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Design, construction and performance of dams in continuous permafrost

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ABSTRACT: Three dams were constructed from a small selection of materials over a short period of time in an area of continuous permafrost in the Canadian Arctic. The design selected for the dams was a rockfill embankment with an HDPE liner. Key features are the geometry of the liner and the planning of the construction schedule that was critical to keep the pervious foundations permanently frozen. This paper summarizes the design, construction and performance of these dams. It highlights the importance of continuous construction control by qualified technical staff. Occurrences of massive ground ice, that required foundation design changes, were encountered and detailed inspection of liner placement/welding during very cold temperatures was required. The dams were completed and are retaining water with a maximum depth of 10 m. Foundation temperature monitoring has shown that the design and the planned construction schedule had resulted in frozen foundations, as required by the design.

1 INTRODUCTION

1.1 *Project site*

The project site is located on a 20 km^2 island in Lac de Gras in the Northwest Territories of Canada. It is located in a continuous permafrost area at Latitude 63°40′N and Longitude 106°30′W, about 320 km northeast of Yellowknife. It has an annual mean temperature of about −12°C, with a monthly mean of −31°C in January and 8°C in July. The location of the project is shown on Figure 1.

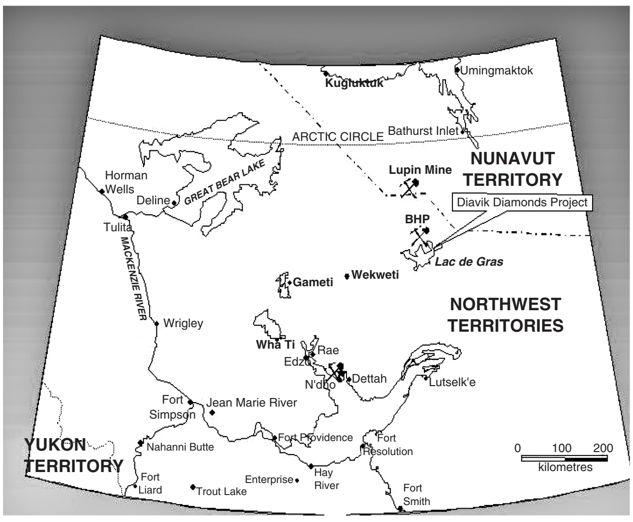

Figure 1. Location of the project.

1.2 *Project overview*

The project consists of the construction of a diamond mine to develop four kimberlite ore bodies located in Lac de Gras, adjacent to the island where the infrastructure is located. To access the kimberlite ore, it is necessary to construct rockfill embankment dikes to allow open pit mining of the kimberlite deposits. Construction of the first dike is a major component of the present project.

Dike construction has required dredging of the lakebed sediments along its footprint. Protection of the water quality of Lac de Gras is an important requirement. As a result, the dredged lakebed sediments had to be stored on-land, allowing settling and subsequent treatment to remove suspended sediments before water is returned to the lake. An on-land sediment storage facility was therefore constructed on the island that would contain all of the dredged sediments and water. The dams creating that storage facility form the subject of this paper.

1.3 *Dredged sediment storage facility*

The facility comprises two ponds, separated by a pervious dam. The objective was to discharge dredged sediments into a sedimentation pond where primary settling of solids would occur. The supernatant water and remaining fine suspended solids would pass through the pervious dam where a geotextile blanket would filter the coarser particles. The partly-clarified water would be retained in the clarification pond for further settling of solids. A water treatment plant would provide final removal of suspended solids before release of the water back to Lac de Gras.

2 SITE CONDITIONS

2.1 *Site description*

The island has an undulating topography with two east-west trending valleys. The sediment storage facility was developed within one of the valleys by constructing three perimeter dams, as shown on Figure 2.

The geotechnical conditions of the foundations are complex (Hu et al. 2003). In the valley area where the North Dam is located, massive ground ice formations were discovered. Also, a 10 m deep talik was identified in the West Dam foundation.

Three small inland lakes lay within the facility area. The lakes drained through two streams that passed through the West and North Dam sites. Part of the North Dam was founded on an esker that was excavated for construction material. The low areas along the alignment of the dams were covered with thick stunted tundra/grass vegetation that was underlain by ice-rich soil.

2.2 *Foundation soil conditions*

The subsurface soil, bedrock and thermal conditions were determined by means of geological and permafrost mapping, geotechnical drilling, ground penetration radar and ground temperature monitoring. The results of these investigations are discussed in a separate paper (Hu et al. 2003).

The area is underlain by frozen silty sand till containing gravel, cobbles and boulders of variable thickness. The general stratigraphy along the dam alignments consisted of ice-rich silty sand in the upper zone, followed by a layer of ice-poor silty sand, underlain by metasedimentary bedrock. Thickness of the organic vegetation varies from about 50 to 200 mm on higher ground and 500 mm in the valley bottoms.

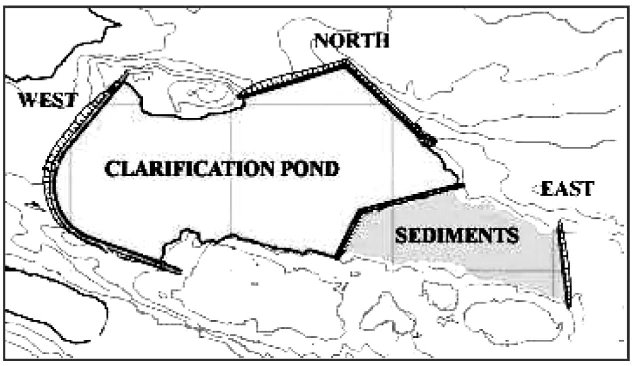

Figure 2. Sediment storage facility layout.

2.3 *Geothermal conditions*

The island is located in the continuous permafrost zone. Ground temperature conditions were investigated at the site through the installation and monitoring of thermistor cables (Hu et al. 2003).

Generally, the mean annual ground temperatures at a depth of about 20 m vary from −3°C to −6°C. The active layer is about 1.5 to 2.5 m deep in silty sand deposits, 2 to 3 m in well-drained granular deposits and about 5 m in bedrock. In poorly-drained areas, with thicker vegetation cover, the active zone is less than 1 m in depth.

3 DAM DESIGN

3.1 *General*

Dam dimensions are given in Table 1.

This facility provided about 0.96 million m^3 of storage in the sediment pond and 3.6 million m^3 in the clarification pond (Fig. 2).

The key factors that influenced the design of the perimeter dams were:

1) Limited selection of construction materials consisting of silty sand from an esker, unfrozen sandy silts beneath the existing inland lakes and granite rock.
2) Various planning and permission constraints resulted in a short construction season, limited to 8 months.
3) Foundations of the dams consisted of ice-rich soils and frozen fractured bedrock. To maintain integrity of the dams, their foundations had to be kept frozen to prevent seepage.
4) The facility was designed for 3 years of operation.

3.2 *Dam design sections*

3.2.1 *Main dam section*

The perimeter dams were designed with a central rockfill zone that supports an impermeable HDPE (high density polyethylene) liner on the upstream dam base

Table 1. Perimeter dam statistics.

Dam	Max. height (m)	Crest length (m)
North	12	720
West	14	870
East	9	280

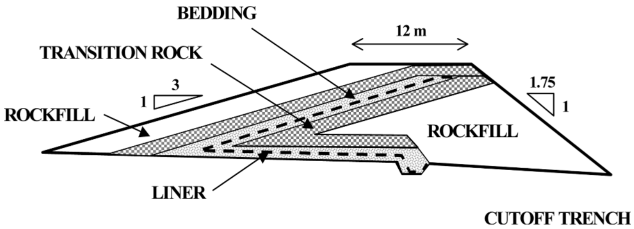

Figure 3. Schematic dam design section.

Table 2. Liner zone dimensions.

	Thickness (mm, normal to face)	
	Above liner	Below liner
Bedding sand (0–13 mm)	700	300
Transition (0–150 mm)	1000	1000

and slope. The dam geometry is illustrated schematically in Figure 3.

The design provided a dam structure consisting of granular materials that could be constructed during cold winter temperatures and that could tolerate significant deformation. Water is retained by a 60 mil (1.52 mm thick) HDPE liner that is protected from the angular rockfill by a crushed rock (1–150 mm) transition zone and bedding sand zones. The flat upstream slope of 3(H):1(V) was chosen to facilitate liner cover placement, and especially the dozing of the transition materials and bedding sands.

The geometry of the liner within the dam is designed to limit the thawing of the foundation caused by storage of water during the dredging operation. The liner was keyed into a cutoff trench that was located on the axis of the dam, i.e. well downstream of the thaw zone. The design criterion was to keep the foundation below the cutoff permanently frozen.

The HDPE liner was protected by the zones given in Table 2.

The actual cutoff trench depth was determined during construction so that its base could be located either within ice-poor soil or in competent bedrock, with a minimum depth of one meter.

3.2.2 *Dam section at talik*

During site studies, a significantly large talik was identified at an effluent stream at the West Dam. A thick organic layer with heavy shrub vegetation, that allowed thick snow accumulation during winter, prevented frost penetration and prolonged seepage flow. This resulted in an unfrozen talik zone, about 40 m wide and 10 m deep.

The presence of this talik required a modification of the foundation geometry of the dam section, as illustrated in Figure 4. This consisted of a large excavation to key the liner into the frozen bedrock.

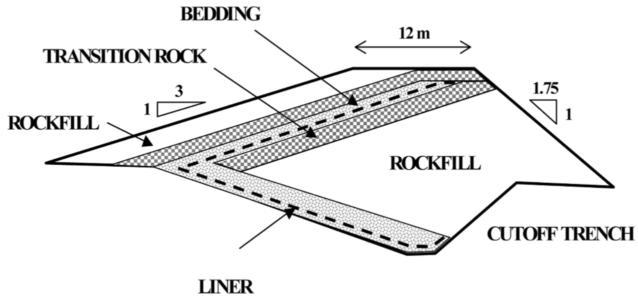

Figure 4. Dam section at the talik.

4 CONSTRUCTION

4.1 *Permafrost considerations*

Massive ground ice and thick ice lenses below the cutoff trench or in the upstream section of the dam were not desired. Geotechnical drilling programs, aimed at establishing soil stratigraphy along the centerline of the dams, provided the basis for the design. However these could not identify all the ground ice. It was decided that this could be done only during cutoff trench excavations that would be inspected closely by a qualified geotechnical specialist with permafrost experience, who would at the same time decide the actual depth of the cutoff trench. Furthermore, permafrost terrain maps based on air photos, borehole logs and field reconnaissance were prepared in advance to assist the construction.

4.2 *Construction planning*

The design of the dams was based on the need for the foundations to be frozen. The winter construction period in extreme weather conditions required diligent planning and the selection of experienced staff and contractors. Detailed and practical construction planning was the key to success. The most important component of the planning was to choose the right contractors, supervision team, the correct construction schedule and a good Quality Assurance (QA)/Quality Control (QC) plan.

4.2.1 *Contractors*

Experienced contractors, who are prepared for all contingencies, are critical because supply is difficult in remote Arctic conditions. The selected earthwork contractor had a large selection of equipment and the ability to supply, in the case of emergency, additional labour and equipment. A sub-contractor with Arctic experience, whose labourforce was composed of local Inuits, who are accustomed to working outdoors during the winter, was selected for the critical liner installation.

4.2.2 *Engineering supervision*

The construction was directed by experienced staff with extensive knowledge of permafrost engineering, construction and design. The supervision team was able to provide immediate decisions on foundations, cutoff trenches, abutments and modifications on the dam designs to meet the actual field conditions. Qualified staff are critical due to the limited construction schedule and stringent design criteria.

4.2.3 *Schedule*

The construction of the dams started in October 2000 and was completed in June 2001. Impoundment of dredged materials began in early July 2001. To achieve the frozen foundations, a construction schedule (summarized in Table 3) was adopted.

4.2.4 *Quality Control/Quality Assurance*

A detailed QA/QC plan was prepared, including checklists for cutoff trench excavation, foundation preparation, liner installation, fill placement, instrument installation, pre-construction and construction responsibilities of QA and QC teams, material placement, compaction and material testing requirements.

4.3 *Materials and placements*

An important part of winter construction is the identification and preparation of the construction materials. Three construction materials, aside from the liner, were required, namely: (a) rockfill consisting of quarried rock smaller than 600 mm in size, (b) transition rock consisting of rock smaller than 150 mm obtained from a crushing plant, and (c) liner bedding consisting of screened sand and fine gravel with the size of 0–13 mm.

Table 3. Construction schedule.

Date	Activities
October 2000	• Pump out inland ponds • Start dam foundations • Start cutoff construction
Nov. & Dec. 2000	• Complete all dam foundations & cutoff • Complete 50% of base liner installation • Excavate & prepare talik foundations • Install thermistor cables at 3 sections
Jan. to Mar. 2001	• Install remaining thermistor cables • Complete base liner installation • Place majority of rockfill
Apr. & May 2001	• Complete rockfill zone • Install slope liner • Place upstream dam slope cover
June 2001	• Final dam slope grading

All rockfill was placed between January and April of 2001. During this period, the foundation temperatures had cooled down significantly due to the constant cold air temperature that also cooled the rock to temperatures between −20°C and −30°C. The combination of pre-cooling of the base of the dam followed by covering the base with cold rockfill, produced the desired cold foundations.

The lower bedding sand to the slope liner was placed in a single lift and manually raked to remove any large particles. The upper bedding sand was placed in a single lift with a light dozer. During placement, the thickness was monitored constantly to avoid damage to the liner by machinery.

The downstream transition material was placed in 0.5 m lifts and compacted with a 10 t vibratory roller. The upstream upper base transition zone was placed in 1 m lifts and compacted with a 10 t roller. The transition material on slopes above the liner was placed with dozers and no specific compaction was required.

4.4 *Liner installation*

The installation of liner and testing of all welds were performed under great scrutiny because of the importance of the liner integrity. This included inspecting all bedding materials.

During winter months, some sand material became frozen. In these circumstances, geotextile sheets were used below and above the liner to prevent any potential damage from angular frozen lumps.

During extreme cold conditions, shelters were built for welding the liner (Fig. 5). These shelters were heated and seams were welded in a protected environment. All liner wedge weld seams were pressure tested and all extrusion weld seams were tested by vacuum. All damaged areas, including holes, blisters, cracks and machinery damage were patched with the same HDPE material and extrusion welded. The destructive tests were carried out in accordance with the requirements of the QA/QC Plan.

The testing results and subsequent dam performance suggested that perfect liner jointing was obtained

Figure 5. Liner installation during the winter.

despite ambient temperatures being in the minus thirties for much of the work.

4.5 *Construction in the talik area*

The entire talik area was excavated to a maximum depth of about 10 m. All broken rock was removed from the base of the excavation and the trench reached competent rock. Water seepage through fractured rock was encountered during the excavation. This water was pumped out and a till blanket was placed on the upstream slope of the excavation to seal off the seepage. Seepage was controlled successfully by the low permeability materials and by subsequent freezing (Fig. 6). This till blanket also smoothed the surface of the excavation for the liner placement.

The excavation was completed in early winter to allow cold temperatures to penetrate and cool the ground. The seepage control till blanket was placed in December 2000 and the area was not covered until March 2001, to allow the entire area to freeze to a greater depth. Snow was removed periodically to enhance the freezing during the non-construction period.

4.6 *Design modifications during the construction*

Construction quality control and the need to adjust the design to accommodate field conditions are always necessary to construct competent dams. The importance of these factors increases in Arctic regions, particularly during winter construction. The following design modifications were made during the construction.

- A later start of the construction due to license issues resulted in insufficient quantity of screened bedding sand. Due to the difficulties of the screening operation during winter, unfrozen silty sand, excavated from the adjacent thawed pond bottoms, was used below the liner at the base of the dam. In other instances, a geotextile was placed on top of the liner to allow the bedding sand to contain some frozen lumps, to a maximum size of 50 mm. Also, crushed rock less than 20 mm in particle size was permitted for the lower bedding, provided that two layers of 7 oz. geotextile fabric were applied immediately below the liner.
- Reduced bedding sand thickness to 400 mm from 700 mm. Field experience demonstrated that a 400 mm thick sand layer would produce adequate protection during placement.
- In many sections, the cutoff trench was excavated to the relatively shallow bedrock surface. Since the bedrock showed minor fracturing, but its surface was greatly undulating, the upstream and base of the trench were smoothed with compacted unfrozen silty sand, allowing for easier liner installation.

Figure 6. Till blanket placed in the talik.

Massive ground ice up to 3 m thick was identified and excavated in the esker and valley sections of the North dam upstream areas (Hu et al. 2003). Thick massive ice, if left in place in the upstream foundation, could produce excessive differential thaw settlement that could over-strain the liner.

5 PERFORMANCE MONITORING

5.1 *Instrumentation*

Three types of instrument were installed in the dams: survey monuments, ground temperature measurement cables and ground water observation wells.

5.2 *Visual inspection and survey*

Survey monuments were installed on all three dams, both on the crest and at the downstream toes. These monuments consisted of 1.5 m long steel pipes with a steel bar in the center, grouted in the rockfill at the crest of the dam and 2.5 m into the ground at the toe of the dams. The survey results during September 2001 showed no appreciable movements.

Visual inspections were carried out daily during the filling of the facility. The inspection reduced to one per week for the next three months after the pond was filled and reduced to once per month thereafter. No visible signs of seepage and instability were found.

5.3 *Temperature monitoring*

5.3.1 *Thermistor installation*

The maintenance of frozen foundations beneath the dams is essential to the stability and seepage control of the dams. To monitor the foundation temperature, vertical ground temperature measurement cables were installed in the foundations at eight dam sections, which were selected by their significance for dam stability.

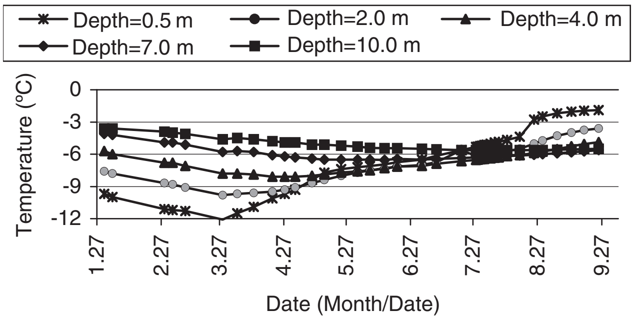

Figure 7. Ground temperatures for the upstream thermistor string at North Dam (0+440).

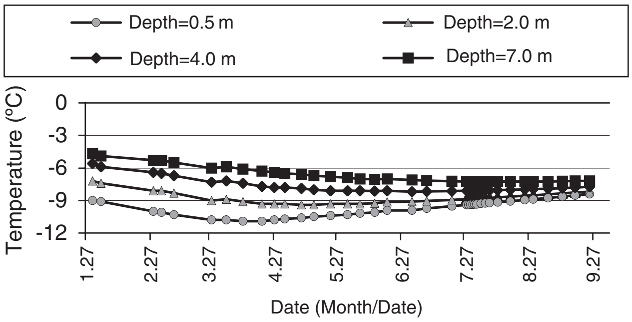

Figure 8. Ground temperatures for the cutoff trench at North Dam (0+440).

Three sections were located in the North and West dams, respectively, and two sections in the East dam.

Each section has three vertical thermistor strings located in the cut-off trench and midway to both toes.

Upstream thermistor strings were designed to monitor the thaw front development in the upstream area. Cutoff thermistor strings were designed to monitor the temperature conditions in the trench, below the liner key. The design required the trench to be permanently frozen to eliminate seepage. Downstream thermistor strings were designed to monitor the foundation temperature changes. As the ground ice in the downstream area was not excavated, it is important to have a frozen condition to ensure dam stability.

The upstream and downstream thermistor strings had five sensors located at 0.5, 2, 4, 7 and 10 m depths. The thermistor strings in the cutoff trench had 4 sensors located at 0.5, 2, 4 and 6 m depths, measured immediately below the liner. All thermistor cables were installed during December 2000 and March 2001, prior to the installation of the base liner.

5.3.2 *Dam foundation temperatures*

The monitoring of ground temperatures has shown that frozen foundations have been achieved. The temperatures met or exceeded the design requirements.

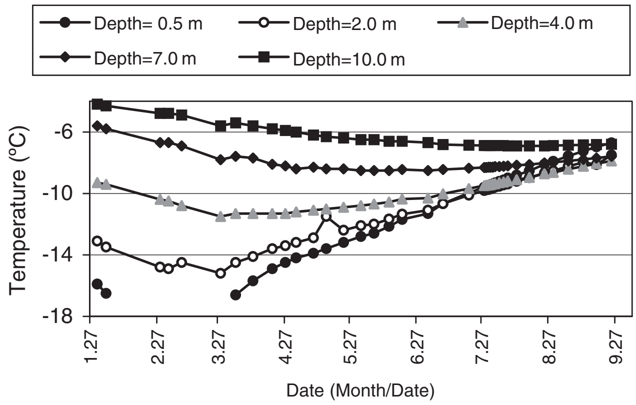

Figure 9. Ground temperatures for the downstream string at North Dam (0+440).

Figures 7, 8 and 9 show the ground temperature variations for the North Dam, at station 0+440.

Ground temperature monitoring indicated that after 3 months of water storage, the entire foundation remained frozen. Ground temperatures in the cut-off trenches were between −6°C and −8°C. The upstream and downstream areas had warmer temperatures than the cutoff trenches, due to the water and closer distances to the downstream toes, respectively.

6 CONCLUSIONS

This paper presents the design, construction and monitoring of three water retaining dams. The dams are uniquely designed to have frozen foundations with HDPE liners incorporated on the upstream base and slopes. The cut-off trenches were located along the centerline of the dams.

The dams were constructed in Arctic winter conditions where the temperatures can be as low as −40°C. The scheduling of excavation and backfill of the excavation is important to develop a frozen foundation. An appropriate rockfill schedule will enhance the freezing/cooling of the foundation. Liner installation is critical, yet it can be performed successfully at −40°C.

Inspections indicated that the dams met or exceeded the design requirements. The dam foundations were frozen as designed, and effectively eliminated seepage through the dam foundation.

REFERENCE

Hu, X., Holubec, I., Wonnacott, J., Lock, R. & Olive, R. 2003. Geomorphological, geotechnical and geothermal conditions at Diavik Mines. In Phillips et al. (eds), *Proc. 8th International Conference on Permafrost. Zurich, Switzerland*. Rotterdam: Balkema.