ANALYSES OF ROCK PERMAFROST THAWING BEFORE GROUT INJECTION FOR THE INNAVIK HYDROELECTRIC PROJECT

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ABSTRACT
The Innavik hydroelectric project is located in Inukjuak and lies within the continuous permafrost zone. The geotechnical design requires the injection of a grout curtain to prevent water migration in the weathered bedrock that will partially thaw after impoundment. The present study analyzes the time required to complete the rock thawing and to determine the optimal forced thawing solution to be implemented on site prior to grout injection. Permafrost temperatures were monitored by thermistor strings which allowed a comparison between the modelling results and the in-situ data. Further analyses were conducted after the completion of the rock thawing to better represent the site measurements and are also discussed in this study.

RÉSUMÉ
Le projet hydroélectrique Innavik est localisé à Inukjuak et se situe dans la zone de pergélisol continu. La conception géotechnique requiert l'injection d'un rideau de coulis pour empêcher la migration de l'eau par le socle rocheux endommagé après l'ennoiement. Cette étude a permis d'analyser le temps requis pour compléter le dégel du roc ainsi que de déterminer la solution optimale à implémenter sur le chantier avant l'injection du coulis. La température du pergélisol a été suivie avec des thermistances ce qui a permis d'établir une comparaison entre les résultats de la modélisation et les données in situ. Des analyses supplémentaires ont été réalisées suite au dégel du roc pour mieux représenter les mesures de terrain et elles sont aussi abordées dans cette étude.

1 INTRODUCTION

Transition from fossil fuel to renewable energy sources has become a main priority of Quebec Northern communities that are isolated from Hydro-Québec's transmission grids. The Innavik project is located in Inukjuak on the shore of Hudson Bay (58°27' N 78°06' W) as shown by the red dot on Figure 1.

Figure 1. Location of Inukjuak (Britannica, 2022).

1.1 Inukjuak site conditions

The area surrounding the project is an alternation of valleys and rocky hills. Glacial and marine deposits are found between the rock outcrops. Inukjuak is within the continuous permafrost zone. The active layer in these deposits has a thickness of 1.0 m to 1.5 m. The mean annual air temperature for the 2008-2018 period was -5.6°C, with an average freezing and thawing index of 3104 °C*days and 1089 °C*days, respectively (St-Amour et al. 2020)

1.2 Innavik project description

This hydroelectric project consists of a 7.5 MW run-of-river power plant built at a distance of 10 km from the mouth of the Innuksuac River. The intake, the powerhouse, the tailrace, the spillway and the diversion were excavated from the permafrost bedrock. The rock in this location is weathered and the ice sealing the fractures was expected to thaw after the impoundment. The injection of a grout curtain was therefore required to prevent water migration. To ensure a successful grouting operation, the rock foundation under the diversion had to be rapidly thawed to maximize the penetration of the grout and its curing, while construction kept going.

1.3 Diversion description

The diversion is a 22 m wide channel on the rocky shore of the river. It is made of reinforced concrete, and it was completed in Autumn 2021. Once the excavation phase was finished, additional thermistor strings were installed under the structure to provide temperature data at 8 m and 12m depth. Following the results obtained by the Neumann solution, the project's design team decided that the grout curtain would be injected to a depth of 8 m and that the primary injection holes would have a maximum spacing of 6 m. The thermistor strings were drilled around the primary injection hole that was the closest to the south excavation wall. The distances from the hole were: 1.78 m (E3), 3.5 m (E2) and 3.8 m (E1). Figure 2 illustrates those dimensions.

To ascertain that the ice contained in the rock fractures was thawed before the grout injection, the design team decided that a temperature of 1°C should be reached and maintained for a few days at the 8m depth.

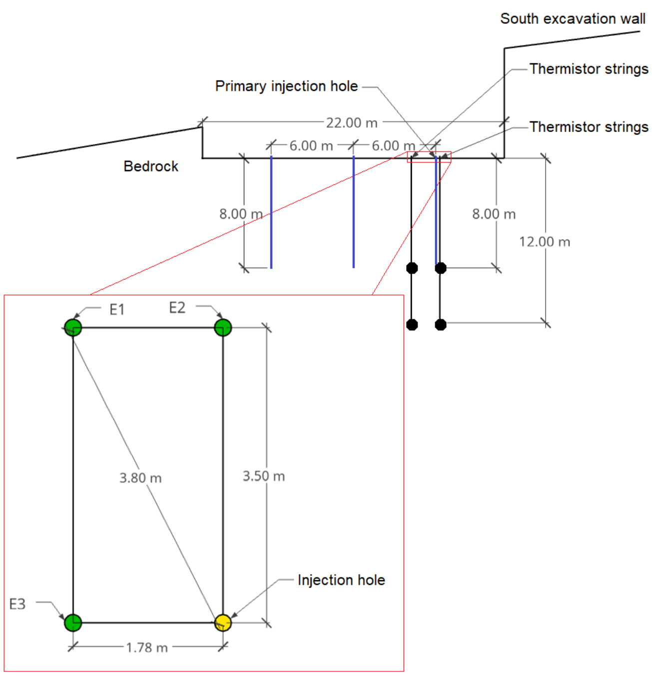

Figure 2. Geometric design of the primary injection holes and adjacent thermistor strings.

1.4 Objective

The main objectives of this study were to evaluate the time required to thaw rock permafrost and to assess which solution would be the most efficient on-site. The reach the objective, this paper proposes three sections describing the methodology (section 2), the modelling results (section 3) and a discussion about the data collected during the thawing operation with comparison between temperature results and actual in situ measurements.

2 METHODOLOGY

Since the project location is far from the village, no ground temperature data were available. A thermistor string was therefore installed in 2019, almost a year prior the start of construction and provided some temperature data for a patch of rock outcrops. At this location, the maximum depth of natural thawing was reached in early October (12.6m below surface). Unfortunately, this instrument was on the opposite shore of the river from the diversion structure, and it could only provide an estimation for this study's area of interest. Nonetheless, it confirmed that the bedrock would be frozen under the level of the diversion's excavation and at the depth of the grout curtain.

Two different methods of thawing were simulated: a) thawing from the surface at natural temperature or controlled temperatures and b) forced thawing from the heating of the grout injection holes also described by Frumkin et al. (2002). Method a) was replicated using the Neumann 1D analytical solution while method b) was simulated using 2D and axisymmetric numerical modelling with Temp/W from GeoStudio (GeoSlope, 2022).

2.1 Thermal properties

The design team established the rock porosity to values between 0.5% and 1%. Using rock cores sampled in 2019 near the thermistor string, the thermal parameters were measured in the laboratory. Table 1 lists the values by porosity (Côté, 2021).

Table 1. Thermal parameters of the rock.

Porosity, n (-)	0.005	0.010
Thermal conductivity (W/m°C)		
Unfrozen	3.203	3.176
Frozen	3.224	3.218
Heat capacity (MJ/m³°C)		
Unfrozen	2.011	2.022
Frozen	2.000	1.999
Latent heat of fusion (MJ/m³)	1.665	3.330

2.2 1D modelling - Neumann solution

Following the determination of the thermal parameters, the unidimensional Neumann solution was used to evaluate the depth of thawing in the bedrock. It considers a phase change within a continuous and homogenous mass having a negative initial temperature but being subjected to a sudden surface temperature change (positive). The depth of thawing is expressed by Equation 1:

$$x = 2\gamma\sqrt{\alpha_1 t} \qquad [1]$$

where x is the thawing depth (m), α_1 is the thermal diffusivity of the unfrozen part of the rock (m²/s), t is the time (s) and γ is a dimensionless parameter obtained by solving Equation 2.

$$\frac{e^{-\gamma^2}}{\mathrm{erf}(\gamma)} - \frac{\lambda_{21}\sqrt{\alpha_{12}}(T_0 - T_f)e^{\alpha_{12}\gamma^2}}{(T_f - T_s)\mathrm{erfc}(\gamma\sqrt{\alpha_{12}})} - \frac{L\gamma\sqrt{\pi}}{C_1(T_f - T_s)} = 0 \quad [2]$$

where T_0 is the initial temperature of the mass (in this study case -1°C), T_f is the phase change temperature of water (0°C without salinity), T_s is the average surface temperature for the duration of the analysis (°C), C_1 is the unfrozen rock heat capacity (MJ/m³ °C), λ_{21} is frozen/unfrozen heat capacity ratio of the rock mass (λ_2/λ_1, dimensionless), α_{12} is the unfrozen/frozen thermal diffusivity ratio of the rock ([λ_1/C_1] / [λ_2/C_2], dimensionless) and L is the latent heat of fusion (J/m³). The erf and erfc represent respectively the error function and the complementary error function.

Equation 2 was solved by the numerical bisector method to determine γ while varying only the surface temperature for a given simulation. The value of γ is then inserted in Equation 1 to calculate the thawing depth for the simulation.

2.3 2D Modelling

By combining the geometric measurements, the thermal parameters of the rock and the temperature data collected on-site, a 2D thermal model was created. It was assumed that the primary grout injection holes of the diversion would be used to warm up the rock mass from within. Consequently, toward the inner part of the structure, each of those holes had to impact a radius of 3 m to interconnect with its neighbour. The construction sequence of the project caused a 5m gap at the edges of the structure since the adjacent injection holes would be done months later. This gap had to be thawed as far as possible so that the grout could penetrate further in.

Initial domain temperature conditions were established through a preliminary analysis run using a surface temperature of 6°C (temperature average for June and July 2021 in Inukjuak) and a temperature of -2°C at the deepest part of the bedrock (Météo Canada, 2021). A square mesh of 0.5 m was used as shown in Figure 3. To model the forced thawing, the surface temperature was increased to 9°C which corresponds to the average air temperature on site from August to September 2021. (Météo Canada, 2021)

2.4 Axisymmetrical Modelling

Another approach to this problem was to model the temperatures using a 2D-asymmetrical analysis for a single injection hole. It is represented by a rectangle of rock that would be rotated 360° around its elevation axis. This type of analysis allows a simple 2D modelling of a vertical linear heat source using cylindrical coordinates. Two radii were modelled: 3.5 m to simulate the interconnection with the next hole within the core of the diversion structure and 12 m to represent the edges of the excavation walls. A sensitivity analysis demonstrated that beyond 12 m, domain size had no impact on the results. The same two boundary conditions as for the 2D modelling were applied with the same mesh size. Furthermore, a 1 m x 1 m top right corner boundary condition of -2°C was added to artificially simulate the effect of the far field of the un-excavated cold rock mass south of the diversion. Figure 4 details the analysis domain for both radii.

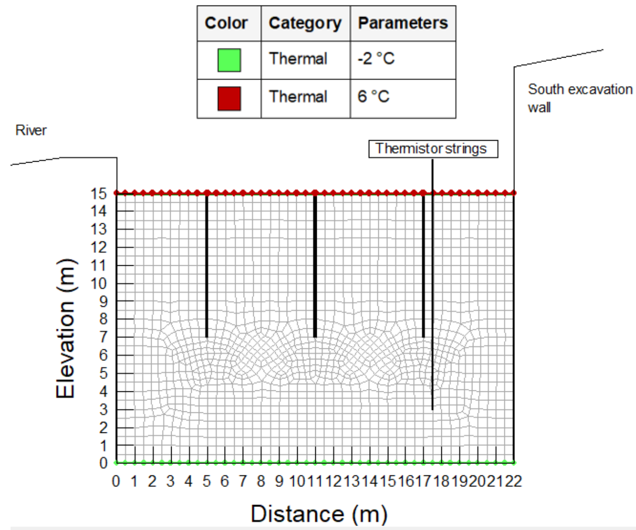

Figure 3. Boundary conditions and calculation mesh of the 2D model.

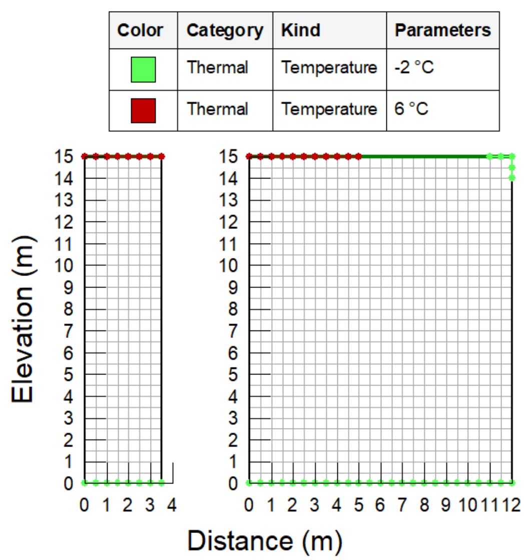

Figure 4. Boundary conditions and calculation mesh of the axisymmetric analysis.

3 RESULTS

3.1 1D modelling - Neumann solution

The unidimensional Neumann solution allowed to evaluate the thawing depth in relation to the surface temperature and the total exposition time if the rock mass was thawed exclusively by its surface. The duration of the exposure is defined as the time interval between the end of the excavation and the beginning of the grout curtain injection. Figure 5 portrays the results of Neumann solution calculations for different target thawing times (60, 90, 120 and 150 days). The solid black line indicates the grout curtain injection depth.

As can be seen on Figure 5, shorter thawing times require higher forced surface temperatures, 33 °C for 60 days compared to 13,5°C for 90 days. In addition, the dashed black lines show the thawing depth assuming that the excavation ends on June 1st or July 1st. The average surface temperature was derived from the climatic data for this area for the given time periods. (Météo Canada, 2021) For instance, finishing the excavation on June 1st and making use of the 90-day period of Inukjuak's summer warmth would thaw the rock only to approximately 7.8 m.

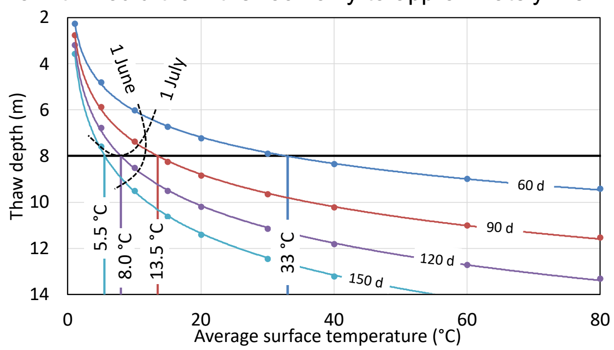

Figure 5. Thawing depth as a function of the surface temperature and the total exposition time.

This scenario is technically feasible but given the 3D nature of the problem, more time would be needed to thaw to an 8 m depth on the edges of the diversion channel. In this case, it would have led to a start of the grouting not earlier than late September. It was deemed too risky given the variable nature of the air temperatures and the sequencing of construction operations.

A forced thawing solution, such as those simulated from 60 to 90 days, would then have to be developed to meet the design's objective with surface temperature maintained above values between 14°C and 33°C, depending on the numbers of days available before grouting.

3.2 2D modelling

The thermal simulation was run with various primary holes temperature (25°C, 50°C and 75°C). Maintaining a temperature of 50°C in the injection holes was considered feasible with the equipment available on-site and resulted in a thawing time of 19 days. Figure 6 shows this scenario at completion with the red dashed line being the 1°C isoline. The duration of thawing for a temperature of 25°C was 25 days and 16 days at 75°C. For all cases, the critical areas were the extremities toward the excavation walls.

The temperature gradient is mainly horizontal with the highest values between the primary injection holes, as is seen on Figure 6. The simulations also showed that the rock temperature increases vertically at a slower rate for the whole width of the structure.

3.3 Axisymmetrical Modelling

The analysis was done for a heating temperature of 50°C only, as it was the most realistic option. It took 18 days to reach the maximum extent of the 3.5m radius cylinder. Figure 7 displays this scenario with the red dashed line being the 1°C isoline.

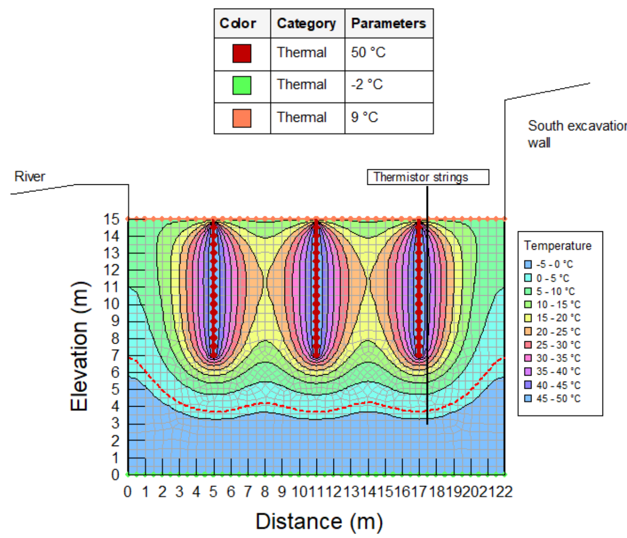

Figure 6. Temperature of the rock mass at the end of the thawing operation (0.5% porosity, 19 days).

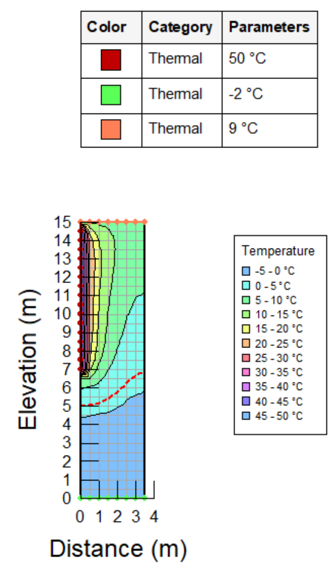

Figure 7. Temperature of the rock mass at the end of the thawing operation (0.5% porosity, 18 days).

For the simulation with the 12m radius, the target temperature at 5 m from injection hole was reached in 61 days. Figure 8 shows the simulation result with the red dashed line being the 1°C isoline.

As for the 2D analysis, the temperature gradient is mainly horizontal. The heating rate was also slower vertically. For the 12 m radius simulation, the time required to reach the 5 m width was longer due to the 3D radial effect of the axisymmetric analysis.

Color	Category	Parameters
	Thermal	50 °C
	Thermal	-2 °C
	Thermal	9 °C

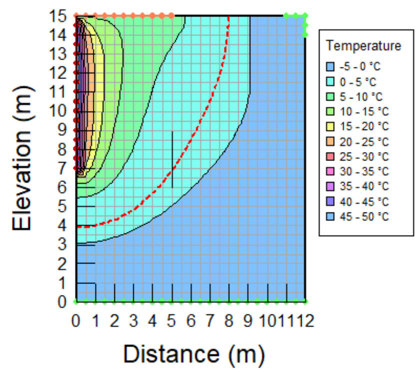

Figure 8. Temperature of the rock mass at the end of the thawing operation (0.5%porosity, 61 days).

4 DISCUSSION

Two methods of thawing derived from the analyses were evaluated for their feasibility and efficiency on-site.
The first one involved the top-down thawing of the rock mass by surface heating and was evaluated with the 1D Neumann solution. Assuming a perfect heat transfer between the heated air and the surface, the results showed it would take 90 days at 13.5°C to thaw to a depth of 8 m. This method would require covering a surface of more than 540 m^2 to thaw a half sphere of 4912 m^3 and reach the final design depth of 8 m under the complete width of the diversion channel.

The second option involved the thawing of the rock mass by directly heating the primary injection holes with hot glycol circulation pipes. To ensure an optimal contact with the surrounding rock mass, water would fill the unoccupied volume of the injection holes. This direct hole-to-hole lateral thawing method would require the heating of a much smaller rectangular volume of approximately 1200 m^3. This would lower the energy need to about one fourth when compared to the top-down method. The water-rock contact is assumed to be more efficient for transferring heat to the rock mass than the air-rock contact.

4.1 Field results

Based on computed time-to-thaw and estimated relative energy consumption, the second option was selected to thaw the bedrock beneath the diversion structure. A hydronic surface heater was installed on site, and glycol temperature was maintained at 73°C. Steady state conditions were not fully assessed, but surface water in the holes stayed at around 55°C after a few days. The hydronic surface heater had two built-in hose loops. It was decided that the most critical injection hole (south side of the diversion channel on Figure 2) would have its own dedicated loop. The second loop would heat the two other holes in series.

The thawing operation and monitoring began in August when air temperature was still above 0°C and thus heating the excavation surface. The measured initial rock temperatures at a depth of 8 m were slightly above 0°C (thermistor strings E1 and E3) and below 0°C (thermistor string E2), while at 12m depth the temperatures were all initially comprised between 0.05°C and -0.2°C. The temperature readings are illustrated in Figure 9 by the E1 to E3 lines for a depth of 8 m. The solid red line indicates the temperature threshold of 1°C. The start of the heating on day 22.5 and the beginning of the grout injection on day 52 are respectively represented by the solid yellow and green line.

The temperature of the rock mass started to increase as a result from heating the injection holes. The impact could be observed almost immediately at the thermistor string E3, which was the closest to the injection hole. The slope of the temperature curves for strings E1 and E2 started slightly increasing after four days of heating. At day eight, a clear inflection point can be observed for those two curves demonstrating that the heating front is effectively reaching a radius greater than 3 m. From that moment, the temperature increased almost linearly until the end of the thawing operation. E1 and E2 had warming rates of 0.044°C/day and 0.049°C/day, respectively.

The analysis of all measurements revealed that the 1°C threshold was reached in 2.5 days for E3, 22.5 days for E1 and 28 days for E2. The heating was maintained for two extra days after the temperature was reached at E2. The surface heater was then removed, and the injection of the grout curtain undertaken. Is it worth mentioning that the south side of the diversion under the un-excavated wall remained frozen for a longer time as evidenced by the response of the thermistor string E2 compared to that of E1 which was closer to the heat source.

At 12m depth, the forced thawing took 14.5 days to impact string E3 and 17 days on E2. The total temperature variation was 0.31°C for E3 and 0.13°C for E2, which stayed under 0°C until the end of the heating period.

4.2 Comparison between modelling and field results

The results from the unidimensional Neumann solution provided an estimation of the time required to reach a thawing depth while maintaining a certain surface temperature. The Neumann solution is based on the hypothesis of a homogenous and continuous mass which was not completely the case on-site. It also assumes that the phase change is unidimensional which cannot account for the complex 3D geometry of the excavation. By considering the limitations of this method, the results obtained were believed to underestimate the time required to reach the thawing depth.

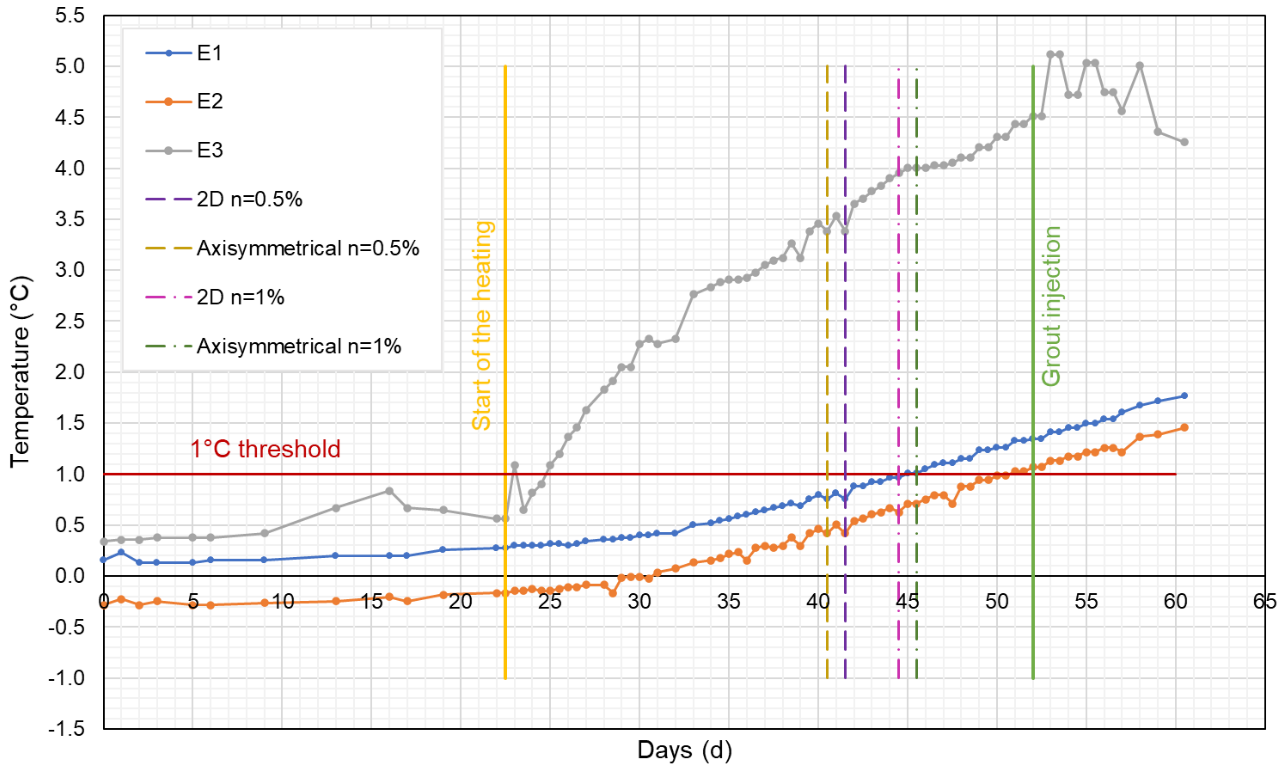

Figure 9. Bedrock temperature at a depth of 8 m.

The 2D modelling provided a powerful tool for decision-making and to forecast the progression of the thawing. The initial analysis (0.5% rock porosity) yielded result that slightly underestimated the thawing time (19 days), as represented by the vertical purple dashed line on Figure 9. These results were, however, considered sufficiently reliable to assess the effectiveness of the heating method from the injection holes. The post-project remodeling with a 1% rock porosity reduced the difference in duration with the site measurements. The computed duration of heating was 22 days (1% porosity with a heating temperature of 50°C) as shown by the pink vertical dashed line on Figure 9 (day 44 – day 22 = 22 days). It corresponds almost to the same time at which the thermistor E1 reached the 1°C target. That thermistor string is located toward the inner part of the diversion structure and was less influenced by the un-excavated rock masses. In addition, the 2D analysis demonstrated that the natural temperature of the rock surface has a small impact compared to the heating of the injection holes. The main limitation of this analysis is that the representation of the edges toward the excavation walls could not be assessed properly, and no monitoring was done at this location to assess the 2D effects. The simulation represents better the thermal response within the vicinity of the three primary injection holes, and therefore the calculated durations to reach the 1°C target are deemed too optimistic for the southern edge of the structure. A possible local variation of the bedrock properties, an unknown ice content at depths and a probable groundwater flow in the upper fractured rock are other unknowns that may have influenced the modelling results.

The axisymmetric analysis with the smaller radius resulted in a heating duration very similar to the 2D modelling for the inner part of the diversion. For a rock porosity of 0.5%, the heating time was calculated to be 18 days and is illustrated by the vertical golden dashed line on Figure 9. The results of the analysis with a rock porosity of 1% were close to those of the thermistor E1. The analysis resulted in a heating time of 23 days to reach the maximum extent of the 3.5 m radius cylinder, as seen on Figure 9 with the vertical green dashed line. The simulation with the larger radius provided an estimation of the site conditions toward the excavation walls. It demonstrated that the thawing 5 m away from the primary injection holes was very long: 76 days with a porosity of 1% and a heating temperature of 50°C.

The actual heating operation lasted for 30 days and it was assumed that a small volume of rock was not completely thawed. Figure 10 presents the simulation with a porosity of 1% at the end of day 30 of heating. The pink dashed line is the 0.1°C isoline which outlines the area where the ice is almost certainly thawed. The volume of rock still below 0°C at the end of the heating operation was estimated to less than 30 m³ toward the south excavation wall as indicated by a dark red triangle on Figure 10. This method was useful to model the inner portion of the diversion but could only approximate the situation at the edges, where the 3D geometry of the excavation could not be accurately represented in cylindrical coordinates even with the introduction of artificial boundary conditions.

Color	Category	Parameters
	Thermal	50 °C
	Thermal	-2 °C
	Thermal	9 °C

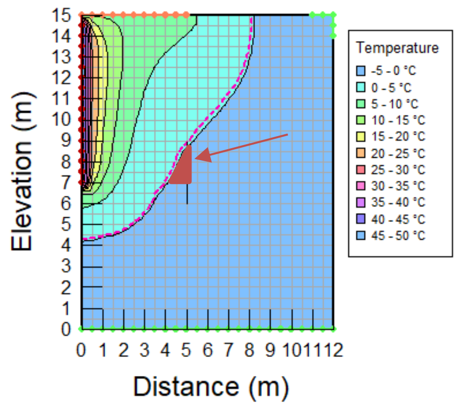

Figure 10. Temperature of the rock mass at the end of the thawing operation (1% porosity, end of the 30 days of heating, un-thawed zone in dark red).

Data extracted from the 12 m wide axisymmetric model were compared to the field data to validate the rate of heating. Points located at similar distances from the injection hole and thermistor strings E2 and E3 were selected. The beginning of the timeline is set at the start of the heating until the end of the field monitoring. Figure 10 displays the temperature data for E2 at a depth of 8 m. Three different stages can be observed for all curves: a) the warming up to 0°C, b) the crossing of 0°C and c) the heating toward 1°C. The slopes of the three curves for stage a) and c) were almost parallel although the moments for crossing the 0°C line varied. This result suggests that the rate of heating of the rock from the model was close to field conditions. The ice content had an impact for stage b) by changing the slope from all curves between stage a) and c). A plateau is clearly observed around day 30 for the field data and the transition is also shown on the other curves.

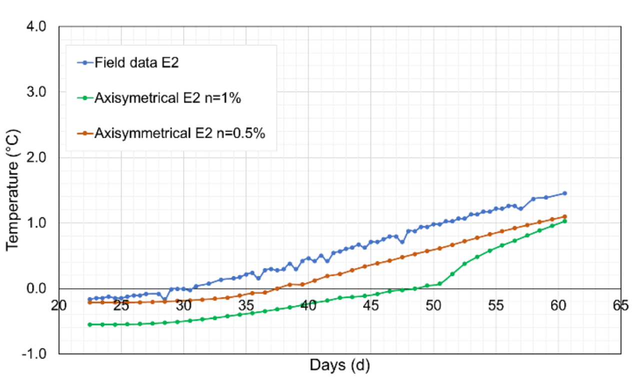

Figure 11. Comparison between field and modelled data for E2 at a depth of 8 m

Figure 12 presents the temperature data for E3 at a depth of 8 m. Except for the field data, which started above 0°C, the same three stages as for Figure 11 are observed on the modelled data. The slopes of the three curves for stage c) were parallel for some segments. This result suggests that the rate of heating of the rock from the model was somewhat similar to field conditions at this distance (1.78 m from the injection hole). The accuracy of the field data from days 53 to 60 is uncertain and this segment is excluded from the comparison.

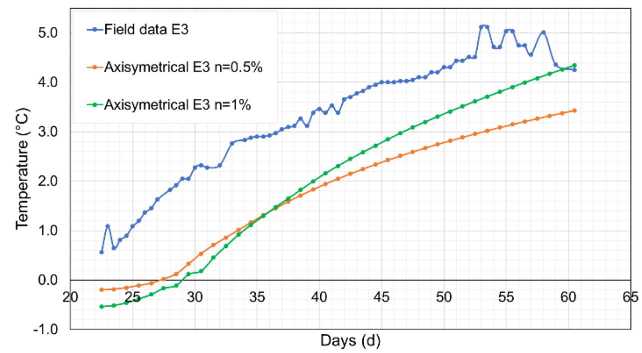

Figure 12. Comparison between field and modelled data for E3 at a depth of 8 m.

The field data revealed a very low impact of the heating operation at 12 m depth. This situation suggests that the thawed volume was limited and that the grout injection was circumcised to the planned area. From a contractor's perspective, it meant that extra grouting caused by an overly extensive thawing was likely avoided. The results from the 2D and axisymmetric analyses (Figure 6, 7, 8 and 10) support this fact. Those figures show a thawing penetration that does not reach the 12 m depth except for Figure 8 which barely hits that mark.

The 2D and the axisymmetric modelling were judged to be accurate enough to fulfill the initial purpose of this study. Real 3D modelling could have better taken into account the geometry of the excavation in the calculations. However, it would have required a different monitoring strategy to gather more information around the area of interest and to be calibrated efficiently and to determine the boundary conditions.

5 CONCLUSION

The hydroelectric project in Inukjuak required the injection of a grout curtain in permafrost rock to prevent water migration under the diversion channel after impoundment. The main objectives of this study were to evaluate the time required to thaw rock permafrost and to establish an efficient solution to be implemented on-site. Top-down thawing from the surface and lateral thawing from the primary grout injection holes were the two methods evaluated in this study. The unidimensional Neumann solution provided an estimate of the thawing duration if the rock was heated only from its surface. It was calculated that 60 days with a surface temperature of 33°C would have been required to completely thaw the rock to the design depth of 8 m. The 2D and axisymmetric modelling provided information on the heat distribution and thawing duration for the injection hole thawing solution. The time required to increase the temperature to 1°C at 8 m depth was 22.5 days on the field (thermistor string E1). The 2D model yielded a duration of 19 days at 0.5% rock porosity and 22 days at 1% rock porosity. The axisymmetric analysis resulted in a heating time of 18 days and 22 days, for a 0.5% and 1% rock porosity respectively. Both of which compared fairly well with monitoring results. The modelling results helped select and validate the injection hole thawing method and provided a satisfactory level of confidence for decision-making in the project.

6 ACKNOWLEDGMENTS

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