PERFORMANCE OF TWO ROCKFILL DAMS WITH THERMOSYPHONS ON PERMAFROST FOUNDATIONS, EKATI DIAMOND MINE, NT

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ABSTRACT
Five water retention dams have been constructed to date at the EKATI Diamond Mine. All of the dams were constructed on permafrost foundations. Three of the dams rely on a permafrost sand and gravel core as the principal impervious zone. Extensive use of passive refrigeration devices known as thermosyphons have been an integral feature in the design of these dams and a significant factor in their successful performance. The construction and performance of two of these rockfill structures – Panda Diversion Dam and Waste Rock Dam – that use thermosyphons in different configurations to provide long-term thermal stability are presented in this paper. Extensive temperature monitoring of the dam and foundation has been carried out at these dams since completion of construction in 1997 and 2002, respectively. In spite of the occurrence of several unusually warm years over the past decade, the dams have remained colder than designed and have functioned as intended.

RÉSUMÉ
Cinq barrages ont été construits à la mine du diamants Ekati. Tous les barrages ont été construits sur les fondations de pergélisol. Trois de ces barrages compte sur un noyau de sable et gravier en pergélisol comme le système principal de retenue. L'usage des thermosiphons, des appareils de réfrigération passifs, fut une caractéristique intégrale de la conception et de la performance de ces barrages. Cet article décrit la construction et la performance de deux de ces structures – Panda Diversion Dam et Waste Rock Dam – qui utilisent les thermosiphons dans les configurations différentes pour fournir la stabilité thermique a longue-échéance. Le régime thermique de ces barrages et leurs fondations était surveillé depuis la fin de construction en 1997 et 2002, respectivement. Malgré que plusieurs années chaudes ont passé au cours de la dernière décennie, les barrages sont plus froids que conçus et ils fonctionnent tel que prévu.

1. INTRODUCTION

The EKATI Diamond Mine (Ekati), which is owned 80% by BHP Billiton Diamonds Inc, 10% Chuck Fipke and 10% Stu Blusson and operated by BHP Billiton Diamonds Inc., is the first operating diamond mine in North America. It is located in the Lac de Gras region, approximately 300 km northeast of Yellowknife, NT, as shown in Figure 1. The mine officially opened in October 1998.

To date, five water-retention structures have been constructed at Ekati (year of completion in parentheses):

- Panda Diversion Dam (1997);
- Long Lake Outlet Dam (1998);
- King Pond Dam (2001);
- Waste Rock Dam (2002); and
- Bearclaw Diversion Dam (2003).

King Pond Dam and Waste Rock Dam are located at the Misery Site, approximately 27 km southeast of the main plant area, as shown in Figure 2.

All of the dams were constructed on permafrost foundations that would be both unstable and/or permeable if they were allowed to thaw. Three of the dams were constructed with a permafrost sand and gravel core as the principal impervious zone. Winter construction ensured that the permafrost foundation and core were maintained. Extensive use of passive refrigeration devices known as thermosyphons have been a part of dam design, construction and performance. The performance to date of two structures, Panda Diversion Dam and Waste Rock Dam, is presented herein. These two dams represent two design concepts that use thermosyphons in different configurations.

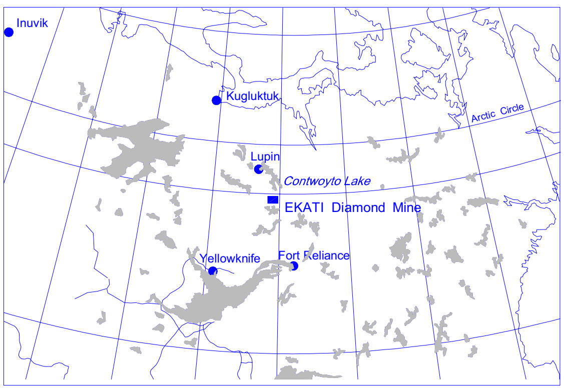


Figure 1 Project Location

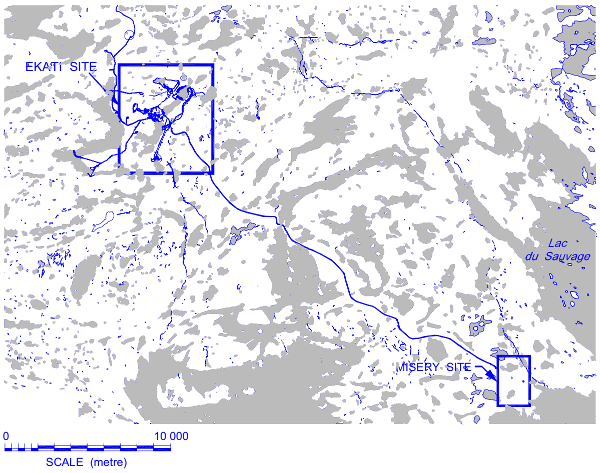


Figure 2 Site Layout

2. BACKGROUND INFORMATION

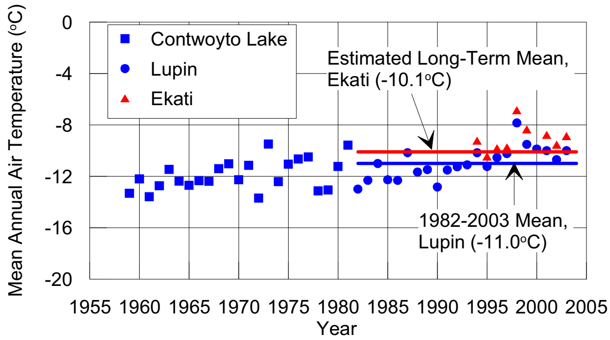
2.1 Surficial Geology

Ekati is situated within the Canadian Shield and is underlain by granitic rocks of the Yellowknife group. The surficial geology of the region has been described in Ward (1993) and mapped by Rampton (1994). The surficial deposits that overlie the bedrock consist of glacial till, glaciofluvial deposits, organics, and alluvial floodplain deposits. The glacial till has a variable thickness up to 20 m and consists of a sand matrix containing silt, gravel, cobbles and boulders. Glaciofluvial deposits (principally eskers) are common throughout the region. Low-lying areas are typically around lake margins and covered by lacustrine sediments on which peat is well-established. The thickness of lacustrine sediments can reach 6 m.

Ekati is situated within the zone of continuous permafrost. Mean permafrost ground temperatures in the area typically range from -4°C to -6°C but may be warmer in the vicinity of water bodies. Deeper than normal thaw have also been recorded below streams at the outlets of some lakes. The permafrost thickness in the area is approximately 300 m to 400 m.

2.2 Climate

Meteorological data have been collected at Ekati since 1993. The closest Environment Canada meteorological station with long-term climatic records is Lupin, located approximately 100 km north of Ekati. This station has operated since 1982 and replaced the station at Contwoyto Lake, located approximately 50 km southeast of Lupin, which had operated since 1957. The historical mean annual air temperature record for Lupin, Contwoyto Lake and Ekati is compared in Figure 3. Since 1993, the mean annual air temperature at Ekati has been, on average, 0.9°C warmer than Lupin. It is noteworthy that of the past seven years since mine development began in 1997, Lupin – and by extension, Ekati – has experienced six of the ten warmest years on record.



Note: Full year's air temperature record at Ekati only available for 1995, 2002 & 2003. For other years, monthly air temperature for months with insufficient temperature data estimated from Lupin.

Figure 3 Historical Annual Air Temperature Record, Contwoyto Lake, Lupin and Ekati

2.3 Thermosyphons

A thermosyphon is a passive two-phase, liquid-vapour convective heat transfer device that has been used for over 25 years to stabilize structures founded at grade on permafrost (Yarmak and Long, 2002). It is a pressure vessel with a radiator section above the ground surface, and an evaporator section installed within the ground. Whenever the ambient air is colder than the ground, thermosyphons remove heat from the ground and release it to the outside ambient air. No heat extraction occurs when the ambient air temperature is warmer than the ground.

Historically, thermosyphons were first designed as vertically-installed pipes with the radiator at the surface. Later, they were designed to be installed with an inclined evaporator section, again with the radiator at the surface. Typical evaporator diameters range from 50 mm to 100 mm. More recently, horizontal thermosyphons have been designed for flat, horizontal or even somewhat undulating configurations using a looped evaporator, made of 20 mm diameter steel pipe, that is connected to an internal accumulator in a riser pipe. Heat transfer occurs in the same manner as inclined thermosyphons; however, the accumulator assures that the flow of the liquid refrigerant is in one direction through the looped evaporator.

Further details on thermosyphon technology and applications are described in Hayley (1982; 1988), Haynes and Zarling (1988), McKenna and Biggar (1998), and Yarmak and Long (2002).

3. PANDA DIVERSION DAM

3.1 Panda Pit Development

Panda Pipe, located beneath Panda Lake, was the first kimberlite pipe to be developed at Ekati. To facilitate the open pit mining of Panda Pit, the southern portion of the lake had to be drained. This required the construction of a diversion dam (Panda Diversion Dam) across the northeast arm of Panda Lake and a diversion channel to divert the water to Kodiak Lake.

Based on the potential for loss of life resulting from catastrophic failure, Panda Diversion Dam is classified as a high consequence dam according to the Dam Safety Guidelines (CDA, 1999).

3.2 Subsurface Conditions

Panda Diversion Dam was constructed over a warm permafrost sand foundation across a narrow (approximately 100 m wide) section of Panda Lake, as shown on Figure 4. Across this section, the lake is less than 1 m deep and naturally freezes to the lakebed each winter.

Bedrock in this area is granite. Subsurface conditions along the east side of Panda Lake consist of glacial till and/or glaciofluvial sand and gravel overlying bedrock. The lake basin itself consists of lacustrine silt and sand overlying bedrock. Along the west side of Panda Lake, glacial till overlies bedrock. Figure 5 shows the subsurface conditions along the dam alignment. Initial ground temperature measurements taken from a borehole located mid-way across the lake along the dam alignment indicated that a talik did not exist below the dam footprint, although permafrost temperatures were approximately -2^{o}C, or warmer than typical overland permafrost temperatures measured on site.

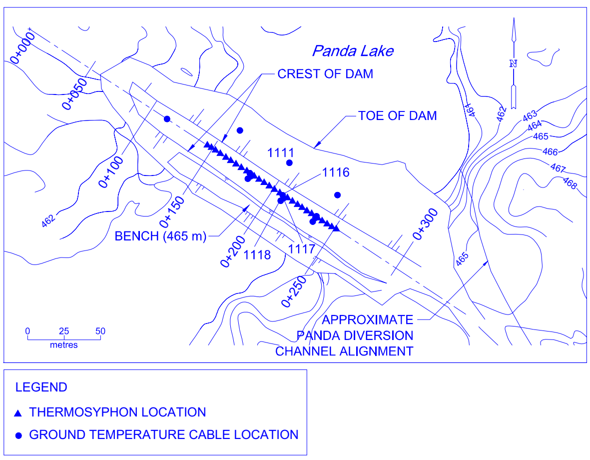


Figure 4 Dam, Thermosyphon and Ground Temeperature Cable Layout, Panda Diversion Dam

3.3 Design Details

Panda Diversion Dam was designed to allow near-immediate dewatering of Panda Lake following construction. The dam was designed as a zoned rockfill dam with a frozen, nearly-saturated sand and gravel core. It is approximately 300 m long and up to 6.5 m high and is designed to retain up to 2.5 m head of water.

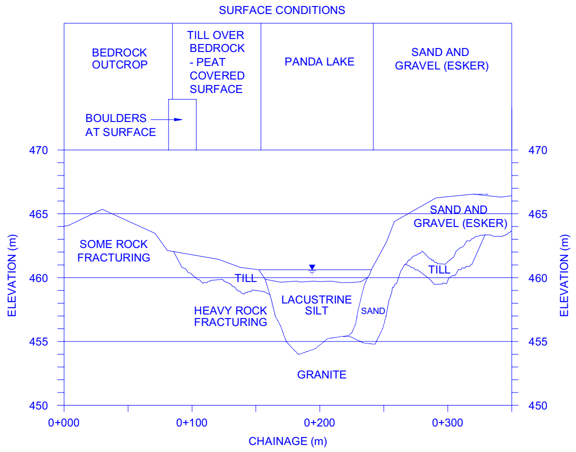


Figure 5 Subsurface Conditions, Panda Diversion Dam

Panda Diversion Dam was designed to maintain the frozen core and permafrost foundation colder than -2^{o}C, the design temperature selected to ensure that these materials formed an impervious barrier to seepage. Given the warm initial foundation temperatures beneath the lake and the requirement to dewater almost immediately following construction, thermosyphons were incorporated in the design to ensure that the core and foundation were colder than -2^{o}C. A single row of 60 vertical thermosyphons, spaced 1.3 to 2.1 m apart centre-to-centre, was installed from the dam crest to 12 m depth. Figure 4 shows the thermosyphon layout. Each thermosyphon consisted of 50 mm diameter evaporator pipe connected to a 6.5 m^2 radiator.

Construction materials consisted of the following:

- Zone A: sandy gravel from the Panda Esker;
- Zone B: crushed 20 mm minus esker sand and gravel;
- Zone C: crushed 150 mm minus granite; and
- Zone D: run-of-mine rock fill.

The dam centreline profile is shown in Figure 6. The dam cross-section at Station 0+193, midway across the lake, is shown in Figure 7.

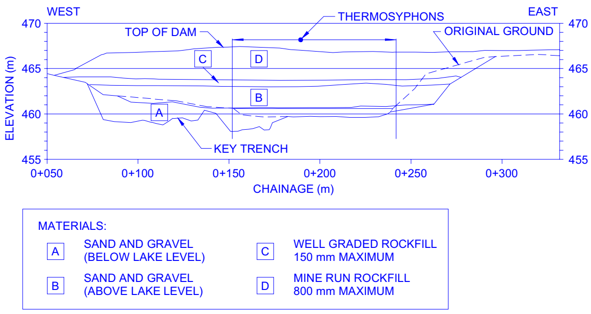


Figure 6 Centreline Profile, Panda Diversion Dam

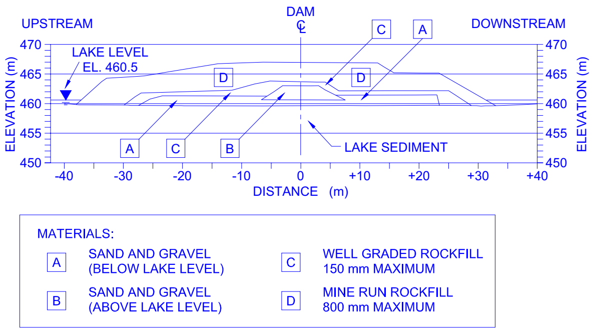


Figure 7 Dam Cross Section, Station 0+193, Panda Diversion Dam

3.4 Dam Construction

Construction of Panda Diversion Dam began in early-January 1997 and was substantially completed in early-April 1997. Daily air temperatures during construction ranged from -15°C to -40°C. On some days, windchill temperatures were colder than -60°C.

The initial construction activity was excavation of the ice cover to expose the lake bottom over the footprint of the dam within the lake. At the time of excavation, the ice cover was approximately 0.6 m to 0.8 m thick. The ice was in contact with the lakebed and a surficial crust of lakebed sediments was frozen to a depth ranging from 0.9 m to 1.2 m.

Zone A material was placed in a submerged manner to ensure saturation. The ice excavation within the lake and the west key trench were flooded prior to placing the Zone A material. The Zone A material was then pushed and spread in place. Following Zone A fill placement, the surface of the material where the core would contact was graded and subsequently compacted. The saturated Zone A material was required to freeze to a temperature of -2°C or colder before adding Zone B (core) material. Zone B material was prepared by mixing 20 mm minus sand and gravel with hot water and placing the mixture in lifts of approximately 0.3 m thickness. The core material was also required to reach a temperature of -2°C or colder before a subsequent lift could be placed. Frozen samples of Zone B material were cored to determine bulk density and moisture content, from which the degree of ice saturation could be calculated. The average degree of ice saturation from recovered samples was approximately 93 percent. Zones C and D materials were each placed in two stages, with the first stage covering the downstream side while the upstream zone was left uncovered to promote freezing of the foundation.

A total of thirteen vertical ground temperature cables were installed at select locations, as shown on Figure 4.

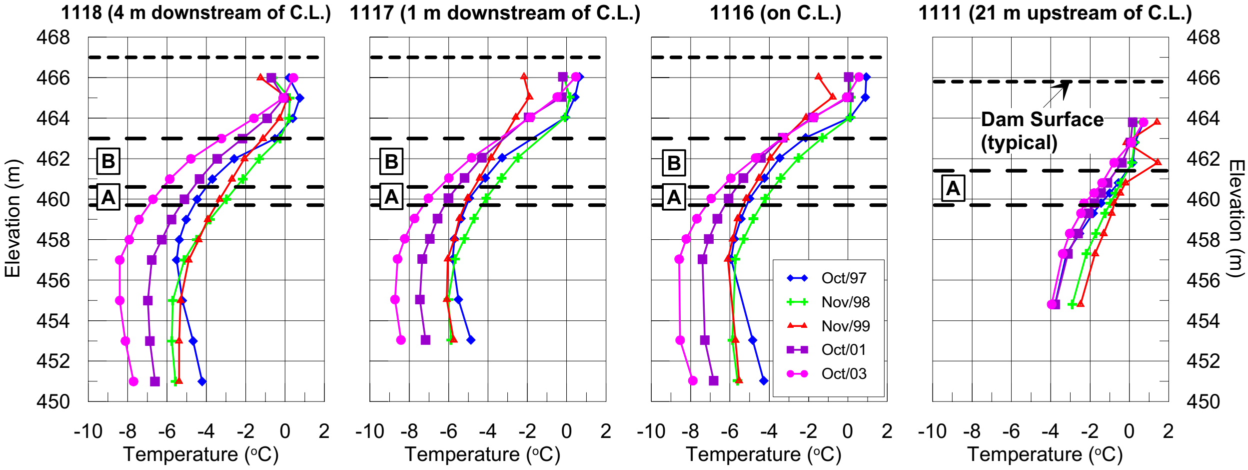
3.5 Dam Performance

The downstream side of Panda Lake was dewatered in March 1997, just before the completion of the dam. The average head of water retained by the dam has been approximately 1.0 m. In early-June 1999, a temporary ice blockage in Panda Diversion Channel caused a rise in water level. The frozen core of the dam was overtopped for a period of 24 to 48 hours, but there was no damage to the frozen core.

By 1999, the ultimate limit of Panda Pit was pushed back towards the dam, with the pit crest approximately 75 m from the dam centerline. Ground vibrations were monitored at Panda Diversion Dam during development of Panda Pit. No signs of slope distress or seepage were observed at Panda Diversion Dam during development of Panda Pit. A photograph of the Panda Pit development is presented in Figure 8.

Figure 8 View of Panda Pit Development (July 2003)

Figure 9 shows selected vertical temperature profiles from Ground Temperature Cable Nos. 1116, 1117, 1118 and 1111 (refer to Figure 4 for locations) since construction. Temperature profiles are presented for the months of October/November, which is the time of year when the frozen core is warmest, with the thermosyphons having been dormant over the summer due to the warm ambient



Notes: C.L. refers to dam centreline. A and B refer to Zones A and B materials.

Figure 9 Selected Ground Temperature Profiles, Panda Diversion Dam

temperatures. Figure 9 shows that the frozen core temperature has progressively cooled over time, from approximately -1°C to -4°C in 1997 to -3°C to -7°C in 2003. Dam temperatures have been colder than the maximum design temperature of -2°C.

4. WASTE ROCK DAM

4.1 Misery Site Development

Waste Rock Dam is located at the Misery site. Development of the Misery site required the construction of three impoundments to control mine site runoff and ensure that discharge from the site meets the requirements of the water licence that governs mining operations at Ekati. The main impoundment is King Pond, which is impounded by King Pond Dam, constructed during the winter of 2001. The sole function of Waste Rock Dam is to retain surface runoff from a catchment adjacent to the waste rock stockpile that drains directly towards Lac de Gras. The impounded water is then pumped to King Pond. A seepage collection dam constructed downstream of Waste Rock Dam was included in the design to temporarily retain any seepage that may have passed through the dam liner system. The seepage collection dam was sized to temporarily contain freshet water from the catchment immediately downstream of Waste Rock Dam that could mix with the collected seepage water. Only temporary containment is required as these waters are to be pumped back behind Waste Rock Dam.

4.2 Subsurface Conditions

The lithology along the dam alignment is summarized as a thin veneer of peat (less than 0.1 m thick) overlying glacial till (from 1 m to greater than 18 m thick) and biotite schist bedrock. The till consists of gravel and sand or silt and contains occasional cobbles and boulders.

Initial ground temperature measurements taken from a borehole located below a creek at the valley bottom indicated the occurrence of a deepened active layer (approximately 5 m thick) and relatively warm permafrost (-1.5°C at 15 m depth) at this location.

A bedrock lineament running northwest-southeast trends approximately perpendicular to the dam alignment through the northeast abutment.

Subsurface conditions along the dam alignment are summarized in Figure 10.

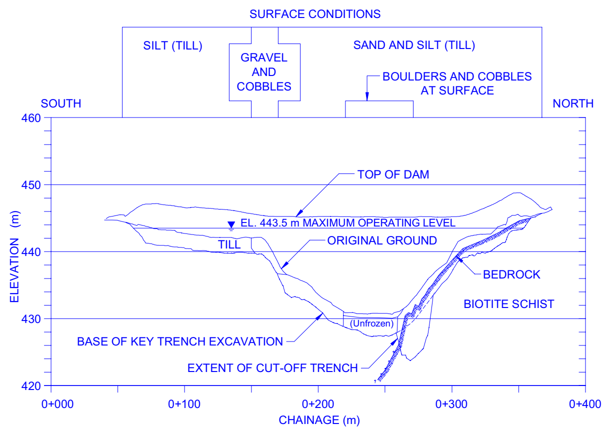


Figure 10 Subsurface and Centreline Profile, Waste Rock Dam

4.3 Design Details

The design concept for Waste Rock Dam was a hybrid lined rockfill dam. The liner system consists of a primary geomembrane liner, a geosynthetic clay liner (GCL) and a nonwoven geosynthetic cushion that was embedded in a frozen key trench that was constructed on saturated frozen ground or competent bedrock. A series of horizontal thermosyphons, placed within the key trench, ensures that the liner interface with the key trench backfill and the underlying levelling course, soil and bedrock remains frozen. The superstructure of the dam was designed with various zones of processed granular fill. The dam is approximately 15 m high with approximately 280 m of crest length and has been designed to intermittently (seasonally) impound up to 13.3 m of water.

The dam layout is presented in Figure 11. A general cross section through Waste Rock Dam is presented in Figure 12.

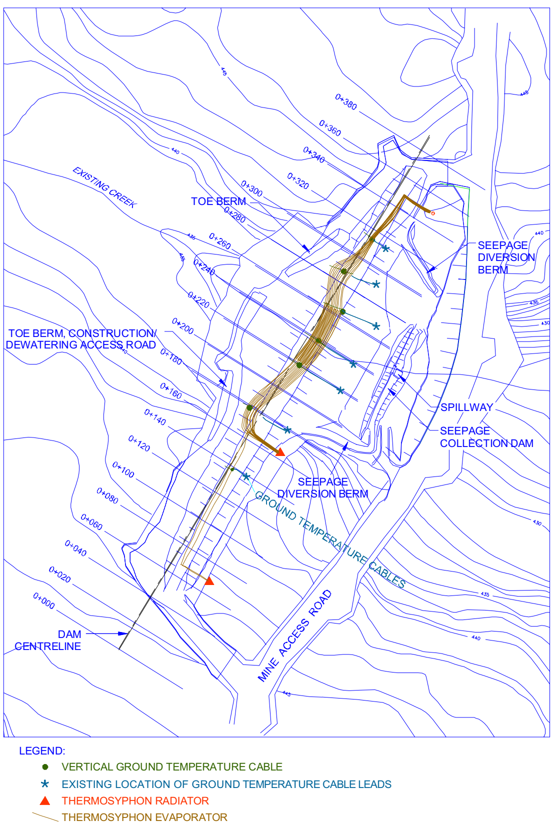


Figure 11 Dam, Thermosyphon and Ground Temperature Cable Layout, Waste Rock Dam

An emergency spillway was not provided for Waste Rock Dam since the operating plan for Misery was to pump impounded water from behind Waste Rock Dam to King Pond during spring freshet.

The design criteria for Waste Rock Dam fall into the following classifications:

- freeboard;
- stability;
- thermal; and
- seepage.

Freeboard design criteria for Waste Rock Dam was to provide 1.0 m (minimum) freeboard as per the requirements of the water license as follows:

- provide impoundment for a 1:100 year water level with 1:100 year wind as well as the minimum required freeboard; and
- provide impoundment for an average year water level (1:2 year) and a 1:1000 year wind.

The stability design criteria suggested by the Dam Safety Guidelines (CDA, 1999) were used as the stability design criteria for Waste Rock Dam.

The thermal design criteria used in the design of Waste Rock Dam was to ensure that the fill and natural materials in the vicinity of the liner interface within the bottom of the key trench were maintained at temperatures colder than -2^{o}C. This necessitated constructing the dam crest higher than required at the dam abutments to provide adequate insulation to the key trench base during warmer months of the year.

The thermosyphons were configured so that their ability to cool the base of the key trench was enhanced in the areas of the deepened active layer and bedrock lineament. This was accomplished by overlapping two sets of loops at the base of the key trench at the valley bottom and by providing an increased number of evaporators above the bedrock lineament. The layout of the thermosyphon evaporators is presented in Figure 11.

4.4 Dam Construction

In February 2001, a percolation-testing program was carried out along the dam alignment to estimate the depth to ice-saturated permafrost soil or competent bedrock. Percolation test holes were drilled to a depth of 5 m to 8 m. The percolation test holes were subsequently filled with water. In most cases, there was an immediate drop in the water level. The water level in the percolation test holes was monitored for up to 48 hours to determine the static water depth. The depth to static water level was inferred as the depth to ice-saturated soil or competent bedrock.

The percolation-testing program highlighted the existence of the following warmer zones beneath the dam alignment:

- A deepened active layer or a talik in the till to a depth of 2.0 m to 3.3 m between Stations 0+220 and 0+260;

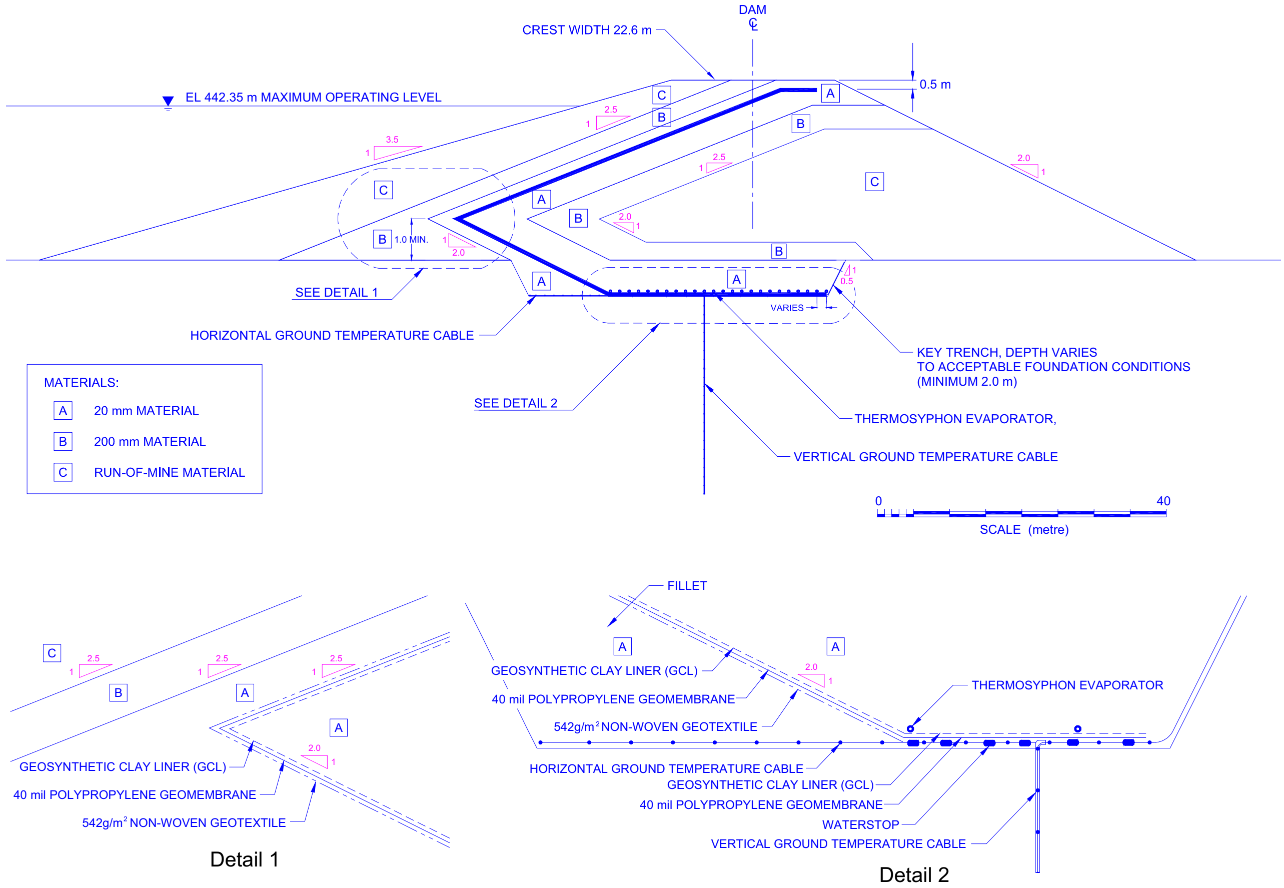


Figure 12 Generalized Dam Cross-Section, Waste Rock Dam

- A deepened active layer or a talik in the bedrock between Stations 0+260 and 0+283 that extended to a maximum depth of 7.9 m below original ground surface.

Foundation preparation began in November 2001. The dam was substantially completed in early-May 2002. Daily air temperatures during this period ranged from -2°C to -43°C.

A cut-off trench was included between 0+260 and 0+285 to remove the deepened active layer or talik. A curtain of geosynthetic clay liner (GCL) was placed over the downstream wall of the cut-off trench prior to backfilling. The GCL was intended to act as a temporary water retention barrier in the event that the cut-off backfill did not completely freeze by the time the dam impounded water during the spring of 2002. Figure 10 shows the excavation profile along the dam alignment.

In January 2002, two weeks of cold air temperatures (colder than -40°C) and/or high winds made the polypropylene liner prone to cracking. During this period, liner installation was delayed, but the key trench and cut-off trench were exposed to the cold ambient conditions. This resulted in the foundation temperatures becoming very cold (-15°C) before the key trench was backfilled.

The 20 mm material was typically placed in 0.3 m lifts. The material was moisture conditioned to a moisture content that was wetter than 2 % dry of the optimum moisture content and compacted to a minimum of 95 % of the maximum dry density. The 200 mm material was placed in 0.5 m thick lifts. The mine-run rockfill was placed in 1.0 m thick lifts.

The liner system was placed in two phases of construction: below the hinge and above the hinge, the hinge being the point at which the liner system changes direction, as shown as Detail 1 in Figure 12. A fillet was constructed from the base of the key trench to provide a subgrade for the liner system.

A total of 13 thermosyphon loops were installed immediately above the composite liner system at the base of the key trench. A single loop connected to a 39 m^2 radiator was installed between 0+070 and 0+140 and two sets of six loops (each loop connected to a 58.5 m^2

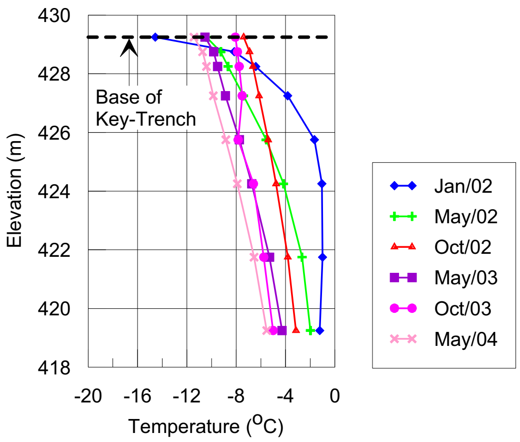
radiator) were installed between 0+165 and 0+265 and between 0+225 and 0+350.

A total of 14 ground temperature cables (7 horizontal and 7 vertical) were installed, as shown on Figure 11.

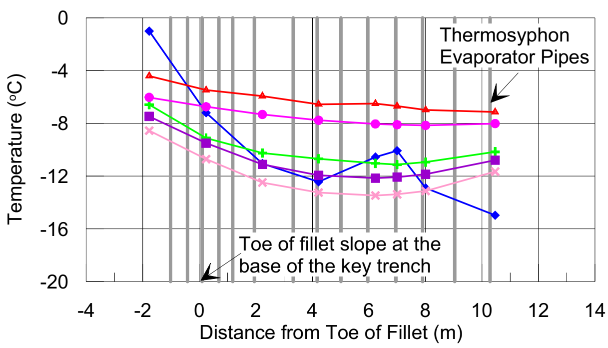
4.5 Dam Performance

Water has collected behind the dam through the spring and summer of 2002 to 2004. The pond behind Waste Rock Dam rose to a maximum elevation of 439.75 m (up to 10 m head of water) in June 2003. Low water levels have been maintained from late-summer through the winter season.

Figure 13 shows selected vertical and horizontal ground temperature profiles at Station 0+265, near the thickest portion of the dam. Temperatures at the base of the key trench have generally been colder than -5°C. Year-to-year, dam and foundation temperatures have become progressively cooler since construction.



a) vertical (below key trench)



b) horizontal (at base of key trench)

Figure 13 Selected Ground Temperature Profiles, Station 0+265, Waste Rock Dam

5. CONCLUDING REMARKS

Performance monitoring to date of the dams at the EKATI Diamond Mine has shown that thermosyphons have been effective in ensuring that frozen core dams built on warm permafrost foundations retain water, and remain frozen even under unusually warm years.

6. ACKNOWLEDGEMENTS

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