The Diavik Waste Rock Project: Heat Transfer in a Large Scale Waste Rock Pile Constructed in a Permafrost Region

Nam Pham[1], Richard Amos[2], David Blowes[2], Leslie Smith[3] and Dave Sego[1]

1. *Department of Civil & Environmental Engineering, University of Alberta, Canada*
2. *Department of Earth and Environmental Science, University of Waterloo, Canada*
3. *Department of Earth, Ocean and Atmospheric Sciences, University of British Columbia, Canada*

ABSTRACT

Mining in permafrost regions of Canada has increased due to the rich natural resources, the offer of increased employment and revenue for the local people. However, Acid Rock Drainage (ARD) is also a major concern for the environment in the permafrost regions that are also being impacted by climate change and other industrial activities. In continuous permafrost regions, cold temperature provides an exceptional means to limit ARD using permafrost encapsulation of reactive waste rock. Oxidation of sulfide minerals in reactive waste rock decreases significantly in a sub-zero temperature environment, in addition, water in a frozen state limits transport of reactants and contaminants.

In this paper, thermal simulations of a full-size waste rock pile constructed in a continuous permafrost region with a Mean Annual Air Temperature (MAAT) of -9.1 °C are examined. Different cover thickness and climatic effects such as wind speed and warming air temperature are evaluated to determine their influences on the internal temperatures of the reactive waste rock stockpile. Under a warming of 5.6 °C/100 year, without a cover, the active layer in the waste rock is around 6 m, 5 m and 4.2 m at 10 %, 20 % and 30 % volumetric moisture content, respectively, after 100 years. However, with the pile covered by layers of 1.5 till and 3 m of a non-reactive rock, the active layer penetrates 3.3 m into cover layers after 100 years under this warming condition. At a permeability of the pile of 10^{-8} m^2, an average wind speed of 20 km/h has insignificant effects on thermal transport near the centre of the pile.

Keywords: Permafrost, Waste rock piles, Thermal modeling, Climate change, Active layer

INTRODUCTION

Mining involves the removal of significant quantities of waste rock to reach ore bodies and this waste is usually placed in engineered stockpiles. The stockpiles are often well above the water table; therefore they are generally unsaturated. In addition, waste rock usually contains some amount of sulfide minerals and the oxidation of sulfide minerals has the potential to produce acid rock drainage (ARD). Acidic drainage (low pH), high dissolved metal contaminants and other harmful components in leaching water from waste rock are a major concern for the receiving environments at and nearby the mine (Olson et al., 1979; Nordstrom and Alpers, 1999; Lefebvre et al., 2001). Based on the closure objectives of waste rock piles at a mine, engineered soil covers can be designed for different types of waste rock and they can be grouped into (MEND1.61.5b, 2010): “isolation covers”, “barriers covers”, “store and release covers”, “water covers”, and “insulation covers”. However, in cold regions, cold temperatures are known to slow chemical and biological processes that are responsible for the oxidation of sulfide minerals and thus limit the generation of ARD (Jaynes et al., 1984; Langman et al., 2014). Therefore, to promote permafrost aggradation into reactive waste rock placed in a continuous permafrost region, insulation covers are a candidate as they transmit significant amounts of heat during the winter months and they serve as an insulation layer during the short summer (Arenson and Sego, 2007).

However, if climate change and warming occur, increasing air temperatures, changes of snow cover thickness and distribution, precipitation and other processes will significantly alter the subsurface thermal regime. The equilibrium between air temperatures and ground temperatures will change and cause a gradual increase in ground temperatures. The effects of warming in continuous permafrost regions would be a thickening of the active layer (the layer undergoing freeze and thaw near the surface) as a result of increases in temperatures. The impacts of warming would be more severe in discontinuous permafrost regions: such as thawing permafrost causing slope instability and loss of bearing capacity of infrastructure in these regions (Esch and Osterkamp, 1990). If a waste-rock pile is placed in a discontinuous permafrost area, the increase in ground temperatures due to warming could trigger the oxidation of sulfide minerals causing ARD. Various methods have been used to protect the underlying permafrost and to overcome the potential global warming in buildings and infrastructure,. These methods can also be used in waste-rock piles. Methods such as: ventilation pipes or ducts, thermosyphons and thermal piles, natural air convection embankments, foam insulation and other artificial ground freezing techniques (Goering and Kumar, 1996; Andersland and Ladanyi, 2004; Arenson and Sego, 2007).

SITE DESCRIPTION

The Diavik Diamond Mine is located on East Island, a 17 km^2 island in Lac de Gras, approximately 300 km northeast of Yellowknife, Northwest Territories in the Canadian Arctic (64°31′ N, 110°20′ W, el. 440 m). The site is located within the continuous permafrost region with an average precipitation of 283 mm including 60 % from snow (Neuner et al., 2013). Based on ground temperature measurements, the permafrost may extend to a depth of around 400 m and the active layer varies from 1.0 m in high moisture content soils to around 5.0 m in bedrock (Hu et al., 2003). Due to the cold and long winter season and relatively high evaporation at the site, water movement is limited to the active layer during the relatively short summer. Therefore, for the purpose of thermal modeling of the subsurface, convection associated with water flow is usually small and neglected; however, convective transport due to air is sometimes significant because of the high permeability of the waste rock.

Depending on the sulfur content, waste rock at Diavik is sorted into: Type I rock (< 0:04 wt % S), Type II rock (0.04 to 0.08 wt % S) or Type III rock (> 0:08 wt % S). Sorting the waste rock was used to classify between acid and non-acid generating waste rock. As a result, Type I rock is non-acid generating, Type II rock is low acid generating and Type III rock is potentially acid generating. At the end of the mine life, about 184 Mt of waste rock will be stockpiled in 60 to 80 m high piles covering about 3.5 km^2. Placement of an insulation cover is a closure concept for the Type II and Type III waste rock, including re-sloping the Type II and III areas to 18.4° (3H:1V) and covering the stockpile with a 1.5 m low permeability layer of till, and a 3 m layer of Type I waste rock to act as an active freeze-thaw layer (Smith et al., 2013).

In this paper, ground temperatures were obtained using drill holes FD4 (39.8 m depth) and FD5 (77.4 m depth) from the top of full scale Type III waste-rock (Figure 1). Thermistor cables were installed into the drill holes at 5 m vertical spacing and ground temperatures are recorded on a 12 h interval. Ambient air temperature is measured hourly at the Diavik meteorological station, which is approximately 1 km from the waste rock dump. Numerical simulations of thermal transfer within the pile were also run under a predicted temperature warming over the next 100 years

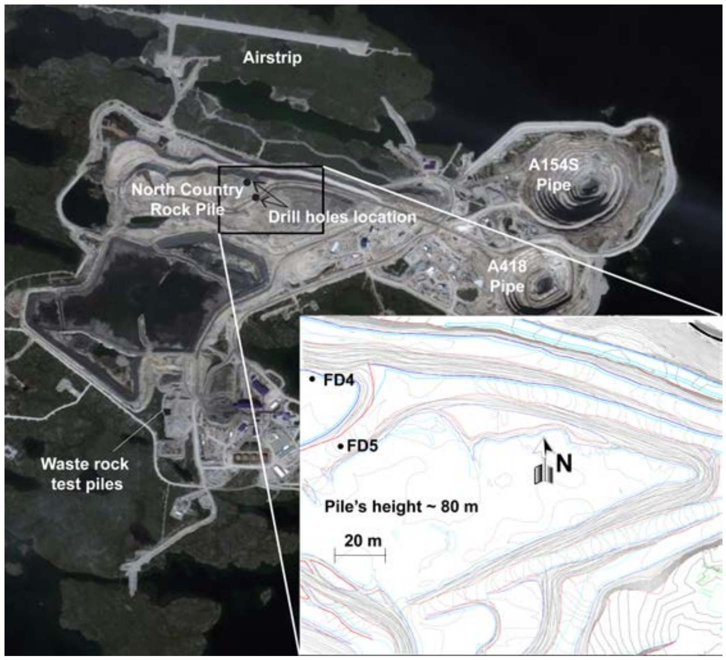

Figure 1 Drill holes location at Diavik diamond mine

Field data in 2013

Figure 2a indicates ground temperatures at depths between 45 m and 77.4 m (both holes) were constant throughout the year between -1.2 °C and -3.5 °C. Based on a thermistor near the ground surface the coldest and warmest temperatures were -28.5 °C and 13.5 °C, respectively. At a depth of 40 m, ground temperatures fluctuated and were much colder than nearby locations, which varied between -9 °C and -14 °C. This response occurs because the pile was built with 40m lifts and therefore permeability of the pile at locations near 40 m depth is higher, due to material segregation during tipping. Figure 2b shows that the thaw depth was at 4.8 m in August and September.

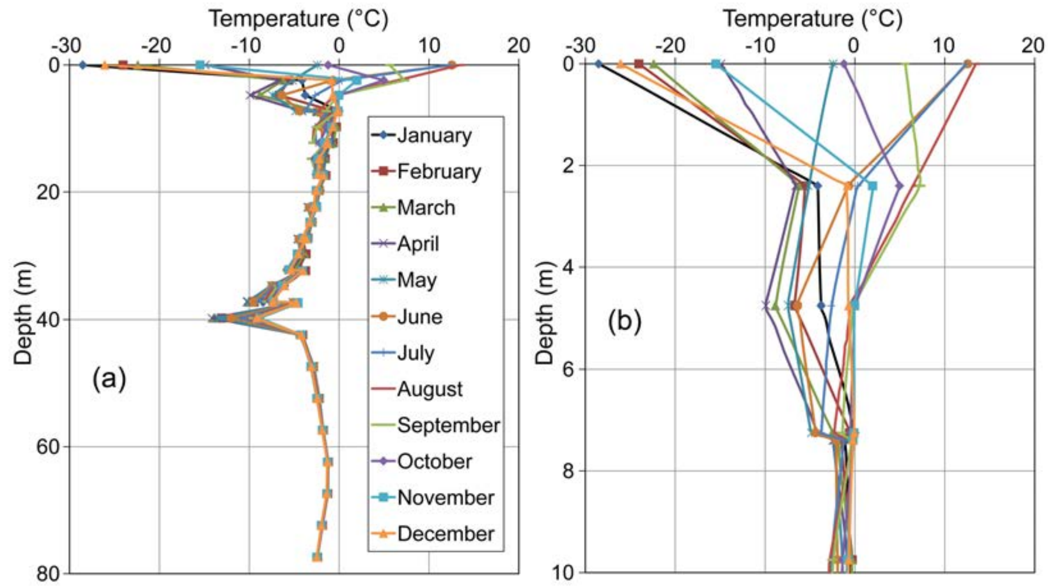

Figure 2 Measured ground temperatures in 2013, entire profile (a) and zoom-in the active layer (b)

NUMERICAL SIMULATIONS

In this section, the governing equations of heat conduction and convection due to moving air associated with density driven and wind effects were solved for temperature within the pile. The commercial Comsol Multiphysics software, which uses the finite element method, was used to solve the governing equations (Comsol, 2008). The mesh of the domain was refined near the surface to capture thaw depth due to the annual variation of air temperature.

Inputs to simulations

One cross section of the pile was chosen for the simulations because it is closely aligned with the dominant wind direction. The cross section is 2.5 km long and 80 m in height and the sides are at 3H : 1V (Figure 3). Furthermore, the bedrock foundation beneath the pile was placed at 100 m depth to complete the domain being analyzed. Air temperature measured at the site varies significantly throughout a year with the warmest and coldest temperatures in July with an average of 11.5 °C, and January with an average of -29.3 °C, respectively (Figure 4). Over the ten year period between 2000 and 2010, the MAAT is -9.1 °C, with 2004 air temperature being the coldest with MAAT of -12.1 °C and in 2010 the warmest with MAAT of -6.7 °C. The values of waste rock properties used in the simulations are listed in the Table 1 (Pham et al., 2013 and Neuner et al., 2013).

The initial in situ temperature profile was obtained using two thermistor cables installed from the top of the pile (FD4 and FD5) (Figure 5). Initial temperatures in bedrock between -15 m and -100 m were set to the same value as at -15 m. Surface temperatures of the pile were determined using measured temperature data from one thermistor near the surface which can be simulated using a sinusoidal function as:

$$T_s = A_s \sin\left(\frac{2\pi t}{365} - 4.34\right) - MAST + \frac{0.056t}{365} = 20.2\sin\left(\frac{2\pi t}{365} - 4.34\right) - 6.2 + \frac{0.056t}{365}$$

(1)

where t is time in days with the initial simulation time is January 1st, 2013, $A_s = 20.2$ is the amplitude, MAST (Mean Annual Surface Temperature) = -6.2 °C, which is different than MAAT due to soil's surface conditions and local climate and the last term represents the predicted potential global warming of 0.056 °C/year (or 5.6 °C/100 years) for the site (Diavik, 2008).

Three scenarios were analyzed to evaluate the thermal behavior of the pile: Scenario 1: the pile was covered with 1.5 m till and 3 m Type I waste rock and no extrenal wind effect is assumed; Scenario 2: wind effects on temperature within the pile without a cover as air advection due to wind may change the thaw depth or active layer within the pile; Scenario 3: the pile without the covered layers and wind effects. All simulation scenarios include the effects of natural air convection, which will occur during winters as cold air sinks into the pile. All simulations were run for 100 years with the volumetric moisture contents of waste rock varying from 10 %, 20 % and 30 %.

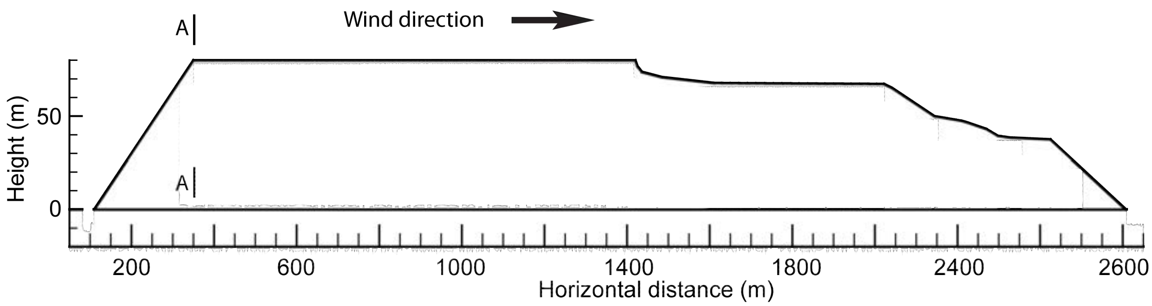

Figure 3 Geometry of the cross-section, the cut A-A is used to show temperature profiles in Figure 9.

Simulation results

Covered with 1.5 m till and 3 m Type I waste rock (scenario 1)

Figure 6 shows that the trumpet curves of ground temperatures at the center of the cross section indicate the waste rock beneath the till layer stays frozen year round. The till layer thaws down about 0.3 m between September and November each year and during the other months the till and Type III waste rock stay frozen (Figure 6). Depths below elevation 65 m are not shown because the temperature profiles remain constant between the elevation 65 m and 0 m. Due to the effects of latent heat in the till cover, ground temperatures in the Type III waste rock beneath the till after 100 years for various moisture contents are similar. Due to the till cover, the results indicate that conduction is dominant within the pile. The calculated pore air velocity beneath the till is on the order of 10^{-9} m/s, which is insufficient to effect heat transfer.

Pile with wind effects and no cover (scenario 2)

In this scenario, wind was assumed to be blowing at steady state at a velocity of 20 km/h, which is a little higher than an average wind speed at the site around 17 km/h (Chi et al., 2013) assuming that future wind speed will increase. Wind direction is from left to right as indicated in Figure 7. Air velocity within the pile was obtained by applying surface pressures around edges and top surface of the pile as boundary conditions. The surface pressures were obtained by solving the simplified 2-D representation of wind flow around the pile (Amos et al., 2009). Figure 7 shows that when using a permeability of waste rock of 10^{-8} m^2 the wind only affects the regions near the leading outer edge of the stockpile. Air velocities within the pile due to wind are also small with an average of about 2 ´ 10^{-4} m/s in the affected region around the edges.

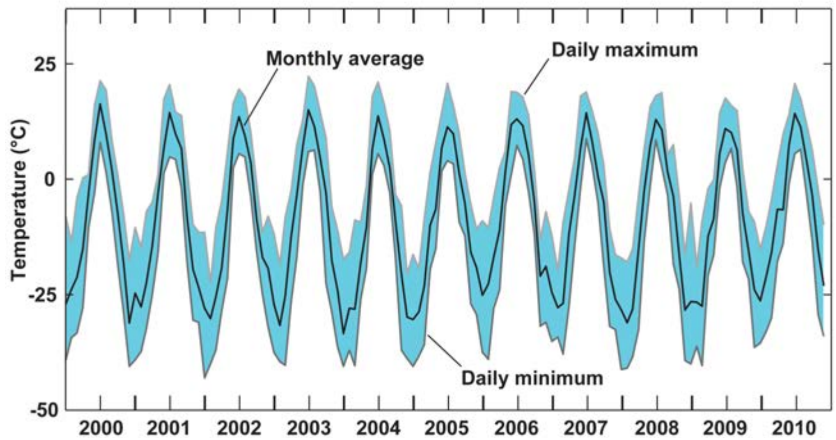

Figure 4 Monthly averaged air temperatures plotted with daily maximum and minimum air temperatures

Table 1 Material properties (data from Pham et al., 2013 and Neuner et al., 2013)

Property	Type I waste rock	Type III waste rock	Till	Bedrock
Porosity	0.25	0.25	0.2	0.003
Thermal conductivity (Frozen / thawed) (W/(m K))	1.7	1.8	3.2 / 2.9	3.0
Frozen bulk heat capacity (MJ/(m^3 K))	2.3	2.1	2.1	2.2
Thawed bulk heat capacity (MJ/(m^3 K))	2.4	2.3	2.5	2.2
Volumetric water content	0.1, 0.2, 0.3*	0.1, 02, 0.3*	0.18	0.0
Permeability (m^2)	10^{-8}	10^{-8}	5 ´ 10^{-16}	0.0

* These values were assumed to examine the effects of moisture on ground temperatures within the pile

At this velocity, the effects of air convection on heat transfer within the pile would be insigficant due to the small specific heat of air. Therefore, the effects of wind on thermal regimes in the pile away from the edges will be negligible. Trumpet curves (Figure 8) show that the active layers are 6 m, 5 m and 4.2 m into the pile for 10 %, 20 % and 30 % volumetric moisture contents, respectively. The shallower active layer at higher moisture content is due to the effects of higher latent heat associated with the additional water. However, at 15 m below the surface, ground temperatures are constant of -2 °C regardless of moisture content.

Figure 9 shows the trumpet curves at 10 % volumetric moisture contents at the edge, 40 m offset and 80 m offset from the edge. The active layers are around 6.1 m and 6.3 m at the edge and 40 m offset (Figure 9a and b) which are larger than at the centre of the pile (6 m). However, at 80 m offset from the edge at active layer is 6 m and the trumpet curve is similar to that of the centre location (Figure 8a and 9c).

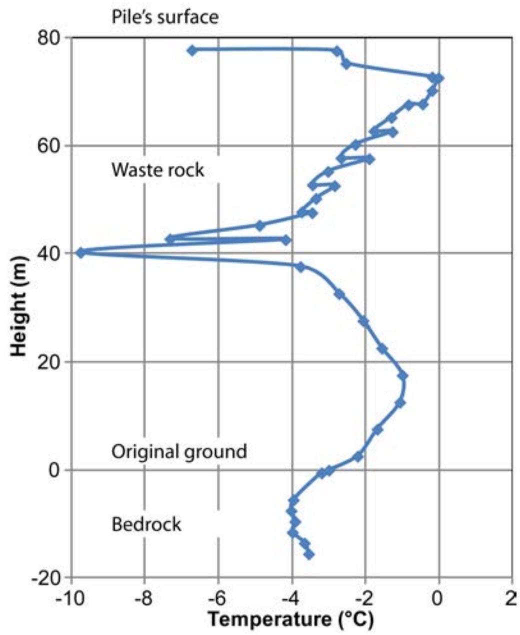

Figure 5 Initial temperature profile used in simulations, which is measured in January 1st, 2013.

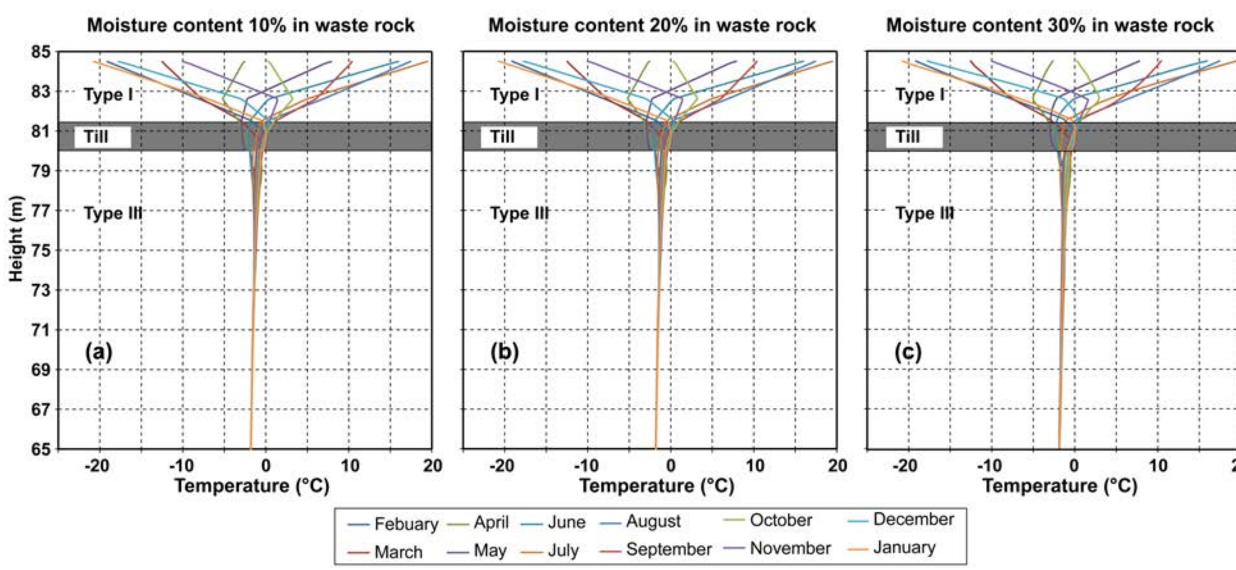

Figure 6 Trumpet curve of temperature profile in the pile for Scenario 1, with cover with 10 % (a), 20 % (b) and 30 % (c) volumetric moisture content in waste rock and no advective wind flow in year 100

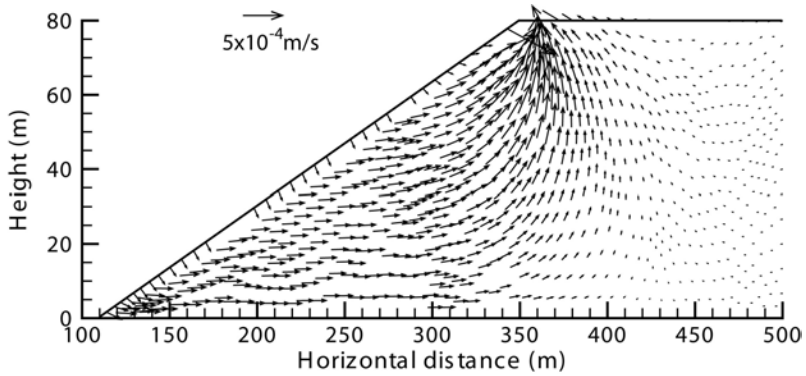

Figure 7 Air velocity within the pile due to wind

Pile without cover and wind effects (scenario 3)

As mentioned earlier, wind affects heat transfer only at the edges of the wind-facing side. Therefore, trumpet curves within the centre of the pile without and with wind effects are similar. The active layers are 6 m, 5 m and 4.2 m for the pile having 10 %, 20 % and 30 % volumetric moisture content, respectively (Figure 10). Figure 11 shows the isotherms during a winter after 100 years with warming and the thermal core with ground temperatures between -2 °C and -4 °C is the greatest in scenario 1 (Figure 11a) and smallest in scenario 3 (Figure 11c). Away from the edge, the thermal regimes between scenarios 1 and 2 are similar (Figure 11a and 11b).

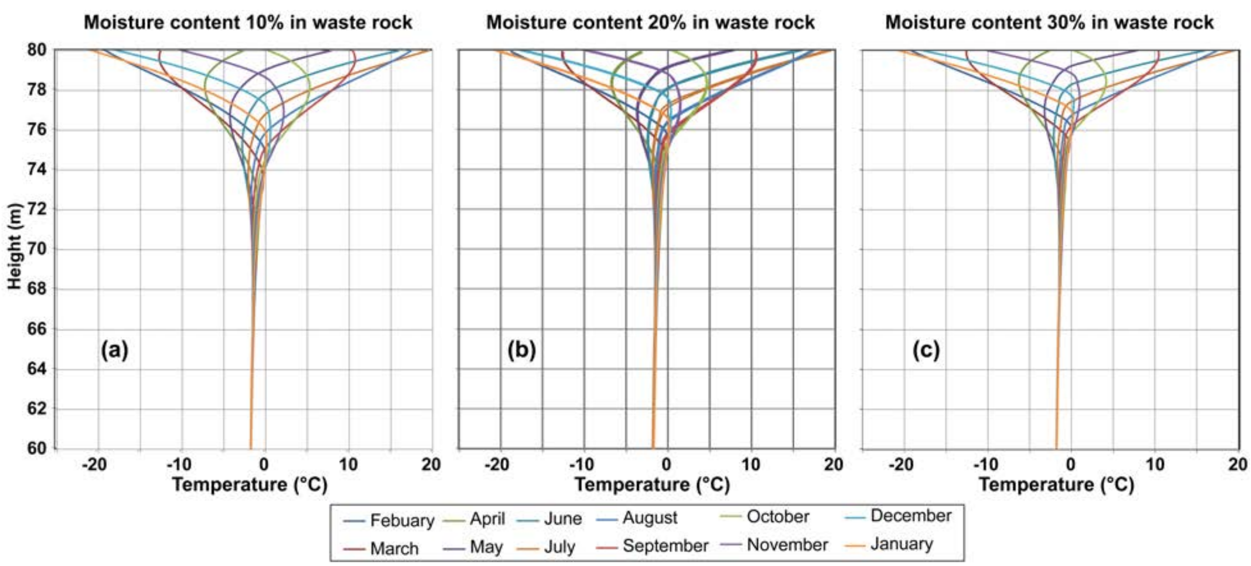

Figure 8 Trumpet curve of temperature profile in the pile for Scenario 2 with no cover, but with wind effects with 10 % (a), 20 % (b) and 30 % (c) volumetric moisture content in waste rock in year 100

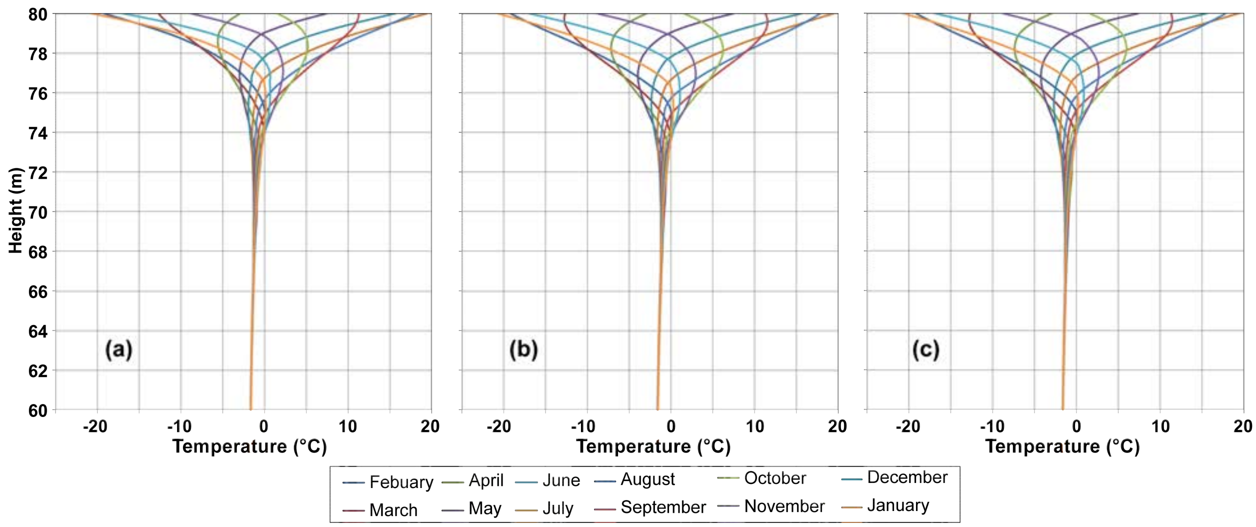

Figure 9 Trumpet curve of temperature profile in the pile with wind effects with 10 % volumetric moisture content in waste rock in year 100 at the edge, section A-A in Figure 3 (a), 40 m offset (b) and 80 m offset (c) from the edge

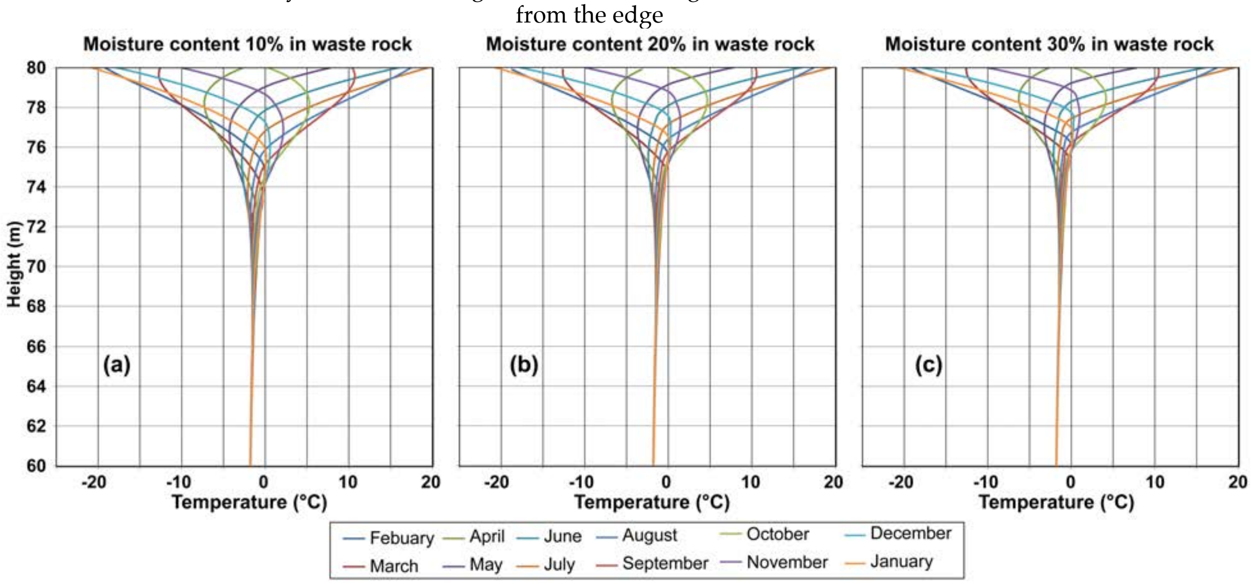

Figure 10 Trumpet curve of temperature profile in the pile for Scenario 3 without cover and wind effects with 10 % (a), 20 % (b) and 30 % (c) volumetric moisture content in waste rock in year 100

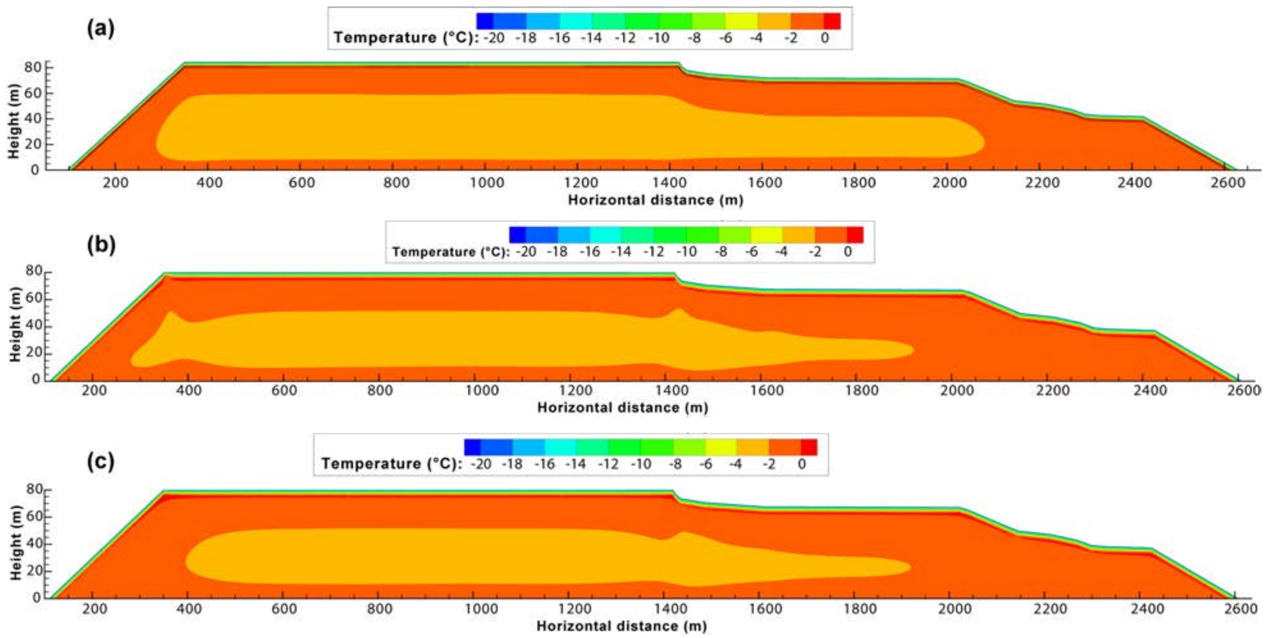

Figure 11 Temperature contours of the pile with cover (a) with wind effects and no cover (b) without cover and wind effects (c) after 100 years during winter at 10 % volumetric moisture content

CONCLUSION

Field temperatures from drill holes on top of waste rock pile indicate that the thaw depth was 5 m in 2013. However, under a warming of 5.6 °C/100 years and with the pile covered by layers of 1.5 till and 3 m of Type I rock, the active layer penetrates 3.3 m into cover layers after 100 years. Without a cover, the active layers will be 6 m, 5 m and 4.2 m at 10 %, 20 % and 30 % volumetric moisture content, respectively. The effects of wind on thermal regimes are insignificant near the centre of the pile. The region near the edge of the pile is affected by the wind with a permeability of the pile is 10^{-8} m^2 and a wind speed of 20 km/h. Therefore, under the predicted warming scenario, oxidation in waste rock may occur within a thin layer of active layer, of up to 6 m in the central portion of the waste rock pile.

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