINE: TEMPERATURES MEASURED IN THE GROUND (GT₂, downstream of dyke №3)
Fig. II - GIANT MINE: TEMPERATURES MEASURED IN DYKE N° 3 (GT₃)
Fig. 12 - GIANT MINE: ISOTHERMS BETWEEN DECEMBER 1971 AND MARCH 1972 THROUGH DYKE № 3
Fig. 13 - GIANT MINE: ISOTHERMS BETWEEN APRIL AND JULY 1972 THROUGH DYKE N° 3
Fig. 14 - GIANT MINE: ISOTHERMS BETWEEN AUGUST AND NOVEMBER 1972 THROUGH DYKE № 3
Fig. 15 - COMINCO MINE, YELLOWKNIFE, N.W.T., GENERAL PLAN OF TAILING DISPOSAL SYSTEM AND DRAINAGE BASIN.

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Fig. 16 - COMINCO MINE: SITE PLAN SHOWING LITHOLOGICAL FORMATION AND THE LOCATION OF INSTRUMENTATION.
Fig. 17: Cominco Mine - Failure of the dyke by erosion during the thawing period.

Fig. 18: Cominco Mine - Dyke in construction on the mining site.
Fig. 19 - COMINCO MINE, DYKE NO. 1, CROSS SECTION I-I AND INSTRUMENTIONS
(See legend page no. x)
Fig. 20 — COMINCO MINE, DYKE NO. 1, YELLOWKNIFE, N.W.T.
LOCATION OF THERMOCOUPLES
(See legend page no.)
Fig. 21 - COMINCO MINE: TEMPERATURES MEASURED IN THE FROZEN GROUND (CT2)
Fig. 22 - COMINCO MINE: TEMPERATURES MEASURED IN THE GROUND DOWNSTREAM OF DYKE N° 1 (CT1).
Fig. 23 - COMINCO MINE: TEMPERATURES MEASURED IN DYKE N° 1 (CT₃)
Fig. 24 - COMINCO MINE: TEMPERATURES MEASURED IN THE POND (CT₄)

Temperature, °F
Fig. 25 - COMINCO MINE: ISOTHERMS THROUGH SECTION 1-1 BETWEEN JANUARY AND APRIL 1972.
Fig. 26 - COMINCO MINE: ISOTHERMS THROUGH SECTION 1-1 BETWEEN MAY AND SEPTEMBER 1972
Fig. 28 — COMINCO MINE, YELLOWKNIFE, N.W.T., DYKE N+1, CROSS-SECTION II-II.