Design, Construction, and Initial Performance Review of a Water Retaining Frozen Foundation Dike in a Permafrost Region

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ABSTRACT
Agnico Eagle Mines Limited, owns and operates the Meliadine Gold Mine, Nunavut, Canada, in an area of widespread continuous permafrost. Water retaining dikes and water diversion structures are used to manage surface runoff and surface contact water at the Meliadine site. Dike D-CP1 was designed as a frozen foundation dam with a liner keyed into competent frozen foundation materials. The design intent was to maintain the original permafrost foundation beneath the liner below specific target temperatures throughout the design service life of the structure. This case study paper summarizes the design, challenges encountered during the construction, and presents the dike performance five years post construction. The monitoring data has shown that the dike has performed as designed and that the long-term thermal performance of the dike is expected to be met under the designed operation conditions and climate change scenarios.

RÉSUMÉ
Agnico Eagle possède et exploite la mine d'or de Meliadine, située dans le territoire du Nunavut au Canada, dans une zone étendue de pergélisol continu. Sur le site minier, des digues de rétention d'eau et des structures de dérivation d'eau sont utilisées pour gérer les eaux de ruissellement et les eaux de contact. La digue D-CP1 a été conçue comme une digue avec un fondation gelée et une géomembrane ancrée dans les matériaux de fondation gelés et compétents. L'objectif de la conception était de maintenir la fondation de pergélisol d'origine sous la géomembrane en dessous des températures cibles spécifiques tout au long de la durée de vie utile de la structure. Cette étude de cas résume la conception, les défis rencontrés pendant la construction, et présente la performance de la digue quatre ans après la construction. Les données de surveillance ont montré que la digue a performé comme prévu et que sa performance thermique à long terme devrait être atteinte dans les conditions d'exploitation et les scénarios de changement climatique prévus.

1 INTRODUCTION

The Meliadine Gold Mine is in the Kivalliq Region of Nunavut (NU), Canada, approximately 25 km northwest of Rankin Inlet on the west coast of Hudson Bay (Figure 1). Year-round access to the mine is by a 25 km private all-weather access road constructed by Agnico Eagle Mines Limited (Agnico Eagle) connecting the mine with the town of Rankin Inlet. Commercial production of gold started at the Meliadine mine in May of 2019 with an average of 3,000 tonnes per day (tpd) in the first several years and will gradually ramp up to 6,000 tpd by 2025.

Various water management infrastructure (water retaining dikes, water collection ponds, diversion channels/berms, and culverts) have been constructed since the initial development stages of the mine to contain and manage contact water from areas affected by mining activities. Dike D-CP1 is one of the water retaining frozen foundation dikes on site that was designed and constructed to create the main water attenuation pond (CP1). Surface contact water is collected and stored in CP1 to ultimately be treated via the effluent water treatment plant before being released to the receiving environment (Meliadine Lake).

Successful performance of a water retaining frozen foundation dike relies on maintaining the underlying permafrost foundation below specific target temperatures throughout its service life. This case study paper describes the design of Dike D-CP1, the challenges encountered during the construction, mitigation measures applied, and the initial performance review five years post construction.

2 BACKGROUND INFORMATION

The Meliadine mine is in an area of widespread continuous permafrost with an estimated permafrost thickness ranging between 360 m to 495 m, and a geothermal gradient ranging from 0.012C°/m to 0.02C°/m (Golder 2012). The active layer (i.e., the active freeze-thaw zone) typically ranges from 1.0 m to 3.0 m in areas of shallow soils and areas away from the influence of lakes. The mean annual air temperature at the Meliadine mine is about -10.5°C, the average monthly maximum temperature of 10.5°C occurs in July, and the average monthly minimum temperature of -30.8°C occurs in January based on Canadian Climate Normals for the period of 1981 to 2010 at Rankin Inlet, NU. Mean annual precipitation is estimated to be 412 mm, with approximately half of it falling as snowfall. Average annual evaporation for small waterbodies in the mine area is estimated to be 323 mm between June and September. Late-winter ice thicknesses on freshwater lakes in the mine area range between 1.0 m and 2.3 m with an average thickness of 1.7 m. Annual spring freshet typically begins in mid-June and continues to early July.

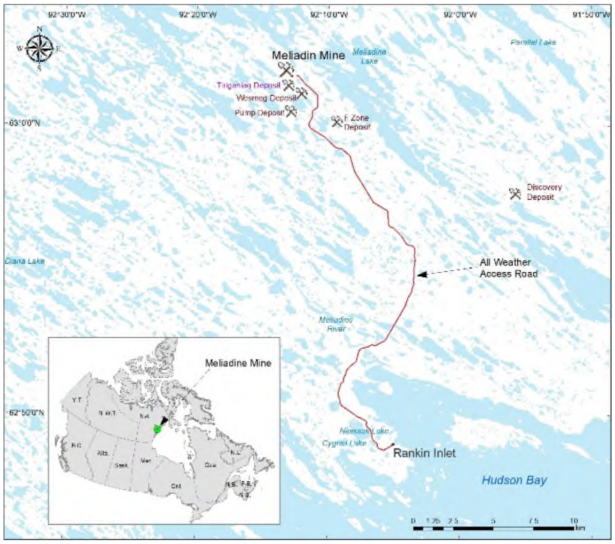

Figure 1. The Meliadine mine location map

3 DIKE D-CP1 DESIGN

3.1 Foundation Conditions

Dike D-CP1 is located at the outlets of two existing lakes with complex subsurface conditions and ice-rich foundation soils underneath its footprint. The subsurface overburden, bedrock, and thermal conditions were determined by means of permafrost mapping, geotechnical drilling, and ground temperature monitoring. Five geotechnical boreholes were drilled along the footprint of the dike and ground temperature cables installed in two of the boreholes to collect data used for the detailed engineering design of the dike. The interpreted ground profile from the drilling program within the dike's footprint is presented in Figure 2.

The overburden soil stratigraphy generally consists of a thin layer of organic matter or peat (up to 0.5 m thick) overlying a layer of non-cohesive soils with variable amounts of silt, sand, and gravel. Overburden soils with excess ice were observed in most of the boreholes. Massive icy beds up to 0.8 m thick were also observed. The estimated percentage (by volume) of excess visible ice ranged from 10% to more than 40% in the overburden soils. Greywacke bedrock was encountered at depths ranging from 2.7 m to 8.2 m from the ground surface.

3.2 Design Features and Typical Section

Dike D-CP1 is predominately a rockfill structure with a bituminous geomembrane (Coletanche) liner keyed into competent frozen ground (ice saturated inorganic permafrost) or competent bedrock to provide containment and storage of surface contact water. The design intent was to protect the original permafrost foundation beneath the liner in the key trench from thawing, thus limiting seepage through the dike and maintaining the integrity of its foundation. The design of Dike D-CP1 called for the depth of key trench ranging from 1.4 m to 1.8 depending on ground conditions. The dike also includes a zone of esker material in the upstream shell which serves as a thermal buffer between the reservoir and the key trench. The esker material has the additional benefit to reduce seepage if there are defects in the liner.

Dike D-CP1 is approximately 600 m long with a maximum height of 6.6 m from original ground (Tetra Tech EBA 2016a). The maximum water heads against the dike are about 3.8 m and 4.2 m under normal operation condition and Inflow Design Flood (IDF), respectively. The collection pond created by the dike is intended to provide a maximum storage capacity of about 0.8 Mm^3 at the maximum water level during IDF. The dike's side slopes were designed to be 2.5H:1V (Horizontal to Vertical) on the upstream side and 2H:1V on the downstream side. A minimum 4 m thick thermal cover over the key trench along the dike abutments was adopted for the design. A typical design section of Dike D-CP1 is shown in Figure 3.

3.3 Design Criteria

Dike D-CP1 is designed to maintain the foundation beneath the liner along the key trench in a frozen condition under mean and extreme warm climate conditions. The following thermal design criteria were adopted for the dike design:

- Under mean climatic and normal operation conditions, ground temperatures in the critical zone beneath the liner in the key trench should be colder than -2.0°C; and
- Under extreme warm (1 in 100 warm) year climatic and normal operation conditions, ground temperatures in the critical zone beneath the liner in the key trench should be colder than -1.5 °C.

Dike D-CP1 has a consequence classification of "Significant" in terms of the Canadian Dam Association (CDA) Dam Safety Guidelines (CDA 2013) and has been designed to align with this guideline.

Settlement was expected post construction. Approximately 120 mm of potential settlement was considered to determine the liner final crest elevation in the design.

3.4 Thermal Analysis

Two-dimensional thermal analyses were conducted to facilitate the detailed engineering design of Dike D-CP1. Thermal analyses were carried out using Tetra Tech's proprietary two-dimensional finite element computer model, GEOTHERM, initially developed in the 1970s and progressively updated to incorporate some unique features. The theoretical basis for the model was described in Hwang (1976). The model simulates transient heat conduction with change of phase for a variety of boundary conditions, including heat flux, convective heat flux, temperature, and ground-air boundaries. The heat exchange at the ground surface is modelled with an energy balance equation considering air temperatures, wind velocity, snow depth, and solar radiation. The model facilitates the inclusion of temperature phase change relationships for saline soils, such that freezing depression and unfrozen water content variations can be explicitly modelled. Other special features incorporated in this model include modelling of global warming (climate change), coupled thermal-seepage, body heat (e.g., heat generation due to acid rock drainage), and a growing mesh over time (simulate waste rock or tailings lift placement). The model has been verified by comparing its results with closed-form analytical solutions and many different field observations. Over the past forty years, the model has been successfully used in thermal evaluations and designs for a substantial number of projects in arctic and sub-arctic regions, including dams, waste rock and tailings storage facilities, foundations, pipelines, utilidor systems, landfills, ground freezing systems, and oil and gas production wells.

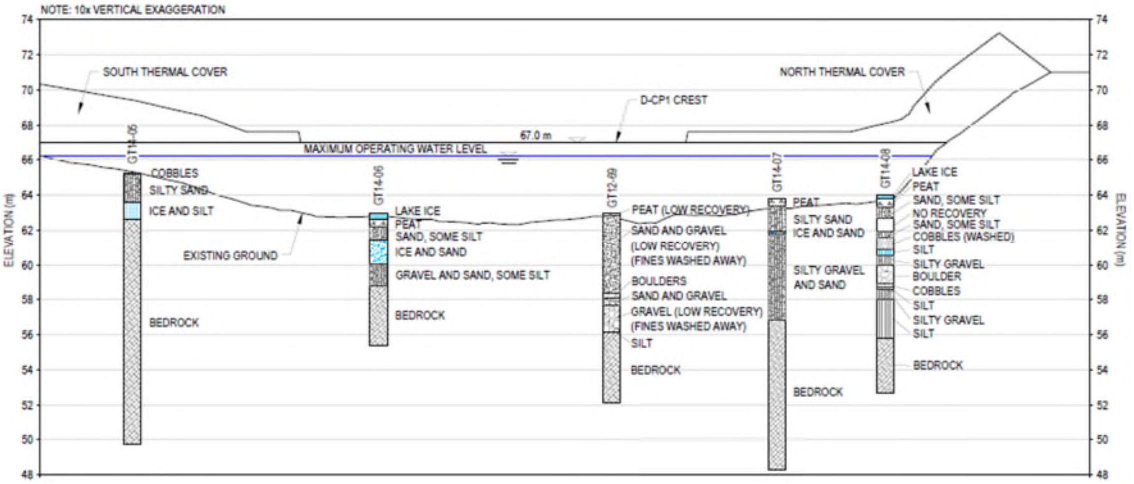

Figure 2. Interpreted ground conditions from the drilling program within Dike D-CP1 area

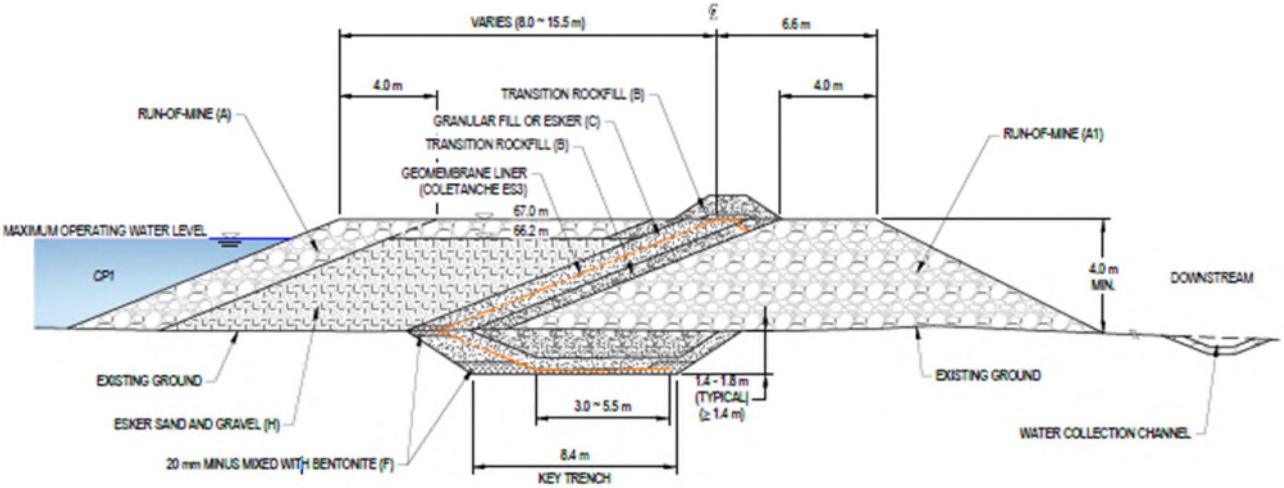

Figure 3. Dike D-CP1 design typical section

One-dimensional calibration thermal analyses were conducted to calibrate the thermal model with measured ground temperatures from a borehole within the dike's footprint. The key input parameters such as snow properties, ground surface properties, and evapotranspiration factors were derived from the calibration analyses. Two-dimensional thermal analyses were then conducted to simulate the dike construction and to predict the thermal performance of the dike under various operational conditions.

A water/ice temperature boundary was applied on the upstream side of the original ground and on the submerged dike surface. Climatic conditions considering air temperature, wind speed, solar radiation, and snow depth were applied at the dike's surfaces that are exposed to air and the original ground downstream of the dike. A snow drift factor of 2 (i.e., 2 times the mean snow depth) was modelled on the upstream and downstream slopes. Snow cover at the dike crest was reduced to 30% of the mean snow depth to account for wind-blown snow cover. Mean snow cover was applied at the toes of the dike and over the natural ground surface. A heat flux boundary was applied at the bottom of the mesh to simulate the assumed geothermal gradient of 0.017°C/m at the Meliadine mine site.

The thermal analyses were conducted by assuming that the dike will impound water at its maximum operating water level (66.2 m, about 3.8 m water head against the dike) at the onset of the freshet (assumed June 1 of each year) and will be maintained at this level until the end of October of that year. From the end of October to the end of May of the following year, the water/ice level is assumed to be at 63.0 m (i.e., approximately 0.5 m deep water against the dike at the deepest section). Two design air temperature conditions were evaluated in the thermal analysis including historical long-term mean (1983 to 2012) and 1 in 100 warm years following long-term mean climate condition. Given the relative short service life of the dike (i.e., 14 years based on the original mine plan), the thermal design of the structure is governed by the 1 in 100 return warm year event as opposed to the long-term global climate change scenarios.

Figure 4 presents the average measured long-term historical temperature and estimated monthly air temperature under a 1 in 100 return warm year condition. As a comparison, estimated monthly air temperature under High (A2) Green-house Gas Emission Scenario (Canadian Standard Association (CSA) 2010) are also plotted in Figure 4.

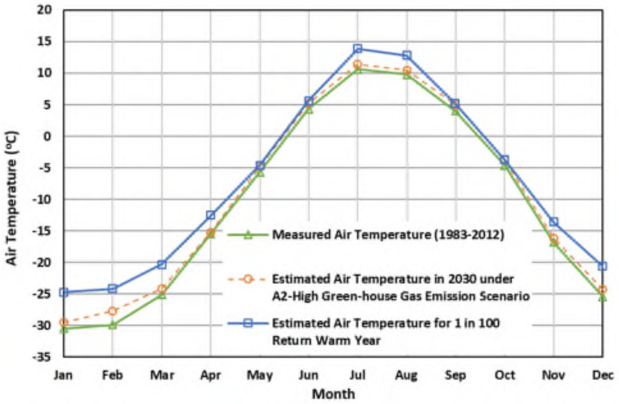

Figure 4. Measured historical mean air temperature and estimated air temperature for a 1 in 100 return warm year condition

Figure 5 presents the predicted isotherms in the dike and its foundation in mid-October after two consecutive 1 in 100 warm years following a mean climatic year after dike construction. Thermal analysis results indicated that the key trench will remain perennially frozen and the temperatures in the critical zone of the key trench will be colder than -1.5°C during the service life. The predicted maximum thaw depth below the dike crest is 3.3 m for mean years and 3.7 m for two consecutive 1 in 100 warm years following a mean climatic year after dike construction. A design thickness of 4.0 m for the thermal cover over the key trench is sufficient to maintain the critical zone below the liner within the key trench and foundation underneath in a frozen condition (Tetra Tech EBA 2016).

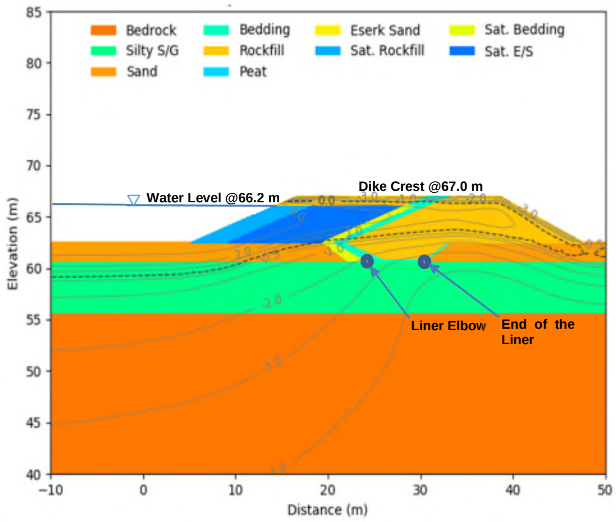

Figure 5. Predicted mid October isotherms under mean air condition followed by two consecutive 1 in 100 warm years

4 DIKE D-CP1 CONSTRUCTION AND CHALLENGES

The construction of Dike D-CP1 started in October 2016 and was completed in July 2017. Tetra Tech Canada Inc. (Tetra Tech) provided construction monitoring, earth-works quality control (QC) material testing and quality assurance (QA) services during construction. Construction management was overseen by Agnico Eagle. MTKSL Contracting Joint Venture (MTKSL) produced construction materials and constructed the dike. Liner installation was performed by Texel Geosol Inc. (Texel) working as a sub-contractor for MTKSL. Liner QC testing and monitoring was performed by Texel. A technical advisory committee reporting to Agnico Eagle was formed and reviewed the dike design and construction.

Dike construction started with foundation preparation which included clearing of snow, loose debris, and boulders from the dike's upstream and downstream sides. Foundation preparation was followed by the placement of an approximately 1 m thick layer of run of mine rockfill (600 mm minus) and esker sand gravel (75 mm minus) on the upstream side and run of mine rockfill on the downstream side which served as working platforms for the key trench construction. Excavation of the key trench was planned in the fall when the active layer is at its maximum depth. The intention was to freely dig the unfrozen overburden and weathered bedrock to top of frozen ground or competent bedrock using CAT bulldozers and excavators. Construction delays pushed back some of the key trench excavation work to occur in the winter 2016/2017 on a frozen active layer and requiring the use of an excavator with a rock breaker attached as the main digging mechanism. Key trench depth varied from 1.6 m to 3.2 m and was governed by where competent bedrock or non-ice-rich, ice-saturated frozen till, or sediments (with an ice saturation of no less than 90%) was encountered. Visual inspections of the excavations and QC testing including moisture content tests and jar thaw tests on the excavation samples to determine the volumetric ground ice content were conducted by onsite QC personnel to define key trench excavation depths. Massive ground ice was encountered in the key trench upstream side between Stations 0+435 and 0+455 and between Stations 0+492 to 0+507. The ice was excavated and removed by cutting approximately 3 m from the crest towards the upstream side for the length of the massive ground ice.

Once desired key trench depths were attained, the base was bulk cleaned with CAT excavators followed by dental cleaning with hand tools which included shovels, brooms, and compressed air. Open joints identified on some isolated areas in exposed bedrock were filled with powdered Sika 100 grout prior to fill placement. Local depressions and voids on rugged solid bedrock surfaces were filled with bentonite-augmented 20 mm minus crushed aggregate; the material produced by adding dry powdered bentonite to the crush to achieve an average bentonite content of 8% to 10% by weight at any grab sample.

Complex and variable ground conditions encountered during the key trench excavation resulted in deeper than designed key trench depths that ranged between 1.4 m and 1.8 m below original ground surface. The design of Dike D-CP1 called for backfilling over-excavated zones with (nearly-saturated 20 mm minus material with a water saturation of 85% to 95% after placement and compaction). Several difficult and unsuccessful attempts at producing the material by mixing hot water and frozen 20 mm minus material in challenging winter conditions resulted in its use being suspended after being placed between Stations 0+090 and 0+310. The key trench excavation geometry and the elevation of the key trench base liner were adjusted for the remaining sections of the key trench to eliminate the use of the material.

A layer of bentonite-augmented crush was placed and compacted at the base of the key trench to serve as a levelling course and the liner bedding and to provide a low permeability seal between the foundation excavation and the liner. The bentonite-augmented crush was also placed below and on the liner at the hinge point and from the hinge point up to elevation 64.7 m between Stations 1+132 and 1+551 on the top liner to provide additional robustness and reduce the risk of potential seepage through the most critical section of the liner. Density testing on the material was carried out using a nuclear densometer and/or the “modified” sand cone method. Based on the test results and field observations, the desired compaction under field conditions was generally achieved when compared to single point “frozen” density test results.

Bituminous geomembrane liner (Coletanche ES2 and ES3) was used for the dike construction. Coletanche ES3 liner was selected during design. A shortage of Coletanche ES3 liner resulted in Coletanche ES2 liner substituted for Coletanche ES3 for all top liner panels from Station 1+521 to 1+570 and intermittent ES2/ES3 panels installed from Station 1+570 to 1+585. This change was checked and approved by the design engineer.

Liner installation was in two phases. Phase 1 (bottom liner) included placing the liner panels within the key trench to the hinge point with an approximately 0.5 m horizontal tie-in length. Phase 2 (top liner) installation took place after the key trench was backfilled and involved welding the bottom liner to the top liner at the hinge and extending the liner to the dike crest (about 66 m elevation).

To mitigate against any potential seepage related to liner damage along wrinkles or punctures if unidentified through QC inspections, the following mitigation measures were applied:

- The liner rolls having storage related wrinkling were heated using frost fighters to remove the wrinkles prior to liner installation.
- Directives were given to make sure liner was appropriately anchored on the crest before the bedding material placement on the slope and the bedding material was placed using bottom-up methodology to limit the liner sliding downhill during the material placement.
- Severely wrinkled liner was either heated and patched or cut and new pieces installed and welded to the existing.

The earthwork structure materials were placed in lifts following the maximum lift thicknesses specified in the material placement specifications (Tetra Tech EBA 2016b). Materials lift compaction was carried out with a CAT smooth drum packer prior to the placement of subsequent lifts.

QC testing on the material placed for the lower and upper earthwork structures including particle size analyses, moisture contents, moisture-density relationships test, and single point frozen dry densities was performed by on site QC personnel in a site laboratory. In general, Dike D-CP1 was constructed according to its design intent and overall specifications with the available construction materials. Some variations were made during construction to accommodate the field material availability, constructability, construction method and schedule, and design changes.

With construction stretching into late spring 2017 when snow melting was active, water was observed seeping from the upstream CP1 pond through to the hinge point liner from Station 1+390 to 1+430 on May 11, 2017. On May 13, 2017 the water level in the CP1 pond was high enough to over-top the 0.9 m high working platform from Station 1+170 to 1+460. These conditions were mitigated by replacing the saturated esker sand and gravel material with non-saturated material and mass bulking of bentonite-augmented crush material and an over build of run of mine material.

5 INSTRUMENTATION

Permafrost exists beneath the footprint of Dike D-CP1. Successful performance of the dike as a water retaining structure relies on maintaining the original permafrost foundation in a frozen condition beneath the liner. Thermal performance is monitored with a series of five horizontal ground temperature cables (GTCs) installed above the liner parallel to the key trench and five vertical GTCs installed upstream and downstream of the key trench. Settlement is monitored through six settlement survey monuments (M-1 to M-6) installed over the liner crest area of the dike. Figure 6 provides a typical instrumentation cross-section through the dike.

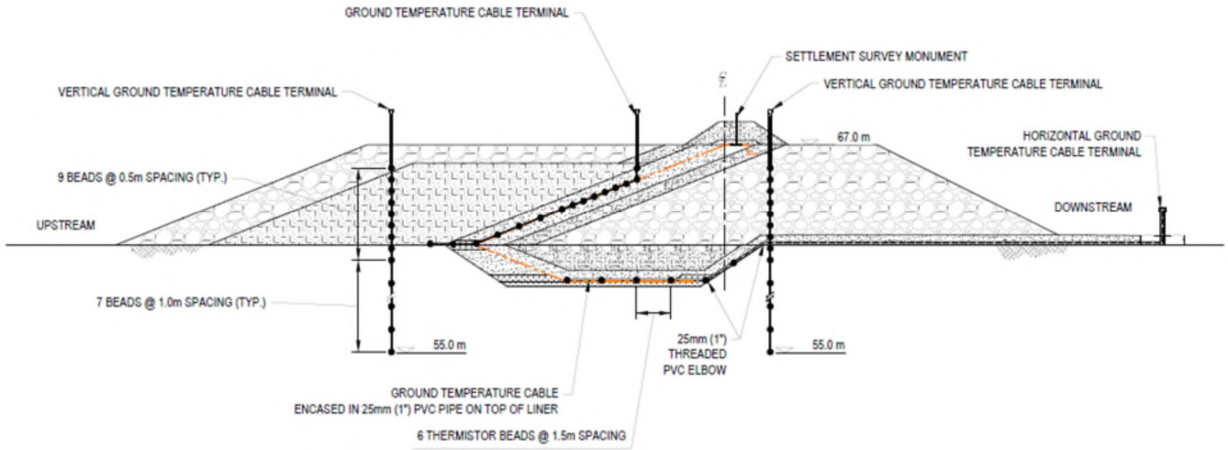

Figure 6. Typical configuration of instrumentation at Dike D-CP1

6 INITIAL PERFORMANCE REVIEW

6.1 Water Level Behind D-CP1

Dike D-CP1 has impounded water from the first freshet after construction in 2017. Figure 7 presents the measured water levels in CP1 and design and operation target water levels for open water seasons and freeze-up. The design and target water levels for Dike D-CP1 operation are:

- 63.0 m at the end of October each year to provide sufficient storage for the following year freshet and IDF event.
- 64.1 m before each freshet to provide sufficient storage for an IDF event.
- 66.2 m for open water season during non-IDF spring freshet or short-term after each spring freshet.
- 66.6 m for maximum short term design level under the design IDF.

The water level upstream of the dike has been effectively managed through controlled discharge via a water treatment plant to maintain it below the maximum short term design elevation of 66.6 m during the freshet. The maximum recorded water level behind Dike D-CP1 is 66.1 m and occurred during the 2020 freshet which represents a water head of 3.7 m against the dike. Maximum water levels for other operation years are 65.8 m, 65.9 m, and 65.1 m for 2018, 2019, and 2021, respectively. The target water level of 63.0 m at end of each October was not achieved, especially for the winter season of 2017/2018 and 2019/2020, with operating water level about 1.8 m and 3.0 m higher than the target water level, respectively.

6.2 Thermal Performance Review

GTC readings are taken and reviewed regularly (i.e., weekly, or monthly depending on the time of the year) since installation in 2017. Figure 8 presents average measured ground temperatures at the base of the key trench for horizontal GTCs HGTC-1 to HGTC-5. Overall, the horizontal GTCs are functioning well with some data losses noted during the period between January 7, 2018 and June 17, 2018 and malfunction for HGTC-2 during the period between June 19, 2019 and August 6, 2019. The average warmest temperature across all horizontal beads at the bottom of the key trench is about -5.1°C based on the measured data collected from 2018 to 2022. As expected, the key trench temperatures are warmest in late fall (October and November) and coldest in late spring (May and June).

A warming trend on the average temperature in the key trench has been observed. The average warming rate is about 0.2°C from 2018 to 2019, and 0.5°C from 2019 to 2020 and from 2020 to 2021. The greater warming rate through the last two years is attributed to the higher water level against the dike and relatively warmer air temperature in 2020/2021. In accordance with the design criteria, the ground temperature at the base of the key trench needs to be maintained below -2.0°C. The average ground temperature at the base of the key trench presented in Figure 7 demonstrate that the temperatures within the key trench have remained well below -2.0°C since the impoundment hence the thermal performance of Dike D-CP1 meets the design intent.

Maximum and minimum ground temperature profiles envelope for the vertical GTCs are presented in Figure 9, to give an indication of the temperature ranges within the dike structure below original ground. As illustrated in

Figure 9, the ground temperature profiles exhibit similar characters at each GTC location, especially below the original ground surface. The temperature at the bottom of the key trench ranges from -12.5°C to -3.8°C with an average of -7.5°C. The minimum temperatures upstream of dike (VGTC-01 and VGTC-03) are slightly colder than downstream (VGTC-02 and VGTC-04) above elevation 62.0 m and slightly warmer below elevation 62.0 m. The maximum thaw depth at the dike crest is estimated to be about 3.7 m, which is about 0.5 m above the original ground surface. The thermal cover adopted for Dike D-CP1 is adequate to prevent the thawing front penetrating into the key trench and maintain the critical zone below the liner within the key trench and foundation underneath in a frozen condition.

The GTC data measured at various locations were compared with the estimated ground temperature from the thermal performance evaluation of Dike D-CP1 undertaken in 2020. Figure 10 presents a comparison between estimated temperatures at the key trench (at elbow points of the liner and end of the liner at the bottom of the key trench) and measured ground temperature at HGTC-4. Figures 11 presents the comparison between the estimated temperatures and measured ground temperature at various selected depths at VGTC-4. The comparisons indicated that good agreement is obtained and the actual ground temperature readings from these GTCs closely follow the predicted ground temperatures from the thermal model.

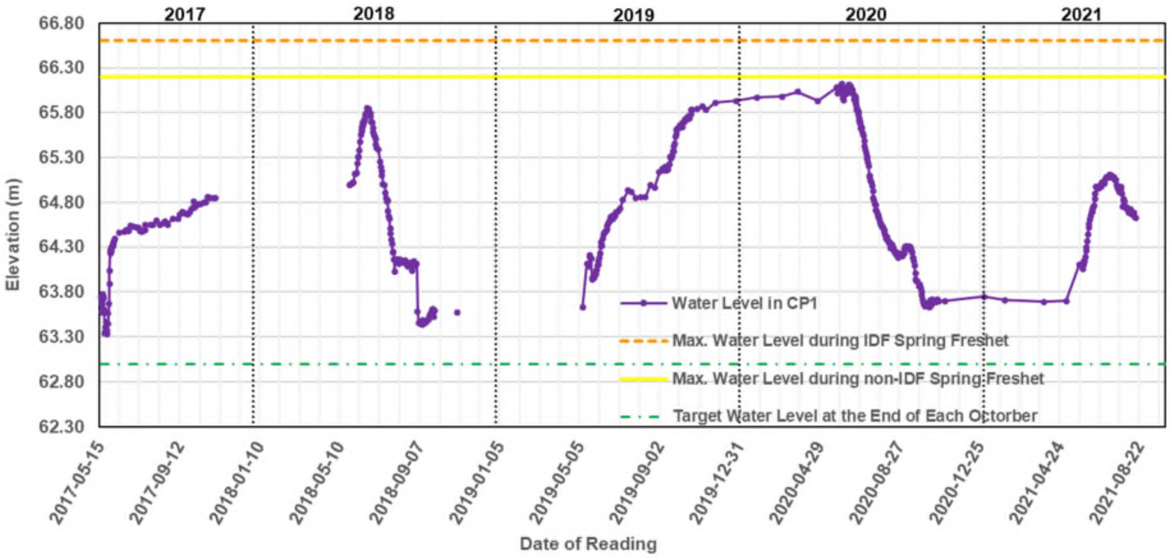

Figure 7. Measured water level in CP1 and design and target water levels

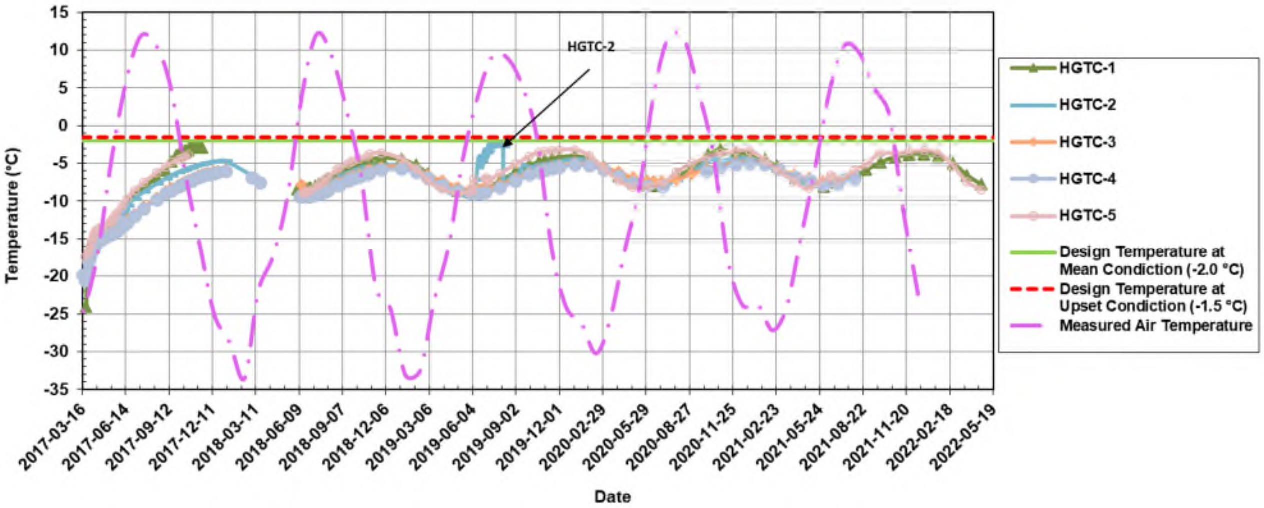

Figure 8. Average measured ground temperature at the base of the key trench for the horizontal GTCs

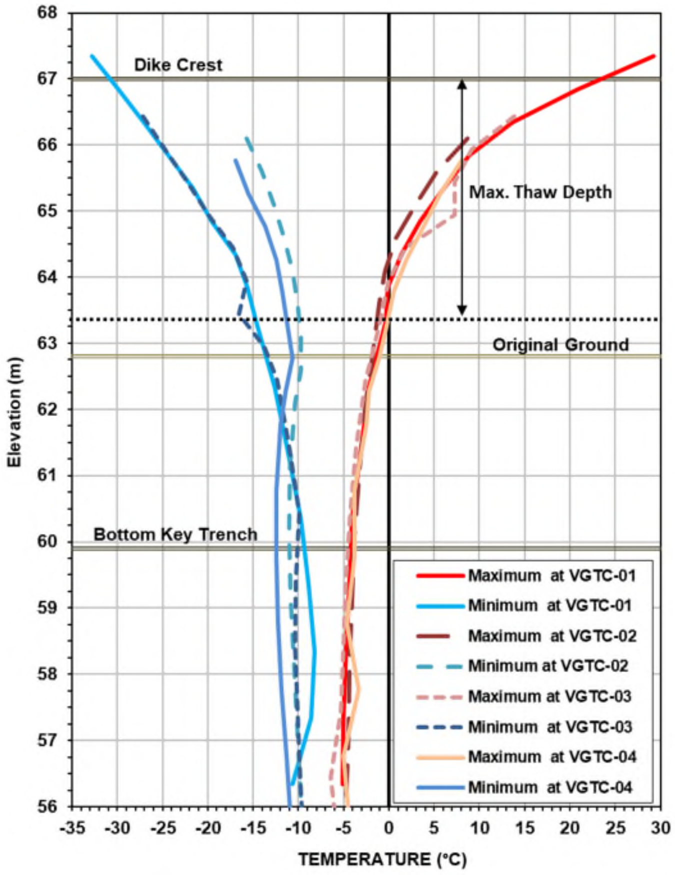

Figure 9. Maximum and minimum ground temperature profiles for the vertical GTCs

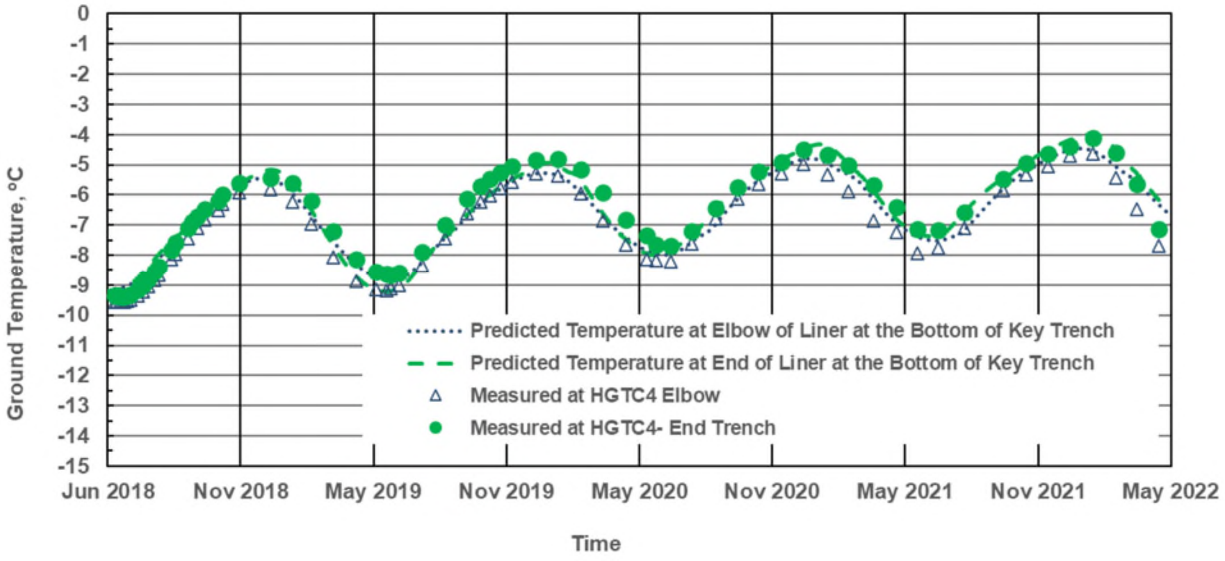

Figure 10. Predicted and measured temperature with time at the elbow and end of the liner at the bottom of the key trench of D-CP1

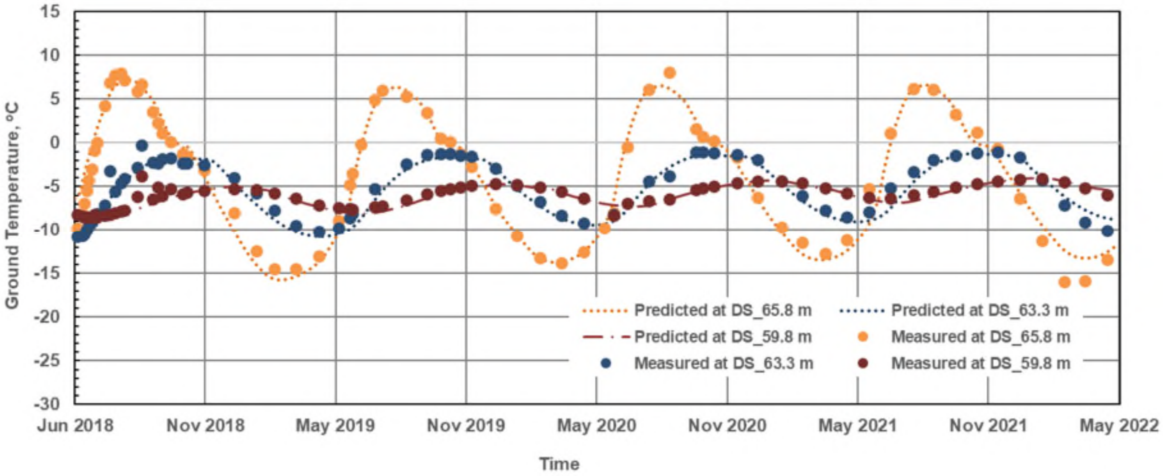

Figure 11. Predicted and measured temperature at various depth at VGTC4 (downstream side)

6.3 Settlement and Stability

Settlement survey has been performed monthly since September 2017. Figure 12 presents the total vertical displacement over time for Dike D-CP1. The survey monitoring points indicate a range of total vertical downward displacement between 32 mm to 80 mm since installation. Most of the displacement occurred within the first year after dike construction. The displacements have been nearly stable with slight fluctuations since summer 2020. So far, the vertical displacement has been less than the estimated total settlement of 120 mm which was used to determine the crest elevation of the dike in the design.

Routine dike visual inspections have been conducted and documented by the field engineer or technician of Agnico Eagle to observe any signs of slope instability, seepage, settlement, cracks, sink holes, and uneven surfaces. An annual geotechnical inspection has been performed by a qualified geotechnical engineer from the detailed design team of Tetra Tech. Overall, Dike D-CP1 appeared stable, with no significant geotechnical concerns identified. Minor cracking and small settlement were observed along portions of the upstream and downstream crest. Since the initial observations in August 2019, the cracks have not shown evidence of widening or extension. Minor settlement and subsidence have been observed between the downstream dike toe and the water collection channel with some in the disturbed original ground area and others in the areas covered with fill for construction access. The settlement and subsidence do not appear to be impacting the dike's performance. No seepage was observed from the downstream toe.

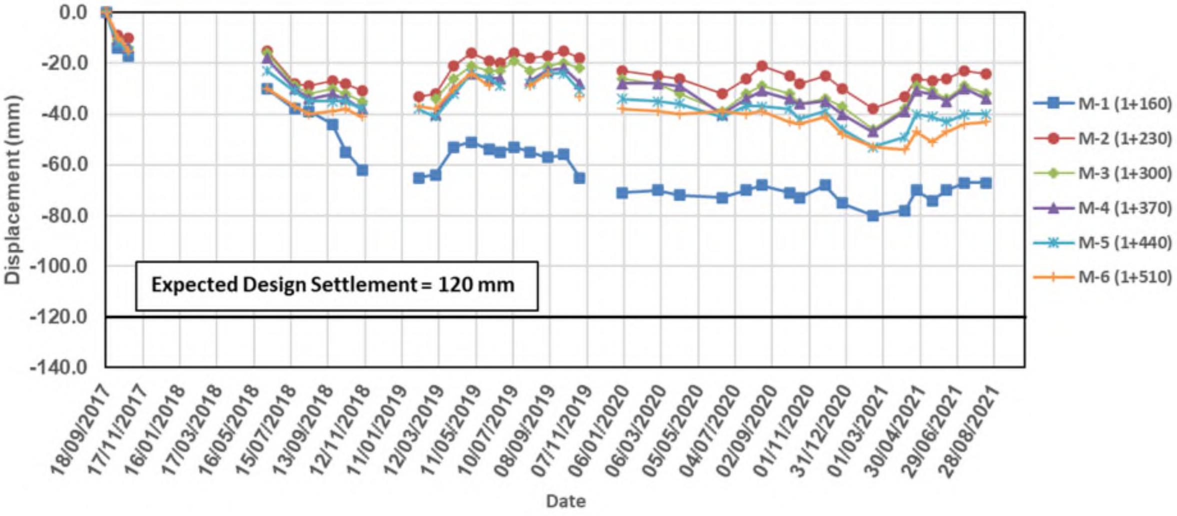

Figure 12. Measured total vertical displacement over time for Dike D-CP1

7 CONCLUSION

This paper presents the design, construction and performance review of a water retaining dike constructed in an area of continuous permafrost at the Meliadine mine. The dike was designed and constructed as a frozen foundation dam with a bituminous geomembrane (Coletanche) liner keyed into competent frozen foundation materials. Various challenges were encountered during the construction, for example, free digging of key trench during Arctic winter period, complex ground conditions, the inability to produce nearly-saturated fill material, and extreme winter conditions. Related mitigation measures were applied to overcome the challenges and to ensure that the construction was completed according to its design intent and specifications.

Following the construction, five years of monitoring data has been collected, analyzed, and compared with the modelled thermal responses. Regular visual inspection and annual geotechnical inspection has been performed. The monitoring data and findings from the inspections indicate that the performance of Dike D-CP1 at Meliadine mine meets or exceeds the design requirement and intents. The dike foundation is in a frozen condition as designed and no seepage has been observed through the dike foundations.

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REFERENCES

Canadian Dam Association (CDA). 2013. Dam Safety Guidelines.

Canadian Standard Association (CSA). 2010. Technical Guide Infrastructure in permafrost: A guideline for climate change adaptation, Canadian Standard Association, PLUS 1011-10: 48-51.

Golder. 2012b. Permafrost Thermal Regime Baseline Studies - Meliadine Gold Project, Nunavut, Canada. A Technical Report Submitted to Agnico-Eagle Mines Ltd. by Golder Associates, September 25, 2012.

Hwang, C.T. 1976. Predictions and Observations on the Behaviour of a Warm Gas Ductline on Permafrost, *Canadian Geotechnical Journal*, 13(4): 452-480.

Tetra Tech EBA (Tetra Tech EBA Inc.). 2016a. Design Report for D-CP1 Meliadine Gold Project, NU. Prepared for Agnico Eagle Mines Limited. August 15, 2016. Document No. 6515-E-132-007-132-REP-003.

Tetra Tech EBA (Tetra Tech EBA Inc.). 2016b. Geotechnical Specifications for Construction of Dike D-CP1 Meliadine Gold Project, NU. Prepared for Agnico Eagle Mines Limited. November 9, 2016. Document No. 6515-E-132-SPT-002.