Wind and barometric pressure effects on the heat transfer fluctuations within Northern waste rock piles

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ABSTRACT
Knowledge of the behaviour of internal pile temperatures is of significance in reaching and maintaining freezing temperatures within potentially acid generating waste rock materials. Convective heat transfer in porous media is a complex process involving free and forced movement of air, which affects the heat transfer in the waste pile. The pressure induced by wind and/or the variation in the ambient atmospheric pressure result in subsurface flow of air within a waste rock pile. The magnitude of pressure fluctuation dissipates rapidly with depth and this pressure is an important boundary condition in the magnitudes and frequencies of the temperature signals deep within the pile.

RÉSUMÉ
La connaissance des températures internes de piles rocheuse est de l'importance dans l'atteinte et le maintien des températures de congélation dans les matériaux potentiellement produisant d'acide. La convection dans des médias poreux est un processus complexe comportant le mouvement libre et forcée d'air, qui affecte le transfert thermique dans la pile de la roche de rebut. La pression induite par le vent et/ou la variation de la pression atmosphérique ambiante produit l'écoulement d'air dans une pile rocheux. L'importance de fluctuation de pression absorbe rapidement avec la profondeur et cette pression est une condition aux limites important dans des signaux de la température interne.

1 INTRODUCTION

High acidity and heavy metal pollution in run-off and seepage water from waste rock piles and tailing dams containing pyritic material is a problem common to many mining operations throughout the world (Moncur et al. 2005; Lefebvre et al. 2001). The reaction between sulphide-bearing waste and oxygen in the presence of water or moisture can produce acid rock drainage (ARD) (Evangelou 1995). Oxidation of pyrite is an exothermic process and can release a significant amount of heat (375 kcal for each mole of pyrite) (Lu, 2001). This amount of heat can raise the temperature of one kilogram of waste rocks by 1.63 °C, if the heat capacity of the mine waste rock is 240 cal/kg. Field measurements of temperature within the wastes with height of 20-30 m can reach 60 °C above ambient atmosphere temperature (Harries and Ritchie, 1981). There are two primary mechanisms to supply the oxygen for oxidation reactions: air diffusion and convection. Pantelis and Ritchie (1992)'s simulations showed that, for a 20-m-radius, 20-m-high pile, convection cells were well established by the end of the first year if $K=10^{-9}$ m^2 but was not significant compared to diffusion in the first 3 - 4 years in a pile having $K=10^{-10}$ m^2. A consequence of the greater permeability, faster gas transport, faster heat convection, and higher oxidation rates was higher internal temperatures in the pile. To eliminate the oxygen supply, several measures have been proposed recently. For example, Guo and Parizek (1990) proposed to keep waste rocks below the water table so that no oxygen will be transported through air convection and diffusion. However, this technique is not feasible for many in-situ or existing conditions. Another approach using low-permeability materials to cover the acid-potential waste rocks has been proposed (Nicholson et al., 1989). Co-disposal of tailings and waste rock is also a recent approach to lower the permeability of the mixture. At the right portions, the values of permeability of the mixtures are similar to values of tailings alone (Wickland and Wilson, 2005) but this technique is difficult to use in the field.

Onset of thermal air convection with incompressible fluid is a classical problem (Lapwood, 1948; Horton and Rogers Jr., 1945) and has been studied intensively for both pure fluid and porous media. A comprehensive survey of the available information on natural convective and heat transfer in both saturated and unsaturated porous media is in the work of Nield and Bejan (1999).

2 GOVERNING EQUATIONS

We consider a 2D problem conductive-convective heat transfer in porous media taking into account natural convection due to density driven and forced convection due to wind and natural pressure fluctuation with time. By assuming the validity of ideal gas of air and of Darcy's law, the following equation holds (Nield and Barletta, 2009).

• Mass conservation described by Darcy's flow law

$$n\left(\frac{\partial \rho}{\partial t}\right) + \vec{\nabla}.(\rho \vec{u}) = 0 \quad [1]$$

• Momentum conservation described by Darcy's flow law

$$\frac{\mu}{K}\vec{u} = -\vec{\nabla} p + \rho \vec{g} \quad [2]$$

• Energy conservation without heat source/sink

$$(\rho c_p)_m \frac{\partial T}{\partial t} + (\rho c_p)_f \vec{u}.\nabla T = k_m \nabla^2 T \quad [3]$$

• Ideal gas law

$$pM = \rho RT \quad [4]$$

where n is porosity, $\vec{u}$ is air velocity vector, p is air pressure, T is temperature, t is time, μ is dynamic viscosity, K is intrinsic permeability, ρ is air density which is defined by eq. [4], $(\rho c_p)_m = (\rho c_p)_s + (\rho c_p)_f + L_w \rho_w \frac{\partial n_w}{\partial T}$ is the lump-volumetric heat capacity in which also includes the latent heat of phase change of water within the porous media. It is calculated by volume average of each phase, $(\rho c_p)_f$ is the volumetric heat capacity of fluid which is air in this case, k_m is the average thermal conductivity of the porous medium calculated by volume average, $\vec{g} = -g\vec{y}$ is the gravitational acceleration with modulus g and parallel to the unit vector $\vec{y}$ in the y-direction (vertical) orthogonal to the boundary planes. M and R are the molar mass and gas constant of air. The Table 1 shows parameter values used in modeling.

3 NUMERICAL MODELING'S RESULTS AND DISCUSIONS

Geometry of a simulated waste rock pile is presented in the Figure 1. Assuming that, the pile was constructed and completed near the end of the summer and had a uniform temperature of 3.6 °C. According to monitoring of bed rock temperature at Diavik mine site, the active layer is about 4m (Pham et al., 2009), hence for a worst case, we assumed at -4m the initial temperature was 0 °C and at -30m (lower boundary of the domain) was -3°C. Surface temperatures induced at the surface simulate measured site's surface temperature as shown in eq. [5]. We also assumed that permeability is linearly distributed from the top at K_{top}=2x10^{-9} m^2 to bottom at K_{bottom}=5x10^{-7} m^2 because of material segregated during end dumping of the waste rock. The variation of permeability with depth can be several orders of magnitude as reported in some mines (Azam et al., 2007; Diodato and Parizek, 1994).

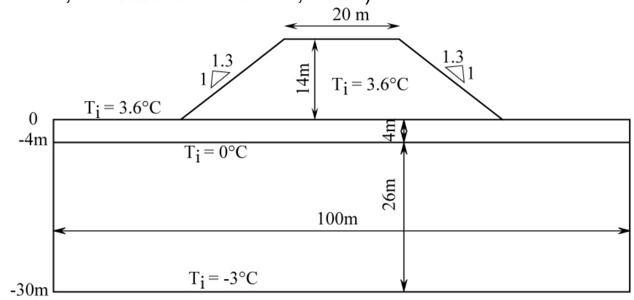

Figure 1. Schematic drawing of geometry and initial thermal conditions of the modeling waste rock pile

$$T_{surface} = -6 + 22\sin\left(\frac{2\pi t}{365} + \frac{33\pi}{180}\right) \quad [5]$$

Table 1. Parameters used in simulations

n	0.3	Porosity
n_w	0.06	Assumed volumetric waster content
ρ_s	2000	Density of waste rock particles
ρ_a		Air density determined through eq. [4]
ρ_i	918 (kg/m^3)	Density of ice
ρ_w	1000 (kg/m^3)	Density of water
c_a	1.0035x10^3 (J kg^{-1} °C^{-1})	Specific heat of Air
c_s	0.866x10^3 (J kg^{-1} °C^{-1})	Specific heat of Solid waste
c_w	4.179x10^3 (J kg^{-1} °C^{-1})	Specific heat of water
c_i	2.025x10^3 (J kg^{-1} °C^{-1})	Specific heat of ice
k_w	0.613 (W/m°K)	Thermal conductivity of water
k_i	2.31 (W/m°K)	Thermal conductivity of ice
k_a	2.24x10^{-2} (W/m°K)	Thermal conductivity of air
k_s	3.0 (W/m°K)	Thermal conductivity of solid waste
L_w	3.33x10^5 (J/kg)	Latent heat of fusion of water
μ	1.72x10^{-5} (kg/m s)	Dynamic viscosity of air
K_{top}	2x10^{-9} m^2	Permeability at the top surface
K_{bottom}	5x10^{-7} m^2	Permeability at the bottom

Pressures acting at the top surface of the pile include two components. The first is the wind-induced pressure oscillations which have high values of frequencies and is called p_{wind}. The second is natural (long term) pressure fluctuations including low frequencies in the pressure signals and is called $p_{natural}$ (Poulsen and Moldrup, 2006; Massman, 2006). The pressure signals at the pile's surface were measured at different locations and the results vary greatly with locations depending on wind magnitudes and directions (Amos et al., 2009). Figure 2 shows one set of results and the signal combines a wide range of periods from a few days up to a month. Thus, to set the pressure signal as a boundary condition for numerical modeling in transient analysis, one needs to filter very high frequencies (noises) and to capture frequencies which contribute the most energy of the signal. A tool to transform a pressure signal in time domain to frequency domain is to use Fast Fourier Transform (FFT). For a complete view of wind induced pressure measurement inside the pile at Diavik, review Amos et al. (2009). For simplicity, the top surface is induced by a pressure fluctuation which combines both effects p_{wind} and $p_{natural}$ shown in eq. [6].

The FFT of the pressure signal is shown in Figure 3. From the figure, the dominant period is at 8 days having magnitude of 5.1 Pa and for more accuracy, one should add more periods such as 18 days (magnitude of 4.3 Pa) and 22 days (magnitude of 4.7 Pa). As a result, the simulated pressure signal is modeled using eq. [6] and plotted in Figure 2b.

$$p_{wind+natural} = 5.1\sin\left(\frac{2\pi 8t}{365}\right) + 4.3\sin\left(\frac{2\pi 18t}{365}\right) + 4.7\sin\left(\frac{2\pi 22t}{365}\right) \quad [6]$$

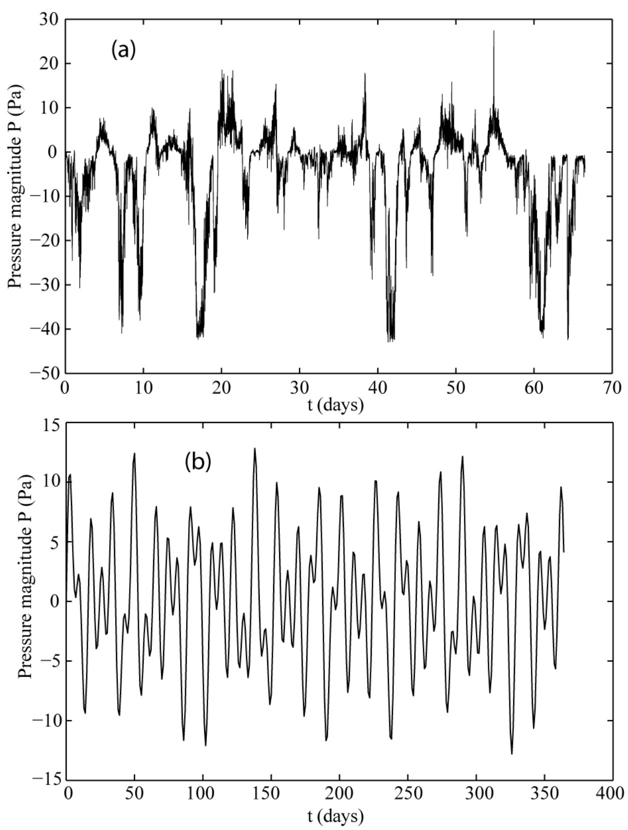

Figure 2. Measured pressure at a location of the surface of the pile (a) and simulated pressure (b) which is a combination of three sine functions

3.1 Results and discussions

Natural air convection occurs when there is an unstable condition of air within the porous media in which cold dense air sits on top of warm less dense air (Pham et al., 2007; Nield and Bejan, 1999). A dimensionless Rayleigh number has been used to characterize fluid convection in porous media which is defined by the ratio of buoyancy to viscous forces (Nield and Bejan, 1999; Saatdjian, 1980; Straus and Schubert, 1977).

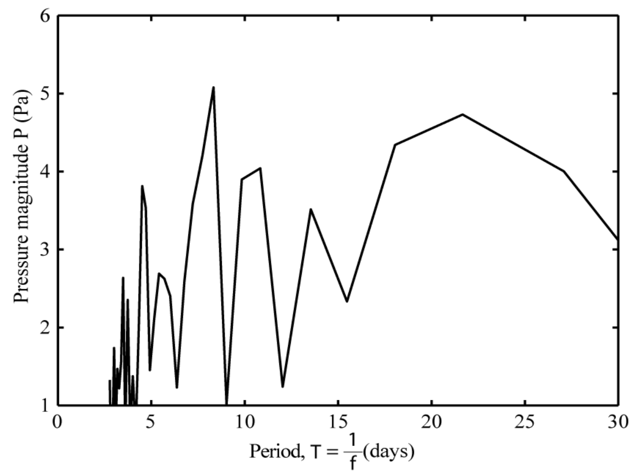

Figure 3. FFT of the pressure signal showed in Figure 2a

$$Ra = \frac{g\beta(\Delta T)H(\rho c_p)_f K}{\mu k_m} \quad [7]$$

Critical values of Ra_{cr} in which natural convection occurs depend on geometry and boundary conditions (Nield and Bejan, 1999). For the case of 2-D infinite horizontal layer, the critical value Ra_{cr} is $4\pi^2$. Air flow pattern in a waste rock pile exposed to a sine variation of ambient temperature is complex because under fixed values of temperature gradient ∇T, some amount of time ∇t needed to form a certain flow pattern however during this time ∇t, the boundary conditions (pressure and temperature) may have been changed. The air convection ceases as soon as $Ra<Ra_{cr}$ and conduction dominates over convection. There are many factors that affect the magnitude of air convection as shown by eq. [7] but the most uncertainty parameter is permeability K which is usually heterogeneous and segregated especially within waste dumps (Azam et al., 2007).

The Figure 4a clearly demonstrates the movement of cold air from the base to the top of the pile during the winter. This fast moving air is very effective at transferring cold ambient temperatures into of the pile and hence cooling the pile. In summer, convection stops due to stable conditions (warm air sitting on top of cold air) and heat transfer occurs by conduction with advection only due to pressure pumping Figure 4b. This is characterized by parallel isotherms near the surface and these isotherms follow the geometry of the pile. Such mechanism, convection in winter and ceasing in summer, has been called a thermal diode (Goering, 2003).

The temperatures in the central base of the waste rock were reduced drastically after one year from the 3.6°C initial condition to around -2°C. A 0°C isotherm with a cone shape and height about 7m measured from the base in the centre (Figure 5a). This thermal condition can only be achieved by convective heat transfer and it would take longer via conduction. At year 2 and 3, the shape of this 0°C isotherm has not changed compare to year 1 however the temperatures at the base are reduced to around -4°C (year 2) and -5°C (year 3) (Figure 5b and c).

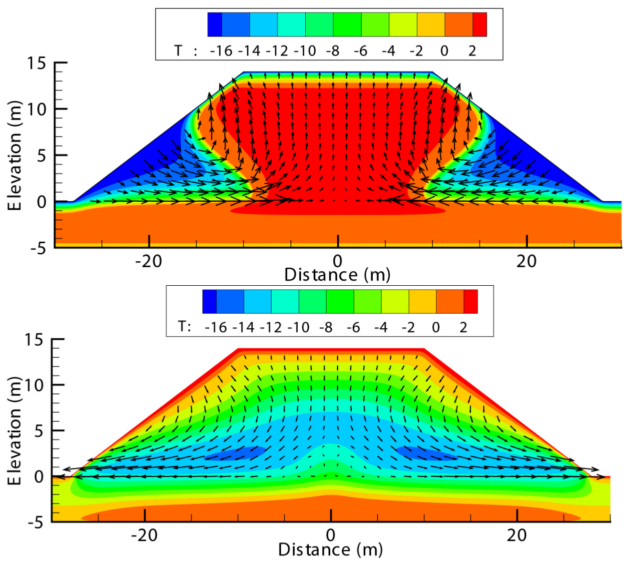

Figure 4. Contour plots showing air convection in winter (a) and conduction in summer (b)

To validate the results of numerical modeling, one desires to compare them with measured values. Figure 9 and Figure 10 show plots of comparison between modeling and measured temperatures at different depths. Measured results were obtained from a vertical thermistor cables installed in a 14-m height waste rock pile at Diavik mine. Figure 9 shows modeling results match well to measured results especially above 3.5m depth where the waste rock is less heterogeneous and low permeability due to segregation of coarser particles along the face dump and also due to repetitively compaction by haul trucks (Azam et al., 2007). Thus, conduction is expected to dominate this region. In the region from 5m to 9m, the modeling results do not compare well to measured data in the first and second winter because of initial conditions (thermal and physical conditions). Furthermore, the measured temperatures do not indicate the waste rock pile having more moisture than we assumed in the modeling because they do not show large latent heat around 0°C (Figure 10).

Along with annual fluctuation of internal temperatures as a result of annual variation of ambient temperature, there are also high frequencies in the temperature signals. These high frequencies are the results of wind and natural pressure pumping at these high frequencies (Figure 9 and Figure 10). It would be suspected that the regions where temperature signals having high frequencies (below 7.56m depth in Figure 9 and Figure 10) have higher permeability compared to the upper region.

When the conduction is the main heat transfer mechanism, there will be a time lag in temperature signals depending on distance to the surface (Figure 7). The figure shows that if there is a peak of the surface temperature, the temperature at 10m depth will be at a peak about 6 months later. However there are no or little time lags in the signals in Figure 9 and Figure 10, this may be due to high air velocity (up to 7.5x10^{-3} m/s) and thus convective heat transfer is much larger than conduction. As a result, there will be no or small time lags in the temperature response.

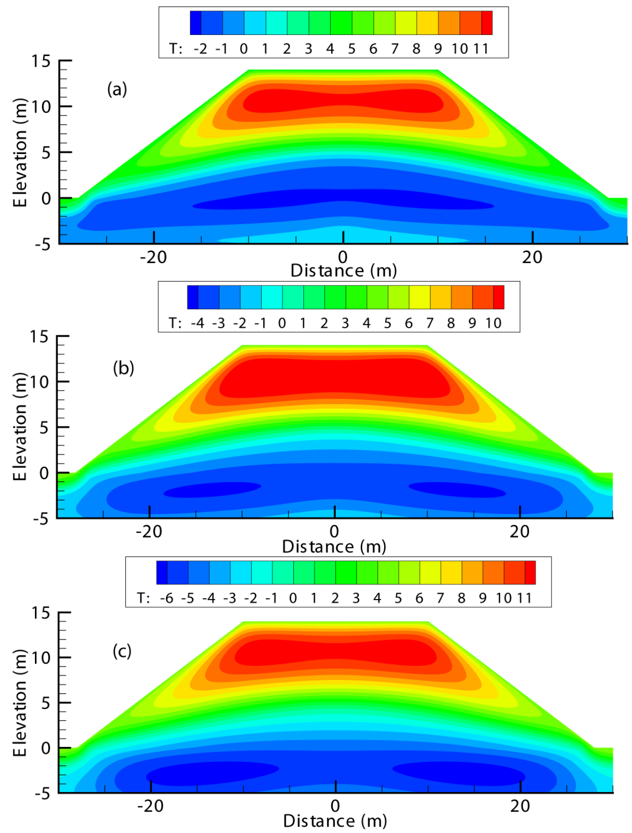

Figure 5. Contour plots of temperature after year 1 (a) year 2 (b) and year 3 (c)

At a point on the central line at 4m depth, the air velocity reaches 7.5x10^{-3} m/s (27 m/h) and 3.0x10^{-3} m/s during winters and summers respectively by the combined effects of pressure pumping and buoyancy force with pressure pumping contributing 2.6x10^{-3}m/s and buoyancy contributing 4.4x10^{-3}m/s (Figure 6).

On average the air velocity within the waste rock pile during winters is about 2.7 times higher than in summers and thus we can conclude that heat transfer during winter is about 2.7 times greater than that in summer. As a result, the lower zone of the pile cools much faster due to air convection compared to warming via conduction in the summer.

The Figure 8 shows the pressure signals obtained from modeling which combines two distinct frequencies. The first one was made using annual variation of ambient temperature and the second included high frequencies created by wind and natural variation of pressure. In addition, this figure also shows that the pressure dissipated rapidly from the surface (0, 14) to 4m depth (0, 10). The figure also indicates there are no or very small time lags between the pressure signals at the surface and at 14m depth because of high permeability of the waste rock materials.

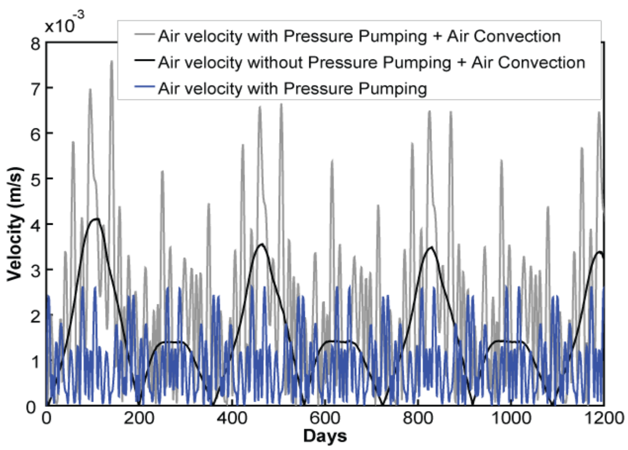

Figure 6. Air velocity at central line of 4 depths with varieties of boundary conditions

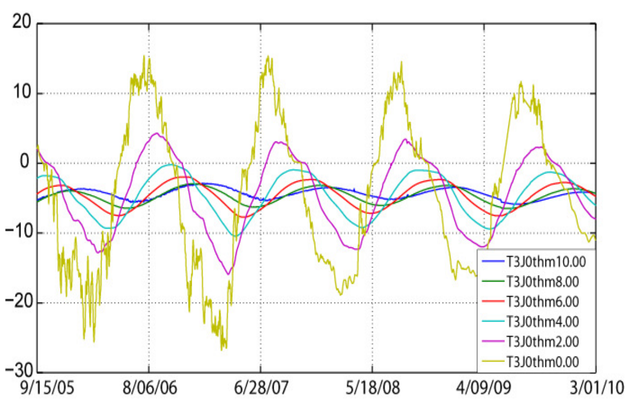

Figure 7. Bedrock temperature at different depths at Diavik mine

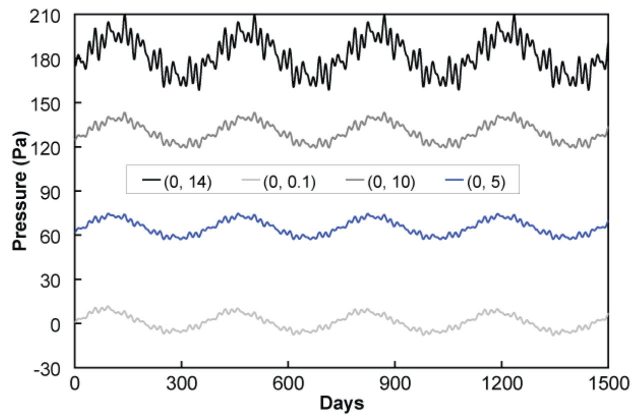

Figure 8. Pressure fluctuations at different points inside the waste rock pile

4 CONCLUSIONS

Numerical modeling of air convective heat transfer in a porous waste rock pile showed the need to couple mass transfer (air movement) and boundary conditions associated with wind and pressure fluctuations is crucial to understand the internal thermal behaviours. The results show that temperatures in the region within 7.0m from the base decrease rapidly and remain below 0℃ over the summers thus preventing potentially contaminated water from seeping into this zone. Convective cooling also has the potential to maintain tailing under frozen condition by overlaying a layer of highly porous waste rock on the surface (Arenson and Sego, 2007).

The effects of pressure variation due to wind and natural fluctuation are vital because they produce high frequencies in the recorded temperature signals even at depth (about 14m) in highly permeable porous. These pressures also create air movement but their magnitudes dissipate greatly with depth. The pressure signals of modeling have two distinct frequencies which are annual due to ambient temperature variation (low frequency) and high frequencies due to wind.

Air permeability governs how much air can actually move within waste and thus controls the amount of convective heat transfer. During winter, warm air moves at greater velocity compare to that of summer from the base to the top by buoyancy force and in opposite direction in summer by gravity. Heat transfer in winter is about 2.7 times that of summer thus it effectively cools the pile.

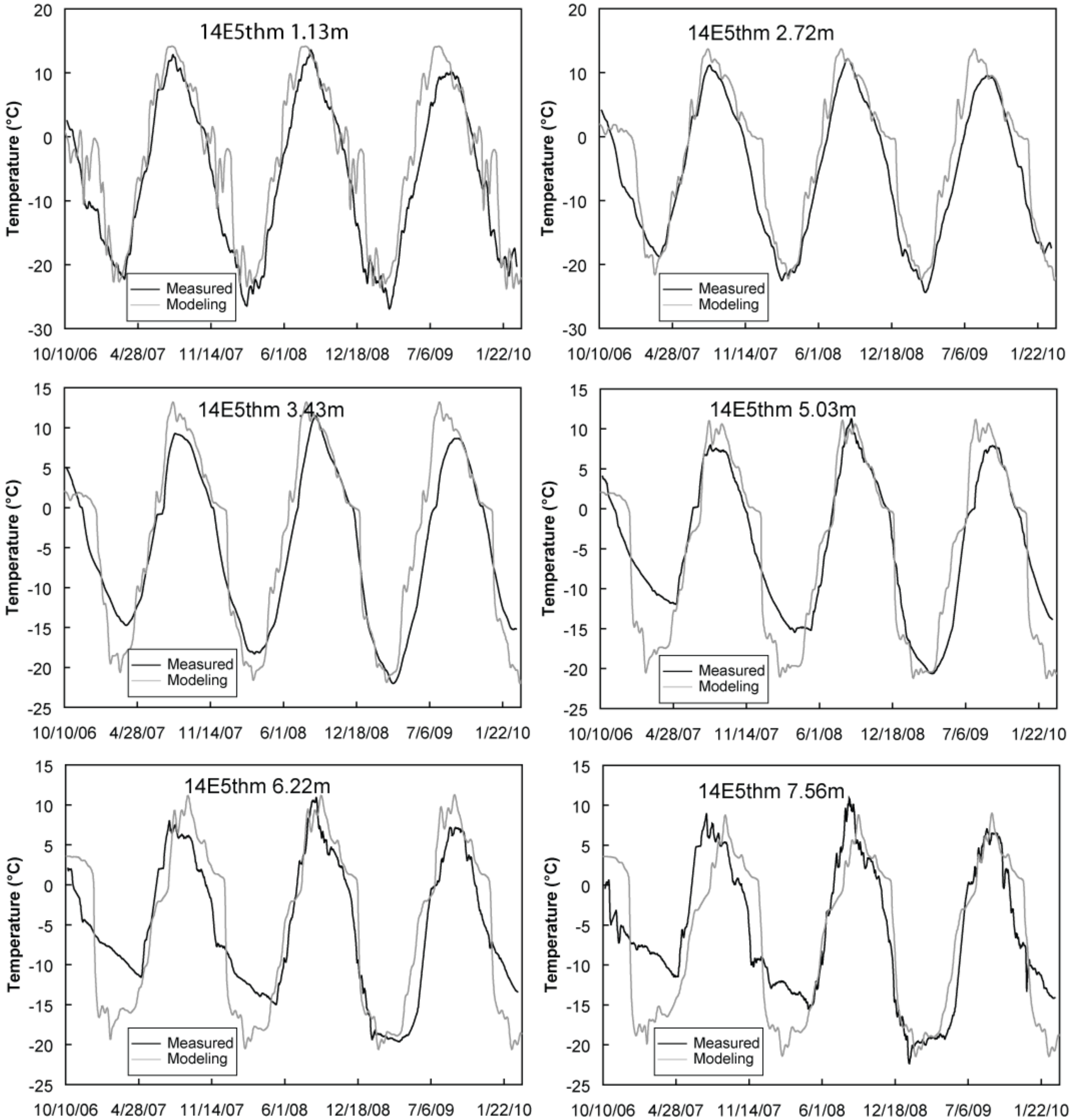

Figure 9. Measured and numerical modeling results of a waste rock pile's internal temperatures are up to 7.56m depth. The symbol 14E5them 1.13m indicates a thermistor at type I pile, face 4, East of central line, 5 offset of central line and at 1.13m depth from the top surface, details of Diavik test pile project mentioned by Smith et al. (2009)

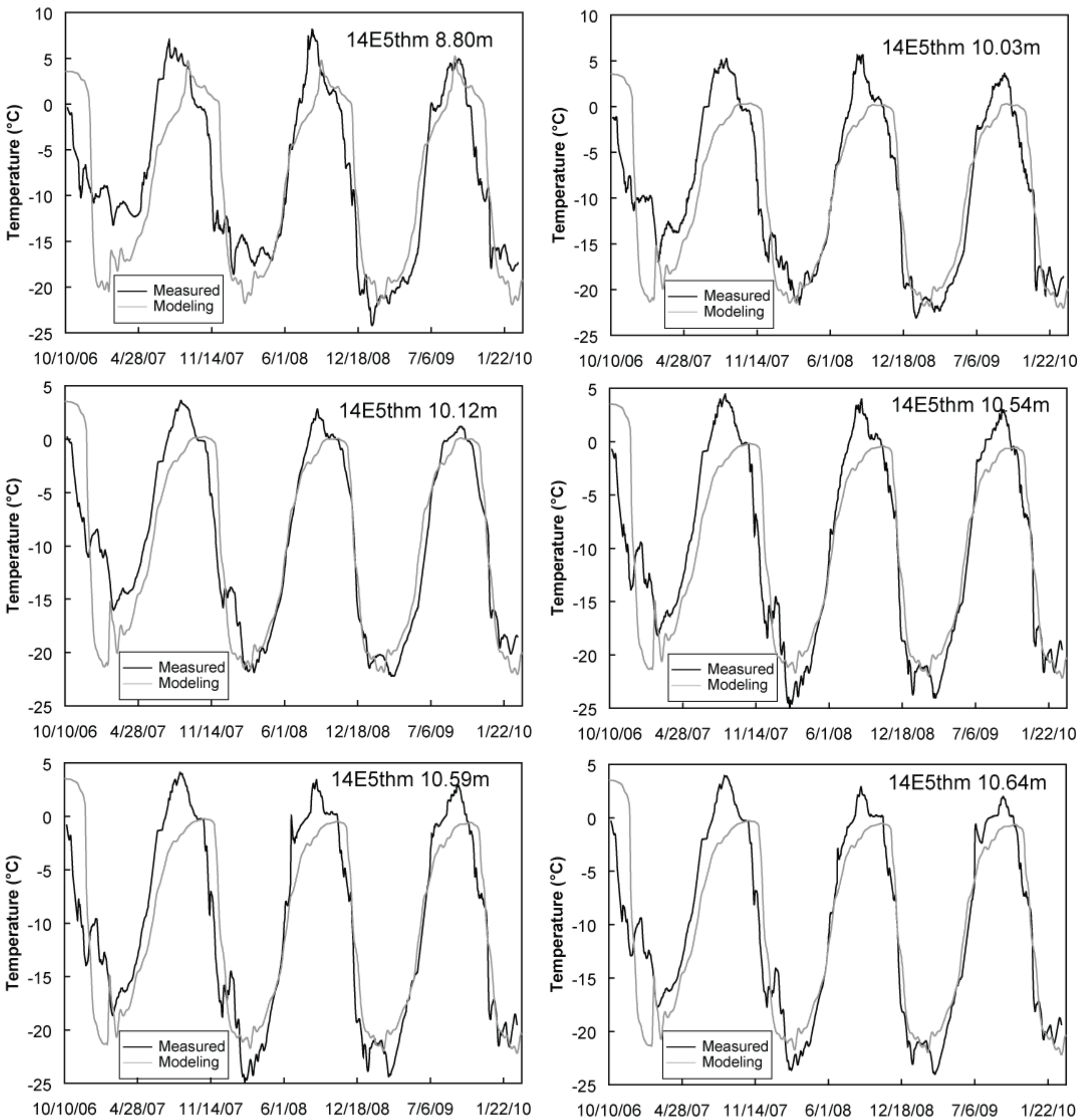

Figure 10. Measured and numerical modeling results of a waste rock pile's internal temperatures are from 8.80 to 10.64m depth

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