Evaluating the Performance of a Frozen Core Dam Founded on Ice Rich Saline Marine Silts and Clays

Maritz Rykaart, Megan Millar, John Kurylo & Lowell Wade
SRK Consulting (Canada) Inc., Vancouver, British Columbia, Canada

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ABSTRACT
A precedent setting frozen core dam was constructed over 30 m thick ice-rich, saline glacial marine silt and clay, and fine sand as part of the tailings management system at the Doris North Project in Nunavut Canada. This water retaining dam was completed in 2012, and two years of monitoring data confirm that the engineered (non-saline) core is maintaining a temperature below -2°C, whilst the underlying saline permafrost foundation is stabilizing with temperatures trending below -8°C as per the design. This paper presents this data, demonstrating the viability of this technology even under such challenging foundation conditions.

RÉSUMÉ
Précédemment, un barrage à noyau gelé a été construit au-dessus d'une couche de matériaux d'une épaisseur de 30 mètres, pour le système de gestion des résidus du Doris North Project au Nunavut. De la glace, un silt et une argile marins, salins et glacials, ainsi qu'un sable fin constituaient cette couche. L'observation du barrage, qui a été complété en 2012, a permis la collecte de données confirmant la maintenance d'une température du noyau (non-salin) sous -2°C, alors que la température de la fondation de pergélisol salin se stabilise sous -8°C, selon la conception. Cet article présente donc ces données et démontre la viabilité de cette technologie sous des conditions de fondations difficiles.

1 INTRODUCTION

The tailings management plan for the Doris North Project in Nunavut Canada entails sub-aqueous tailings deposition into Tail Lake, an existing shallow lake which has been delisted in accordance with Schedule II of the Metal Mining Effluent Regulations. To ensure containment, two precedent setting water retaining frozen core dams (North and South Dams) were designed (SRK 2005, 2007). The first, the North Dam was constructed over the winter seasons of 2011 and 2012 (SRK 2012). Following two years of rigorous monitoring data, preliminary conclusions regarding the performance of the dam can be made, and are the subject of this paper.

2 TAILINGS MANAGEMENT SYSTEM

The size of Tail Lake, relative to the anticipated volume of tailings, provided the ideal conditions for consideration of sub-aqueous tailings disposal for the Doris North Project, which after closure would allow for a permanent water cover in excess of 3 m with no requirement for perpetual water retaining structures (SRK 2005, 2007). During the operational stage, water retaining structures are however necessary to retain the processing fluid, site contact water as well as provide a reservoir for reclaim water.

Due to the unique foundation conditions and limitations regarding the availability of suitable borrow materials, the use, planning, and design of conventional unfrozen dam types proved to be extremely challenging, necessitating development and adoption of a precedent setting frozen core dam design.

3 FOUNDATION CONDITIONS

Rigorous site characterization (including specialised drilling and long-term ground temperature monitoring) confirmed the presence of approximately 15 m to 30 m ice-rich, saline glacial marine silt and clay or fine sand below the footprint of the North Dam. These factors led to the decision to construct a frozen core dam which would ensure a continued bond between the cold permafrost and the dam core. Figure 1 illustrates a simplified long-section of the North Dam foundation conditions.

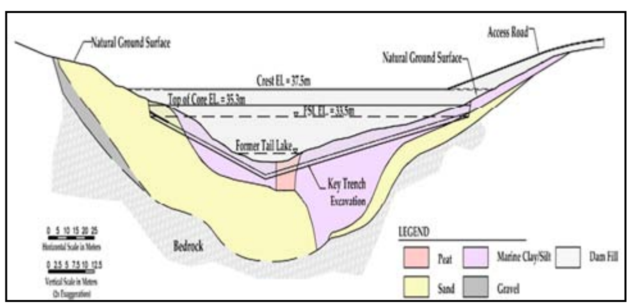

Figure 1. Long section along the North Dam illustrating the unique permafrost foundation conditions

The project site is located within the continuous permafrost region of Canada, and site specific measurements confirm that the total permafrost thickness is in the order of 500 m. The active layer thickness at the site is about 1 m, and the surficial equilibrium permafrost temperature is about -8°C.

4 DAM DESIGN

The North Dam is approximately 200 m long, with a maximum overall height of 10 m. 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) core must maintain a temperature below -2°C, whilst the underlying saline permafrost foundation must be maintained at temperatures at or below -8°C, under normal operating conditions. Under these conditions the dam will act as an impermeable barrier to seepage while mitigating against creep deformation, differential settlement, and maintaining overall long-term stability.

What makes this design so unique is that, due to the high ice content and salinity of the foundation, 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 for the dam.

A key trench, approximately 2 m to 5 m deep, was excavated prior to core construction to allow complete bonding of the core to the continuous permafrost foundation. As an added mitigation, especially for upset conditions (including climate change), 12 sloped single pipe passive thermosyphons were used in the base of the key trench to enhance foundation cooling. The typical design cross section of the North Dam is illustrated in Figure 2, and the maximum as-built cross section is illustrated in Figure 3.

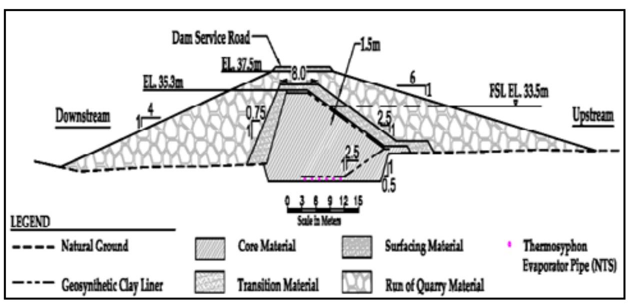

Figure 2. Typical design cross section through the North Dam

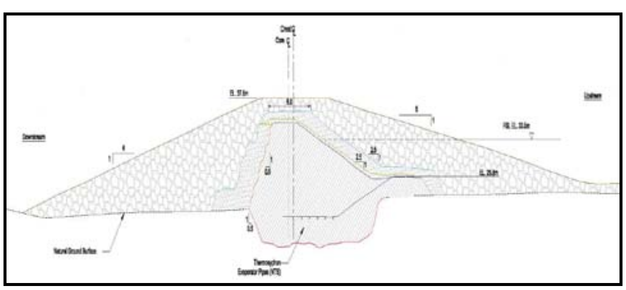

Figure 3. Maximum as-built cross section through the North Dam

The core comprises of a frozen mass of fine crushed basaltic rock placed in a near saturated state. Along the upstream side of the core, geosynthetic clay liner (GCL) was included as a precautionary measure to provide secondary water-retaining capability should cracks develop in the core due to thermal degradation, creep deformation or differential settlement.

The core is surrounded by a transition layer, consisting of crushed rock that acts as a filter, should the dam thaw. An outer shell constructed of run-of-quarry (ROQ) 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 generally planned to be constructed using construction techniques similar to other recent frozen core dams successfully completed at the Ekati Mine (EBA 1998, 2003). The site specific climate, material, and foundation conditions however necessitated innovative construction adaptations (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).

Percolation testing was completed immediately prior to construction to help determine the extent of the key trench excavation. These tests helped confirm the depth of the active layer and identified pockets of massive ice, hyper salinity (values in excess of 90 parts per thousand or higher than that of seawater) and organics (peat zone) that had to be removed via drill and blast methods to ensure proper dam performance.

Following completion of the key trench excavation, the frozen core was constructed using thin (approximately 0.2 m to 0.3 m) lifts of core material (crushed rock and water, heated and processed through an asphalt plant). Stringent quality control and quality assurance procedures were followed that included: continuous material testing (laboratory and field), visual inspections, and constant and open communication with the client and contractor. These procedures ensured subsequent lifts of core material were not placed until the underlying lift of material were frozen (at or below -2°C), and 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 would be cleared before continuing with core placement. To ensure that the core material lifts would freeze within a reasonable timeframe, frozen core placement was not attempted when ambient air temperatures were warmer than -10°C.

At the end of the 2011 construction season, the 12 sloped horizontal thermosyphons were installed and covered; however, the central frozen core was not completed. A 2 m thick temporary thermal rock cover was placed over the partially constructed core to protect the works until construction could recommence in the winter of 2012. At recommencement of construction, the temporary cover was removed and the core construction was completed. The GCL was completed in stages based on the location and stage of the core.

The transition zone and ROQ shell were generally raised simultaneously with the core, lagging behind by a few lifts only. This facilitated general construction access and helped manage snow drifting.

6 INSTRUMENTATION

Successful performance of the North Dam relies on maintaining the core and foundation design temperatures. Thermal monitoring includes 13 horizontal ground temperature cables (GTCs) to monitor the core temperature, and 11 vertical ground temperature cables to monitor the foundation temperature, all connected to an automated data logger system. Figure 4 provides a typical dam cross section illustrating the location of GTCs. Horizontal GTCs (HTS) are positioned at three different elevations within the core, and vertical GTCs (VTS) are located upstream (US), downstream (DS) and immediately below the key trench (KT).

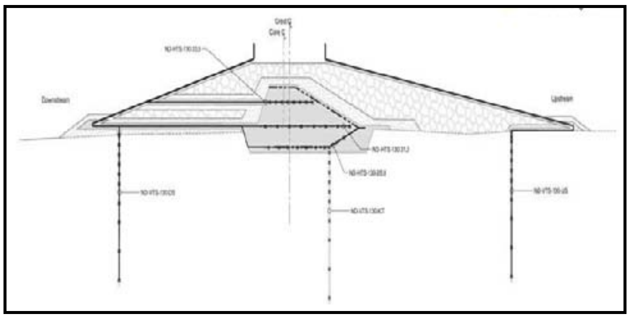

Figure 4. Typical North Dam cross section illustrating the location of horizontal and vertical ground temperature cables

Thermosyphon performance is continuously monitored using thermistors attached to each radiator riser.

As a result of the high salinity and variable ice content of the foundation soils, creep deformation is expected over the life of the structure. This coupled with the variability of the foundation soils, will manifest in differential settlement longitudinally and transversely across the dam. To track whether deformations are within the design limits, instrumentation was installed that includes three deep settlement points, 18 surficial survey points, 14 crest monitoring points, and six inclinometers.

Deep settlement points and surficial survey points are located on the downstream slope of the dam and are designed to track deformations of the foundation soils in close proximity of the shell and at the location of maximum expected deformation. Crest monitoring points are located along the crest and designed to monitor differential settlement, as well as deformation of the upper part of the core. Inclinometers are located on the downstream slope of the dam along the zone expected to experience maximum deformation.

7 MONITORING

North Dam monitoring requirements are outlined in the North Dam Monitoring Standard Operating Procedure (SRK 2012). This includes automated ground temperature cable measurements via data logger, and monthly manual deformation (i.e. survey and inclinometer) measurements.

Daily water level behind the dam is recorded using an automated pressure transducer connected to a data logger. Finally, monitoring of the North Dam includes visual inspection of the dam structure by Project staff as required, and a formal annual geotechnical inspection by a Professional geotechnical engineer, who is also the engineer-of-record.

After two complete years of performance monitoring, there is clear evidence that the North Dam is performing as expected, providing early indicators of the success of the structure. This paper presents continuous performance monitoring data between August 2012 and September 2014.

8 NORTH DAM PERFORMANCE

8.1 Water Level behind North Dam

The North Dam has a design full supply level (FSL) of 33.5 m, and the normal water level in Tail Lake, prior to dam construction was 28.3 m. Since completion of the dam, the water level behind the dam has been actively managed through controlled discharge to minimize the water level rise until actual tailings deposition starts. As a result, the maximum water level behind the North Dam was 29.5 m in 2013. This constitutes a maximum head of water behind the dam of 1.2 m, or about 23% of the maximum design head. By August 2014 the water level had been drawn down to 29.0 m.

8.2 Core and Foundation Temperature

Ground temperatures from the 24 installed cables at the North Dam is recorded every six hours using two automated data loggers. Data is manually downloaded from these data loggers by site staff. Since monitoring started in August 2012, data from two time periods (June 14 to July, 9 2014 and August 6 to August 31, 2014) were unavailable due to data logger card reading errors. This constitutes a data loss of 6.8% (50 days out of 730 days).

Two GTCs, ND-VTS-060-US and ND-HTS-085-33.5 were irreparably damaged during construction (note the naming convention for the GTCs: North Dam (ND) – Vertical (VTC) or Horizontal (HTS) – Chainage along dam crest (e.g., 0+60 m) – Location i.e., Upstream (US); downstream (DS); key trench (KT); or elevation (e.g., 33.5 m)). The remaining 22 GTCs are functional; however, some beads on ND-HTS-060-28.8 malfunctioned in 2014, and ND-HTS-040-33.5 was inadvertently disconnected from the data logger from October 10, 2013 to May 13, 2014. Prior to June 16, 2014, ND-HTS-175-33.5 and ND-VTS-175-KT were interchanged and subsequently incorrectly wired to the data logger; as a result the bottom three beads of ND-VTS-175-KT were not recorded.

None of the data errors or losses described are considered material, since there is sufficient redundancy built into the monitoring system.

In accordance with the design criteria, the North Dam core must at all times remain at a temperature below -2˚C. The horizontal GTCs which are specifically focussed towards confirming this, clearly demonstrate that this design criteria is comfortably being met. This is illustrated in Figures 5, 6 and 7 for the horizontal GTCs at chainage 0+130 m. Note (A) on these figures denotes a period when the data logger was not functioning supporting the conclusion that the data loss experienced does not detract from the ability to reach definitive conclusions about the dam performance. Not surprizing, this data also shows greater annual variability in the core temperature where the core is closer to the surface.

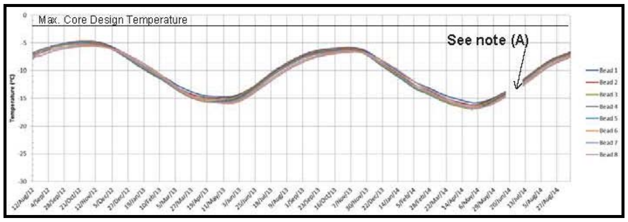

Figure 5. Time series data for ground temperature cable ND-HTS-130-33.5

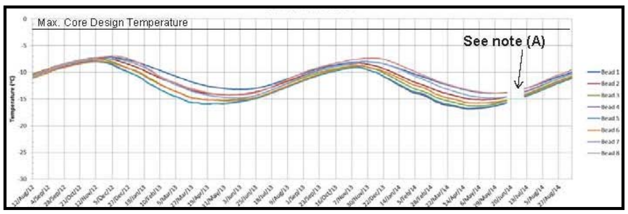

Figure 6. Time series data for ground temperature cable ND-HTS-130-31.0

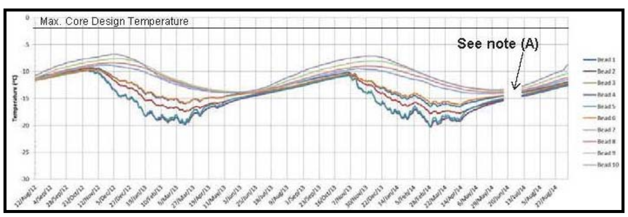

Figure 7. Time series data for ground temperature cable ND-HTS-130-28.8

Figure 7 also demonstrates how effective the thermosyphons are in cooling down the core and foundation. The lower three beads of GTC ND-HTS-130-28.8 shows markedly lower temperatures than the other beads of the same strings. These beads are in close vicinity of the thermosyphons and are therefore the lowered temperatures are recorded.

The vertical GTCs are intended to demonstrate that the critical section of the foundation immediately below the key trench will remain below -8˚C in accordance with the design criteria. The monitoring data shows that this criteria is generally being met, although not as consistently as for the core. Figure 8, illustrates a time series plot for vertical GTC ND-VTS-060-KT which is an example where the criteria is being met, while Figure 9 and 10 show some of the exceptions.

Note (B) on Figure 8 provides another example of how the cooling effect of the thermosyphons is confirmed through monitoring.

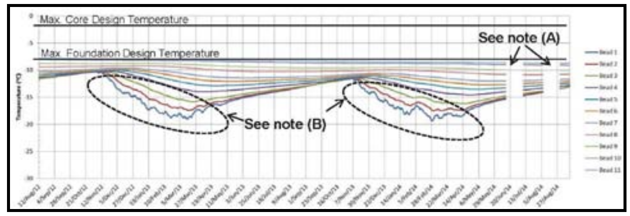

Figure 8. Time series data for ground temperature cable ND-VTS-060-KT

The bottom two beads (beads 10 and 11) of ND-VTS-085-KT have a measured maximum temperature between -7.5˚C and -8˚C (Figure 9). This is sufficiently close to the required design temperature to suggest that the design target has been met.

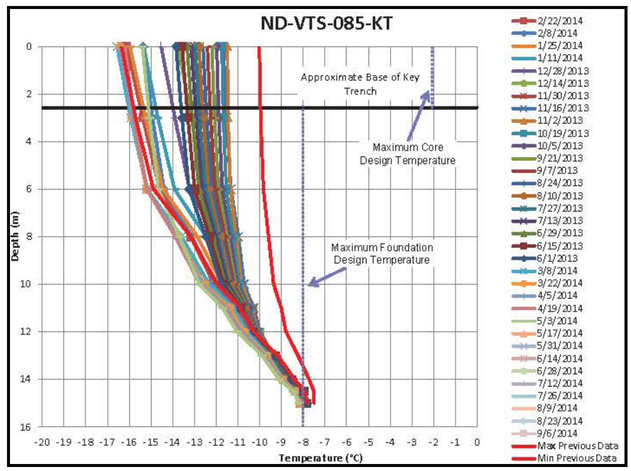

Figure 9. History of ground temperature cable data for ND-VTS-085-KT

The measured maximum foundation temperatures directly below the frozen core for GTC ND-VTS-175-KT were approximately -6˚C from May 2013 to September 2014. However, the maximum measured temperature has decreased from the maximum measured temperature May 2012 to May 2013 (Figure 10). Should this cooling trend remain consistent, it is expected that the required design temperature would be reached within the next year.

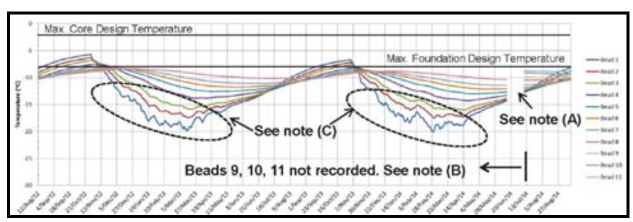

Figure 10. Time series data for ground temperature cable ND-VTS-175-KT

The maximum measured temperatures of near surface beads for vertical GTCs upstream and downstream of the key trench were between 0°C and -1˚C in 2014. These maximum measured temperatures were generally colder than what was recorded in 2013 suggesting a definitive cooling trend. These warmer temperatures are however consistent with the design thermal modeling. Figure 11 provides an example of this for GTC ND-VTS-085-US.

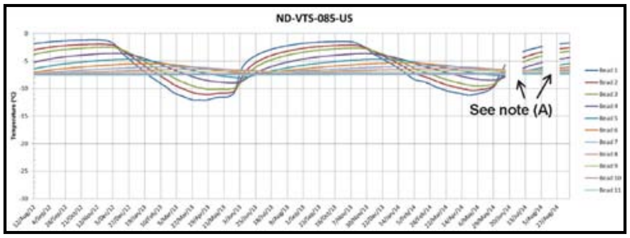

Figure 11. Time series data for ground temperature cable ND-VTS-085-US

8.3 Thermosyphons

Thermosyphon monitoring for the North Dam has been automated. Single bead thermistors connected to the data logger system are attached to each thermosyphon evaporator pipe below the ground surface, and insulation has been placed around the thermistor beads to ensure the evaporator pipe temperature, and not the ambient air temperature is measured. Data loggers record the contact surface temperature of each thermosyphon pipe and the air temperature every six hours.

To evaluate the performance of the thermosyphons, thermosyphon evaporator pipe contact temperatures and air temperature are plotted against time. During the winter months, when thermosyphons are working, the thermosyphon pipe temperature should be roughly 5°C warmer than the air temperature. If the thermosyphon pipe temperature during the winter months is approximately the same as the air temperature, it indicates that the thermosyphon is not working correctly.

All six of the southern embankment thermosyphons have been confirmed to function correctly. Figure 12 illustrates that all but one (North 2) of the six northern embankment thermosyphons are functioning as intended. During the winter months of 2012/2013 and 2013/2014, the measured pipe temperature for thermosyphon North 2 was only slightly higher than the measured air temperature.

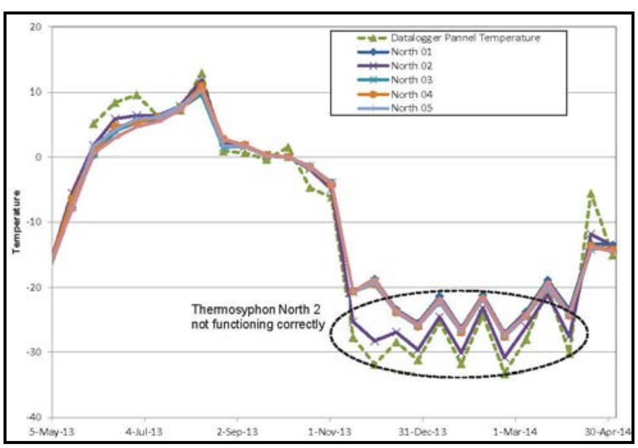

Figure 12. North Dam northern embankment thermosyphon performance time series

8.4 Inclinometers

Six inclinometers were installed within the downstream face of the North Dam. These inclinometers are used along with the survey monitoring points to monitor deformation within the dam and dam foundation.

Generally, to date, the inclinometer profiles show only small displacements (less than 20 mm), in the portion of the inclinometer above the natural ground surface. There is no trend emerging, suggesting that there is not any measurable movement at this time. This is consistent with performance expectations.

8.5 Survey Monitoring Points

A series of fourteen crest survey monitoring points, three deep survey monitoring points, and eighteen surficial survey points were installed in the North Dam upon completion. These survey monitoring points were installed to monitor any surface movement of the downstream face and deep settlement of the downstream foundation of the dam.

Survey monitoring of the North Dam has only occurred three times since the survey monitoring points were installed, once in 2013 and twice in 2014.

Overall the measured horizontal and vertical displacement for the crest survey monitoring points (SMP) and deep survey monitoring points (DSP) is less than 0.1 m which is considered to be close to the survey accuracy. As expected the surficial survey points have larger measured displacement with horizontal and vertical displacement in the range of 0.2 m for most points. Generally these measured displacements have not changed since the 2013 survey, indicating that most of the movement was from settlement directly following construction, which was to be expected given the ROQ material used for the shell construction. At this time none of these displacements are considered indicative of any long term trends.

9 CONCLUSION

The precedent setting frozen core North Dam has been designed to retain water at its FSL 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 two years of monitoring data suggest that the dam is generally performing in accordance with the design expectations.

The performance of the North Dam is encouraging, demonstrating the advantages of continuing to advance the boundaries of knowledge through pushing the limits of best practice.

ACKNOWLEDGEMENTS

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