Settlement and Temperature Monitoring of a Frozen Tailings Impoundment, Kam Kotia Mine, Timmins, Ontario, Canada

Bruce Polan, M.A.Sc., P.Eng. and Michael Braverman
GHD Limited, Waterloo, Ontario, Canada

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ABSTRACT
The Kam Kotia Mine is an orphaned mine, located northwest of Timmins, Ontario, Canada, that began operation in the 1940s. The mine was closed in 1972, leaving behind a large open pit mine that had been used later as a tailings pond, with over 50 m deep of impounded tailings and sludge, and large scattered piles of acidic waste rock across the mine site. As part of an on-going environmental remediation of the site, over 700,000 cubic metres of waste rock was moved into the open pit mine, followed by construction of an impermeable geosynthetic cap over the impoundment. A large portion of the waste rock and tailings was placed in a frozen state into the open pit, during winter earth works. This case study presents the results of an investigation and monitoring program of the frozen waste material and capped impoundment, and an assessment of the implications of long term settlements of the frozen impoundment.

RÉSUMÉ
La mine Kam Kotia est une mine orpheline, située au nord-ouest de Timmins, Ontario, Canada, qui a commencé ses activités dans les années 1940. La mine a été fermée en 1972, laissant derrière elle une grande mine à ciel ouvert qui avait été utilisée plus tard comme bassin de résidus, avec plus de 50 m de profondeur de résidus et de boues retenus, et de grands tas dispersés de stériles acides sur le site minier. Dans le cadre d'une réhabilitation environnementale continue du site, plus de 700 000 mètres cubes de stériles ont été déplacés dans la mine à ciel ouvert, suivis de la construction d'un revêtement géosynthétique imperméable au-dessus du bassin de retenue. Une grande partie des stériles et des résidus a été placée à l'état congelé dans la fosse à ciel ouvert, lors des travaux de terrassement hivernaux. Cette étude de cas présente les résultats d'un programme d'investigation et de surveillance des déchets gelés et de la retenue recouverte, ainsi qu'une évaluation des implications des tassements à long terme de la retenue gelée.

1 BACKGROUND

The Kam Kotia mine is a former copper and zinc mine, located north of Timmins, that began operation in the 1940s to support Canada's mineral needs during World War II. The mine was closed in 1972. The remediation of the orphaned mine was handed over to the Ministry of Northern Development and Mines (ENDM). The closure and environmental clean-up activities for the Kam Kotia Mine have been on-going for the last decade. As part of the clean-up activities, large amounts of waste rock piles were relocated into the existing open pit mine. Some 700,000 cubic metres of material was placed into the open pit during the clean-up of the site in 2016 to 2019. Part of the relocation of waste materials work was carried out over a six month period of winter, during very cold winter temperatures (in the range of minus 30 degrees Celsius), resulting in a large portion of the tailings being placed into the open pit in a frozen state.

GHD was retained by ENDM to design and oversee the relocation of the waste rock, and closure of the open pit tailings and waste rock impoundment area. During the course of waste rock and tailings placement in late 2018 and early 2019, the Contractor was permitted to move large portions of tailings during the winter construction season into the open pit. Working in cold temperatures allowed for easier access to the waste tailings area, and easier trucking on frozen construction roads, resulting in substantial cost savings to the project. Record snow falls also occurred in 2019, and there was no practical way of separating the bulk of the snow from the hauled material. The snow made its way into the open pit along with the tailings.

The existing open pit was excavated during the active mining operations into the host rock, some 60 m below existing grade into the native bedrock, and filled with tailings during the closure of the mine. The concept for waste rock placement into the open pit consisted of relocating approximately 700,000 cubic metres of waste rock and tailings to the open pit over the period of 2016 to 2019. The open pit had high bedrock walls, and a large portion of the waste rock was placed below site grades. The area was mounded to form a permanent impoundment. Approximately 20 m of waste rock and tailings were placed in the highest portion of the impoundment. The entire impoundment was capped with a bitumous geomembrane liner (BGM) overlain by 0.7 m thick cover soil in 2021.

The footprint of the open pit, and longitudinal east-west cross-section is shown on Figure 1.

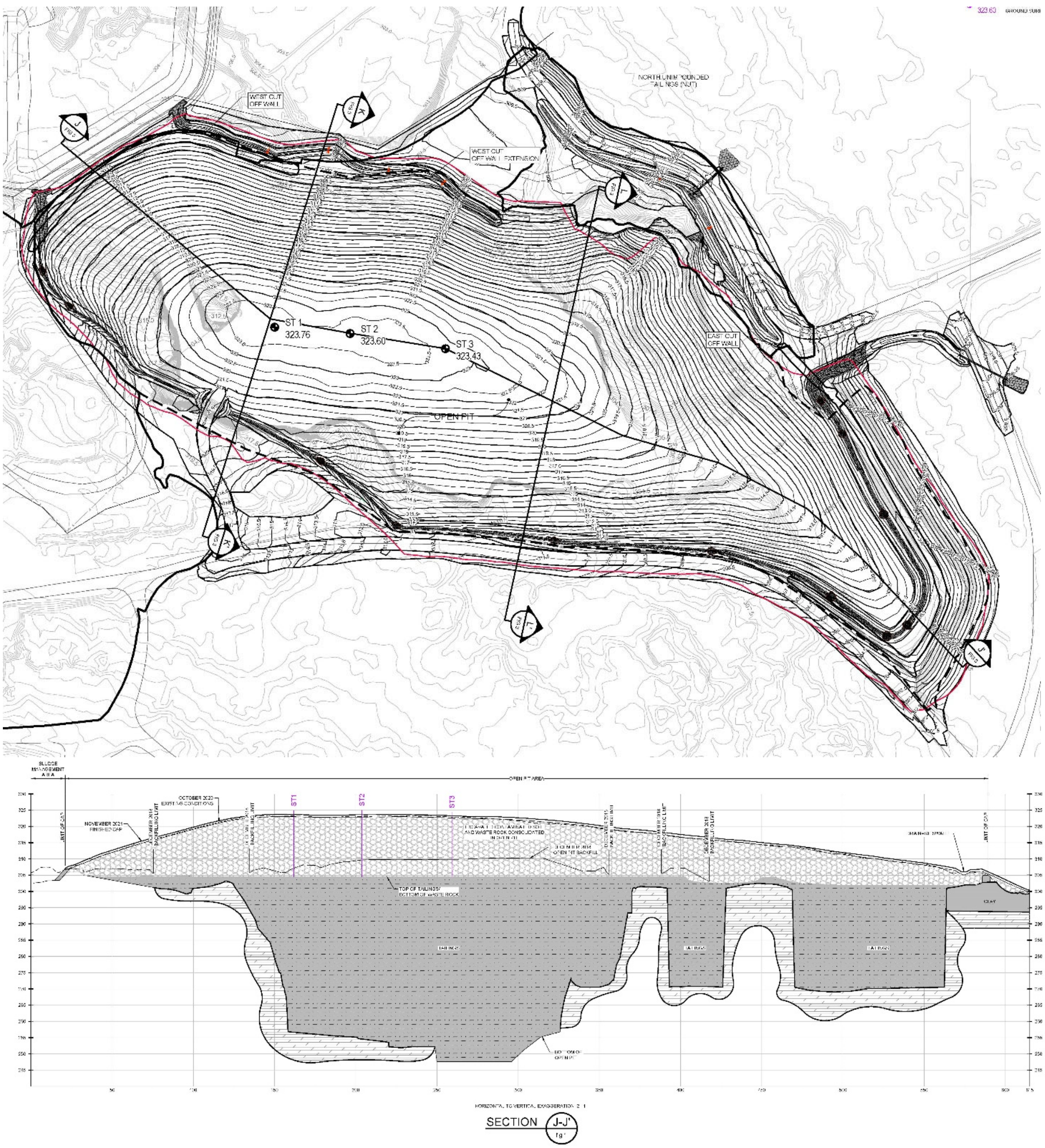

Figure 1. Footprint and longitudinal East-West Cross-Section of the Open Pit Impoundment, Kam Kotia Mine

2 GEOLOGIC SETTING AND OPEN PIT EXISTING CONDITIONS

The Kam Kotia mine is located in the southwestern portion of the District of Cochrane, approximately 30 km northwest of Timmins, and north of Kamiskotia Lake.

The bedrock geology of the Timmins area is described in detail by D.R. Pyke (1982). Since the discovery of gold in the Timmins area in 1909, numerous investigations have contributed to the understanding of the bedrock geology in this area. The Kam Kotia mine site has mostly shallow bedrock outcrops, and some extensive clay and sandy lacustrine deposits. Bedrock outcrops are common, and the bedrock surface is hummocky and varies significantly in elevation across the site. The bedrock is mostly early Precambrian (Archean) metavolcanic formations, consisting of mafic, felsic, and sulphidic metavolcanic bedrock. The ore occurred as steeply dipping shallow plunging, massive sulphide lenses (Golder, 2009). The ore and waste rock is acid-generating, and waste rock pile surface water run-off causes large areas of low pH soil and groundwater in the surrounding natural environment.

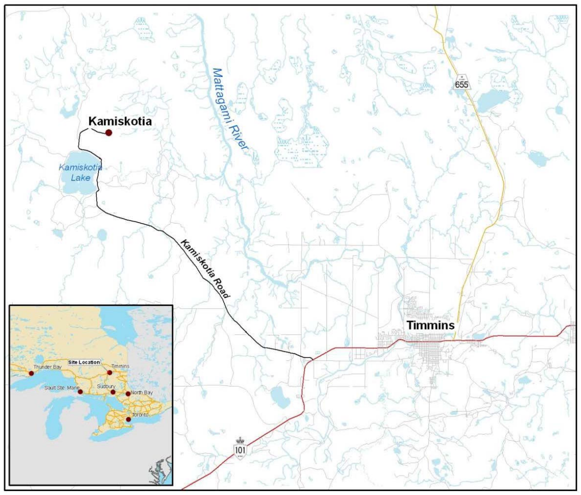

Figure 2. Site Location- Kam Kotia Mine, Timmins, Ontario (from Golder, 2009)

There was limited geotechnical information on the existing tailings in the open pit, however, the profile and depth of the open pit was well documented. The deepest central portion of the open pit contained 50 m deep deposits of fine grained tailings, placed during the operational period of the mine. The open pit had steep vertical bedrock sidewalls, as high as 10 m above the tailings in some areas. The surface of the open pit was generally ponded, and the tailings were in a saturated condition.

3 GEOTECHNICAL CHARACTERIZATION OF WASTE ROCK AND REMNANT TAILINGS

Various geotechnical investigations were completed during the design phase of the open pit closure. These included geotechnical boreholes around the perimeter of the open pit, visual characterization of the waste rock, and collection of samples and geotechnical characterization of remnant tailings areas. The waste rock was present in large piles surrounding the open pit, and consisted of large chunks of angular rock, with little fines. The rock pieces were mostly in the 0.3 to 0.6 m diameter, but some larger rocks of over 1 m were present.

The tailings that were to be relocated in the open pit come from shallow remnant tailings area in an area known as the South Unimpounded Tailings (SUT) area. These remnant tailings were typically less than 0.3 m deep, and were intermixed with the existing organic topsoil layer. In general, the tailings consisted of silts and fine sands, with organics (GHD, 2016). Due to the low-lying area that the tailings were to be removed from, they were in a very wet to saturated condition.

4 SETTLEMENT PREDICTIONS AND CAP CONSTRUCTION

Due to the large volume of waste rock (some 500,00 m^3), and remnant tailings (some 200,000 m^3), to be relocated to the open pit, the organic saturated nature of the remnant tailings material, and the deep deposits of existing tailings of up to 50 m thick, settlements of the open pit prior to construction of the final cover were a concern at the design stage. In order to minimize the potential for differential settlements of the final cap, the design for placement of these materials required that an attempt to be made to place the waste rock and tailings simultaneously, and mix the materials as much as practical. The materials were also required to be uniformly placed in 1 m thick lifts, with less than 3 m thick being placed in any week, and the materials had to be compacted during placement (GHD. 2016).

Estimates were made of the predicted settlement of the impoundment area after waste rock and tailings placement. Predictions were made with finite element modelling, using the GeoStudio Sigma/W module, but the possibility of placing large volumes of frozen material was not considered at the design stage. Figure 3 shows the predicted cap settlement and time frame as presented in the design report.

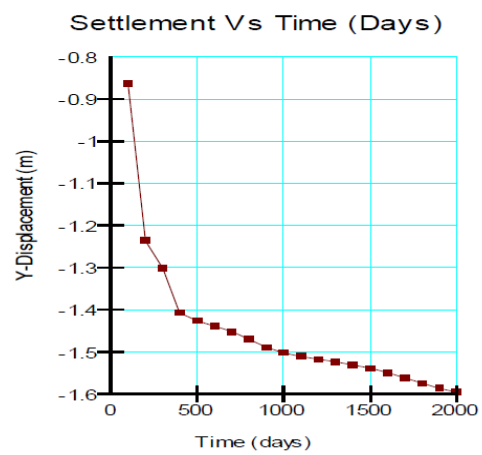

Figure 3. Predicted Cap Settlement after Closure

The settlement modelling simplified the placing of the waste material to assume that the waste was placed in a very short period of time, which was unrealistic of actual construction conditions. The modelling predicted that settlements in the range of 1.3 m would occur within the first year of waste placement. Remaining settlements would be in the order of 0.5 m, and would occur over the next five years.

Parameters were assumed from geotechnical investigations and published values for tailings. Table 1 summarizes the input parameters for the model.

Table 1. Input Parameters for the Settlement Calculations, Kam Kotia Open Pit Closure

Material	Material Model	Material Category	Unit Weight (kN/m^3)	Poisson's Ratio 'μ'	Modulus of Elasticity 'E' (MN/m^2)	Hydraulic Conductivity 'k' (m/day)
Rock Fill + Cap	Linear Elastic	Effective with PWPC	24	0.33	100	24
Sandy silty tailings	Elastic-Plastic	Effective with PWPC	18	0.33	11.0	0.8
Clayey tailings	Elastic-Plastic	Effective with PWPC	19	0.4	12.5	0.003
Bedrock	Linear Elastic	Effective with PWPC	24	0.33	10,000	1E-8

PWPC – Pore water pressure changes

There were concerns at the design stage that the magnitude of potential differential settlement might impact the performance of the impermeable cover, causing cracking of the cover soil, and potential damage to the impermeable bitumous liner. Based on this analysis, it was decided that the best approach would be to limit differential settlements would be to place the new material in uniform layers, intermix the waste rock and remnant tailings as much as practical, and compact the new material during placement. In addition to these efforts during placement of the new material, the impoundment would be allowed to settle for a 1-year construction season prior to placing the final cap.

The movement of the waste material into the open pit took place in two stages, with approximately 170,000 m^3 occurring in 2017, and the remaining 530,000 m^3 occurring during the winter construction season of 2018/2019. The impoundment was left to settle during 2020, while other construction activities took place. Final grading took place during the summer of 2021, and the impoundment area was capped with a bitumous geomembrane and 0.7 m of cover soil. Following cover placement, the landfill cap was covered with biotic earth and seeded.

This construction sequence allowed for some of the expected settlements to take place prior to final cap construction. However, as stated above, a large portion of the waste material (tailings) was placed in a frozen state, and the modelling did not consider this condition.

5 COST BENEFITS OF ALLOWING FROZEN MATERIAL TO BE PLACED IN THE IMPOUNDMENT

A large portion of the tailings material to be placed in the open pit (approximately 200,000 m^3) was planned to be excavated from a remnant tailings area. This campaign involved removing the impacted organic soils, consisting of mainly silt particles, and fine grained tailings, to an average depth of 0.3 m, over an area with a footprint of 650,000 square metres. Most of this area was essentially a low-lying wet area, which would be very difficult to access during wet construction seasons. Wet construction seasons were difficult to avoid in Timmins. One option considered prior to the work starting in the remnant tailings area, was importing and aerially distributing large quantities of agricultural lime (aglime) over the tailings area, to stabilize the material, and allow it to be moved efficiently. Based on bench-scale testing completed by GHD, it was estimated that approximately 5 percent aglime by volume would be required, or some 20,000 metric tonnes. The material would be difficult to source, and would add somewhere in the range of $500,000 to the cost of moving this material.

The Contractor proposed working during the winter season, and to excavate and haul the remnant tailings in a frozen state. The Contractor had considerable experience working in cold conditions, and came up with a plan to build ice roads, and haul the remnant tailings on a 24 hour, 7 day per week schedule during the winter of 2018/2019. ENDM and GHD recognized the cost benefits of doing this work during the winter season, and accepted the Contractor's approach. Hauling proceeded in late December 2018, and was finished during the early Spring of 2019. Record snow falls occurred during this period, and there was no practical way to separate the snow from the excavation area, so large quantities of snow were also hauled with the remnant tailings.

6 TEMPURATURE AND SETTLEMENT MONITORING INSTALLMENTS

Due to the placement of large quantities of frozen material into the impoundment, GHD recommended that ENDM consider a long-term temperature and settlement monitoring program for the completed cap. Three instrumented boreholes were installed in the central portion of the impoundment in August 2020, where the new waste rock and frozen tailings were the thickest, and the existing sludge and tailings were on the order of 50 m deep below the newly placed frozen material. Details of the temperature and settlement monitoring installations are shown on Figure 4.

The boreholes were cased with standard 75 mm O.D. inclinometer casing, within the entire length of the new waste rock/tailings (approximately 20 m). The thermistors consisted of five thermistors in a string, supplied by Cryogeeks (Ottawa, Ontario) at depths of approximately 2, 6, 10, 14, and 18 m below grade. Settlement points, consisting of spider magnets, were fixed to the outside of the casing, at depths of approximately 2, 6, 10, 14, and 18 m below grade. These spider magnets have spring-loaded “legs”, which are released at the time of installation, so that the legs dig into the soil surrounding the casing pipe. The spider magnets are free to slide on the casing pipe, so that they move with the surrounding soil, not the casing pipe. The spider magnets were supplied by Durham Geo Slope Indicator of Vancouver, Canada.

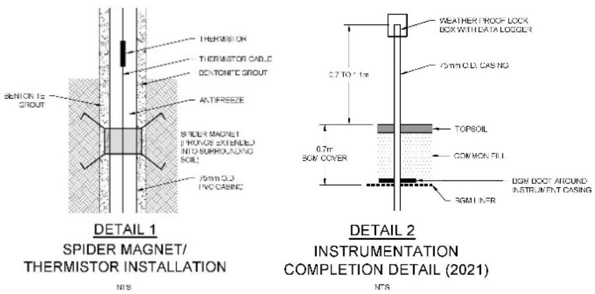

Figure 4. Thermistor and Spider Magnet Installation Details

A series of steel settlement plates were placed on top of the bitumous geomembrane in the summer of 2021. The plates were then buried with the cover soil. Each plate has a central vertical bar that protrudes above the finished cover surface, to accommodate future manual elevation surveys.

7 INSTRUMENT READINGS

The temperature thermistors are read through a radio frequency (RF) USB dongle, using a laptop to collect the data from the thermistor data loggers. The laptop must be close to the instruments (within 3 m) to collect the data. The downloaded data from the data loggers is processed through software (FG2_Shell) supplied from the thermistor supplier, and then tabulated in an excel sheet. A typical profile of the temperature with depth is shown on Figure 5.

The seasonal profile shows an expected thermal variation in the upper thermistor due to surface temperature influences. Air temperatures vary typically vary from -25 degrees Celsius (C) in the winter, to plus 25 degrees or more in the summer. The measured subsurface temperatures at the 6 m depth and below do not vary with time, and show essentially constant temperatures at around zero degrees C. This shows that the waste material that was placed in a frozen state remains frozen some two years after placement.

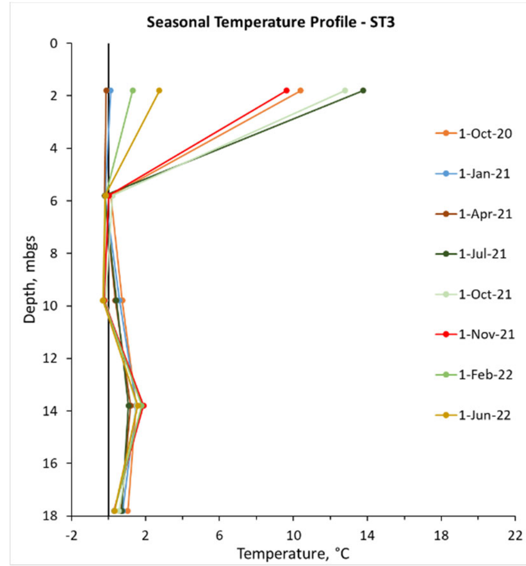

Figure 5. Seasonal Temperature Profile with Depth (ST-3)

To verify the accuracy of the thermistor readings, and to refine the thawing profiles, an additional temporary thermistor installation was installed in the summer of 2021. This profile used additional thermistors at roughly 1 m intervals, to a depth of 10 m. Figure 6 shows the data obtained from the temporary installation.

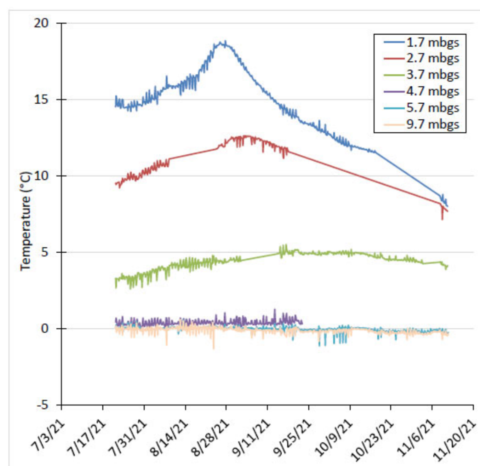

Figure 6. Seasonal Temperature Profile with Depth at the Temporary Installation

Figure 6 shows that thawing of the new waste material has occurred to an approximate depth of 4 m below grade. The material below 5 m remains frozen at around zero degrees C. The upper shallow soils are influenced by seasonal air and surface temperatures. The thermistors at 1.7 and 2.7 m below grade show an increase in temperature during the summer season, and a decrease in temperature during the winter season. However, as shown on Figure 5, the upper soils to a depth of at least 2 m refreezes during the winter season. The published frost depth in the Timmins area is in the range of 2.4 to 2.5 m (Ontario Provincial Standard Drawing, 2010).

The below-ground settlement points (spider magnets) are read manually by lowering a magnetic probe sensor down the borehole casing, and recording the depth of each magnet. An audible tone is sounded when the probe sensor reaches the magnets. The depth of the magnet is obtained from the markings on the tape (measured from the top of the casing pipe), and is manually recorded. The spider magnets are not physically attached to the instrument casing, so the casing is free to move independently. Figure 7 shows a plot of settlement readings with depth at one of the instrument locations.

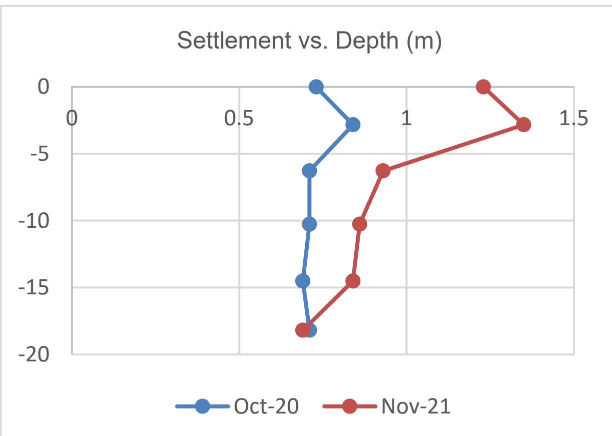

Figure 7. Settlement Profile with Depth- ST1 Location

As can be seen in Figure 7, higher settlements have occurred in the upper 4 m, consistent with the thawed zone of the frozen material. The magnitude of settlements generally decreases with depth, as would be expected in frozen material. However, further settlements will occur over time as the material continues to thaw.

8 SURFACE SETTLEMENTS

The ground surface at the instrument locations remained unchanged after 2019, and this area was not regraded or reworked until final cap placement. Manual surveys and drone aerial elevation surveys were utilized to track surface settlements at the instrument locations. These surveys and total recorded surface settlements are shown on Table 2.

Ground surface elevations at the instrument locations were not accurately surveyed until December 2019. For the purposes of plotting the settlement data with time, December 2019 is considered to be zero days after impoundment filling.

Table 2. Ground Elevations at Instrumented Boreholes

Instrument	Dec 2019 (Time= 0 Days) (m)	Oct 2020 (303 Days) (m)	Nov 2021 (696 Days) (m)	Jun 2022 (944 Days) (m)
ST-1	0.0	-0.32	-1.23	-1.52
ST-2	0.0	-0.33	-1.27	-1.48
ST-3	0.0	-0.20	-1.15	-1.38

These ground settlements are plotted below on Figure 8, including data to July 2022 (944 days from December 2019).

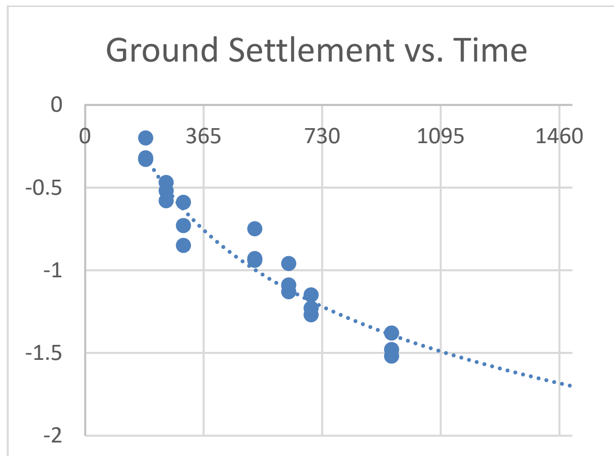

Figure 8. Ground Settlements at Instrument Locations. Logarithmic best fit curve shown as the blue dashed line

As can be seen in Figure 8, the ground settlements follow an expected logarithmic settlement curve. The initial settlement of the waste rock/tailings was not captured, as the waste rock/tailings placement took place over several construction seasons prior to detailed surveys being recorded for the cap and instrument locations. Based on the logarithmic trend line, the rate of settlement appears to be slowing, however, this may change as more of the frozen waste rock and tailings begins to thaw over time.

Based on a comparison of drone surveys completed after the cap construction in November 2021, and in June of 2022, no areas of significant differential settlements have occurred over the completed cap area.

9 CONCLUSIONS

The following conclusions are provided:

- The temperature thermistors show that the bulk of the waste rock/ tailings in the Open Pit are in a frozen state, hovering around 0 to 2 degrees C. The upper 4 m of this material is considered to be "thawed", as the temperature is generally above freezing. This will decrease the rate of settlement of this material over time, as it is acting as a semi-frozen mass.

- The bulk of the waste rock/tailings material was placed in the open pit for almost two years prior to constructing the permanent cap in 2021. The top of the open pit has settled approximately 1.3 m from December 2019, prior to cover construction in August 2021.
- Overall settlements to date exceeded the original design estimated settlements of 1.3 m, as the initial settlements occurring during the bulk of the waste placement could not be accurately recorded.
- Settlements are expected to continue to occur as the waste rock/tailings material thaws over time. Based on the data collected, further settlements in the range of 1 m can be expected as the waste continues to thaw.
- Further data collection and research is required to assess the time frame required to fully thaw the impoundment, and refine the expected settlements.
- The construction approach of taking several years to fill the impoundment, and allowing frozen material to be placed in the impoundment, allowed for a cost efficient project completion, without compromising the final cap structure.

10 REFERENCES

Pyke, D.R 1982. *Geology of the Timmins Area, District of Cochrane*. Ontario Geologic Survey Report 219. Ontario Ministry of Natural Resources, Ontario, Canada.

GHD Limited, 2016. *Design Brief for the Closure of the Open Pit, Kam Kotia Mine Site, Timmins, Ontario*. October 6, 2016.

Golder Associates, 2009. *A Study to Determine the Stability and Design the Most Appropriate Rehabilitation Measure for the Crown Pillars and Open Pit at Kam Kotia Mine Site, Timmins, Ontario*. December 4, 2009.

Conestoga Rovers and Associates Limited, 2015. *Design Report, Construction of a Sludge Management System and Waste Rock Impoundment, Kam Kotia Mine Site, Timmins, Ontario*.

Conestoga Rovers and Associates Limited, 2015. *Design Report, Construction of a Sludge Management System and Waste Rock Impoundment, Kam Kotia Mine Site, Timmins, Ontario*.

Ontario Provincial Standard Drawing, 2010. *Foundation Frost Penetration Depths for Northern Ontario*. OPSD 3090.100, November 2010, Revision 1.