GeoStudio Example File
Line-Source Heating Experiment

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Introduction

The dual-probe heat-pulse method is commonly used to determine the thermal properties of soils in the laboratory (e.g., Bristow et al., 1994; Liu and Si, 2011). Similar (larger) field testing methods have recently been developed to assess in situ thermal properties of formations surrounding ground-coupled heat pump systems (Raymond et al., 2010) and of large tailings deposits (Dompierre and Barbour, 2017). Both laboratory and field methods involve a line-source heating element, which heats the surrounding material. The measured change in temperature over time and the applied heating rate are then used to determine thermal conductivity of the in-situ formation.

This example will illustrate the use of SEEP/W and TEMP/W to simulate a field-scale line-source heating test. The modelled scenario is based on in situ testing of oil sands fluid fine tailings as presented by Dompierre and Barbour (2017). Results from the simulation are compared to the analytical solution for an infinite wire or line-source heating element.

Background

The dual-probe heat-pulse method is based on the analytical solution for an infinite wire or line-source heating element (see Kluitenberg et al., 1993). This solution calculates the temperature change ΔT (°C) within the soil as a function of the thermal properties of the soil and elapsed time as:

Equation 1

$$\Delta T = \begin{cases} \dfrac{-q}{4 \cdot \pi \cdot k} \cdot Ei\left[\dfrac{-r^2 \cdot C_p}{4 \cdot k \cdot t}\right] & 0 < t \leq t_0 \\ \dfrac{q}{4 \cdot \pi \cdot k} \cdot \left\{Ei\left[\dfrac{-r^2 \cdot C_p}{4 \cdot k \cdot (t - t_0)}\right] - Ei\left[\dfrac{-r^2 \cdot C_p}{4 \cdot k \cdot t}\right]\right\} & t > t_0 \end{cases}$$

where q is the heating rate from the line-source (W/m), k is the thermal conductivity of the soil (W/m/°C), C_p is the soil volumetric heat capacity (J/m^3/°C), r is the radial distance (m) from the line source, t_0 is the time when heating stops (s), and Ei is the exponential integral.

Heat transport from the line-source occurs radially via conduction. Only sensible heat transfer is assumed to occur in the modeled system (i.e. no phase change). The thermal conductivity and volumetric heat capacity values were based off the typical values found for oil sands fluid fine tailings at the Base Mine Lake study site (Dompierre and Barbour, 2016).

Numerical Simulation

An axisymmetric simulation was used to represent a heating wire installed vertically into tailings (Dompierre and Barbour, 2017). The centerline of the domain is offset from the y-axis (i.e. $r = 0$) by the radius of the heating wire (0.0005 m). The domain extends 0.5 m in the horizontal direction (Figure 1).

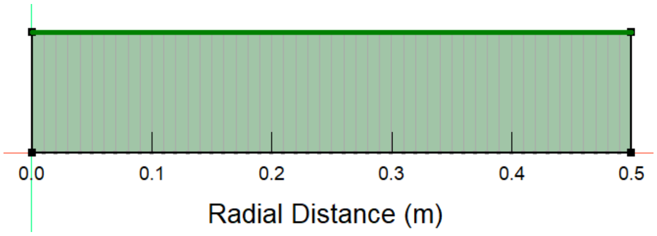

Figure 1: Domain and mesh configuration.

The project file contains two transient TEMP/W analyses. The first transient analysis simulates two hours of heating from the central heating wire. The second transient analyses involves cooling of the domain after the heating wire is turned off.

Material Properties

The Simplified Thermal material model defines the properties within the domain. A value of 0.91 J/s/m/◦C (W/m/◦C) was used for the thermal conductivity and the volumetric heat capacity was set to 3610 kJ/m^3/◦C. These properties are based on the results presented by Dompierre and Barbour (2017), as was the volumetric water content value of 0.84. The initial temperature was established by specifying an activation temperature of 9˚C in the material properties.

Boundary and Initial Conditions

In the first analysis, a heating flux boundary condition of 2.865 kJ/sec/m² is applied along the interior line of the domain. This represents the energy added to the domain by the heating element during the initial portion of the experiment, and was calculated by:

$$q = \frac{Q}{A} = \frac{j \cdot L}{C \cdot L} = \frac{j}{2\pi \cdot R} = \frac{9}{2\pi \cdot 0.0005} = 2865\,\frac{J}{s\,m^2}$$ Equation 2

where Q is the heat flow (J/s), A is the area over which the heat flow occurs (m^2), j is the heating rate per meter length of wire (J/s/m), L is the length of the wire (m), and C is the heating circumference (m) based on the radius (R) of the heating wire. As with the material properties, the heating rate per length of wire is based on the study presented by Dompierre and Barbour (2017).

The far field (i.e. right) boundary condition is unspecified and therefore exhibits the default condition of zero heat flux. This boundary is assumed to be far enough from the heating element such that there is no change in temperature observed at this boundary by the end of the simulation. Similar default boundary conditions are present along the top and bottom of the domain ensuring that heat transfer is only in the horizontal direction. In the second analysis, all of the boundary conditions are set to the default (zero heat flux) boundary condition. This ensures that there is no heat flux out of the model domain during the cooling period.

Results and Discussion

Simulated Temperatures

The temperatures simulated 1 cm from the heating element increase rapidly as the heating flux is applied (Figure 2). As heating continues, the rate of change in temperature begins to decrease as the applied heat is distributed further into the domain by conduction. When the heating element is turned off, the temperature drops near the heating wire as the applied heat is distributed across the domain.

As expected, the material near the heating element exhibited the greatest change in temperature (Figure 2). The temperature near the far field boundary can be checked to ensure that this boundary is sufficiently far from the heating wire to justify the assumption of a zero heat flux boundary. For example, Figure 2 shows that temperature 40 cm from the heating element is constant during the simulation.

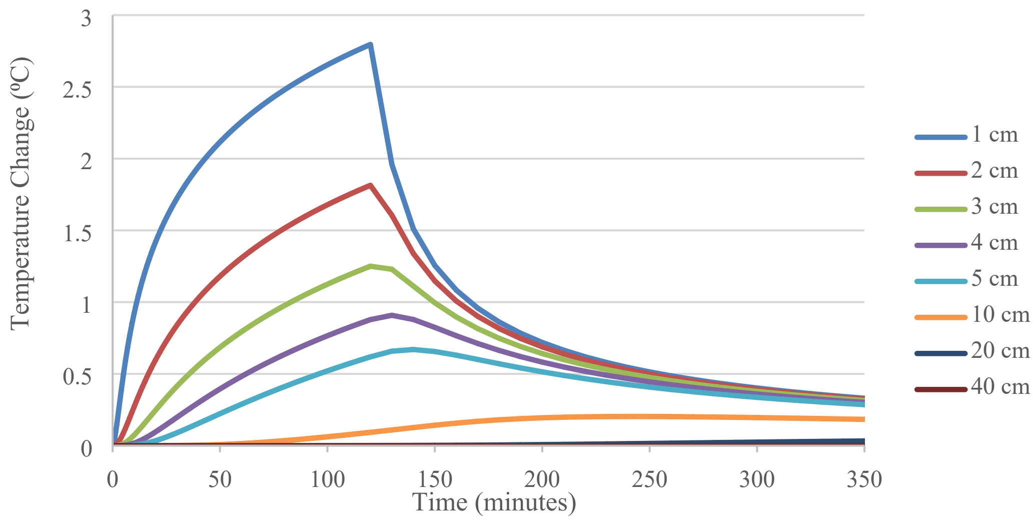

Figure 2. Temperature change over time simulated at the specified distances from the heating element.

The heating rate at the center of the domain is constant over the first 7200 s (2 hours) of the simulation (Figure 3). A graph of the heat rate along this boundary (with the Sum Y vs. Average X option toggled on) provides a check that the applied boundary condition is correct as the simulated heating rate value, $9x10^{-5}$ kJ/s, corresponds to the desired heating rate per meter (9 J/s/m).

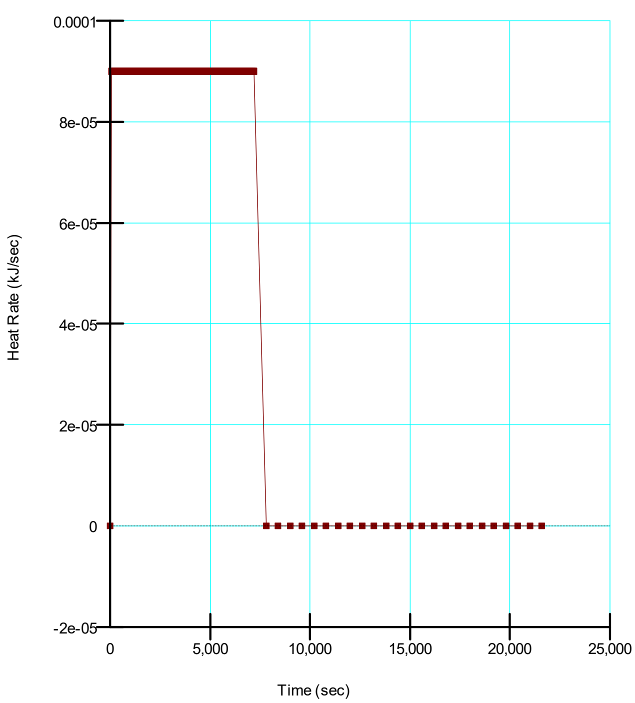

Figure 3: Sum of heating rate at the two central nodes over time.

The cumulative energy transfer at the central nodes may also be plotted (Figure 4). During the heating portion of the analysis, the cumulative energy applied to the domain increases linearly, as expected given the constant heating rate. Once the heating boundary condition is removed, the cumulative energy transfer remains the same as no boundary conditions were applied to the domain (i.e. no energy transfer was allowed across the domain extents). The total energy added to the domain was 648 J. This can be confirmed by the following equation:

$$E = \sum_{i=1}^{n} C_p \cdot (T_f - T_0)_i \cdot \left[\left(\frac{x_{i+1} + x_i}{2}\right)^2 - \left(\frac{x_i + x_{i-1}}{2}\right)^2\right] \cdot \pi \cdot dy$$

Equation 3

where n is the total number of nodes in the x-direction, T_f is the final temperature at each node, T_0 is the initial temperature (9 °C), x is the x-coordinate, and dy is the vertical dimension (0.01 m). Given this equation and the simulated results, the calculated energy, E, added to the domain was 648 J – the same as illustrated in Figure 4.

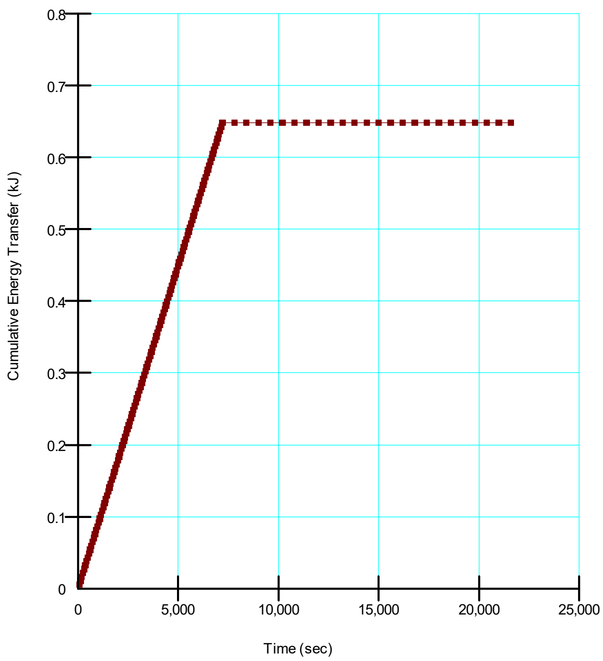

Figure 4: Simulated cumulative energy transfer from the heating wire.

Comparison to Analytical Solution

The results from the numerical analysis can be compared to the analytical solution for a line-source heating element. The temperature change 1 cm from the heating element was calculated using Equation 1, given a heating rate of 9 J/s/m, a 2-hour heating time, and the thermal properties used in the simulation (C_p = 3610 kJ/m³/°C; k = 0.91 J/s/m/°C). The analytical results are plotted with the simulated values in Figure 5. The two methods produced the same pattern of temperature change over time.

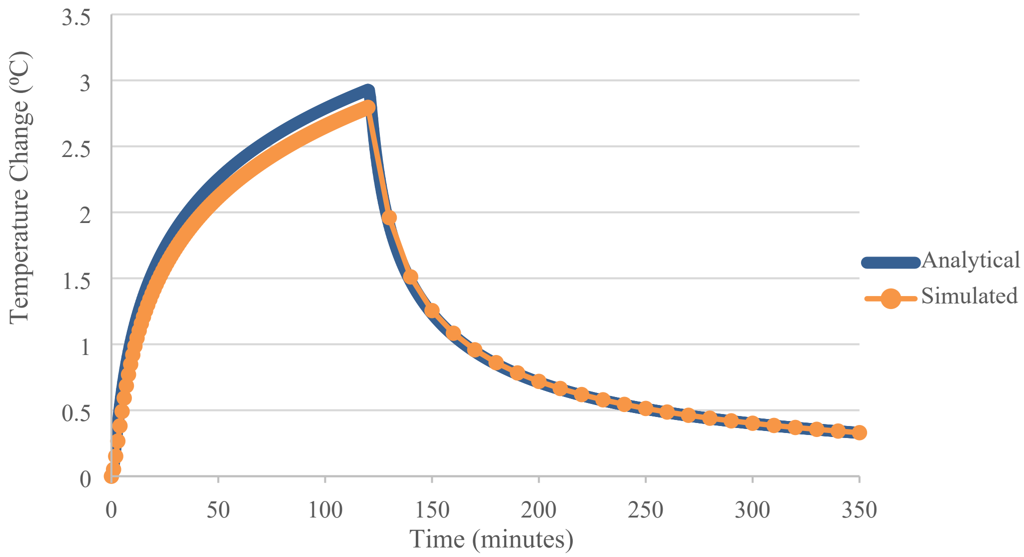

Figure 5. Simulated temperature change 1 cm from the heating element compared to the temperature change calculated at the same distance using the analytical solution (Equation 1).

Summary and Conclusions

This example file demonstrates axisymmetric, lateral conductive heat transfer from a heating element in an atypical geotechnical medium. The transient heating and cooling analyses produced similar trends for temperature change over time as the analytical solution for an infinite wire or line-source heating element (Kluitenberg et al., 1993). For heterogeneous systems, this model could be extended to evaluate both horizontal and vertical flow, by creating a larger domain with variable material properties.

References

Bristow, K.L., White, R.D., Kluitenberg, G.J. 1994. Comparison of single and dual-probes for measuring soil thermal properties with transient heating. Australian Journal of Soil Research, 32(3): 447-464.

Dompierre, K.A., Barbour, S.L. 2017. Thermal properties of oil sands fluid fine tailings: Laboratory and in-situ testing methods. Canadian Geotechnical Journal, 54(3): 428-440.

Kluitenberg, G.J., Ham, J.M., Bristow, K.L. 1993. Error analysis of the heat pulse method for measuring soil volumetric heat capacity. Soil Science Society of America Journal, 57(6): 1444-1451.

Liu, G., Si., B.C. 2011. Single-and dual-probe heat pulse probe for determining thermal properties of dry soils. Soil Science Society of America Journal, 75(3): 787-794.

Raymond, J., Robert, G., Therrien, R., Gosselin, L. 2010. A novel thermal response test using heating cables. In: Proceedings of the World Geothermal Congress, Bali, Indonesia, 25 – 30 April 2010. International Geothermal Association, Bochum, Germany.