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FROZEN CORE DAM PERFORMANCE: FOUR YEARS POST CONSTRUCTION

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ABSTRACT

As part of the tailings management system for the Doris Project in Nunavut Canada, a frozen core dam was constructed in 2012 on a foundation of thick ice-rich, saline glacial marine silt and clay, and fine sand. This dam will not have a tailings beach against it, and as a result has been designed as a water retaining dam for its design life of 20 years. Environmental containment is provided by a frozen core keyed-in, and permanently bonded with the underlying permafrost. To ensure this bond, the engineered (non-saline) frozen core must maintain a temperature below -2°C, and the underlying saline permafrost foundation must be at or below -8°C, under normal operating conditions. To ensure continued successful performance of the dam it has been rigorously instrumented and this paper describe the dam performance four years post construction.

RÉSUMÉ

Dans le cadre du système de gestion des résidus pour le projet Doris au Nunavut Canada, un noyau barrage congelé a été construit en 2012 sur une base de glace épaisse riche, une solution saline de limon glaciaire de marine et d'argile, et de sable fin. Ce barrage aura pas une plage de résidus contre elle, et par conséquent a été conçu comme un barrage de retenue d'eau pour sa durée de vie de 20 ans. Confinement de l'environnement est assurée par un noyau congelé claveté -in, et collé en permanence avec le pergélisol sous-jacent. Pour assurer cette liaison, la (non saline) noyau congelé conçu doit maintenir une température inférieure à -2°C, et la fondation du pergélisol salin sous-jacente doit être égale ou inférieure à -8°C, dans des conditions normales de fonctionnement. Pour assurer la bonne exécution du barrage, il a été rigoureusement instrumenté et le présent document décrit la performance du barrage de quatre ans après la construction.

1 INTRODUCTION

The tailings management plan for the Doris Project, in Nunavut, Canada, entails sub-aerial tailings deposition into the tailings impoundment area (TIA). The 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 2005, 2007), and constructed over the winter seasons of 2011 and 2012 (SRK 2012). Following four years of monitoring, preliminary conclusions regarding dam performance can be made, and is presented in this paper.

2 TAILINGS MANAGEMENT SYSTEM

Rigorous alternative analyses were performed to select the location for the Doris TIA. Due to its size, remoteness and capacity, the former Tail Lake was selected. The TIA will consist of one frozen core water retaining dam (the North Dam), and one frozen foundation dam (South Dam). The TIA will be split into two areas; the Reclaim Pond, and the tailings disposal area, by an Interim Dike (SRK 2015). The North Dam will provide water containment for the Reclaim Pond, and no tailings will be in contact with the dam. At closure, the Reclaim Pond will be drained and the North Dam will be breached, with no need for a permanent water retaining dam.

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 to 1.7 m, depending on the material type. The temperature at the depth of zero annual amplitude is -8°C, and the geothermal gradient is 0.021°C/m.

Numerous drill programs have been performed within the alignment of the North Dam, to characterize the foundation conditions. Programs included installation of ground temperature cables (GTC), long-term ground temperature monitoring, percolation testing, and ground penetrating radar, in addition to drill hole logging and laboratory testing.

The North Dam is located in a narrow valley approximately 200 m downstream of the northernmost extent of the former Tail Lake, over the former lake outflow. The stratigraphy under the dam has two distinct zones; the southwest side is dominated by ice-saturated sand deposits 10 to 15 m thick, overlain by up to 3 m of silt and clay, while the northwest side is dominated by ice-saturated marine clayey silt with a maximum thickness of 15 m. A thin layer of sand and gravel overlies the bedrock surface in the upper portions of the valley. In addition, a peat unit was encountered near the center of the dam, in the area of the lake outflow.

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

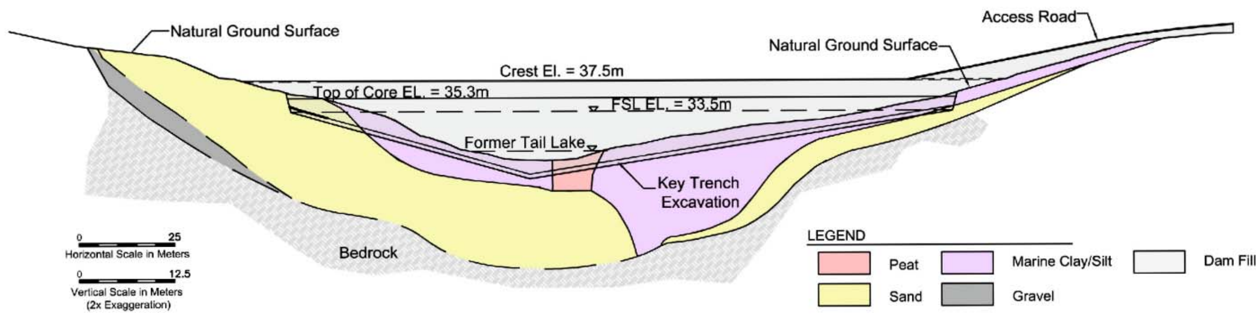

Figure 1: Long section of North Dam, displaying the complex foundation conditions

4 DAM DESIGN

Due to the deep saline permafrost foundation, remote site, and lack of suitable low-permeability borrow material, a conventional unfrozen dam was not suitable for this location. Additionally, the 15 m thick overburden meant a frozen core dam constructed on a bedrock foundation, similar to those constructed at the Ekati Mine (EBA 1998, 2003), was not feasible. Therefore, to accommodate these challenging foundation conditions, a unique frozen core dam was designed.

The North Dam is approximately 200 m long, with a maximum overall height of 10 m. Containment is provided by a frozen core keyed-in, and permanently bonded with the underlying permafrost. To ensure this bond, the engineered (non-saline) frozen core must maintain a temperature below -2°C, and the underlying saline permafrost foundation must be at or below -8°C, under normal operating conditions.

What makes this design unique, is that due to the high ice content and salinity of the foundation, the dam is particularly susceptible to creep. Therefore the dam was designed accommodate long-term shear strains in the core and foundation approaching 2% and 10%, respectively (SRK 2007). To help manage these levels of deformation, very shallow slopes of 6H:1V (horizontal to vertical) on the upstream, and 4H:1V on the downstream were adopted.

The dam design included a key trench approximately 2 m to 5 m deep, to allow complete bonding of the core to the permafrost foundation. To account for upset conditions, including climate change, twelve sloped thermosyphons were used in the base of the key trench to enhance foundation cooling. 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.

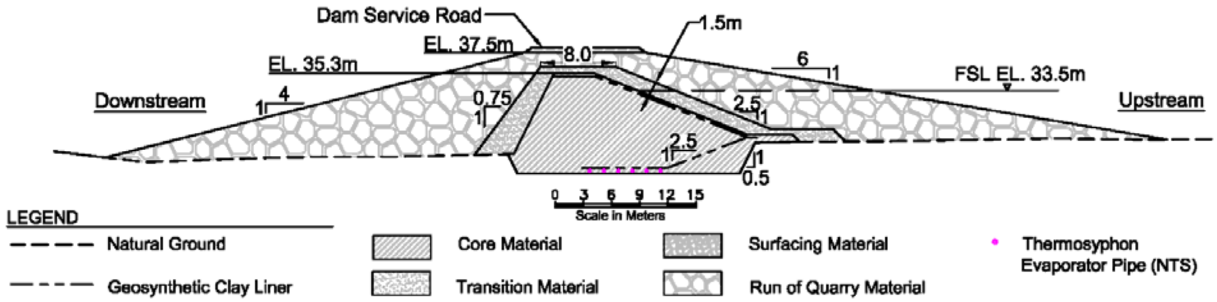

Figure 2: Typical design cross-section of the North Dam

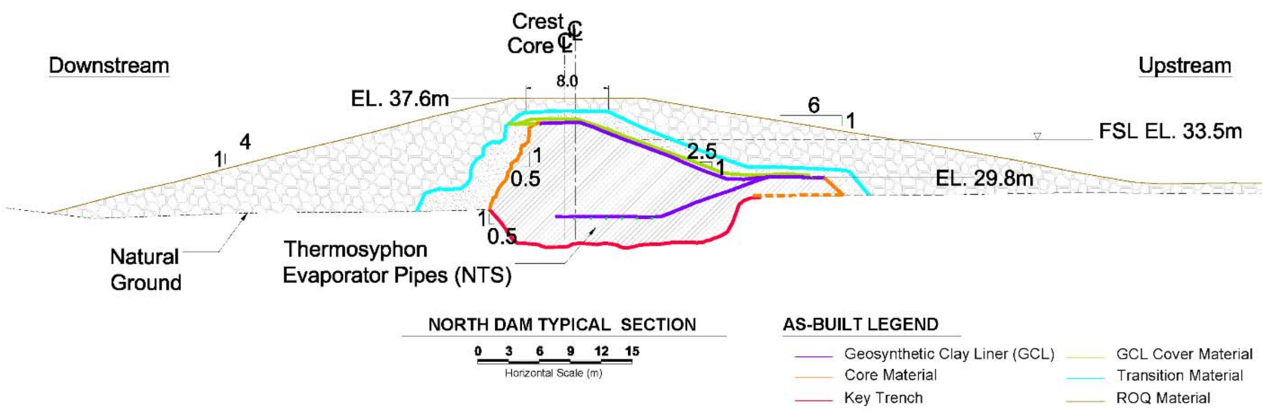

Figure 3: Typical as-built cross section of the North Dam

The core comprises of a frozen mass of gravel to sand sized crushed basalt, placed in a near saturated state. Along the upstream side of the core, a geosynthetic clay liner (GCL) was included to provide secondary water-retaining capability should cracks develop in the core due to creep deformation or differential settlement.

The core is surrounded by a transition layer, consisting of jaw 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.

5 CONSTRUCTION

The North Dam was designed to be constructed using construction techniques similar to those employed for the frozen core dams constructed at the Ekati Mine (EBA 1998, 2003). However, the site climate, available quarry rock material, and foundation conditions necessitated adaptations to the construction method (SRK 2012); some of which are summarised 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 the excavation of a hypersaline zone which had salinity values in excess of 90 ppt. Following completion of the key trench excavation, the frozen core was constructed by placing and compacting 0.2 to 0.3 m thick lifts of core material. Core material was produced in a modified ashphalt plant by mixing and heating crushed rock and water. The lifts of hot core material were then left to freeze back (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 requirements were being 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 saline 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, and instrumentation on the downstream side of the dam was installed in August 2012.

6 INSTRUMENTATION

Performance of the North Dam is dependent on the core and foundation maintaining design temperatures. 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.

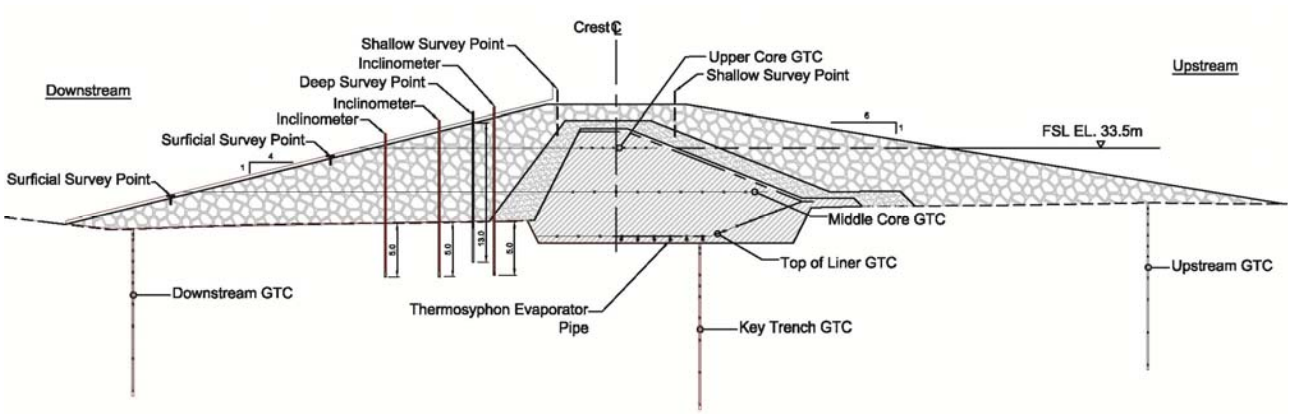

Figure 4: North Dam Typical Instrumentation

Thermosyphon performance is continuously monitored using single bead thermistors attached to each radiator riser, and ambient air temperature measurements.

Deformations are monitored by a series of surficial, shallow, and deep survey points and six inclinometers. Eighteen surficial survey 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 survey 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.

7 MONITORING

North Dam monitoring requirements include six hourly temperature measurement via the GTCs connected to a data logger, and monthly manual deformation measurements (i.e. survey and inclinometer). 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 required (SRK 2012).

8 NORTH DAM PERFORMANCE

8.1 Core and Foundation Temperatures

Since September 2012, North Dam GTC measurements have been recorded every six hours, using two separate data loggers, with data manually downloaded by site staff monthly. Since installation, 215 of over 1,420 days' worth of data from one of the GTC's has been lost, due to the cable becoming disconnected by unknown means. Additionally, a few beads from select GTCs are providing erroneous data, and prior to June 16, 2014 two cables at station 0+175 m were incorrectly connected to the data logger and consequently the three bottom beads of 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 systems and the overall trends in ground temperatures can still be observed.

Foundation and core temperature for the North Dam are all at or below design temperatures, with the exception of one vertical GTC in the key trench at station 0+175 m (ND-VTS-175-KT); which has shown a steady cooling trend since 2012. Since completion of construction, all core GTC measurements have cooled slightly, and all core GTCs are measuring temperatures well below -2°C, with the warmest temperature measured in the last year being approximately -5°C. While these temperatures are colder than design, and colder than thermal modelling would predict, these values are can easily be explained by the lack of water along the upstream face of the dam. Production has not yet started and therefore water levels within the TIA are only marginally higher than the original lake level, with less than 1.5 m of water against the dam face. The lack of latent heat of water along the upstream face and the increased freezing during the winter months have allowed the core temperatures to become colder than expected.

Unlike the core, key trench foundation temperature measurements indicate that after construction the foundation temperatures in a few places were warmer than design temperatures. In 2012, the ground temperature cables ND-VTS-175-KT, ND-VTS-085-KT and ND-VTS-040-KT all had some foundation measurements warmer than -8°C, with no areas warmer than -5.7°C. Since 2012 a cooling trend has been observed, and all foundation measurements for both ND-VTS-085-KT and ND-VTS-040-KT are now below -8°C (Figure 5 and Figure 6). While ND-VTS-175-KT (Figure 7) still has two beads warmer than design temperature, the maximum measured temperature in the last monitoring year is -7.1°C, and the measured temperatures have decreased more than 1°C since 2012.

The maximum measured temperatures of near surface beads for vertical GTCs upstream and downstream of the key trench have been between 0°C and -2°C since 2015. These warmer temperatures are consistent with the design thermal modeling, and are a function of the ambient conditions. Figure 8 provides an example of this for the upstream vertical GTC at station 0+085 m.

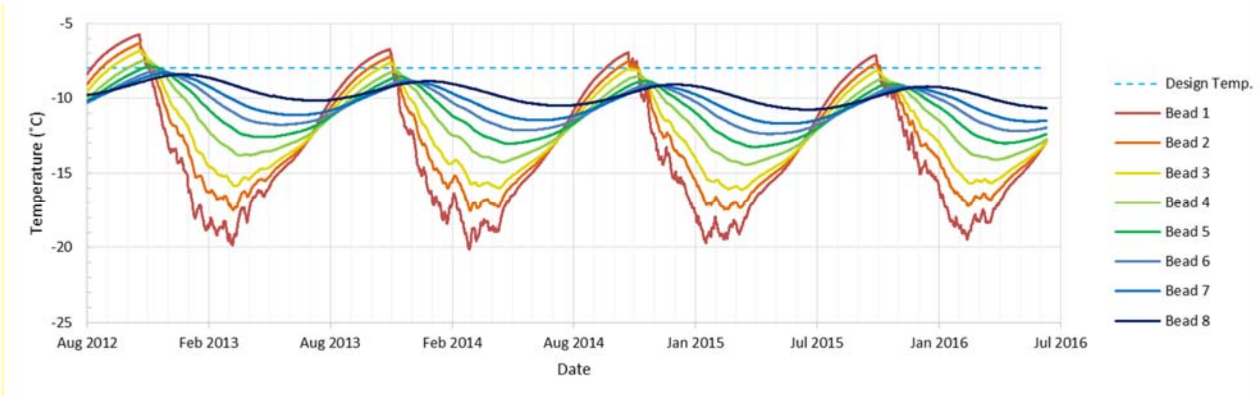

Figure 5: Temperature versus time of GTC ND-VTS-175-KT

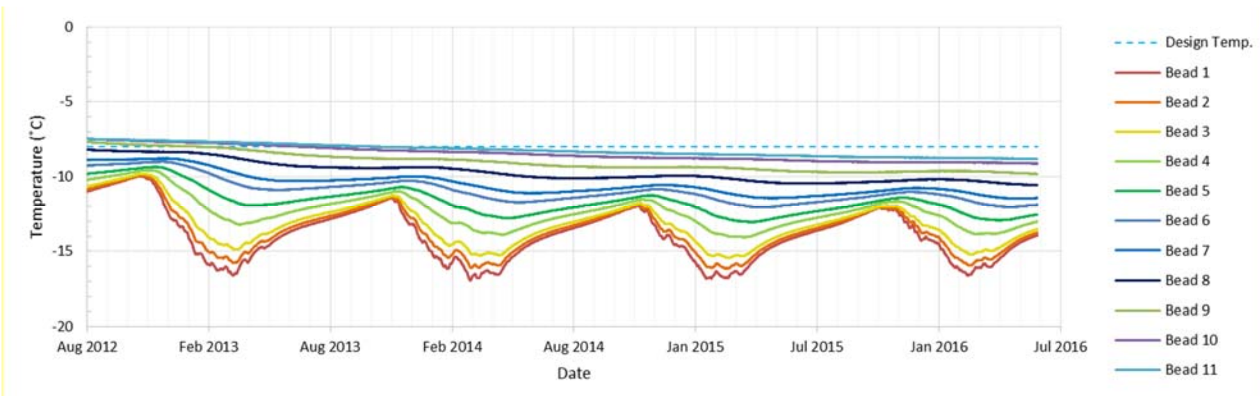

Figure 6: Temperature versus time of GTC ND-VTS-085-KT

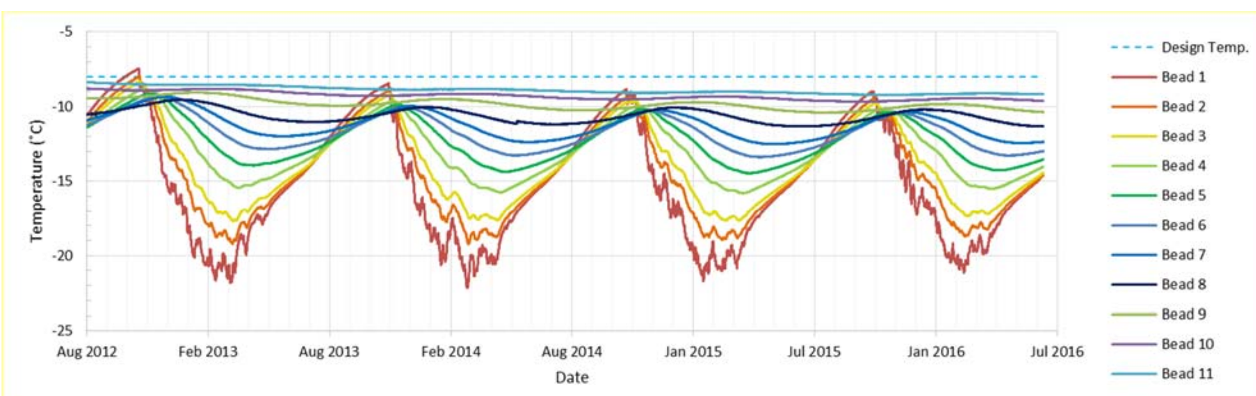

Figure 7: Temperature versus time of GTC ND-VTS-040-KT

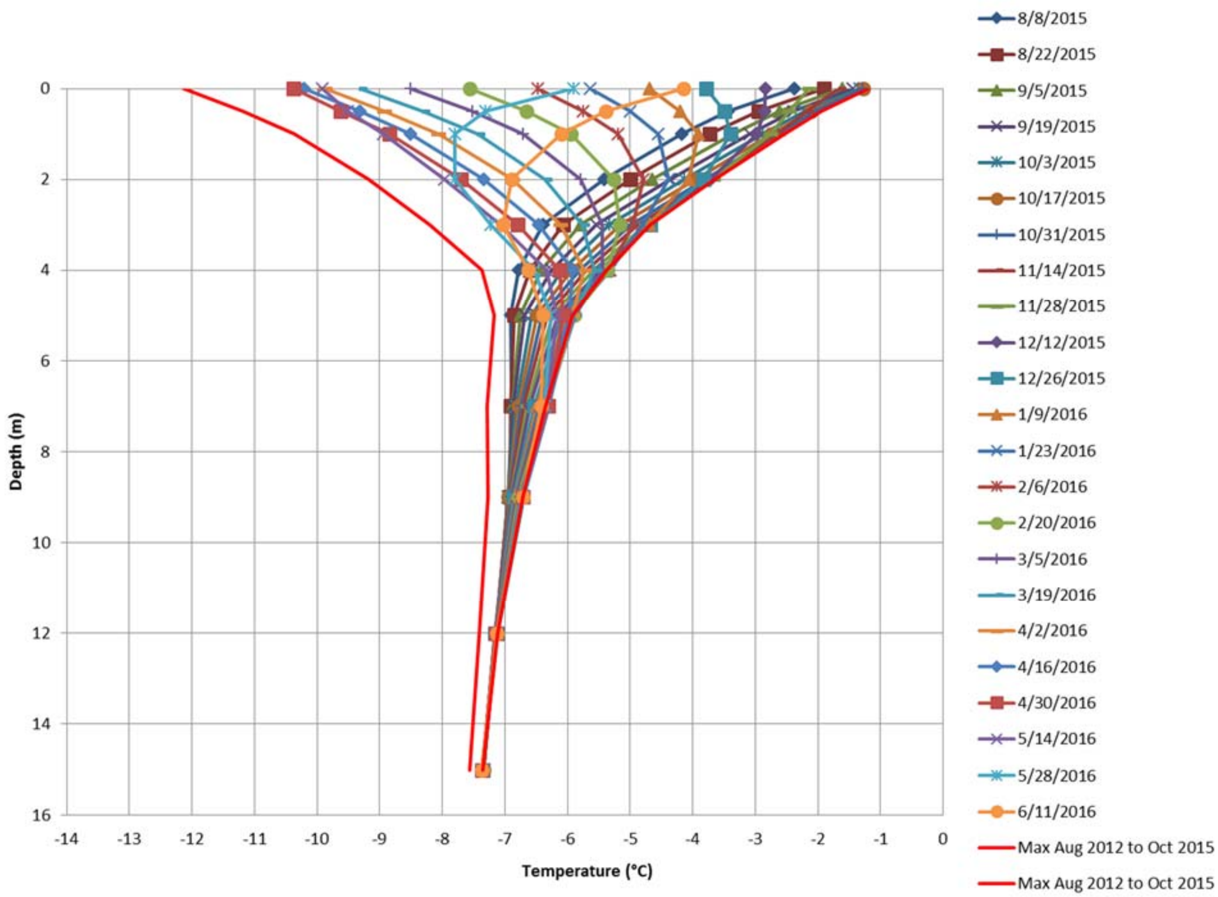

Figure 8: 2015-2016 Temperature profile of GTC ND-VTS-085-US

8.2 Thermosyphons

Thermosyphon pipe temperatures combined with air temperature measurements and horizontal GTC measurements at the base of the key trench provide an indication of thermosyphon performance. Thermosyphon pipe temperatures for functioning thermosyphons should measure approximately 5°C warmer than air temperature during the winter months when the thermosyphons are active.

Thermosyphon pipe temperatures and horizontal GTC measurements both indicate that eleven of the twelve installed thermosyphons are working as expected. Temperature measurements for North 02, however indicate that it has not been functioning correctly since monitoring started. Figure 8 shows the measured pipe and air temperatures for the north thermosyphons versus time since 2012. The non-functioning thermosyphon is however not impacting the dam performance as illustrated by the thermal data.

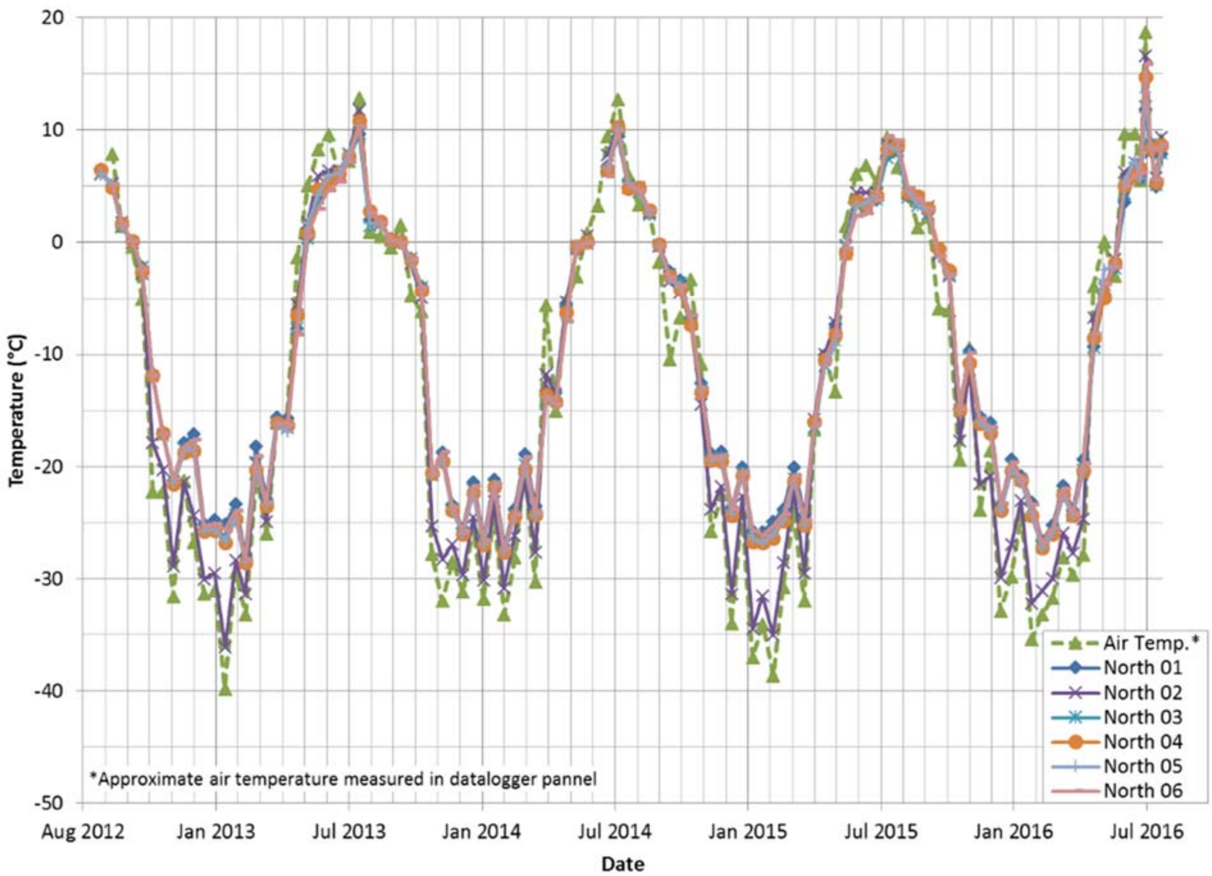

Figure 8: North thermosyphon pipe temperature versus air temperature

8.3 Deformation

Deformations measured by the deep survey monitoring points, the crest survey monitoring points and the inclinometers has generally been small. The measured horizontal and vertical displacement of the crest survey monitoring points and the deep monitoring points has been less than 10 mm which is close to survey accuracy. Deformations along the inclinometer profiles have shown only small displacements (less than 20 mm) in the portion of the profile which is within the shell of the dam, and displacements within the foundation material are very small with a maximum measured displacement of 5 mm.

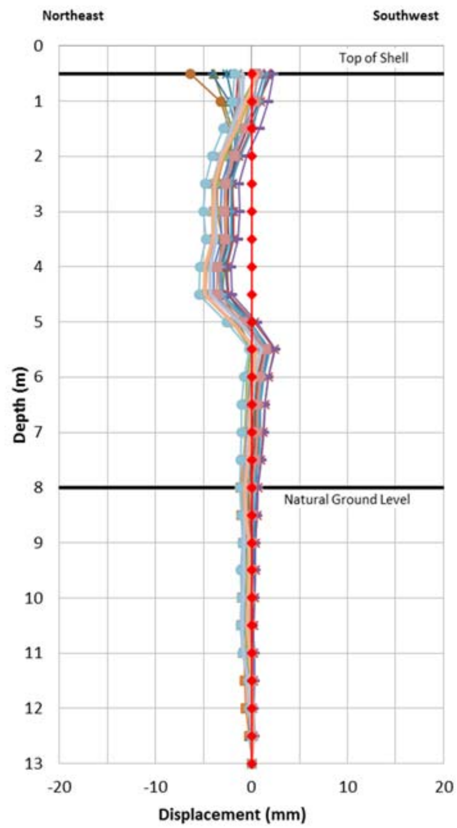

Figure 2: Typical Longitudinal Displacement of Inclinometer

As expected the measured horizontal and vertical displacements of the surficial survey monitoring points are larger than the crest and deep survey points, with measurements in the range of 20 mm. All of these results suggest that the dam is not currently experiencing creep deformation.

9 CONCLUSIONS

The frozen core North Dam has been designed to retain water at its full supply level for a period of at least 20 years. During this period the core is expected to remain a design temperature of -2˚C, while the foundation immediately beneath the key trench must remain at -8˚C. Due to the presence of deep ice rich, saline marine silts and clays in the dam foundation, long term creep deformation is expected and as such the dam side slopes and crest elevation has been designed to accommodate these deformations.

The North Dam construction was completed during two winter seasons, and the completed dam was commissioned in the spring of 2012. Comprehensive monitoring instrumentation was installed, and the first four years of monitoring data suggest that the dam is performing in accordance with the design expectations.

The performance of the North Dam is encouraging, demonstrating the advantages of prudent design and comprehensive monitoring in advancing the boundaries of practice in cold regions dam design.

10 ACKNOWLEDGEMENTS

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