Surface Water Infiltration Impacts on the Performance of Thermal Capping Systems for Waste Rock in Continuous Permafrost

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Des défis du Nord au Sud

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ABSTRACT
The use of thermal caps for reclamation of acid generating waste piles or backfilled open pit mines in continuous permafrost requires long-term simulations of the ground thermal regime. The common approach models heat conduction through materials to design the thermal cap thickness, but the thermal impacts of surface water infiltration are often ignored. This paper describes modeling the effects of snowmelt and summer rainfall on the performance of two cover concepts at a pit in a Canadian sub-arctic continuous permafrost zone. The cover concepts modelled were Thermal Cap #1 (65-200 millimeter [mm] sized clean rockfill) and Thermal Cap #2 (0-600 mm sized coarse rockfill overlying a densely compacted till layer). The pit is located on sloping terrain and underground site observations indicate infiltration into frozen waste rock during the thawing season. The modelling results show that thermal infiltration effects depend highly on the hydrogeological properties of coarse materials (waste rock and rockfill) and the presence a low permeability barrier in the cover design.
RÉSUMÉ
Dans les zones de pergélisol continu, l'utilisation des recouvrements thermiques pour la réhabilitation des mines à ciel ouvert remblayées par des stériles générateurs de drainage minier acide nécessite des modélisations à long terme du régime géothermique. Pour déterminer l'épaisseur du recouvrement thermique, l'approche la plus courante est de modéliser la transmission de la chaleur dans les matériaux par conduction sans considérer les impacts thermiques de l'infiltration d'eau de surface. Dans cette étude, les effets de la fonte des neiges et des précipitations estivales sur la performance thermique de deux concepts de recouvrement d'une fosse à ciel ouvert dans une zone de pergélisol continu subarctique ont été évalués. Deux concepts de recouvrement ont été analysés : la couverture thermique #1 (65-200 millimètres [mm] taille de l'enrochement) et la couverture thermique #2 (0-600 mm taille de l'enrochement recouvrant une couche de till densément compactée). La fosse est située sur un terrain en pente et les observations souterraines au site indiquent l'existence d'infiltrations en profondeur dans les stériles pendant la saison de dégel. Les résultats de la modélisation géothermique montrent que les effets thermiques d'infiltration dépendent fortement des propriétés granulométriques des matériaux grossiers (stériles et enrochement) et de la présence d'une barrière de faible perméabilité dans la couverture thermique.

1 INTRODUCTION

In Canadian Arctic and sub-arctic regions, reclamation of open pit mines with potentially acid generating pit walls and waste rock piles in continuous permafrost presents many geotechnical challenges, such as cover construction in cold conditions and the long-term uncertainty of the ground thermal regime. Thermal capping, based mainly on site climate conditions, is often used to reclaim waste rock piles. The goal of thermal capping systems is to maintain the waste rock in a frozen state (i.e. below the maximum active layer depth) to prevent acid mine drainage and metal leaching. Freezing conditions have been recognized to reduce chemical reaction rates and water flow through material, thus contributing to the control of acid generation and metal leaching (Dawson and Morin 1996). Thermal caps are attractive because they are generally less costly and easier to complete during the short warmer construction season than non-thermally dependent infiltration-control alternatives like bituminous liners and capillary break covers.

Design of thermal caps in continuous permafrost regions calls for an evaluation of the active layer thickness usually with thermal modelling simulating heat conduction through cover materials. However, the potential impact from surface water infiltration on thermal caps is not well understood and is often neglected in long-term simulations of the active layer thickness when used as a basis for cover design. Surface water infiltration could have a significant impact on permafrost temperatures and the active layer (de Grandpré et al. 2012); therefore, it was considered in the models.

Infiltration into frozen ground has been observed in waste rock (Neuner et al. 2013), coarse soils (Granger et al. 1994), and porous media in alpine permafrost environments (Woo et al. 1994). The hydraulic properties of waste rock depend largely on its granulometric characteristics. Water flow may be dominated by the finer-grained matrix if the waste rock contains sufficient fines or by gravity-driven macropore flow in coarse waste rock (e.g. Nichol et al. 2005).

This paper explores the long-term performance of two thermal cover concepts by assessing the thermal impact of surface water infiltration through both covers and the backfilled waste rock underneath. Given the hypothesis that surface water infiltrates into the frozen coarse materials due to the presence of large voids, two-dimensional (2D) heat conduction and convective heat transfer models (for flowing water from snowmelt and summer rainfall) were conducted.

2 STUDY SITE

The mine site is located in the Canadian sub-arctic in a zone of continuous permafrost with a mean annual air temperature of -9.2 °C for a 1981-2010 climate normal period (Environment Canada 2014). Data collected at a nearby tailings storage facility (TSF) show that average annual rainfall and maximum snow accumulation from 2000-2010 were 270 and 180 mm, respectively. In 2011, snowmelt was also monitored at the TSF. For a maximum snow accumulation of 300 mm, the snowmelt period lasted 40 days from May 12th to June 21st. Similar to the TSF, the pit is characterized by a flat wind-exposed surface with few topographic depressions and obstacles.

Mining activities at the pit, which is the subject of this study, have ceased over five years ago. Since then, it has been backfilled with waste rock. The open pit prior to deposition is shown in Figure 1 and a typical cross-section is shown in Figure 2. The pit is open to the higher level of the underground workings and the temperature of the air in the tunnels was approximately -5 °C in summer 2014.

The pit is located in the upstream portion of a watershed characterized by annual floods during the spring freshet and little to no flow during the winter. There is already an existing drainage network around the pit for surface water diversion, so the pit's only source of water is expected to originate from the top of the waste rock pile. Therefore, the snow and precipitation data from the TSF was assumed to be representative of the pit being modelled. The pit, located on sloping terrain, acts as a drain towards which surface water is converging. Underground site observations suggest that surface water is infiltrating into the waste rock. A significant volume of the waste rock is expected to be frozen since the backfilling of the pit included the deposition of frozen waste rock at freezing temperatures. An instrumentation program is planned to verify the ground thermal regime.

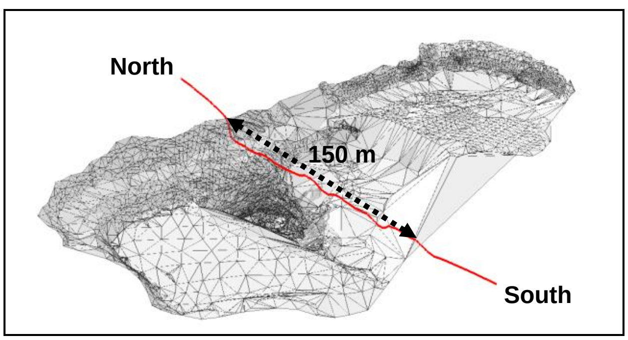

Figure 1. Open pit topography prior to backfilling with the cross-section used for modelling studies and the 2014 ground surface topography shown in red.

3 MODELLING METHODOLOGY

3.1 Model

Convective heat transfer simulations were carried out by coupling TEMP/W and SEEP/W software by GEO-SLOPE International Ltd. The configuration shown in Figure 2 was used for 2D TEMP/W heat conduction models not discussed in this paper. For the convective heat transfer models in this article, a segment of the Figure 2 cross-section 20 m in length was used (Figure 3). It was concluded that this was reasonable to improve modelling efficiency and that any differences between flow velocities for a 20 m cross-section and a full cross-section were negligible for analysing the impact of infiltration.

The following two cover concepts were modelled: Thermal Cap #1 (65-200 millimeter [mm] sized clean rockfill) and Thermal Cap #2 (0-600 mm sized coarse rockfill overlying a densely compacted till layer). Note that the rockfill was assumed to have the same hydraulic properties as the waste rock in each simulation as their grain size distributions are expected to be similar.

Waste rock is a highly heterogeneous material and water flow may occur as channelized flow in large pores or may be dominated by matrix flow in different parts of the pile. Observation of infiltration underground suggests that channel flow may occur in some areas of the pit. To capture both types of flow behaviour, two types of waste rock/rockfill were considered: waste rock/rockfill with constant permeability where flow is possible at freezing temperatures under an assumption that large pore spaces remain open and are not blocked by ice; waste rock/rockfill with permeability decreasing with freezing temperatures and where flow is restricted to the active layer. For simplicity, these two hydraulic cases will be referred to as permeable frozen waste rock (PFWR) and waste rock/rockfill (WR) for the remainder of this paper.

Sensitivity analyses were also conducted on climate change for both covers. The simulations are summarized in Table 1. For each case, models were carried out with no infiltration (base case) and with infiltration. The WR scenario was not modelled for Thermal Cap #1 because the rockfill size ranges from 65-200 mm and is not expected to contain fines. The modelling geometry and simulation details are summarized in Table 2 and Table 3.

Table 1. Scenarios modelled for TEMP/W and SEEP/W coupled simulations

Permeable Frozen Waste Rock/Rockfill	**Cover Option**	**Climate Change Scenario**
Yes	Thermal Cap #2	Optimistic
No	Thermal Cap #2	Pessimistic
Yes	Thermal Cap #1	Optimistic
Yes	Thermal Cap #2	Pessimistic
No	Thermal Cap #2	Optimistic
Yes	Thermal Cap #1	Pessimistic

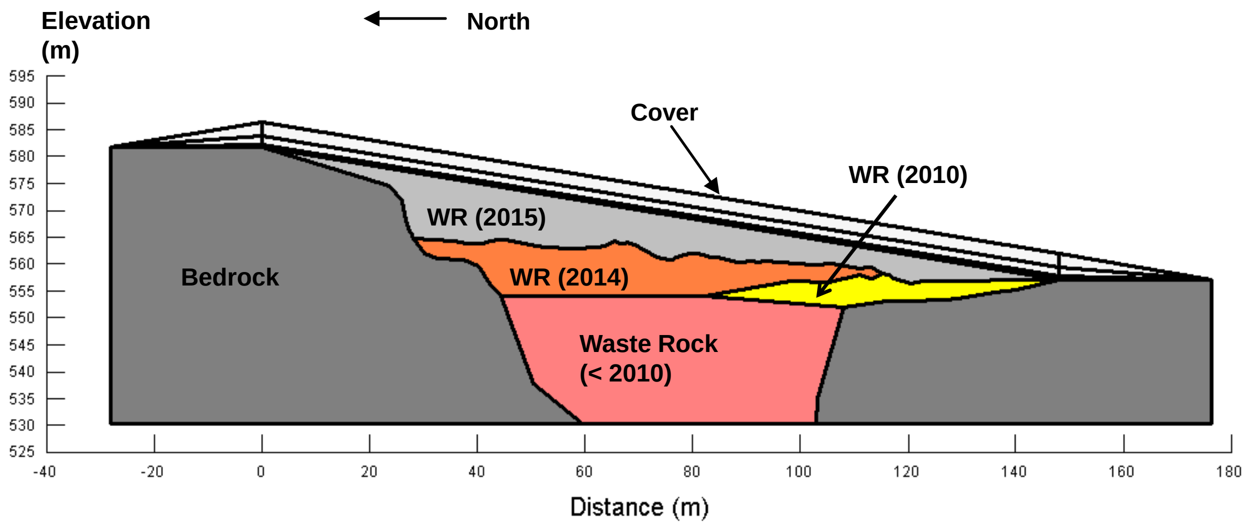

Figure 2. The modelling cross-section represents the red line shown in Figure 1 (2014 waste rock ground surface) and was used in 2D heat conduction models not discussed in this paper. The TEMP/W and SEEP/W coupled models explored in this paper represent the middle of the cross-section (60-80 m). The waste rock (WR) ground surface history is also shown. At the time of the study, additional waste rock deposition for 2015 was planned, as well as the cover installation.

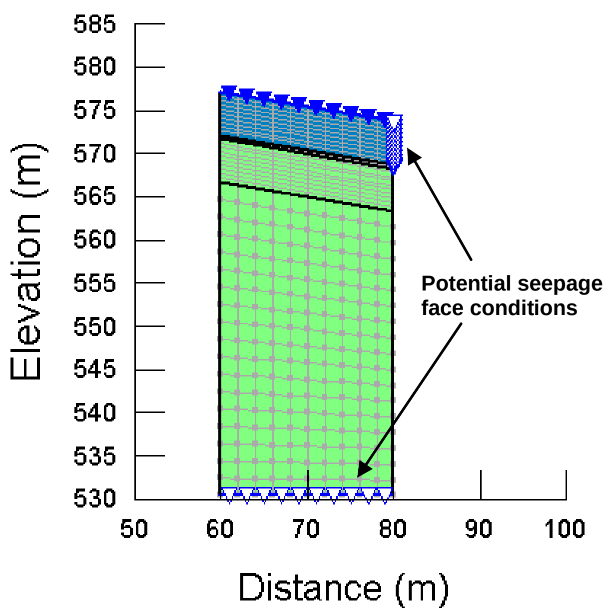

Figure 3. Modelling cross-section used for TEMP/W and SEEP/W coupled simulations.

3.2 Boundary Conditions

3.2.1 Thermal Boundary Conditions

Prior to running a long-term simulation, the ground thermal regime was modelled to be in equilibrium with the air temperatures of a regional climate normal (1981-2010) from Environment Canada (2014) adapted to the Canadian sub-arctic mine site. To incorporate time steps into the thermal model, a sinusoidal wave function was fit to monthly average mean air temperature climate normal points available from a nearby town. The amplitude and mean annual air temperature of the sine wave were also adjusted to match climate normal freezing and thawing degree-days (Riseborough et al. 2008). Subsequently, a linear air temperature correction function was applied to the curve to adapt the data to the mine site. The latter was derived from previously conducted studies at the site.

In TEMP/W, ground surface temperatures (GSTs) as opposed to air temperatures are required as input for the upper boundary condition. While TEMP/W has the functionality to incorporate rigorous climatic datasets as a boundary condition to calculate GSTs, the preferred method to calculate GSTs was based on N-factors. N-factors are multipliers that relate air and ground temperatures (Riseborough et al. 2008). The reader is also referred to GEO-SLOPE (2010).

Table 2. Model geometry and mesh properties

Depth Below Ground Surface (m)	Material		Mesh Thickness (m)
	Thermal Cap #1	Thermal Cap #2	
0.0-5.0	65-20 mm Clean Rockfill	0-600 mm Rockfill	0.5
5.0-5.5	65-20 mm Clean Rockfill	Till	0.05
5.5-10.5	Waste Rock	Waste Rock	0.5
> 10.5	Waste Rock	Waste Rock	2.0

Table 3. Sequence for simulations

Start Date	January 1, 2010
Cover Activation	October 1, 2015
End Date	October 1, 2055
Time Step	Daily

Calibrated N-factors of 0.65 (Nf) and 1.4 (Nt) were initially selected and were based on a previous thermal evaluation performed for the mine site at the TSF. Hence, the N-factors in combination with the adapted climate normal air temperature sine wave were used to generate daily ground surface temperatures. For sub-zero (freezing) air temperatures the site air temperature was multiplied by Nf and for air temperatures greater than or equal to 0°C (thawing) the site air temperature was multiplied by Nt. The model does not account for the expected lag between the peak negative air and ground surface temperatures. The surface boundary conditions used to for the initial ground temperatures are shown in Figure 4.

To calculate the geothermal heat flux, deep subsurface temperature data was required to determine the rate of change of temperature as a function of depth below the depth of zero annual amplitude. The rate of change of temperature was 1.25 °C per 100 m and the thermal conductivity of bedrock needed to calibrate the depth of zero annual amplitude to 15 m was 275 kilojoules per day per m per °C (KJ/day/m/°C). Therefore, the calculated heat flux was 3.43 KJ/m^2/day, but for simplicity a value of 3.50 KJ/m^2/day was assigned.

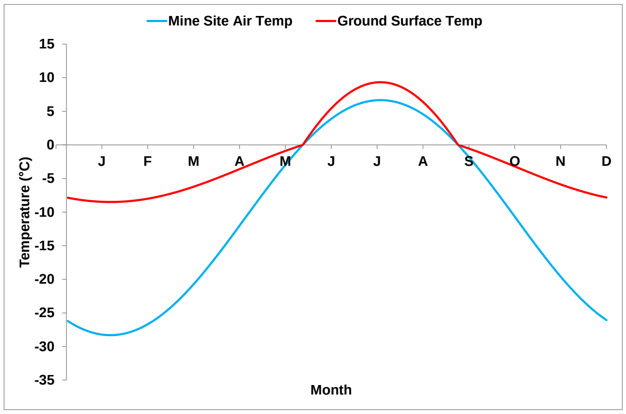

Figure 4. Surface boundary conditions used for the initial ground thermal regime.

3.2.2 Seepage Boundary Conditions

For models with infiltration, the upper boundary condition for the SEEP/W model was a daily infiltration rate calculated from average snowmelt infiltration and precipitation values at the TSF near the pit. In the model, the first day of snowmelt corresponded with the beginning of the thawing season in the first year of the simulation. Note that the snowmelt period and associated infiltration rate remained constant through time in the model, despite extensions of the thawing season due to climate warming. To calculate a daily snowmelt infiltration flux, the total snow accumulation (180 mm) was divided by the snowmelt period. Subsequently, the daily infiltration flux from precipitation was calculated by dividing a month's total precipitation by the number of days in that month. Subsequently, a spline function was fit to the data (Figure 5) to assist model convergence by avoiding drastic changes in the surface boundary fluxes. No evaporation was considered. Potential seepage faces allowed water to exit the model through the downslope boundary of the cover and the bottom of the pit (Figure 3). For models without infiltration, a daily flux rate of 0 mm/day was assigned.

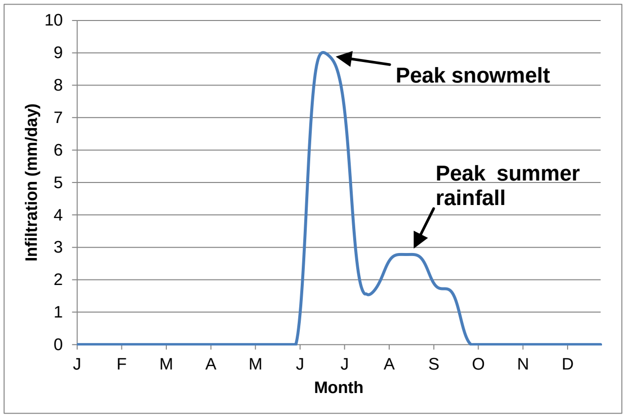

Figure 5. Daily infiltration flux used as an upper hydraulic boundary condition in the TEMP/SEEP convective heat transfer models. The daily infiltration flux is fixed at 0 mm/day for the freezing season.

3.3 Material Properties

3.3.1 Thermal Material Properties

In TEMP/W and SEEP/W coupled models, the thermal properties are dependent on variable moisture contents. The dry (volumetric moisture content = 0%) thermal conductivity is a function of the dry density of the material (Johansen 1975). As moisture contents increase under unfrozen conditions, the thermal conductivity increases logarithmically. The rate at which the thermal conductivity increases with moisture content depends also on the mineral thermal conductivity. Mineral thermal conductivities of 129 and 246 kJ/day/m/°C for the till and coarse materials (waste rock and rockfill were used, respectively. The till mineral thermal conductivity is a calibrated value based on a previous study and that of the rockfill is based on information in the TEMP/W manual (GEO-SLOPE 2010). The dry volumetric heat capacity is a function of the dry density and mass specific heat capacity. A mass specific heat capacity of 0.71 kJ/kg/°C was used for all the materials and is a typical value used for soil and rock minerals in TEMP/W (GEO-SLOPE 2010). As moisture contents increase under unfrozen conditions, the volumetric heat capacity increases linearly. TEMP/W automatically adjusts the thermal properties during ice/water phase transitions. The thermal conductivity and volumetric heat capacity functions used in the model are shown in Figure 6 and Figure 7.

3.3.2 Seepage Material Properties

The water retention curves (WRC) for modeling in unsaturated conditions are based on the SEEP/W database. The permeability functions were estimated from the WRC using the Fredlund and Xing model (Fredlund and Xing 1994). The porosity, saturated hydraulic conductivity, and SEEP/W material function used for the WRC are shown in Table 4. The hydraulic conductivity for till is based on laboratory measurements from samples taken from the site. To simulate WR type material where the hydraulic conductivity decreases with freezing temperatures, the permeability functions were used. To simulate PFWR material where water flow is permitted at freezing temperatures, the hydraulic conductivity remained fixed at its saturated value irrespective of the porewater pressure calculated by the SEEP/W model.

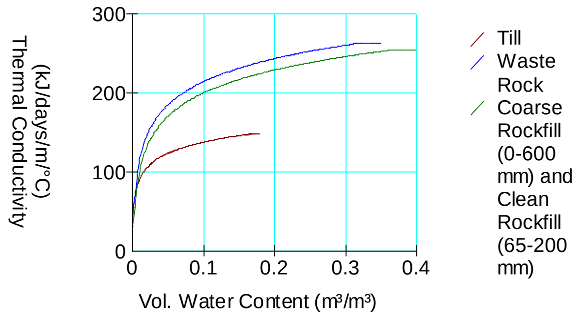

Figure 6. Thermal conductivity functions calculated from TEMP/W software

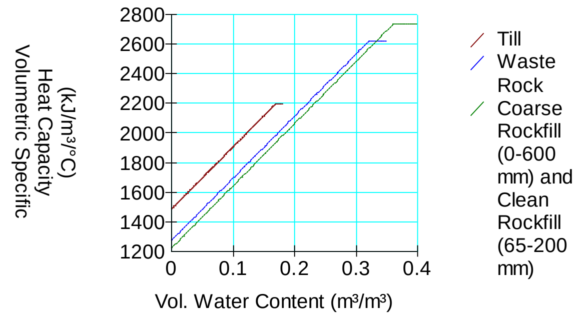

Figure 7. Volumetric heat capacity functions calculated from TEMP/W software

3.4 Initial Conditions

For each of the model scenarios presented in Table 1, the initial ground thermal regimes were identical (Figure 8). The backfilled waste rock was in equilibrium with the mine site ground temperature curve shown in Figure 4 after a 100-year spin-up model without infiltration effects. The initial temperature of the cover materials upon placement was -1 °C on October 1, 2015. The initial volumetric water content of the waste rock was approximately 1-2% to represent dry conditions and the initial volumetric water content of the till was 17% to represent saturated conditions. Till at saturation is ideal to maximize the thermal buffering capacity of the soil, which is generally associated with high ice contents.

Table 4. Material Properties Used in SEEP/W

Material	Porosity	Saturated Hydraulic Conductivity (m/s)	SEEP/W Material Function for WRC
Waste Rock	0.36	$1x10^{-2}$	Gravel
Till	017	$1.29x10^{-7}$	Silt
Coarse Rockfill (0-600 mm)	0.36	$1x10^{-2}$	Gravel
Clean Rockfill (65-200 mm)	0.36	$1x10^{-2}$	Gravel

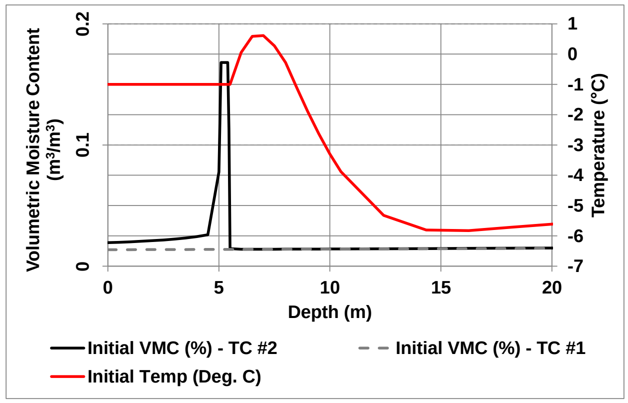

Figure 8. Initial ground temperature and moisture content conditions for all models. TC = Thermal Cap.

3.5 Climate Change Scenarios

Global climate change models from the International Panel on Climate Change (IPCC) were adapted to the Canadian high-arctic mine site in a previous study. To incorporate the climate change scenarios into the thermal model, the average annual air temperature for the sinusoidal climate normal air temperatures adapted for the pit was increased at the following rates for an optimistic climate change scenario: 0.047 °C/year from 2010-2020 and 0.039 °C/year from 2020-2050. For a pessimistic climate change scenario, the rates were 0.083 °C/year from 2010-2020 and 0.054 °C/year from 2020-2050.

4 RESULTS

The maximum active layer thickness values for the pessimistic and optimistic climate change scenarios 5, 20, and 50 years after cover placement are presented in

Table 5 and Table 6, respectively. The results were extracted from the model cross-section shown in Figure 3.

For the base case scenario (no infiltration), the active layer is 0.5 and 0.3 m thicker for Thermal Cap #1 compared to Thermal Cap #2 for pessimistic and optimistic climate change scenarios, respectively. For the PFWR scenario, the magnitudes of the differences are greater when surface infiltration inputs are included in the models. For pessimistic and optimistic climate change scenarios, the active layer for Thermal Cap #1 with infiltration is 0.6-0.8 m thicker compared to the non-infiltration case for 5, 20, and 50 years after cover placement. However, for Thermal Cap #2 with infiltration, the active layer is only 0.1-0.3 m thicker compared to the non-infiltration case for the same timeline. Therefore, the effects of warming air temperatures have very little effect on the thermal impacts of surface water infiltration for the conditions modelled.

For the WR scenario, the ground thermal regime is significantly colder compared to the PFWR scenario. Figure 9 shows the results for a pessimistic climate change scenario on March 15 and September 15, 2055 (50 years after cover placement). For the PFWR and WR models, the active layer depth is 4.2 m and 2.3 m when infiltration is considered. The depth of zero annual amplitude is approximately 15 m for both cases, but the temperature at the bottom of the zero annual amplitude is -3.5 °C for the WR scenario compared to -2.5 °C for the PFWR. For the WR case, the volumetric water content increases in the rockfill between the ground surface and the till layer at depths ranging from 1.5 – 3.5 m in the first 5 years of the simulation (2010-2015). From 2015-2055, the peak volumetric moisture content (100% saturation) decreases from a depth of 2 m to 2.5 m (Figure 10).

Table 5. Maximum Active Layer Thickness Projections for Pessimistic Climate Change Scenario

Cover (TC = Thermal Cap)	Surface Water Infiltration	Permeable Frozen Waste Rock/ Rockfill	Maximum Active Layer Depth (m) and Years (yrs) After Thermal Cover Placement		
			5 yrs	20 yrs	50 yrs
TC #1	No	Yes	3.2	3.6	4.5
TC #1	Yes	Yes	3.9	4.3	5.3
TC #2	No	Yes	3.2	3.5	4.0
TC #2	Yes	Yes	3.3	3.7	4.2
TC #2	Yes	No	1.8	1.8	2.3

Table 6. Maximum Active Layer Thickness Projections for Optimistic Climate Change Scenarios

Cover (TC = Thermal Cap)	Surface Water Infiltration	Permeable Frozen Waste Rock/ Rockfill	Maximum Active Layer Depth (m) and Years (yrs) After Thermal Cover Placement		
			5 yrs	20 yrs	50 yrs
TC #1	No	Yes	3.1	3.3	3.9
TC #1	Yes	Yes	3.7	4.1	4.6
TC #2	No	Yes	3.1	3.2	3.6
TC #2	Yes	Yes	3.3	3.5	3.8
TC #2	Yes	No	1.7	1.8	2.2

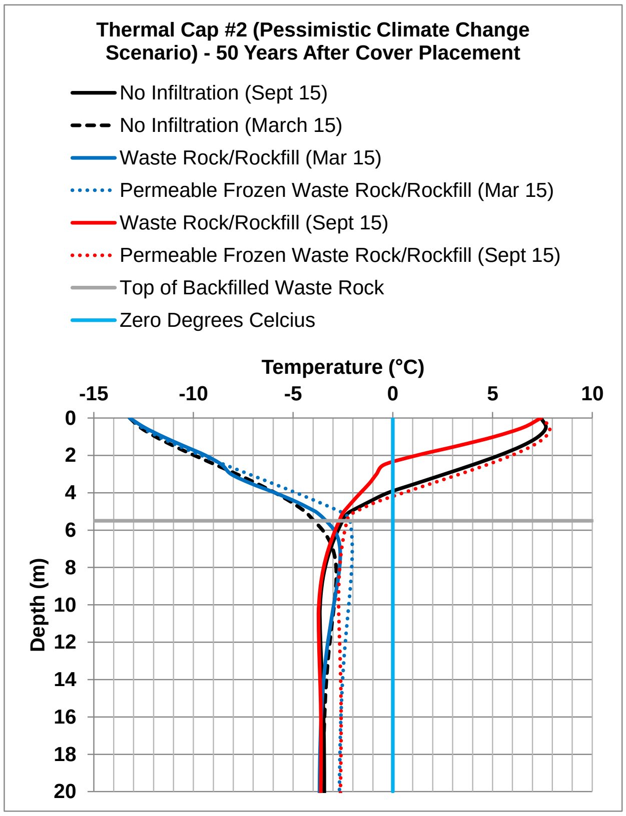

Figure 9. Surface water infiltration impacts on the thermal regime for WR and PFWR scenarios.

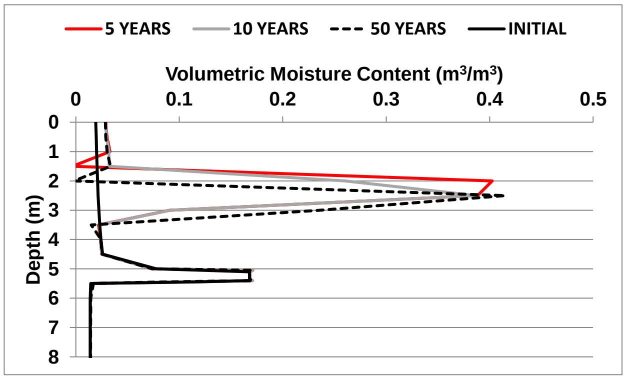

Figure 10. The evolution of volumetric moisture content for Thermal Cap #2 under a pessimistic climate change scenario and WR conditions.

5 DISCUSSION

When surface water infiltration is not included in the PFWR models, the thicker projected maximum active layer depth for Thermal Cap #1 compared to Thermal Cap #2 can be attributed to the 0.5 m thick till layer in Thermal Cap #2, which is not present in Thermal Cap #1. As shown in Figure 6 and Figure 7, the saturated till layer (volumetric moisture content = 17%) has a lower thermal conductivity and higher volumetric heat capacity compared to the backfilled waste rock and rockfill cover materials. Hence, its thermal diffusivity is relatively low.

However, when surface infiltration is added to the PFWR models, the even larger projected active layer depth difference between the two covers can be explained by the heat transfer associated with flowing water. This is primarily due to the till acting as a low permeability barrier in Thermal Cap #2 and directing the water downslope above the till layer instead of into the waste rock, as was the case for the Thermal Cap #1. The thermal impact from flowing water in the same direction as the thawing front should be greater than the impact of flowing water in a direction perpendicular to the thawing front (Lunardini, 1998).

When surface infiltration is added to the WR scenario models, the maximum active layer depth is much lower compared to the zero-infiltration baseline for Thermal Cap #2 (2.2 and 4.2 m). This can be explained by ice forming at the base of the active layer early in the model simulation as shown in Figure 12. Due to the latent heat effects associated with phase transitions, the ice provides the rockfill with a high buffering capacity to resist warming ground surface temperatures. Over the long-term, the latter also helps limit the increase in the temperature at the depth of zero annual amplitude (Figure 9).

Since infiltration at the base of the waste rock pile has been observed at the mine site and reported in other studies (e.g. Neuner et al. 2013), cover designers should consider the effects of convective heat transfer from flowing water depending on the material available for cover construction and material placement. For waste rock, Neuner et al. (2013) reported infiltration into frozen waste rock as deep as 6.8 m for an applied rainfall event of 29 mm (8 mm per hour) and flow velocities ranging from 5 to 72 cm day^{-1}. The waste rock studied in Neuner et al. (2013) was highly heterogeneous and granulometric tests showed that 40-45% of the material was finer than 50 mm. For the waste rock studied at the mine site in this paper, only 10% of the waste rock is finer than 50 mm. Therefore, the deeper infiltration observed on site compared to Neuner et al. (2013) was expected due to the coarser nature of the waste rock, which results in greater flow velocities.

Heat transfer effects from convective air cells in coarse materials were not modelled, but any effect was expected to be positive for cover performance based on previous study results (e.g. Coulombe et al. 2010). Therefore, thermal models that do not account for convective air cells represent conservative conditions suitable to predict thermal evolution due to climate warming. These thermal models also do not account for heat generated from chemical reactions of the waste rock materials. Heat generated from chemical reactions could have an effect on the thermal regime, possibly delaying material freezeback. Future models should also consider snow sensitivity analyses as convective heat transfer effects from flowing water could be much greater in thicker snow accumulation areas.

6 CONCLUSIONS

The impacts of surface water infiltration on the long-term performance of two cover concepts to maintain potentially acid generating waste rock piles in a frozen state were evaluated by coupling 2D heat conduction and convective heat transfer models using TEMP/W and SEEP/W software by GEO-SLOPE International Ltd. The cover concepts modelled were Thermal Cap #1 (65-200 millimeter [mm] sized clean rockfill) and Thermal Cap #2 (0-600 mm sized coarse rockfill overlying a densely compacted till layer). The pit under investigation is located in the Canadian sub-arctic in continuous permafrost and is partially backfilled with waste rock. Surface water infiltration has been observed at the base of the pit and the hypothesis is that there was water infiltrating through frozen waste rock due to the coarse nature of the waste rock.

When surface infiltration is accounted for in thermal modelling of waste rock and thermal caps, the projected active layer thickness is thinner than models with no infiltration if water flow is through waste rock with a matrix containing fine-grained material. This occurs because the rockfill, which is dry upon placement, develops ice at the base of the active layer. In the case of PFWR, the projected active layer thickness is greater when surface infiltration is included in the models compared to simulations without infiltration. This effect is due to heat transfer effects from flowing water, which results suggest can be mitigated by including a low permeability till barrier in the cover.

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