GeoStudio Example File

Seasonal Temperature Trends in Water Capped Tailings

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Introduction

Bitumen extraction from oil sands generates large volumes of soft tailings, referred to as fluid fine tailings. Fluid fine tailings are generally placed in surface impoundments where they gradually undergo self-weight consolidation; however, an alternate disposal strategy is to place these tailings in mined-out pits beneath a water cap. This mine closure strategy is called an End Pit Lake. One example of this type of tailings disposal, as described by Dompierre and Barbour (2016, 2017) is Base Mine Lake, operated by Syncrude Canada Ltd.

One aspect of the long-term evolution of these tailings following placement that has not been extensively studied is the change in temperature within the tailings. For example, the tailings at Base Mine Lake have elevated temperatures (11-19 ^oC) as compared to the background regional shallow groundwater temperature (4 ^oC) and the average annual air temperature (1 ^oC; Environment Canada, 2016). Long-term cooling of these tailings may take many hundreds of years and the associated energy movement will continue to influence the overlying water cap and adjacent groundwater system. Settlement of the tailings over time generates upward pore water flow, which will also contribute to heat transfer from the tailings to the overlying water cap.

This example illustrates the use of SEEP/W and TEMP/W for simulating seasonal temperature trends within water-capped tailings, and the corresponding heat flux to the overlying water. The numerical inputs are based on the study published by Dompierre and Barbour (2016).

Background

The Base Mine Lake site is located within the Athabasca Oil Sands Region of Northern Alberta. Approximately 45 m of fluid fine tailings were placed in a mined-out pit and were capped with approximately 9 m of water. The tailings had an initial temperature between 11 and 19 ^oC during placement. Base Mine Lake covers an approximate area of 8 km^2.

The tailings are comprised of quartz and clay minerals suspended in a fluid matrix (Kasperski and Mikula, 2011). When FFT is first generated, it has a solids content of 25 to 35 % (w/w) corresponding to a bulk density of approximately 1200 kg/m^3 (Suthaker and Scott, 1996). The tailings solids content and density gradually increase over time as the tailings dewater via self-weight consolidation. Although the mechanisms and processes controlling self-weight consolidation of fluid fine tailings are still a subject of active research within the industry, the annual tailings settlement rates within Base Mine Lake are measured and can be used to quantify the rates of water flux associated with ongoing settlement.

Upward pore water movement causes vertical advection of sensible energy, also known as forced heat convection. Additionally, at the interface between the water cap and the tailings, the predominant heat transfer mechanism is conduction, either into or out of the FFT, in response to seasonal fluctuations in the temperature of the water cap.

Numerical Simulation

Heat transport through the FFT is assumed to be one-dimensional (i.e. vertical) given the large area of tailings at the study site (minimal perimeter effects). The seasonal temperature changes are simulated using a 1D finite element model as specified under the Settings tab in the Define Analyses window. Field monitoring found that less than 5 m of the tailings exhibited seasonal temperature variation with more constant temperatures below this depth. Consequently, the simulation includes the top 10 m of tailings to ensure the applied bottom boundary condition does not affect the simulated seasonal temperature cycles in the upper 5 m of tailings (Figure 1).

A steady state SEEP/W analysis was used to generate a constant upward water flux associated with the annual FFT settlement. The second analysis in the project file is a TEMP/W analysis simulating heat transfer by conduction (the default heat transfer process) and forced convection with water transfer. The addition of water transfer physics to the second analysis was not necessary because the results from the parent SEEP/W analysis can be used, as defined under the Water tab. The simulated duration is 162 days, which corresponds to the extent of field measurements.

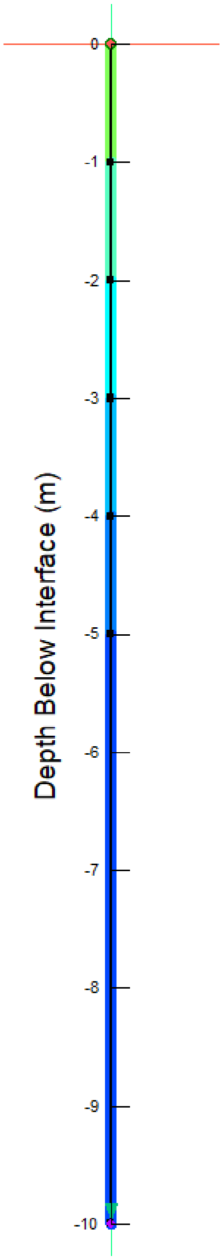

Figure 1: Domain configuration.

Material Properties

Field measurements indicated that the solids content of the saturated tailings increases with depth. Thus, the top 5 m of the vertical tailings profile was divided into 1 m sections, with gradually increasing water content with depth (0.86 to 0.82 m^3/m^3; Table 1). The bottom 5 m of tailings had the same properties applied throughout. The thermal properties of each section also changed with depth according to the relationships presented by Dompierre and Barbour (2017) and the associated water content. The tailings hydraulic conductivity is not required for the water transfer analyses because the water flux through the tailings is specified. Thus, a nominal value of $1x10^{-7}$ m/s is applied throughout the entire profile. The material properties for each layer are provided below (Table 1).

Table 1: Material properties assigned to each tailings layer.

Material	Depth Below Interface	Volumetric Water Content	Thermal Conductivity	Volumetric Heat Capacity
	m	m^3/m^3	J/s/m/^oC	$MJ/m^3/^oC$
FFT 1	0 - 1	0.86	0.75	3.74
FFT 2	1 - 2	0.85	0.77	3.70
FFT 3	2 - 3	0.84	0.78	3.67
FFT 4	3 - 4	0.83	0.79	3.65
FFT 5	4 - 5	0.82	0.80	3.63
FFT 6	5 - 10	0.81	0.81	3.61

Initial and Boundary Conditions

The steady-state SEEP/W analysis establishes the water content distribution and rate of water flow through the FFT as required by the transient heat analysis. A constant head boundary condition is applied to the top of the tailings profile (5 m) and a constant flow rate of approximately 1.5 m/year/m^2 ($5x10^{-8}$ $m^3/s/m^2$) is imposed on the bottom. This flow rate is based on the measured tailings settlement rates. The water flux is applied as a positive flux value on the bottom of the tailings column to represent water entering the domain. In the one-dimensional analysis, the water flux applied to lower boundary is multiplied by a unit cross-sectional area (i.e. one unit width by one unit in the out-of-plane direction) to calculate the nodal flow rate.

The initial temperatures for the transient analysis are established with a Temperature Spatial Function, based on the in-situ tailings temperatures at the beginning of the measurement period. During the transient heat and water transfer analysis, a constant temperature is applied to the bottom boundary, corresponding to the average temperature of the deep tailings (10.16 ^oC). Temperature as a function of time is imposed at the top boundary based on field measurements at the interface between the tailings and water cap.

Results and Discussion

Simulated Temperatures

The simulated temperatures shift from warmer to cooler conditions (Figure 2) as the temperature within the water cap at the tailings-water interface decreased from 14.6 ^oC (initial condition) to 6.1 ^oC over the 162-day period. The heat and water transfer analysis indicates that the greatest shift in seasonal temperatures occurs within the top 3 m of tailings. The temperature at the bottom remains constant throughout (10.16 ^oC), as specified.

The heat rate from the top of the tailings profile was plotted over time (Figure 3). In a 1D analysis, the heat rate is equal to the heat flux (kJ/s/m^2) because of the implicit unit cross-sectional area. The heat flux exhibits the largest change within the first 60 days when the water cap was undergoing cooling. Decreasing temperatures in the water cap lead to larger temperature differences between the water and the underlying tailings, causing increased conduction. The heat flux from the top of the tailings begins to level out after about 80 days when the water temperature stabilizes. However, it is important to note that even though heat flux from the top of the tailings does change over time, the range of values is relatively small (-0.058 to -0.064 kJ/s/m^2).

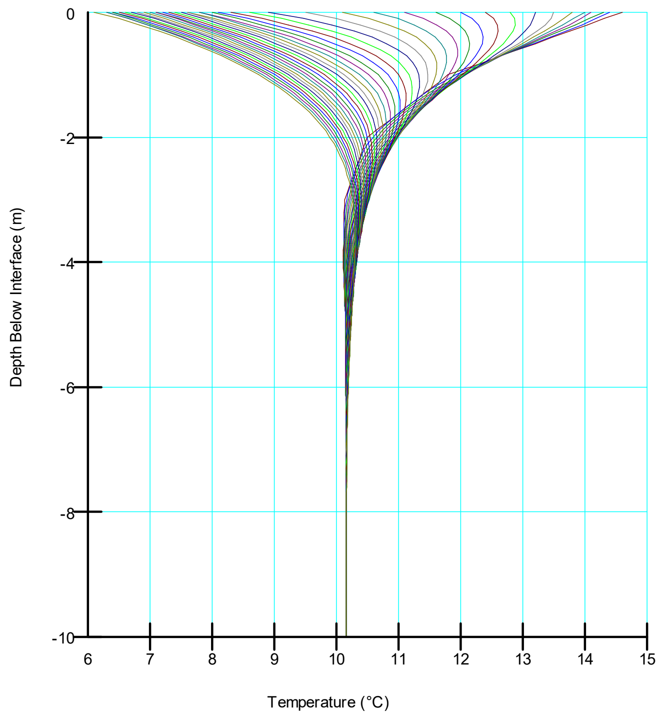

Figure 2. Simulated seasonal temperature trends in top 5 m of FFT.

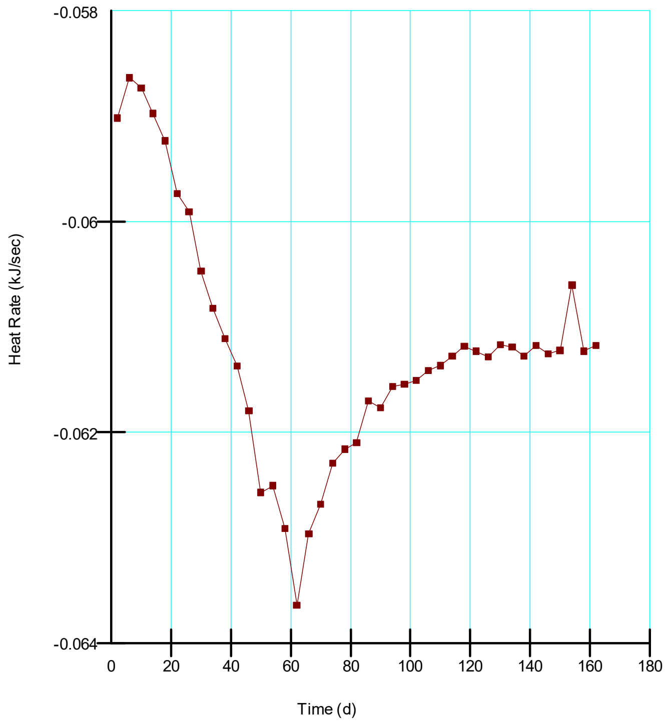

Figure 3: Heat rate from the top of the tailings column.

The cumulative energy released from the top of the tailings column was plotted (Figure 4). The simulated energy values represent both convection and conduction, and are negative because heat is leaving the domain (and entering the overlying water cap). The plotted values create a near linear trend, indicating that heat transfer from the tailings to the overlying water cap is fairly constant over time. The approximate heat flux due to convection, $q_{convection}$, can be calculated by:

$$q_{convection} = q_w \cdot T_{avg} \cdot C_{pw} \quad \text{Equation 1}$$

where q_w is the water flux due to tailings settlement (5x10^{-8} m^3/s/m^2), T_{avg} is the average tailings temperature at depth (283.31 K), and C_{pw} is the volumetric heat capacity of water at this average temperature (4191 kJ/m^3/K). The calculated heat flux due to convection alone is 5129 kJ/day/m^2. If this value is plotted over the entire simulation period in terms of cumulative energy released, it is similar to the cumulative energy release produced by the transient water and heat transfer analysis (Figure 3). This indicates that convection associated with tailings settlement is the main form of heat transfer in this system. Over time, the calculated cumulative energy released for convection-only is less than the simulated values for convection and conduction. Thus, conduction does contribute to heat transfer from the tailings, but to a lesser degree.

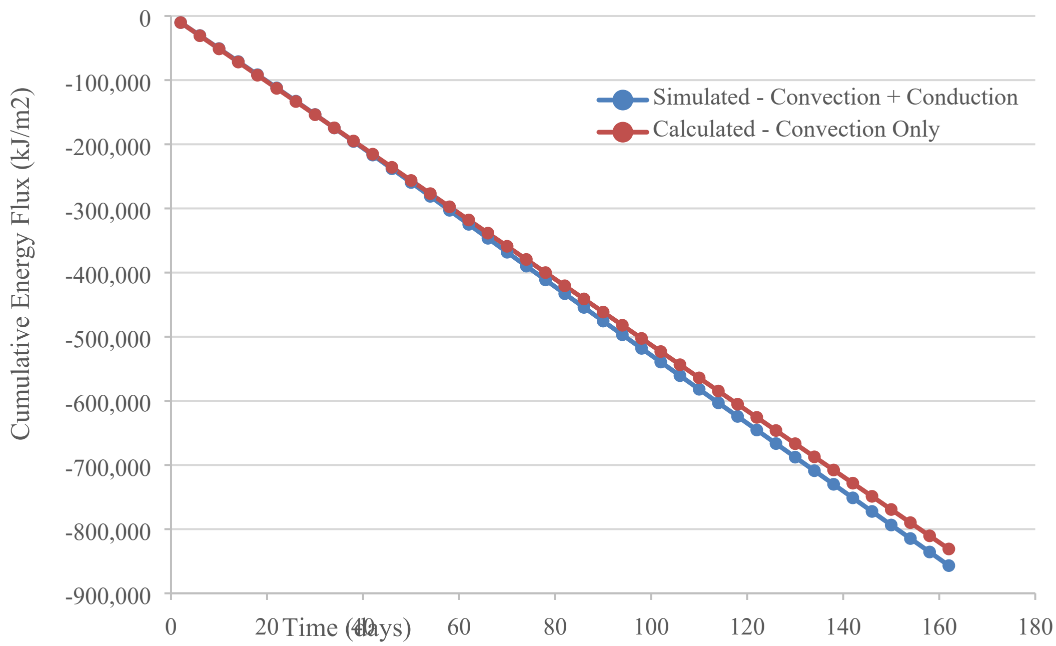

Figure 4: Cumulative energy released over time from the tailings to the overlying water cap.

Comparison to Field Measurements

The results from a numerical simulation are often compared to field monitoring data in order to further refine or calibrate material parameters. The maximum temperatures generated by the transient heat and water transfer analysis are plotted with the maximum temperatures measured at each thermistor over the entire period (Figure 5). The transient analysis generated very similar results as measured in the field, indicating that sensible heat advection and conduction – the heat transport mechanisms included in this simulation – provide a good explanation for the observed temperature profiles. Dompierre and Barbour (2016) were then able to use this simulation to find a range of water flow rates that best represented the settlement rates within the FFT.

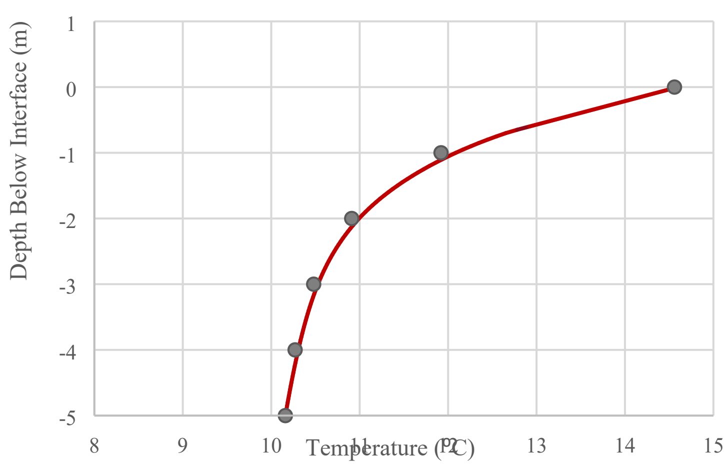

Figure 5. Maximum temperatures measured in the field (grey circles) and simulated by the transient analysis (red dashed line) over the entire 162-day period.

Summary and Conclusions

GeoStudio can be used to integrate water flow and heat transfer to replicate multi-physics behavior. Unique features of this simulation included the use of the 1D functionality, multiple regions to capture water content variation, a spatial temperature function to capture initial conditions, and the incorporation of field monitoring data to set the boundary conditions. The generated transient analysis, including conduction and sensible heat advection, produced temperature trends similar to those measured in the field.

References

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