Applications of Numerical Thermal Analysis in Engineering Designs and Evaluations for Northern Mines

Guangwen (Gordon) Zhang and William (Bill) T. Horne
EBA Engineering Consultants Ltd., Edmonton, AB, Canada

ABSTRACT
Numerical thermal analysis has been effectively used in engineering designs and evaluations for northern regions. This paper presents six typical example applications of numerical thermal analysis in designs and evaluations of site facilities and pits for six mines in northern Canada and Russia. The applications cover the stages of design and construction, operation, and closure of the mines. Key features, methodology, and results for each example are presented.

RÉSUMÉ
L'analyse thermique numérique a été efficacement utilisée dans l'ingénierie des conceptions et les évaluations pour les régions du nord. Ce papier présente six applications d'exemple typiques d'analyse thermique numérique dans les conceptions et les évaluations de l'infrastructure du site et de fosses pour six mines dans Canada et de Russie du nord. Les applications couvrent les étapes de conception et la construction, l'opération, et la fermeture des mines. Les caractéristiques clés, la méthodologie, et les résultats pour chaque exemple est présenté.

1 INTRODUCTION

Numerical thermal analysis has been effectively used in engineering designs and evaluations for northern regions. This paper presents six typical example applications of numerical thermal analysis in designs and evaluations of site facilities and pits for six mines in northern Canada and Russia. The applications cover the stages of design and construction, operation, and closure of the mines. These examples include 1) thermal design of a frozen core dam with thermosyphons for a tailings management facility; 2) thermal design of a ventilated duct system for a process plant foundation over ice-rich permafrost; 3) feasibility of artificial ground freezing around an ore body for managing seepage during underground mining; 4) thermal evaluation of water filling into a mined-out pit within a permafrost zone close to an active underground operation; 5) thermal evaluation of dewatered stacked tailings placed over ice-rich permafrost; and 6) evaluation of long-term thermal performance of a tailings dyke with a closure cover. Key features, methodology, and results for each example are presented.

2 NUMERICAL THERMAL ANALYSIS MODEL

Thermal analyses for the examples presented in the following sections were carried out using a proprietary two-dimensional finite element computer model, GEOTHERM, initially developed in the 1970s and progressively updated later by EBA Engineering Consultants Ltd. 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 any 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, and a growing mesh over time. The model has been verified by comparing its results with closed-form analytical solutions and many different field observations. Over the past thirty 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, foundations, pipelines, utilidor systems, landfills, ground freezing systems, and oil/gas production wells.

3 THERMAL DESIGN OF A FROZEN CORE DAM WITH THERMOSYPHONS FOR A TAILINGS MANAGEMENT FACILITY

A water-retention dam for a tailings management facility was required for a mine (Mine A) located within the continuous permafrost region in Nunavut, Canada. The dam was designed as a zoned rockfill, frozen core dam with a maximum upstream operating water depth of 5 m. The dam design life was seven years. An effective frozen core dam requires that the central core and underlying foundation remain frozen year-round to act as an impervious barrier against seepage. Preliminary thermal analysis results indicated that horizontal thermosyphon loops were required near the base of the core to meet thermal design criteria.

Two-dimensional calibration thermal analyses were conducted to calibrate the thermal model with measured ground temperatures at a borehole within the dam footprint. Input data such as snow properties, ground surface conditions, and evapotranspiration factor were modified in the calibration analyses to obtain a good agreement between the modelled and measured ground temperatures. Figure 1 compares the measured ground temperatures with those estimated from the calibration thermal analyses. The calibrated input data were then used in the thermal analyses for the dam design.

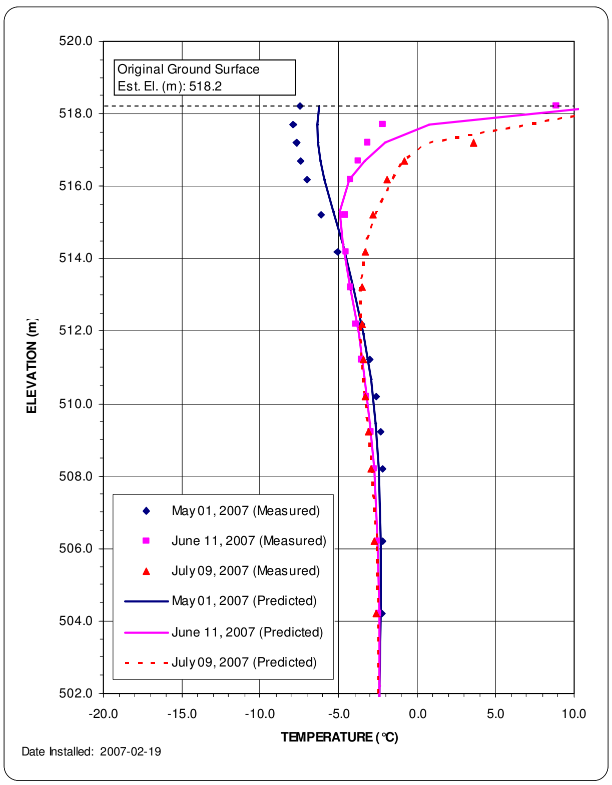

Figure 1. Comparison of measured and predicted ground temperature profiles at a borehole location.

Two-dimensional thermal analyses of the dam with thermosyphons were carried out to predict the thermal performance of the dam under various design conditions. The thermosyphon system for the dam included four horizontal evaporator loops with a 2 m pipe-to-pipe spacing and four radiators, each with a surface area of 39 m^2.

A thermosyphon is a passive heat transfer device that operates by convection through vaporization and condensation. It consists of a sealed vessel with an upper part working as a condenser and a buried part in the ground functioning as an evaporator. Heat transfer is driven by the temperature difference across the unit. For ground cooling applications, thermosyphons remove heat from the ground beneath a structure and release it to the outside ambient air, as long as the air is colder than the ground. A detailed description of thermosyphon technology is presented in Yarmak and Long (2002).

The initial ground temperatures in the dam foundation were estimated from thermal analyses considering the thermal impacts of a small lake upstream of the dam and snow drifting in the valley. A water/ice temperature boundary was applied on the upstream side of the original ground and on the submerged dam surface. Climatic conditions considering air temperature, wind speed, solar radiation, and snow depth were applied at the dam surfaces exposed to air and the original ground downstream of the dam. The thermosyphons were simulated as a convective heat flux boundary. The convective heat transfer characteristics of the thermosyphons were estimated based on empirical expressions established from laboratory experiments of full-scale horizontal thermosyphons (Haynes & Zarling, 1988).

Figure 2 presents the predicted isotherms in the dam and its foundation in early October after two consecutive 1 in 100 warm years following a mean climatic year after dam construction. Thermal analysis results indicated that the core will remain perennially frozen and the temperatures in the critical zone of the core will be colder than -2°C during the dam design life. The predicted maximum thaw depth below the dam crest is 3.1 m for mean years and 3.7 m for two consecutive 1 in 100 warm years following a mean climatic year after dam construction. A design thickness of 4 m for the thermal cover over the core is sufficient to maintain the core in perennially frozen conditions.

4 THERMAL DESIGN OF A VENTILATED DUCT SYSTEM FOR A PROCESS PLANT FOUNDATION OVER ICE-RICH PERMAFROST

A slab-on-grade foundation was proposed for a process plant of a mine (Mine B) in northern Russia. The process plant has a width of 75 m and length of 200 m. The mine site is located in a continuous permafrost zone with a mean annual ground temperature at depth of -4°C to -5°C. The original ground at the proposed process plant site comprises a layer of ice-rich overburden soil (clayey silt) overlying ice-rich weathered bedrock, fractured bedrock, and weak bedrock. A ventilated duct system was selected as a foundation cooling system to contain the depth of thaw within thaw-stable bedding and structural fills beneath the process plant concrete floor slab. The system was designed to maintain the permafrost condition below the fills throughout the 22 year process plant design life.

Numerical thermal analyses were conducted to determine the design configurations of the ventilated duct foundation system. Various sensitivity thermal analyses were carried out to evaluate thermal sensitivity to potential variation of input data. Three design air temperature conditions were evaluated in the thermal analyses, including historic long-term mean, long-term

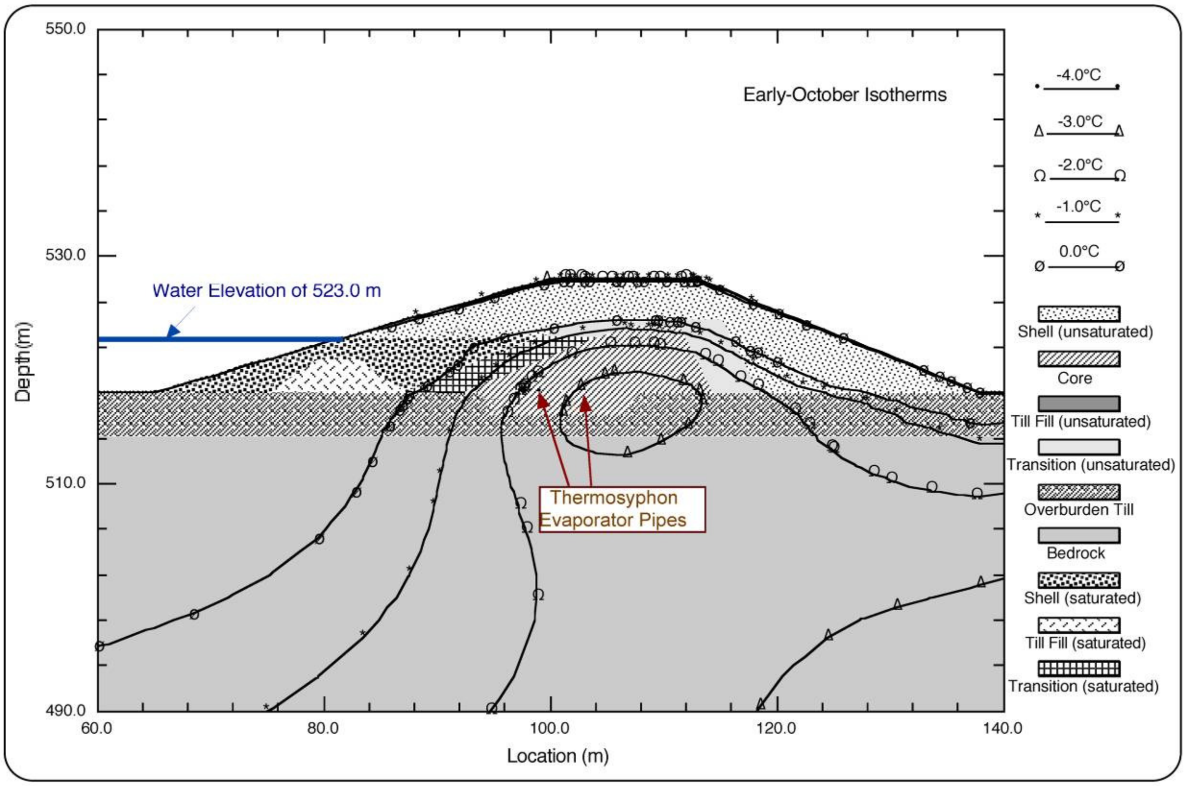

Figure 2. Predicted isotherms in the thermosyphon-stabilized dam at Mine A

climate warming trend, and 1 in 100 warm years following long-term climate warming.

Climatic conditions were applied to the ground surface beyond the process plant building. A temperature boundary was applied to the top of the concrete slab with assumed monthly temperatures from 15°C in winter months to 20°C in summer months. A heat flux boundary was applied at the bottom of the mesh to simulate the assumed geothermal gradient of 0.02°C/m at the mine site. Convective heat flux boundary conditions were applied to the inside surface of the ducts. The convective heat transfer coefficient, calculated from heat transfer equations in Ozisik (1985), varies depending on the inside duct diameter, air temperature, air velocity, and duct inside surface conditions. It was specified that the forced air would have a velocity of 3 m/s. The air will flow through the ventilation ducts when ambient air temperatures are colder than -7°C in late fall (in October) but the system will be shut down in late spring (in April) when ambient air temperatures are warmer than -7°C. No air will flow through the ducts during the remaining time of a year.

Air temperatures will change as the air flows through the ventilation ducts. Heat will transfer from the inside ventilation duct surfaces to the air. The air temperature changes along each of the ventilation ducts can be estimated from a formula in Smith et al. (1991). Iterations were required to estimate the air temperature changes between the air inlet and outlet since the heat fluxes through the duct also depend on the air temperature changes in the duct. Figure 3 shows the predicted isotherms in mid-October, when the thaw depth below the ducts is at the deepest, for one of the cases evaluated in the thermal analyses. The case simulated a cross-section through the air duct inlet areas under climatic conditions of two 1 in 100 warm years following five mean years.

The following design parameters for the ventilated pad were adopted based on the thermal analysis results:

- 0.2 m thick concrete slab over 0.15 m thick Styrofoam Highload 100 insulation;
- A minimum total thickness of 1.65 m of non-frost-susceptible, thaw-stable bedding and structural fills below the insulation and above the excavated surface of the original ground at the air inlet areas, and a minimum total thickness of 2.4 m of the fills at the air outlet areas;
- HDPE ventilation ducts with an outside diameter of 0.315 m and a duct centre-to-centre spacing of 3 m, buried in the thaw-stable fills; and
- Ventilation ducts sloping at a slope of 1% downwards from the inlets to outlets across the width (75 m) of the process plant to promote drainage in case potential condensation inside the ducts is thawed during the summer.

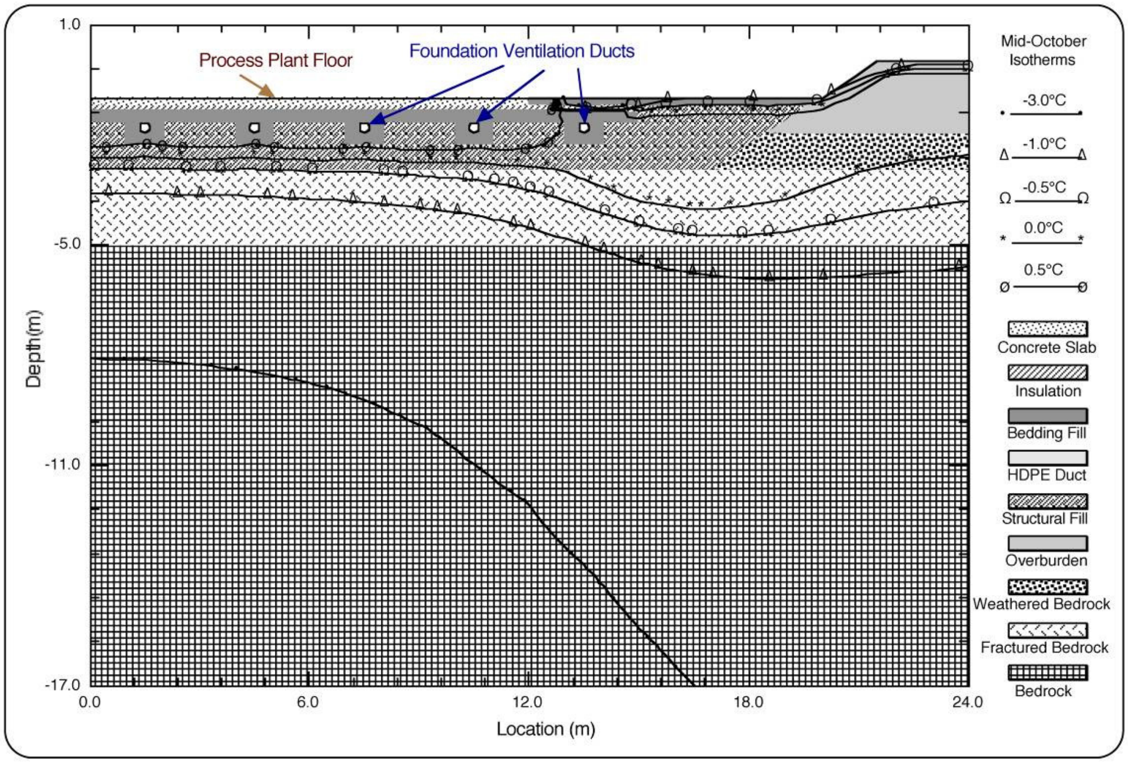

Figure 3. Predicted isotherms in the process plant foundation with a ventilated duct system at Mine B

5 FEASIBILITY OF ARTIFICIAL GROUND FREEZING AROUND AN ORE BODY FOR MANAGING SEEPAGE DURING UNDERGROUND MINING

Numerical thermal analyses were conducted to evaluate the feasibility of artificial ground freezing around an ore deposit for managing seepage during underground mining for a proposed mine (Mine C) in the Northwest Territories, Canada. The ore body at the mine site extends from approximately 122 m to 168 m depth from the ground surface. The general soil profile in the mine area consists of 26 to 45 m of gravels and glacial till overlying mudstone, limestone, dolomite, and dolomitic sandstone. The ground in and around the ore body within the top 170 m depth is very porous and permeable. The dolomitic sandstone below the ore body is less porous and permeable. One method being considered to manage seepage during mining is to develop a frozen wall around the perimeter of the ore deposit. The design intent of the proposed ground freezing system is to seal off seepage by creating a frozen wall of ice-saturated soil or rock of sufficient thickness that it is a nearly-impermeable barrier to seepage. This method is technically feasible as long as the base of the frozen wall extends into tight, low permeability rock such that groundwater inflow through the floor below the frozen curtain is manageable.

The frozen mass around vertical freeze pipes generally proceeds first radially around each pipe to form a cylinder until it coalesces with adjacent cylinders to form a continuous frozen wall that then grows in a lateral direction perpendicular to the axis of the row or circle of freeze pipes. Consequently, the lateral freezing process at a given depth can be simulated in a two-dimensional model by analyzing a horizontal slice through the freezing pipes and surrounding soil/rock. The simulated geometry can be further simplified if one or more symmetrical axes exist. In this study, a single row of vertical freeze pipes at a centre-to-centre spacing of 1.5 m has been evaluated. Heat transfer between the freeze pipe wall and the surrounding soil or rock has been simulated as a convective heat flux boundary.

The initial ground temperatures at the mine site were assumed to be 0°C at the ground surface, increasing linearly with depth at a rate of 0.03°C/m.

The following assumptions have been applied in the thermal analyses:

- Thirty percent calcium chloride solution as the circulating fluid in the freeze pipes;
- Brine temperature of -30°C; and
- Brine fluid flowing down through an inner pipe inside a larger diameter pipe and flowing up through the annulus between the two pipes.

The sensitivity of freeze pipe dimensions and brine pumping rates were also considered:

- Freeze pipe dimensions:
  1) 51 mm (2”) diameter inner pipe inside a 102 mm (4”) diameter, schedule 40 steel pipe, and
  2) 38 mm (1.5”) diameter inner pipe inside a 76 mm (3”) diameter, schedule 40 steel pipe.

- Fluid flow rates:
  1) a flow rate that maintains the fluid in the annulus within a laminar flow range (<5.0 L/s for 51/102 mm pipes and <3.9 L/s for 38/76 mm pipes), and
  2) a very high flow rate that produces a thermal boundary condition, inside the outer pipe wall, that is equivalent to a fixed temperature boundary condition.

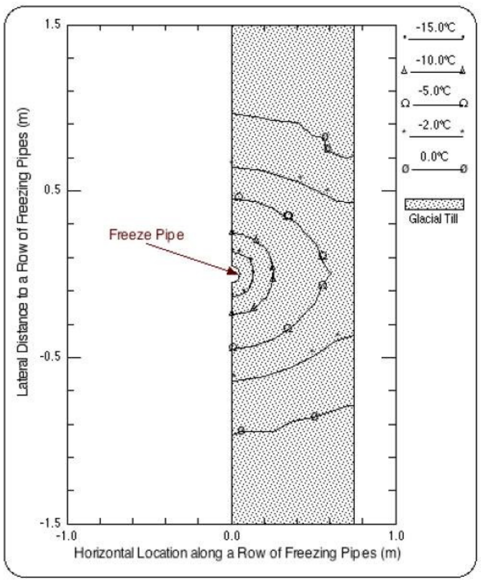

Figure 4. Example plot showing temperature distribution around a freeze pipe after one month of freezing in glacial till.

As expected, the ground temperature increases with increasing radial distance away from the freeze pipe (Figure 4). Figure 5 shows the estimated minimum thicknesses of the frozen wall at or colder than -2°C with freezing time for four different ground types (Cases 1 to 4).

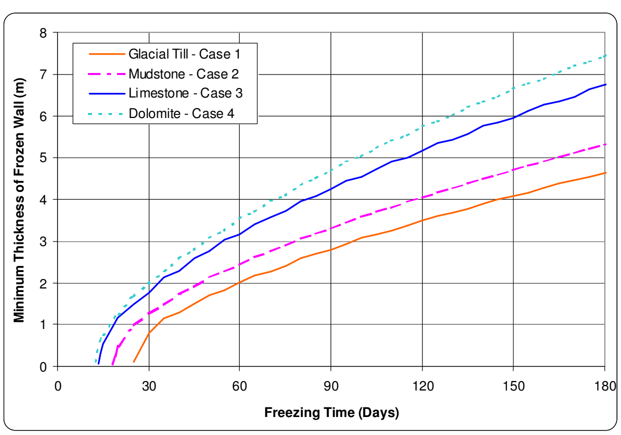

Figure 5. Freezing time vs. estimated minimum thickness of frozen wall at or colder than -2°C for four cases.

The ground releases heat to the chilled fluid through a freeze pipe wall during the freezing process. The heat flux varies with time and depth (i.e., lithology and initial temperature). The total heat flux through the freeze pipes can be used to determine an appropriate refrigeration plant capacity. Figure 6 presents the predicted heat flux with freezing time for Cases 1 to 4.

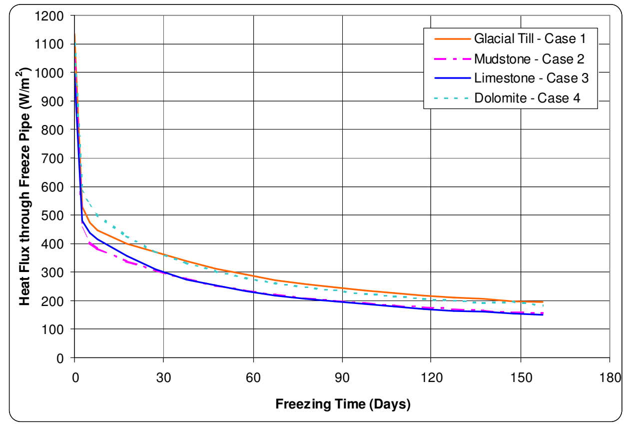

Figure 6. Freezing time vs. estimated heat fluxes through freezing pipe surface for four cases

The major findings from the analyses are summarized below:

- A continuous frozen wall with sufficient thickness can be developed from artificial ground freezing.
- The estimated minimum thickness of the frozen wall at or colder than -2°C ranges from 2.8 to 4.7 m after three months of freezing and 4.1 to 6.6 m after five months of freezing for the various cases studied.
- Both the moisture content (or porosity) of a soil/rock and the boundary condition (or the fluid flow rate) inside a freezing pipe affect the estimated frozen wall thickness. High moisture contents and low brine flow rates retard the rate at which the frozen wall develops.
- The rate of the frozen wall growth is less sensitive to the initial ground temperature.

6 THERMAL EVALUATION OF WATER FILLING INTO A MINED-OUT PIT WITHIN PERMAFROST ZONE CLOSE TO AN ACTIVE UNDERGROUND OPERATION

Consideration is being given to pumping mine water into a mined-out pit (Pit A) at a northern mine (Mine D) in the Northwest Territories, Canada. The mine is situated within the zone of continuous permafrost with a permafrost thickness of 300 m to 400 m. Pit A has an approximate diameter of 460 m at the ground surface and is approximately 200 m deep. Currently, underground mining is taking place beneath another mined-out open pit (Pit B). Pit B has an approximate diameter of 720 m at the ground surface and is approximately 300 m deep. The centre-to-centre distance between the two pits is approximately 900 m. The underground operations are within the depth range of 350 to 500 m from the ground surface. Underground operations are planned to continue until 2020.

Pumping mine water into Pit A will change the ground thermal conditions both laterally around the pit and vertically beneath it. The depth of thaw under the pit during the period of underground mine operations is particularly important if the thaw zone intersects the base of permafrost, thereby creating a potential hydraulic connection between Pit A and the underground workings.

Finite element thermal analyses were conducted to assess the thermal implications to the local permafrost conditions after filling Pit A during the period of underground mine operations. The analyses simulated a three-dimensional axi-symmetric geometry around the vertical axis of Pit A. A five-stage simulation was conducted as a base case to approximately model the pit development and its gradual filling with mine water. It was assumed that the pit would be filled with mine water over four years. Two sets of additional thermal analyses were conducted to evaluate the sensitivity of the analysis results to warmer initial ground and filling water temperatures.

A ground-air boundary was assigned to the walls and bottom of the complete Pit B during the simulations. A temperature boundary was assigned to the submerged walls and bottom of Pit A after filling. The water temperatures were assumed to be 4℃ from mid-October to mid-June, 10℃ for mid-July, 15℃ for mid-August, and 10℃ for mid-September. These water temperatures are approximately 1℃ or 2℃ warmer than those measured in some northern lakes deeper than 2 m and are therefore conservative.

A heat flux boundary was assigned to the bottom of the mesh to simulate the natural geothermal gradient that was estimated to be 0.0152℃/m from the measured ground temperatures at depth at the mine site. A zero-heat flux boundary was assigned to the right vertical boundary of the model, which was 400 m away from the far edge of Pit B.

Figure 7 illustrates the predicted ground temperatures around the water-filled Pit A in early September after ten years from initial filling.

The following conclusions can be made based on the thermal analysis results:

- Filling Pit A with mine water would thermally affect only the areas adjacent to the pit and, within ten years after filling, would have negligible effects on the thermal regimes in areas laterally more than 250 m from the Pit A walls.
- Filling Pit A would have little or no effect on the thermal conditions in the areas around the Pit B underground workings within the planned lifespan (2020) of the underground operations.

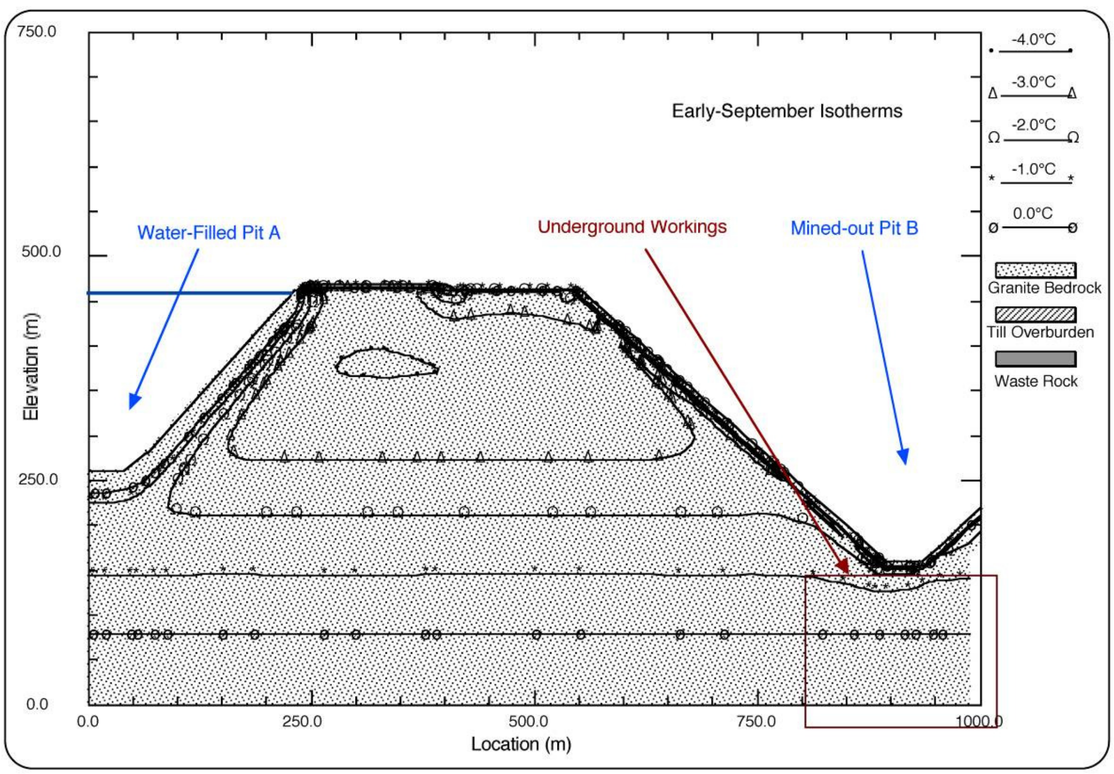

Figure 7. Predicted isotherms around water-filled Pit A after ten years from initial filling for a case studied.

7 THERMAL EVALUATION OF DEWATERED STACKED TAILINGS PLACED OVER ICE-RICH PERMAFROST

A mine (Mine E) site in Yukon Territory, Canada, is situated within a warm permafrost region with a mean ground temperature of -0.8°C at 10 m from the ground surface. The original ground in the proposed area for placing dewatered stacked tailings consists of ice-rich organic silt/sand over sand/silt over granite bedrock. As part of the design of the associated facilities for tailings placement, thermal analyses were carried out to predict the thermal regime of dewatered stacked tailings placed over a 1.5 m thick, sandy gravel drainage blanket overlying the original ground and to evaluate the impacts of the placed tailings on the thermal regime of the native subgrade during the mine life.

The thermal model was calibrated against the measured ground temperatures at the site. Various cases with different assumed tailings placement rates and final heights were simulated. Parametric and sensitivity studies for some cases were also conducted.

One-dimensional thermal analyses with a growing mesh were conducted to simulate thin layer placements of tailings.

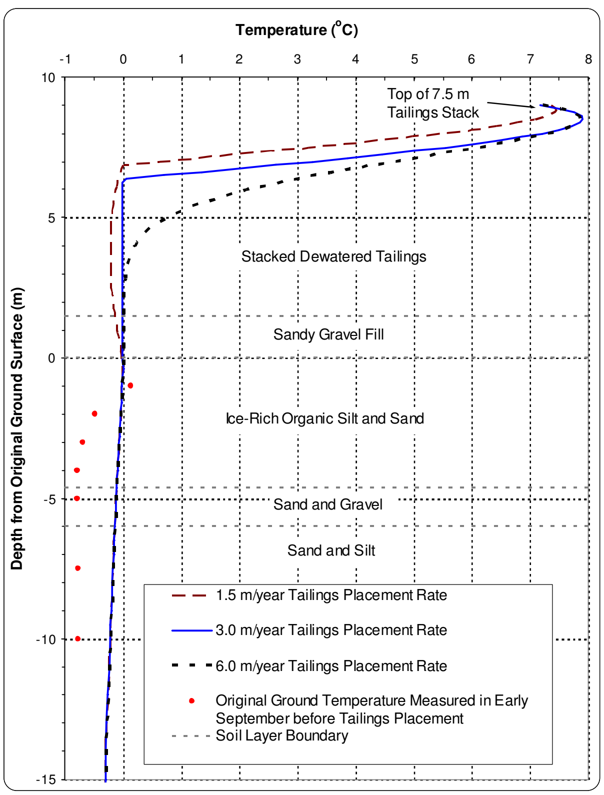

Figure 8. Predicted tailings/ground temperature profiles in mid-September for cases with different tailings placement rates.

The following findings can be drawn from the thermal analysis results:

- The 1.5 m thick sandy gravel drainage blanket proposed to be placed over the original ground can provide benefit in limiting thaw penetration into the original ground due to tailings placement.
- The predicted tailings temperatures for tailings placement rates of 1.5 m/year and 3.0 m/year are colder than those for a tailings placement rate of 6.0 m/year (see Figure 8). Therefore, it is recommended to limit the tailings placement rate to less than 3.0 m/year to promote freeze-back of the summer-placed tailings.
- A thin initial summer-placed tailings layer would promote freeze-back of the tailings, underlying sandy gravel fill, and original ground during the following winter and result in colder tailings/ground temperatures during the later stage of the mine life. The initial summer-placed tailings should be spread over a large area and in thin lifts to promote freeze-back of the tailings, underlying sandy gravel fill, and original ground during the following winter.
- Reduced snow cover results in colder tailings/ground temperatures. It is recommended that snow be regularly cleared off the tailings surface.

8 EVALUATION OF LONG-TERM THERMAL PERFORMANCE OF A TAILINGS DYKE WITH A CLOSURE COVER

Mine F is situated within an area of continuous permafrost in Russia. The depth of the permafrost was estimated to be approximately 150 m at the tailings disposal area. The mean ground temperature in the disposal area prior to tailings deposition varied from -1.3 to -2.2°C. Thickened tailings were deposited during mine operation from the top of a basin down towards a tailings dyke constructed with rock fill. Free water in the tailings was allowed to pass through the dyke and collected downstream of the tailings dyke in a water reservoir. The soil units in the tailings disposal area typically consist of a thin layer of peat overlying 1 to 4 m of overburden and weathered/fractured bedrock.

The maximum height of the tailings behind the dyke was about 40 m. The tailings surface had an average slope of approximately 2.4%. Sampling and temperature measurements indicated that the tailings contained alternating layers of frozen and unfrozen layers at variable elevations across the facility. On average, 63% of the tailings sampled were in a frozen state. The frozen tailings were relatively warm (-0.2°C or warmer). The tailings appeared to behave in frozen state at or below a temperature of approximately -0.15°C.

One-dimensional thermal analyses were firstly carried out to calibrate the thermal models based on measured ground temperatures and to estimate the values of several key input parameters. Two-dimensional thermal analyses were then conducted to predict the short- and long-term thermal performance of the tailings dyke with a closure cover consisting of 0.5 m waste rock overlying 0.5 m sandy gravel.

Thermal analysis results indicated that the thaw depth from the cover surface would gradually increase from 2.5 m in five years to 8 m in 50 years after mine closure. Figure 9 shows the predicted thawed zones for 5, 10, 20, and 50 years after mine closure. The initially frozen tailings will be gradually thawed with time after closure due to snow accumulation over the cover surface in winter and effects of the combination of lower frozen thermal conductivity in winter and higher unfrozen thermal conductivity in summer of the cover material when compared with those for the tailings. Further analyses indicated that permafrost could be maintained and further developed for another cover design when the ground surface is covered with trees and vegetation.

9 SUMMARY

This paper presents six typical example applications of numerical thermal analysis in thermal designs and evaluations for six mines in northern Canada and Russia. The applications cover the stages of design and construction, operation, and closure of the mines. Numerical thermal analysis is an effective and useful tool in engineering designs and evaluations for northern mine development, operation, and closure.

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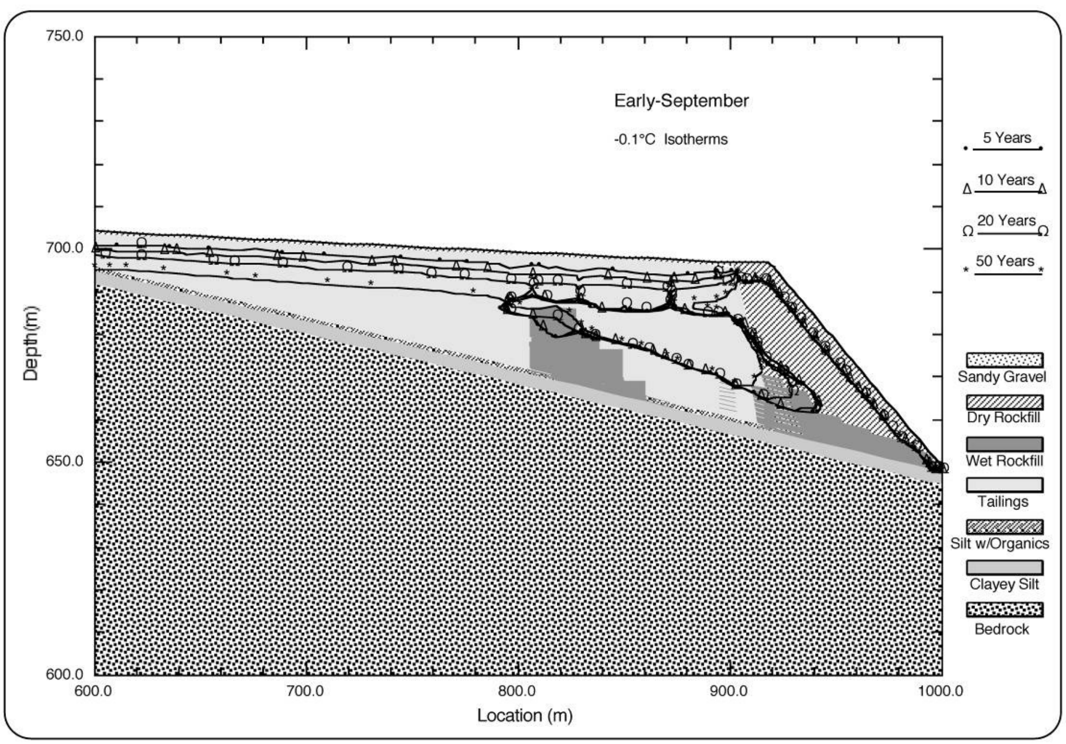

Figure 9. Predicted thawed zones with time in a tailings dam after mine closure.