Frozen Core Tailings Dam: Part 1, Long-Term Thermal Performance

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ABSTRACT: Tailings management at the Hope Bay Project in Nunavut, Canada, includes reliance on an innovative frozen core dam. This dam does not have a tailings beach against it, and has been designed as a water retaining dam with a 30-year design life. Successful performance of the dam relies on both the core and the underlying foundation maintaining specific target temperatures throughout its service life. This paper, which is the first in a two-part series, describes the dam performance six years post construction, and compares modelled thermal response with field performance data collected from multiple ground temperature cables. The data and modelling confirm that the dam has performed in accordance with expectations and that it is on track to meet long-term performance targets, including for conservative climate change scenarios. The second paper in this series describes creep deformation of the dam, which uses the thermal response as a key parameter.

1 INTRODUCTION

The tailings management system for the Hope Bay Project, in Nunavut, Canada, includes sub-aerial tailings deposition into the Doris tailings impoundment area (Doris TIA). The Doris TIA is located in the basin of the former Tail Lake, a shallow lake which has been delisted in accordance with Schedule II of the Metal Mining Effluent Regulations. To provide containment, a frozen core water retaining dam (North Dam) was designed (SRK 2007, 2017a), and constructed over the winter seasons of 2011 and 2012 (SRK 2012). Following six years of monitoring, conclusions regarding dam performance can be made, both with respect to thermal response and creep deformation. This paper, which is Part 1 of a two-part series, describes the thermal performance monitoring and associated modeling, while Part 2 (Rykaart et al. 2018) describes the creep deformation monitoring and associated modeling. Section 1 through 6 of Part 1 and Part 2 is identical to allow the papers to be read independently.

2 TAILINGS MANAGEMENT SYSTEM

The Doris TIA, when fully developed, will consist of one frozen core water retaining dam (North Dam), and two frozen foundation dams (South Dam and West Dam). Tailings will be discharged from the South and West Dams, as well as select locations around the perimeter of the facility. The North Dam will provide water containment for the Reclaim Pond, and no tailings will be in contact with the dam during its 30-year design life. At closure, the Reclaim Pond will be drained, and the North Dam breached, with no need for a permanent water retaining dam (SRK 2017a).

3 FOUNDATION CONDITIONS

The project is located within the continuous permafrost region of Canada, approximately 140 km north of the Arctic Circle. Site measurements indicate that permafrost in the area is approximately 570 m thick, with an active layer of 0.9 m to 1.7 m, depending on the material type. The ground temperature at the depth of zero annual amplitude is -8°C, and the geothermal gradient is 0.021°C/m (SRK 2017b).

Numerous geotechnical characterization programs have been completed within the alignment of the North Dam, to characterize the foundation conditions. Programs included boreholes, test pits, in-situ hydraulic conductivity testing, installation of ground temperature cables (GTCs), long-term ground temperature monitoring (starting in 2002), percolation testing, geophysics, and both undisturbed and disturbed sample collection and laboratory testing (SRK 2017b).

The North Dam is located in a narrow valley approximately 200 m downstream of the northernmost extent of the former Tail Lake. The stratigraphy under the dam has two distinct zones; the southwest abutment is dominated by ice-saturated sand deposits 10 m to 15 m thick, overlain by up to 3 m of silt and clay, while the northeast abutment is dominated by ice-saturated marine clayey silt with a maximum thickness of 15 m. Excess ground ice, averaging 10 % to 30% by volume, occasionally as high as 50%, is also present on both abutments.

A thin layer of sand and gravel overlies the bedrock surface in the upper portions of the valley, and a peat unit was encountered near the center of the dam, in the area of the lake outflow. The average pore water salinity is 39 parts per thousand (ppt), with a freezing point depression of -2.2°C (SRK 2017c). During construction, an isolated hypersaline zone, with salinity values in excess of 90 ppt, was also encountered within the key trench (SRK 2012). Bedrock is generally competent basalt.

Figure 1 provides a generalized longitudinal section of the North Dam foundation conditions, as understood prior to percolation testing and key trench excavation.

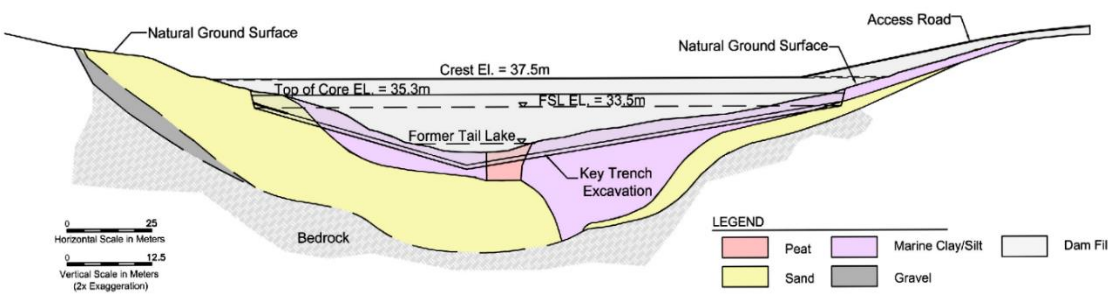

Figure 1. Longitudinal section of the North Dam showing generalized foundation conditions.

4 DAM DESIGN

A conventional unfrozen dam was not suitable for this location due to the thick ice-rich overburden foundation, remote site location, and lack of suitable low-permeability borrow material (Miller et al. 2013). Additionally, the thick overburden meant a frozen core dam founded on bedrock, similar to those constructed at other Canadian mines (Miller et al. 2013) was not feasible. Therefore, an innovative frozen core dam was designed to accommodate these challenging foundation conditions.

The North Dam is approximately 200 m long, with a maximum overall height of 10 m. The frozen ice-saturated core, keyed-in to the frozen foundation are designed to ensure water retention properties and containment. A geosynthetic clay liner (GCL) was installed along the upstream side of the frozen core to provide secondary water-retaining capability in case cracks develop in the core caused by thermal expansion, thermal erosion, differential settlement, or creep deformation. Thermal design to ensure primary containment requires that the frozen core maintains a temperature at or below -2°C, at a width that is at least twice the head of water impounded against the dam. In addition, the saline foundation needs to maintain a temperature at or below -8°C for the same width, extending to bedrock under normal operating conditions (SRK 2007).

The dam was uniquely designed for the saline ice-rich foundation that is particularly susceptible to creep deformation. Therefore, the dam was designed to accommodate long-term shear strains in the core and foundation approaching 2% and 10%, respectively, and maximum shear strain rates at or below 1.0E-05 sec^{-1} (3.2E+02 $year^{-1}$) (SRK 2007).

The dam design included a key trench ranging from 2 m to 5 m deep to allow complete bonding of the core to the permafrost foundation (SRK 2012). Twelve sloped thermosyphons, six extending from each abutment of the dam, were installed at the base of the key trench to adequately cool the core and foundation over the design life assuming water permanently impounded against the upstream face to full supply level, and with consideration for climate change. The typical design cross section for the North Dam is illustrated in Figure 2, and the equivalent as-built cross section is illustrated in Figure 3 for comparison.

The core material is comprised of sand-sized crushed basalt, placed in a near saturated state and allowed to freeze during construction. The core is surrounded by a transition layer, consisting of jaw crusher run rock that acts as a filter, should the dam thaw. An outer shell constructed of run-of-quarry rock acts as a thermal protection layer for the frozen core, provides buttressing against creep deformation, and provides ice and wave run-up protection.

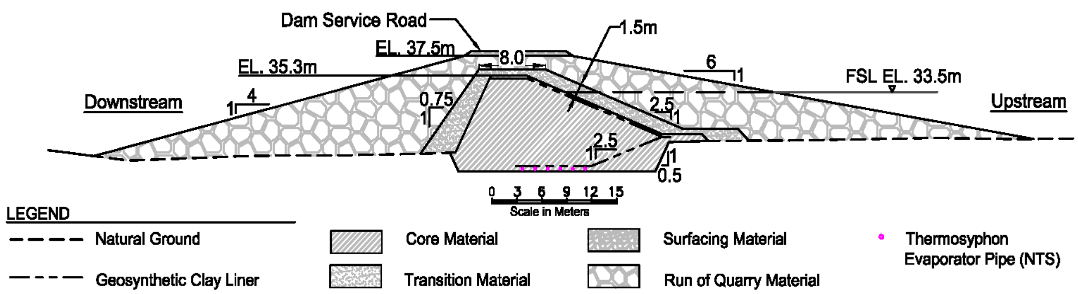

Figure 2. Typical design cross-section of the North Dam.

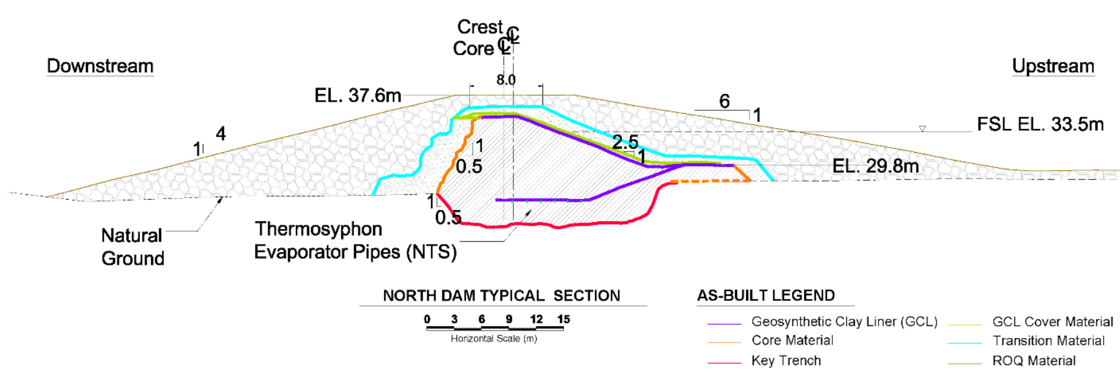

Figure 3. Typical as-built cross section of the North Dam.

5 CONSTRUCTION

The North Dam was designed to be constructed using construction techniques similar to those employed for the frozen core dams constructed at other Canadian mines (Miller et al. 2013). However, the site climate, available quarry rock material, and foundation conditions necessitated adaptations to the construction method (SRK 2012); some of which are summarized in Kurylo et al. (2013). Details on lessons learned from the North Dam construction are presented in Miller et al. (2013).

Drilling and blasting were used to excavate the key trench. Key trench excavation included the removal of all peat from the center portion of the dam, and over-excavation of the hypersaline zone. Following completion of the key trench excavation, the frozen core was constructed by placing and compacting 0.2 m to 0.3 m thick lifts of core material. Core material was produced in a modified asphalt plant by mixing and heating crushed rock and water. The lifts of saturated hot core material were then left to freeze back to target temperature (at or below -2°C) prior to the placement of the next lift.

Core placement required stringent quality control and quality assurance to ensure that saturation, freeze-back, density, and material specification requirements were met. Quality control and quality assurance included continuous material testing (laboratory and field), visual inspections, and constant and open communication with the client and contractor. These procedures ensured freeze-back, saturation (average 85% or greater, with no test below 80%), and compaction requirements (90% or greater of standard Proctor) were met. Between each lift, loose material and snow was cleared. To ensure that the lifts would freeze within a reasonable timeframe, frozen core placement was not attempted when ambient air temperatures were warmer than -10°C.

Due to the larger than expected excavation required to remove the peat and hypersaline soils, and a warm spring, the dam could not be completed in one winter season as originally planned. At the end of the 2011 construction season, the lower GCL and horizontal thermosyphons were installed and covered. However, the frozen core was not completed. To protect the core during the subsequent summer, a temporary 2 m thick run-of-quarry cover was placed over the partially constructed core. Work recommenced in the winter of 2012, and the dam was substantially complete by April 2012. The last remaining instrumentation on the downstream side of the dam was installed in August 2012 (SRK 2012).

6 INSTRUMENTATION

Performance of the North Dam is dependent on the core and foundation maintaining design temperatures, and the long-term strains, and strain rates remaining below target limits (SRK 2012, 2018a). Thermal performance of the dam is monitored with a series of thirteen horizontal GTCs, and eleven vertical GTCs. Figure 4 provides a typical dam cross section, including the location of these GTCs. Three horizontal GTCs are positioned at the top, middle and base of the core, while vertical GTCs are positioned along the foundation on the upstream side, in the center of the dam (key trench) and on the downstream side.

The working condition of each thermosyphon unit is confirmed using a single bead thermistor attached to the radiator riser pipe and compared with ambient air temperature measurements collected over the same period of time.

Deformations are monitored by a series of surficial, shallow, and deep settlement points and six inclinometers. Eighteen surficial settlement points are located on the downstream face of the dam, to monitor deformation of the dam shell in the location of the greatest expected deformation. Three deep settlement points are used to monitor deformation of foundation soils, again at the location of the greatest expected deformation. Fourteen shallow settlement monitoring points were installed on the crest of the dam to monitor crest deformation and differential settlement. The inclinometers are installed along the location of the greatest expected deformation and monitor deformation of both the dam shell and foundation. The instrumentation layout at the area of greatest expected deformation can be seen in Figure 4.

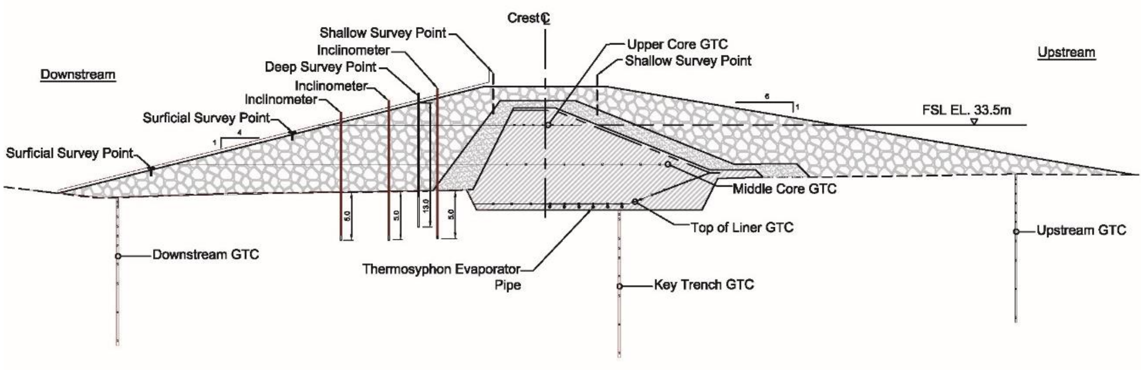

Figure 4: North Dam typical instrumentation.

7 THERMAL MONITORING DATA

North Dam monitoring includes ground temperature measurements recorded every six hours with data loggers, and monthly manual deformation measurements (i.e. survey settlement and inclinometers). Additionally, ongoing visual inspection of the dam structure by Project staff, and a formal annual geotechnical inspection by a Professional Geotechnical Engineer, who is also the engineer-of-record, is conducted (SRK 2018a).

Annual inspections (SRK 2018b), and review of monitoring data, suggest the dam is performing in accordance with the design expectations. The North Dam has had impounded water since the first winter of construction in 2011. The operating water level impounded against the upstream face of the dam has averaged 29.8 m, with a maximum level of 30.2 m over the period from May 2011 to June 2018. The original water level of Tail Lake prior to construction of the North Dam was 28.3 m, and the design full supply level is 33.5 m. Deformation measurements suggest movements less than predicted at this point in time (Rykaart et al. 2018).

Since the dam was commissioned in 2012, the GTC measurements have been recorded every six hours, using two separate data loggers and are manually downloaded by site staff monthly. During that time over 2150 days of monitoring data have been collected with minimal interruption from instrument malfunction or human error with the exception of 215 days of data lost from one of the GTCs becoming disconnected by unknown means, and 169 days of data lost following vehicle damage to one of the GTCs. During recalibration of the dataloggers in early 2018, no data was recorded for 70 days. This scheduled recalibration (every 5 years) was intentionally completed during the cooling cycle to limit data loss during the critical thaw period.

A few GTC beads (e.g. thermistor sensors) from select GTCs have recorded erroneous readings, and prior to June 16, 2014 two GTCs at chainage 0+175 m were incorrectly connected to the data logger, and consequently the three bottom beads of GTC #ND-VTS-175-KT were not recorded. None of these errors or data losses are considered material, as there is sufficient redundancy built into the monitoring system, and the overall trends in ground temperatures can still be observed with confidence.

Since completion of construction, all core GTC measurements are well below the required design temperature of -2°C, with the warmest temperature measured to be about -4.5°C, over the most recent year of monitoring. The colder than expected temperatures, when compared to what was originally predicted by thermal modeling, are explained by the lower water level presently impounded against the upstream face of the dam. Impoundment started in 2011 and tailings deposition began in 2016, and over this period the water level in the impoundment has on average been about 1.5 m above the original lake water level as opposed to having total head of 5.2 m at full supply level as it was modelled. The lower water level has resulted in greater exposure of the upstream face to atmospheric cooling during the winter, limited saturation and latent heat effects of the material upstream of the liner, and limited heat gain to the core that would normally result from the impounded water.

Figures 5a, 5b and 5c presents an example of the core temperatures recorded at chainage 0+130 m. Figure 5a shows the uppermost horizontal GTC (ND-HTS-130-33.5), Figure 5b the middle GTC (ND-HTS-130-31.0), and Figure 5c the lower GTC (ND-HTS-130-28.8), located immediately above the thermosyphons. The uppermost GTC, located 1.8 m below the dam crest at the top of the core, not surprisingly shows the greatest seasonal range as compared to the middle and lower GTCs. Similarly, the outermost beads on the middle and lower GTCs shows the greatest seasonal range. The apparent erratic response on some of the beads in the lowest GTC is not an error, but rather clearly shows the effect of the thermosyphons which act to significantly cool the core and associated foundation.

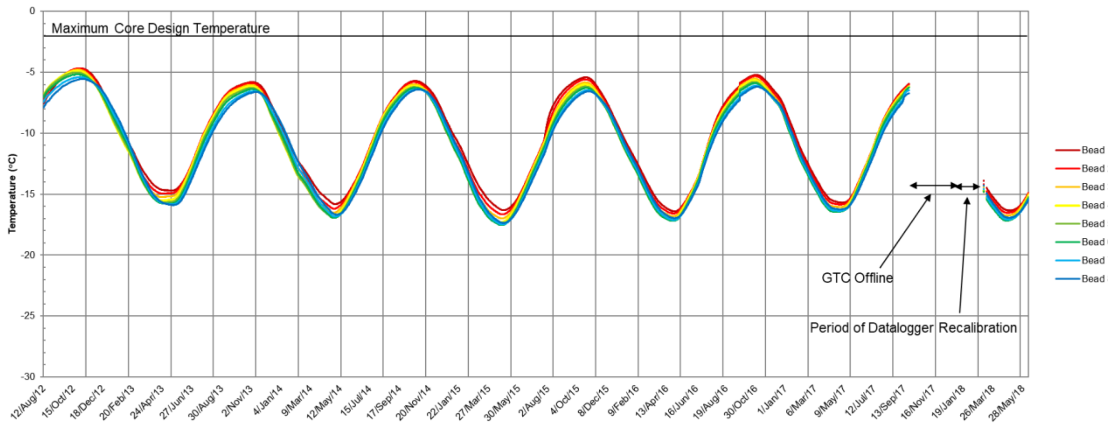

Figure 5a. Upper horizontal GTC at chainage 0+130 m, located at elevation 33.5 m (ND-HTS-130-33.5).

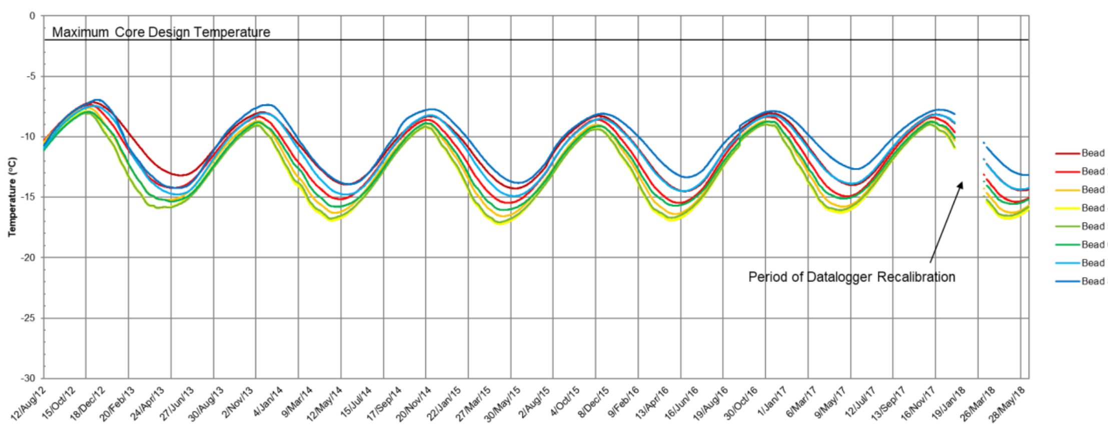

Figure 5b. Middle horizontal GTC at chainage 0+130 m, located at elevation 31.0 m (ND-HTS-130-31.0).

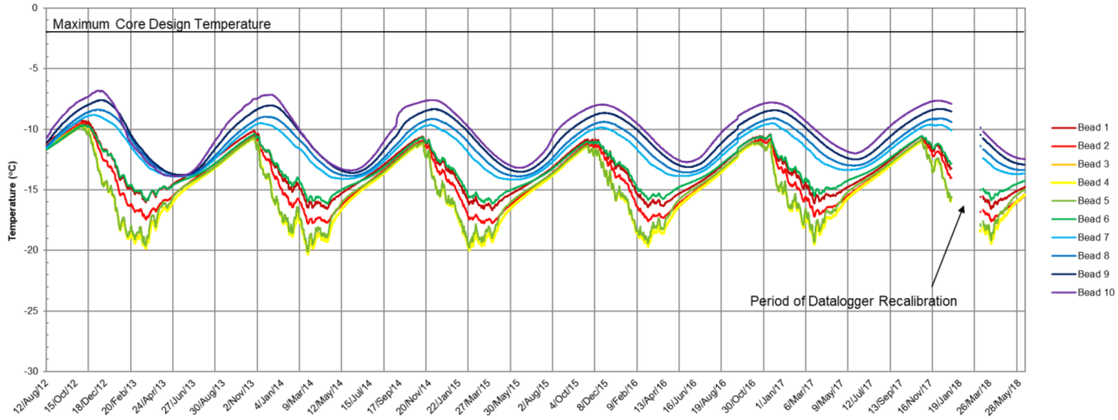

Figure 5c. Lower horizontal GTC at chainage 0+130 m, located at elevation 28.8 m (ND-HTS-130-28.8).

Measured foundation temperatures for the North Dam are all at or below design temperatures, except for three beads of one vertical GTC in the key trench at chainage 0+175 m (ND-VTS-175-KT). This GTC has remained stable, at or below -6.7°C.

Key trench foundation temperature measurements indicate that after construction the foundation temperatures in a few places were warmer than design temperatures. In 2012, the vertical key trench GTCs at chainage 0+040 m, 0+085 m, and 0+175 m (ND-VTS-175-KT, ND-VTS-085-KT and ND-VTS-040-KT) had some foundation measurements warmer than the design temperature of -8°C, at shallower depths, with no areas warmer than -5.7°C. Since 2012, a cooling trend has been observed and all foundation measurements for both GTCs ND-VTS-040-KT and ND-VTS-085-KT, which are now below -8°C (Figures 6a and 6b). GTC ND-VTS-175-KT has consistently had two beads with measurements peaking above the design temperature for a maximum of 60 days during the warmest period of each year as shown in Figure 6c. In the last monitoring year, the maximum temperature was -6.8°C, more than 1°C cooler than after construction in 2012.

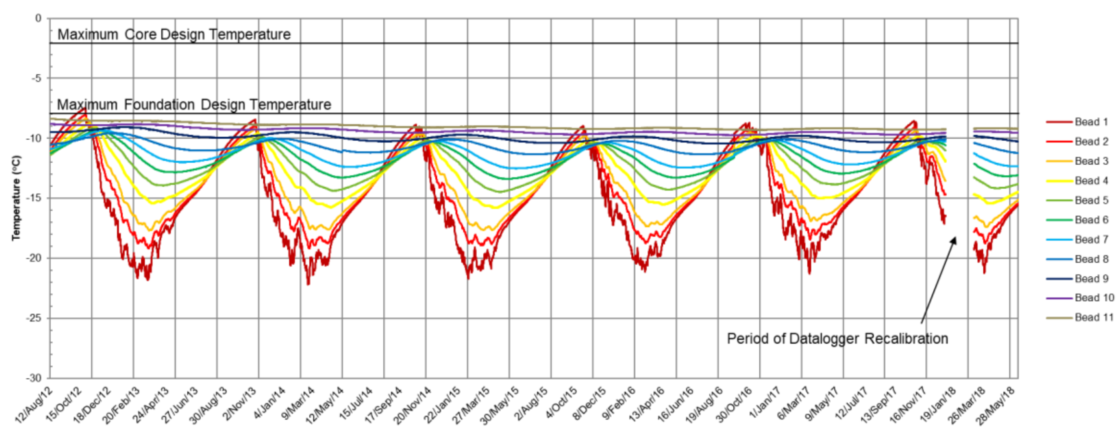

Figure 6a. Time series data for the key trench vertical GTC at chainage 0+040 m (ND-VTS-040-KT).

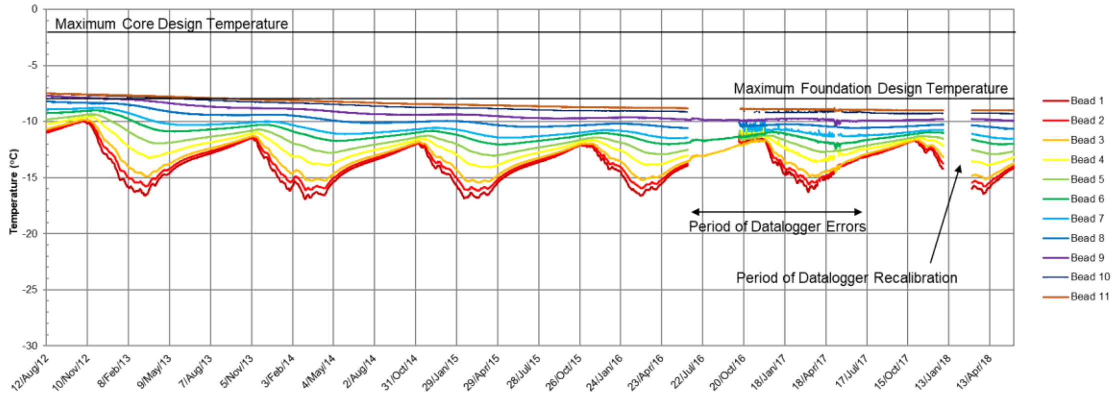

Figure 6b. Time series data for the key trench vertical GTC at chainage 0+085 m (ND-VTS-085-KT).

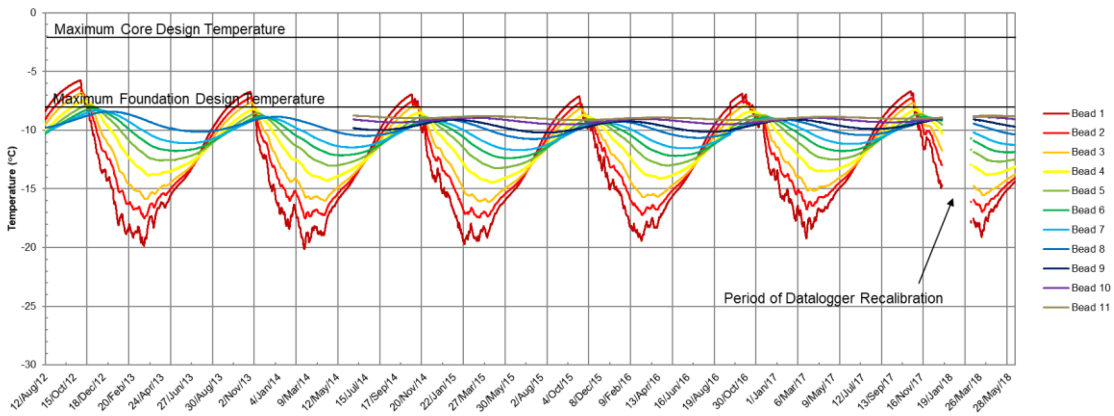

Figure 6c. Time series data for the key trench vertical GTC at chainage 0+175 m (ND-VTS-175-KT).

The maximum measured temperature of the near surface beads for vertical GTCs upstream and downstream of the key trench have been between 0°C and -3°C since 2015. These warmer temperatures are consistent with the design thermal modeling, and are a function of the ambient conditions. Figure 7a shows an example of the thermal behavior for the upstream (ND-VTS-130-US), and Figure 7b, the key trench (ND-VTS-130-KT) vertical GTCs at chainage 0+130 m. Because there is not much head of water behind the dam, there is currently no discernable difference between the ground temperature profiles in the upstream and downstream CTGs.

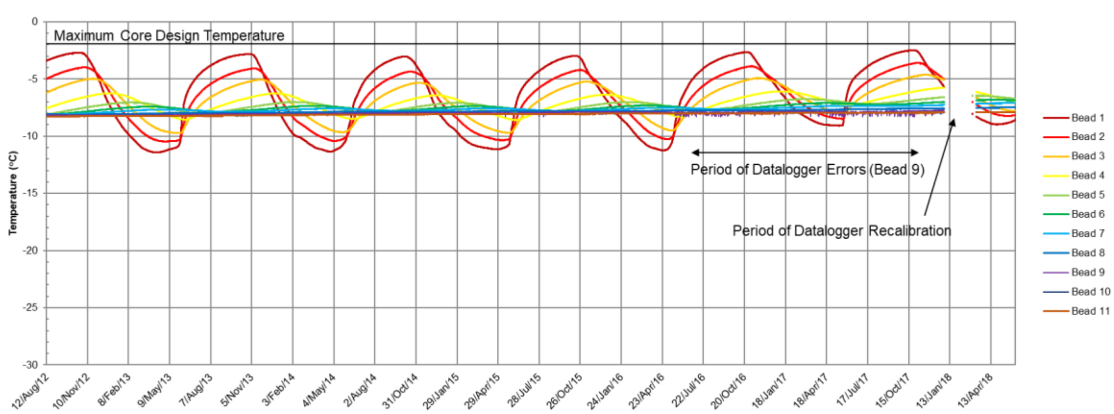

Figure 7a. Time series data for the upstream vertical GTC at chainage 0+130 m (ND-VTS-130-US).

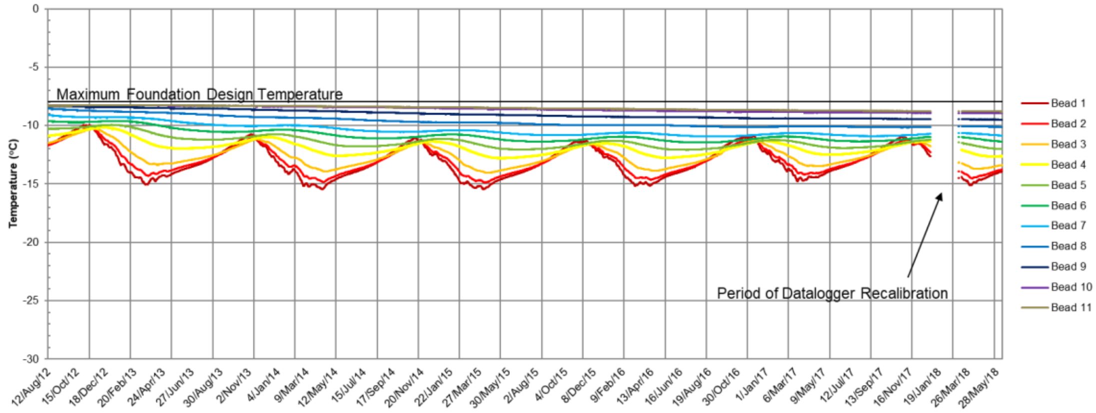

Figure 7b. Time series data for the key trench vertical GTC at chainage 0+130 m (ND-VTS-130-KT).

8 LONG-TERM THERMAL PERFORMANCE

As part of the design for the Phase 2 Doris TIA, additional North Dam thermal modeling was completed to determine if the current configuration of the North Dam is suitable to maintain the thermal design criteria over the intended design life of 30 years. The existing GTC monitoring data, water levels, and climate data were used to calibrate and validate the thermal model to observed conditions. The validated model was then used to model long-term performance over an extended 40-year design life (10 years beyond the planned 30-year design life) with consideration for climate change.

Figures 8a, 8b and 8c shows select calibration model results for chainage 0+085 m. The modeled temperatures at the thermosyphon evaporator pipe closely matches the measured temperature at an equivalent position, and are conservatively warmer during the winter heat extraction period (Figure 8a). The modeled evaporator pipe temperature agrees with the timing of heat extraction from the thermosyphon evaporator pipe which is observed as a rapid decrease in temperature, and the timing of warm and maximum temperature are reached when the thermosyphons are seasonally inactive.

Figures 8b and 8c show calibration model temperatures for the middle of the frozen core and the foundation below the key trench, respectively. The frozen core and foundation temperature also shows good agreement with measured temperature over the calibration period. The combined agreement between the measured and modelled results confirms the model surface boundary conditions, thermosyphon heat extraction, and material thermal properties input to the model are reasonable.

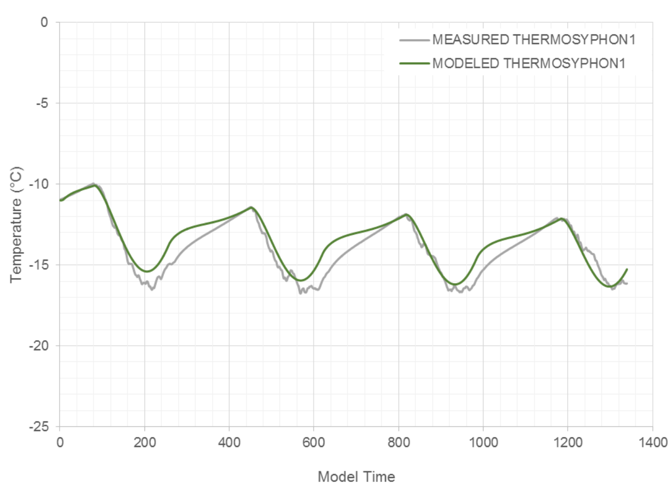

Figure 8a: Thermosyphon evaporator pipe temperature calibration model at chainage 0+085 m.

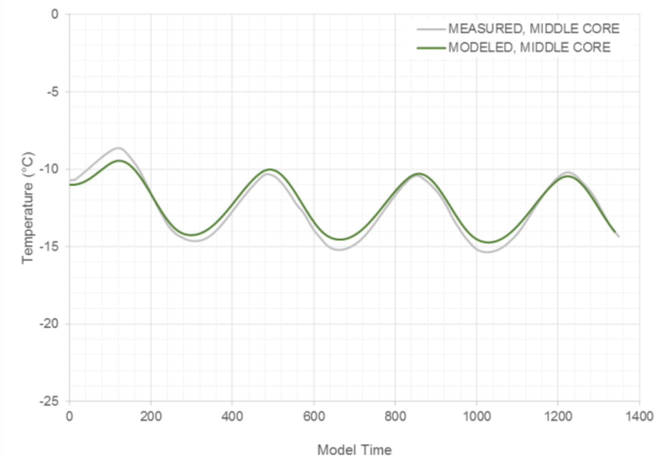

Figure 8b: Middle core temperature calibration model at chainage 0+085 m.

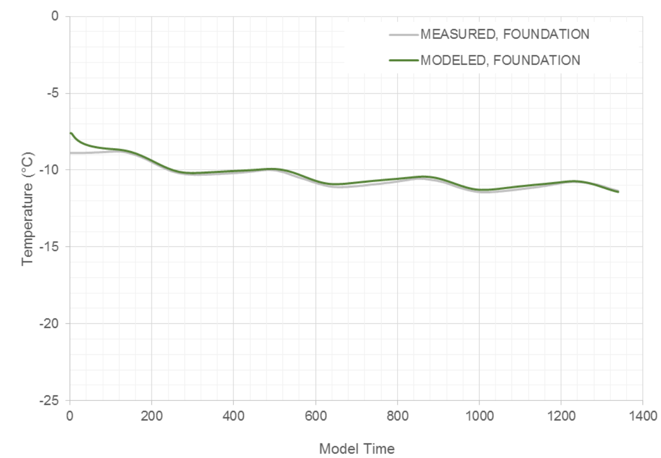

Figure 8c: Foundation temperature calibration model at chainage 0+085 m.

Figure 9 shows the long-term model results for chainage 0+85 m, at the end of the 30-year design life. The critical section of the dam used to assess performance is shown as a yellow bounding box in Figure 9. The results over the critical section indicate the frozen core and foundation will remain below -2°C and -8C, respectively.

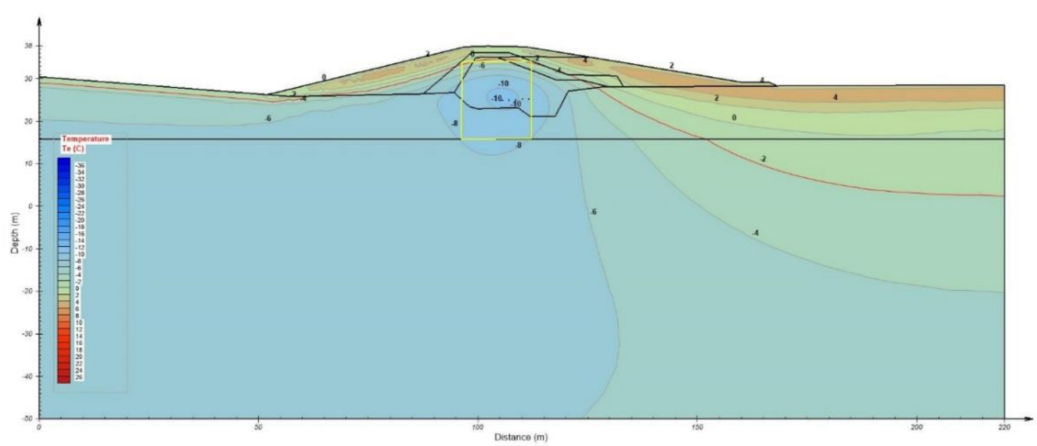

Figure 9. Long-term thermal model results for chainage 0+85 m.

Additional modeling completed for smaller sections of the dam indicate the core temperature over the critical section remains below -2°C for the design life and most, but not all, of the foundation remains at or below -8°C. A smaller portion of the foundation (approximately 8%) is warmer than -8°C at the end of 30 years. The increase in ground temperature outside the critical section of the foundation will result in a higher fraction of unfrozen water and a greater potential for creep deformation (Rykaart et al. 2018).

9 CONCLUSIONS

The frozen core North Dam of the Doris TIA has been designed to retain water at its full supply level over the 30-year design life. Based on thermal modelling and observational monitoring data, the core and foundation are expected to meet the overall thermal design requirements of -2°C and -8°C respectively. Following construction over two winter seasons, six years of monitoring data has been collected and suggests the dam is performing within the design expectations.

While the modelling and monitoring data validates the design, the deep, ice-rich saline marine silts and clays in the foundation will result in long-term creep deformation, and therefore the design geometry has been specified to accommodate large deformations.

The observed and long-term modelled performance of the North Dam continues to exemplify the advantages of prudent design, comprehensive monitoring and observational validation in advancing the state of practice in the challenging conditions of cold regions dam design.

10 ACKNOWLEDGEMENTS

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REFERENCES

Kurylo J., Rykaart M., Wade L. 2013. Engineering challenges for tailings management facilities in permafrost regions. Proceedings of Tailings 2013, Santiago, Chile, August 28-30.

Miller M., Kurylo J.B., Rykaart M. 2013. Frozen dams in permafrost regions. Proceedings of Mine Water Solutions, Lima, Peru, April 15-17.

Rykaart M., Barrero A., Lizcano A. 2018. Frozen Core Tailings Dam: Part 2, Long-Term Creep Deformation. Proceedings of Tailings and Mine Waste 2018, Colorado, USA, September 30 – October 2.

SRK Consulting (Canada) Inc. 2007. Design of the tailings containment area, Doris North Project, Hope Bay, Nunavut Canada, Report prepared for Miramar Hope Bay Ltd. 326 p.

SRK Consulting (Canada) Inc. 2012. Hope Bay Project, North Dam As-built Report, Report prepared for Hope Bay Mining Ltd. 41 p.

SRK Consulting (Canada) Inc. 2017a. Doris Tailings Management System Phase 2 Design, Hope Bay Project. Report prepared for TMAC Resources Inc., November.

SRK Consulting (Canada) Inc. 2017b. Hope Bay Project, Geotechnical Design Parameters and Overburden Summary Report. Report prepared for TMAC Resources Inc., November.

SRK Consulting (Canada) Inc. 2017c. Hope Bay Project: Doris Tailings Impoundment Area North Dam Thermal Modeling. Memo prepared for TMAC Resources Inc., November 30.

SRK Consulting (Canada) Inc. 2018a. Hope Bay Project, North Dam Monitoring: Standard Operating Procedures – Revision 2. Report prepared for TMAC Resources Inc., May.

SRK Consulting (Canada) Inc. 2018b. 2017 Annual Geotechnical Inspection Tailings Impoundment Area Doris Project, Hope Bay, Nunavut. Report prepared for TMAC Resources Inc., March.