Freezing Around a Pipe with Flowing Water

1 Introduction

Groundwater flow can have a significant effect on ground freezing because heat flow via convection is often more effective at moving heat than conduction alone. Numerical analysis of the conduction-convection process requires a coupling of the heat and water transfer equations. This example discusses the methodology and material properties required for conducting a heat transfer analysis involving groundwater flowing around a freeze pipe. The results are compared to the conduction-only scenario.

2 Feature Highlights

GeoStudio feature highlights include:

- Convective heat transfer using TEMP/W and SEEP/W
- Coupling heat and water transfer analyses
- Analysis tree for a convective analysis

3 Numerical Model

Figure 1 presents the model geometry and mesh. The domain is 4 m wide and 2 m in height with a circular opening in the middle representing the pipe. The automatic meshing results in a finer discretization around the opening, which is desirable as the phase change front will propagate radially outward from the pipe wall.

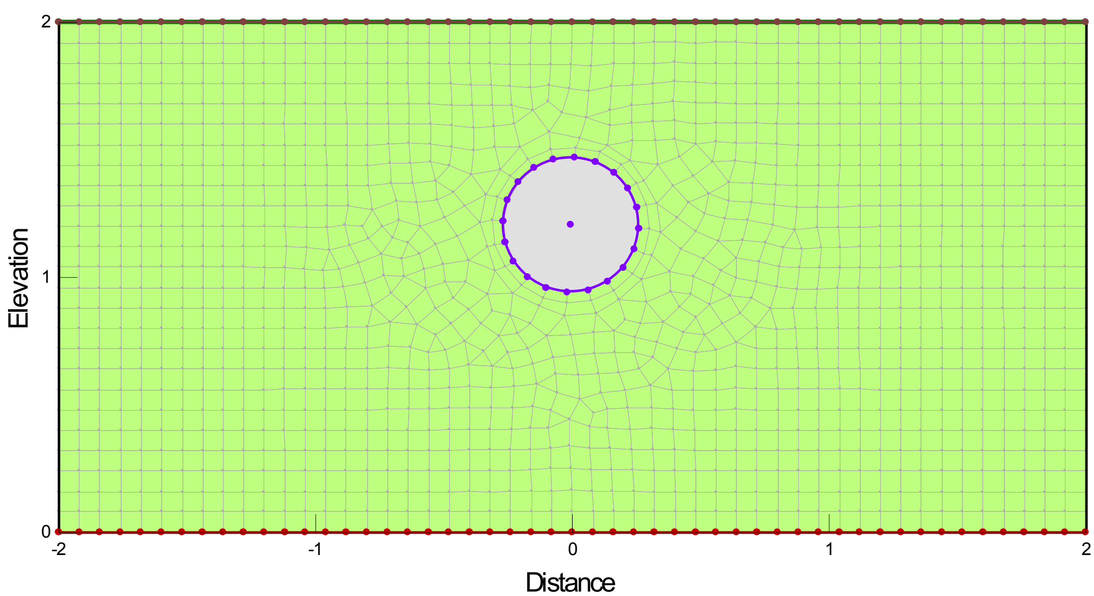
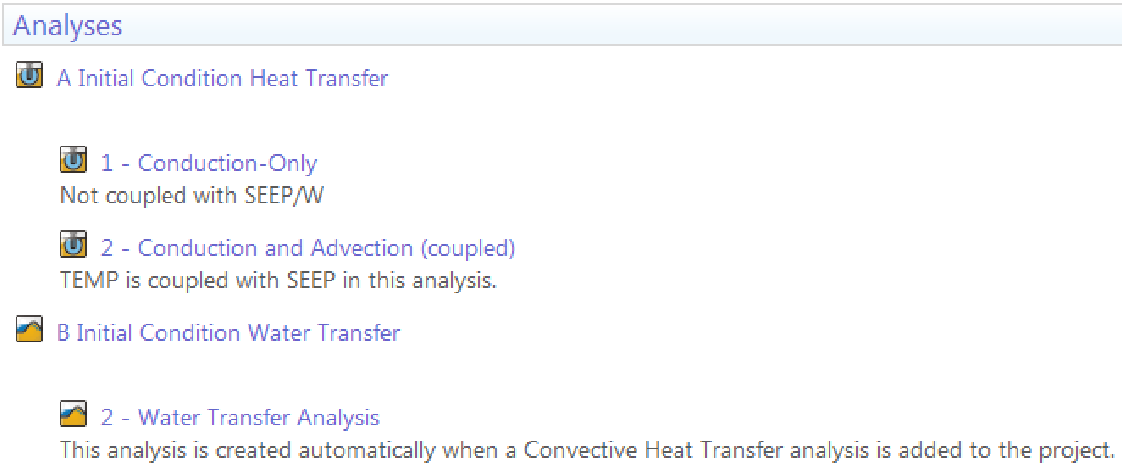


Figure 1 - Model domain

The GeoStudio project analysis tree is shown in Figure 2. There are a total of five analyses in this file, including a steady-state TEMP/W analysis (A) and a steady-state SEEP/W analysis (B). These two analyses were created in order to establish initial conditions for the transient conduction-convection analyses. Accordingly, the steady-state analyses are designated as the Parent analysis.



The analysis entitled '1 – Conduction-only' is a transient TEMP/W analysis that is not coupled with SEEP/W. A Convective Heat Transfer analysis was also added to the project (2 – Conduction and Advection). In doing so, a transient SEEP/W analysis is automatically added to the file (2 – Water Transfer Analysis) as these two analyses are coupled, but each domain requires its own boundary conditions and material properties. It is noted that the initial conditions for all three transient analysis are set to the Parent, which are the steady-state TEMP/W and SEEP/W analyses (Figure 3).

Figure 2 - Analysis tree for the project

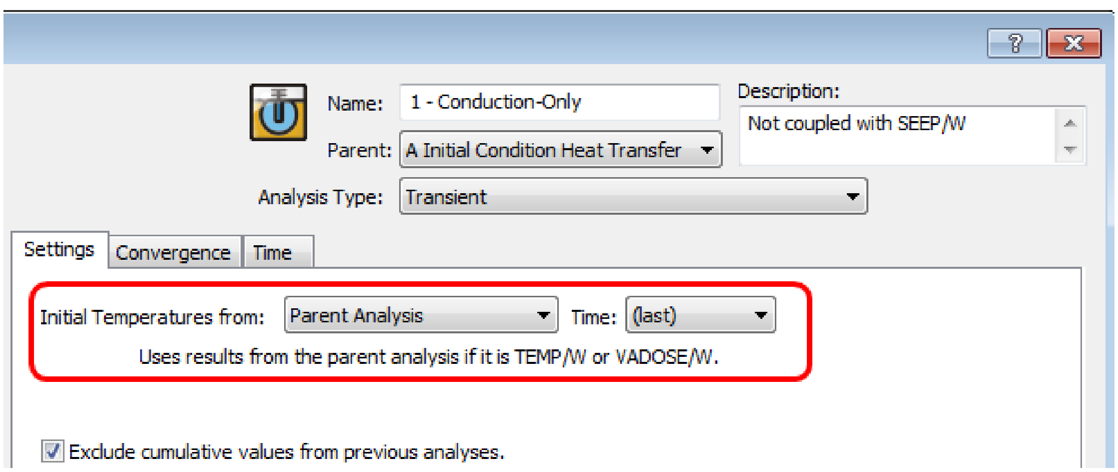


Figure 3 - Example of establishing the initial conditions for a transient analysis

The thermal boundary conditions at the top and bottom of the TEMP/W analyses are 3 °C and 3.1 °C, respectively. For the transient TEMP/W analyses, a thermal boundary condition with a temperature verses time function has been applied to the pipe surface such that the temperature cools from 3 °C to – 2 °C over a period of 1 day (Figure 3). The temperature remains constant at – 2 °C from Day 1 onward. Using a function is a better approach than applying an instantaneous freezing temperature because sudden changes in temperature can lead to numerical oscillation when phase change is involved.

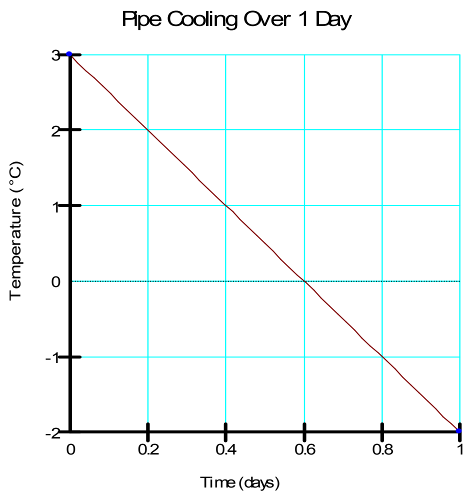


Figure 4 - Temperature verses time boundary function used to model pipe cooling

The hydraulic boundary conditions were selected in this analysis to establish a lateral groundwater flux of 0.75 m/day. A total head boundary condition of 3.0 m and 3.02 m was applied to the left and right edges of the SEEP/W analyses, respectively. The model is 4 m across, so the gradient is 0.02 m / 4 m = 0.005. This gradient yields the desired flux rate of 0.75 m/day for an assumed saturated hydraulic conductivity of 150 m/day.

The total duration of the transient models is 811 days using ten time steps with an exponential sequence and an initial time increment of 2 days.

4 Material properties

The heat transfer material properties differ between a conduction-only and a conduction-convection analysis. In a conduction-only TEMP/W model, a full-thermal material model is used and the thermal conductivity is input as function of temperature (Figure 5). The volumetric heat capacity for frozen and unfrozen soil is input and a fixed water content is entered (Figure 6). The key assumption is that the water content is constant at the user-entered value for the duration of the analysis.

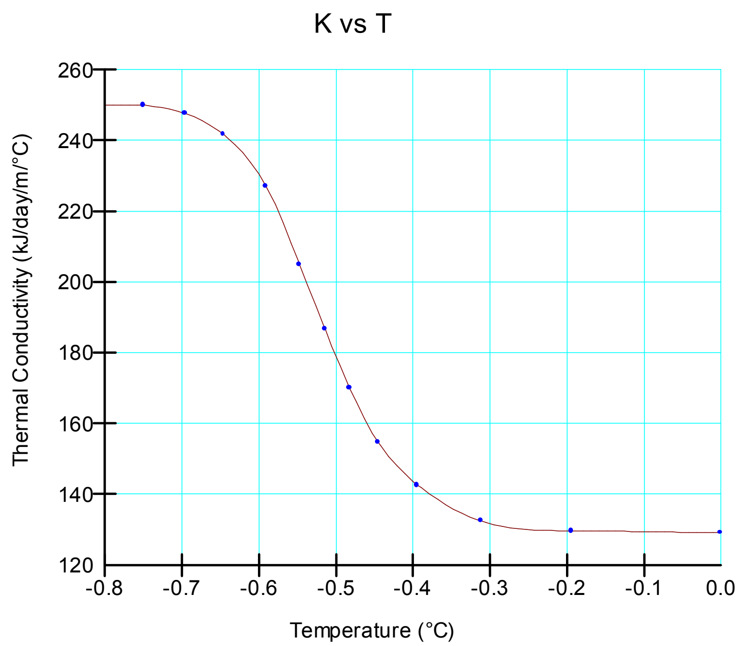


Figure 5 - Thermal conductivity function for a full-thermal material model

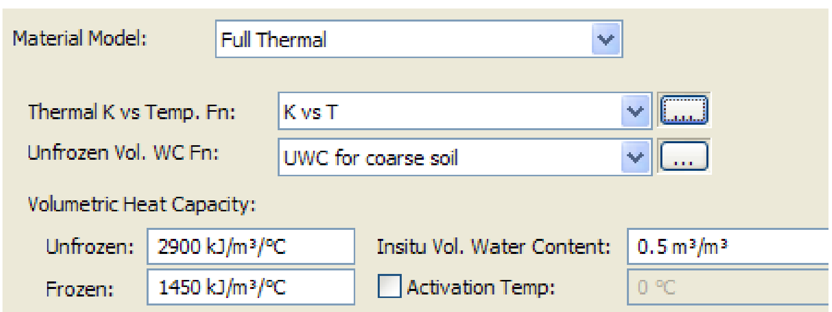
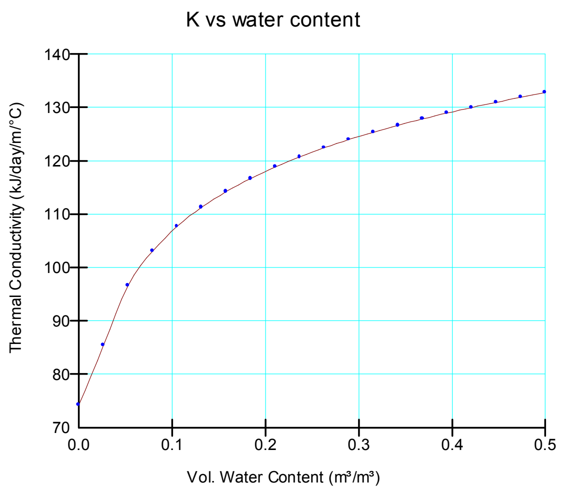


Figure 6 - Material inputs for a full-thermal material model

In a convective heat transfer analysis, the water content within any part of the domain is known from the SEEP/W analysis. For this reason, the thermal conductivity and volumetric heat capacity are input as a function of water content (Figure 7). It should be noted that the estimation feature can be used to generate both the thermal conductivity and volumetric heat capacity functions. In the former case, the user enters a thermal conductivity for the soil mineral grains and TEMP/W generates the function based on the percentage of water and soil. A similar procedure is used for the volumetric heat capacity function. More details on this estimation are provided in the TEMP/W Engineering Book.



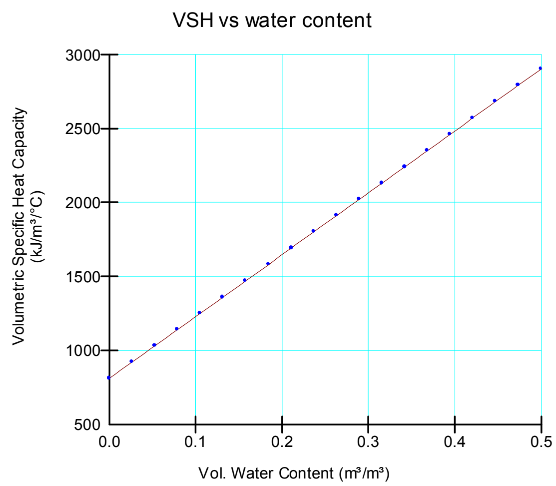


Figure 7 - Thermal property functions for a convective heat analysis

Naturally, the thermal properties are still a function of temperature in a convective analysis. TEMP/W automatically adjusts both the thermal conductivity and volumetric heat capacity if soil undergoes freezing or thawing. This information can be viewed by clicking on View Results Information or Draw Graph options in Results view. Figure 8 presents the results for two gauss regions in which the thermal conductivity increases from about 130 (unfrozen) to 250 in the frozen element, while the heat capacity drops from 2900 to 1450.

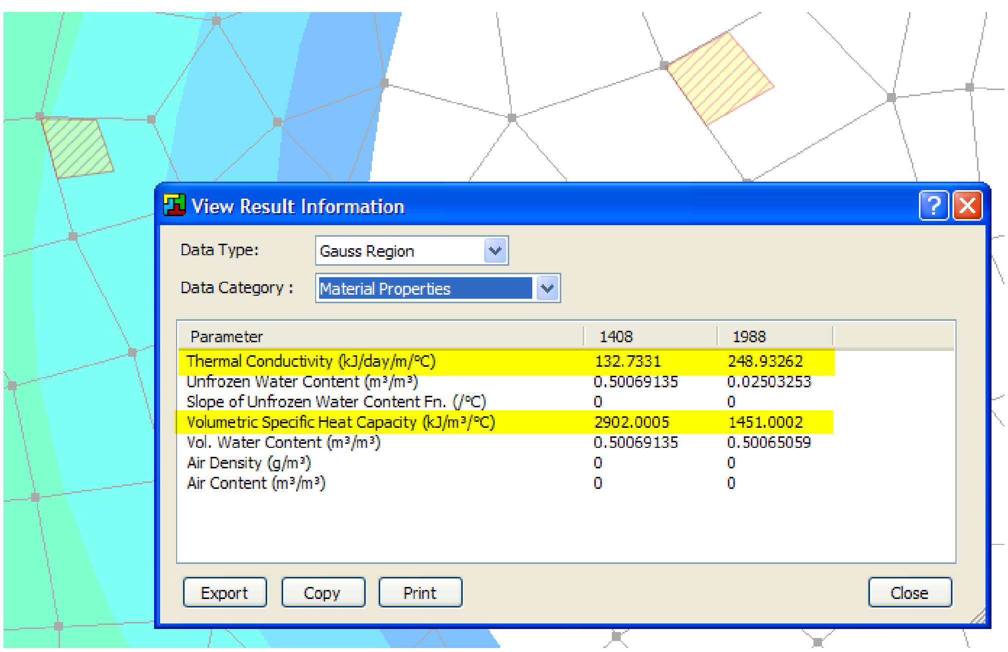


Figure 8 - View result information for a gauss region

5 Results and Discussion

Figure 9 presents a Gauss Region result from the steady-state seepage analysis. The x-flux rate is 0.71 m/day and the gradient is 0.005, which is consistent with the boundary conditions and hand calculation presented above. The x-gradient is slightly less than 0.005 because the reduced area for flow caused by the pipe is altering the total head distribution.

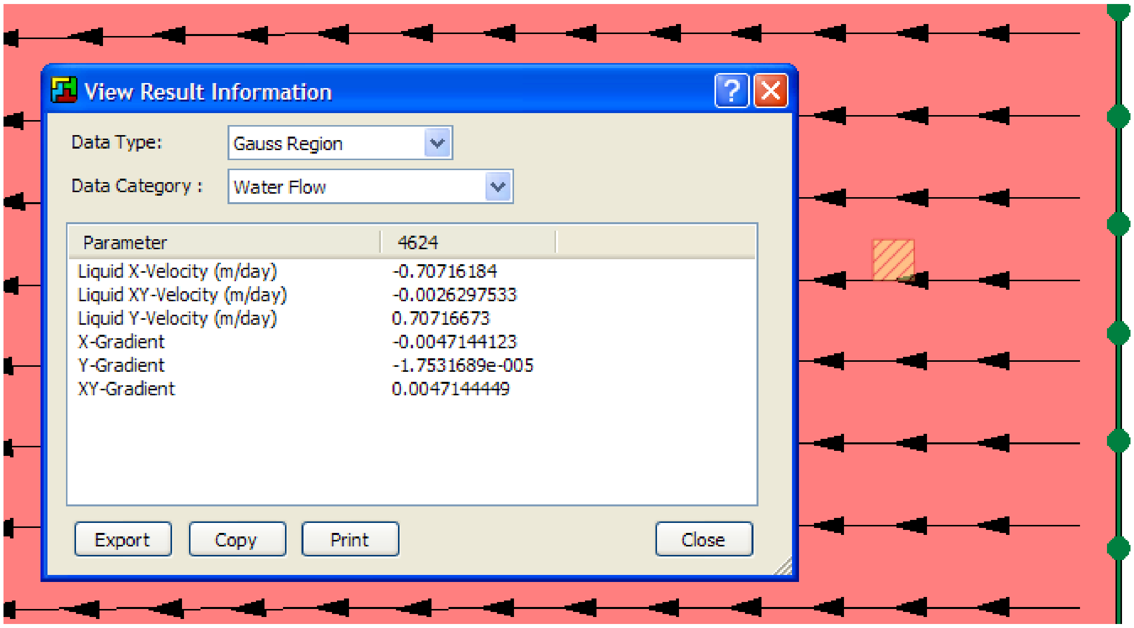


Figure 9 - Gauss region results from the steady-state seepage analysis

Figure 10 presents the temperature contours and freezing front location for the conduction-only case on Day 811. As expected, the freezing front has propagated radially outward from the pipe. The shape of the freezing zone is somewhat oblong because of the constant temperature boundary conditions on the top and bottom of the domain. The freezing front has propagated slightly further downward than upward because the top invert of the pipe is closer to the upper constant temperature boundary.

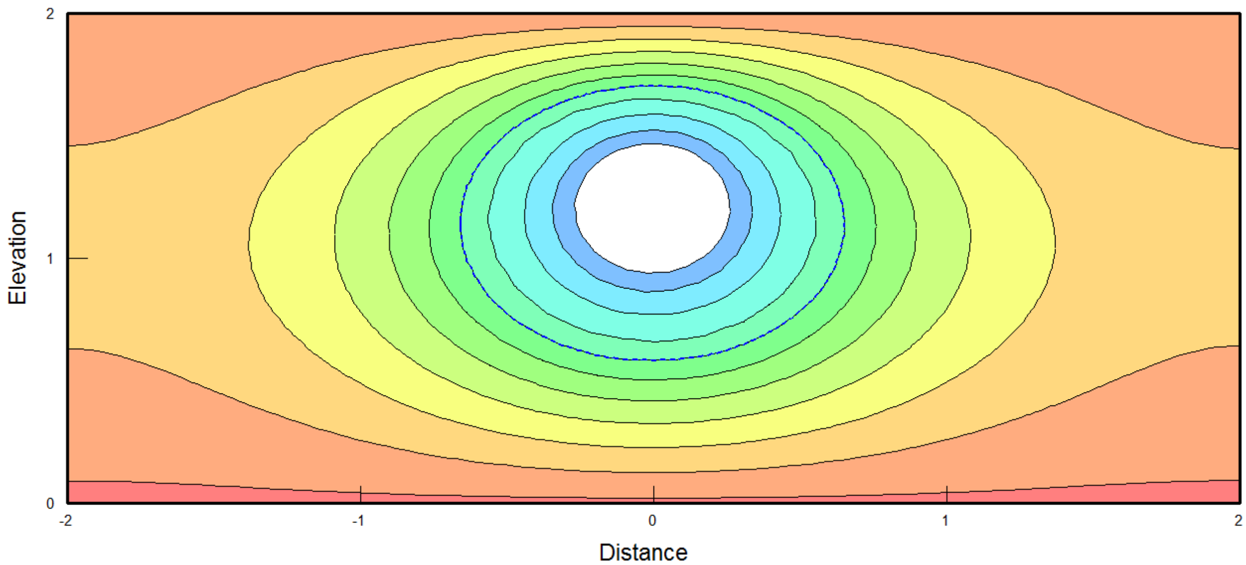


Figure 10 - Temperature contours and freezing front location for conduction-only analysis

The results for the convection analysis are presented in Figure 11. The flow of heat from right to left via convection with the flowing water has mitigated the propagation of the freezing front compared to the conduction-only analysis. Interestingly, the freezing front on the ‘downstream’ side of the pipe (left side) has expanded almost as far due to the relatively stagnant water movement in this zone (Figure 12).

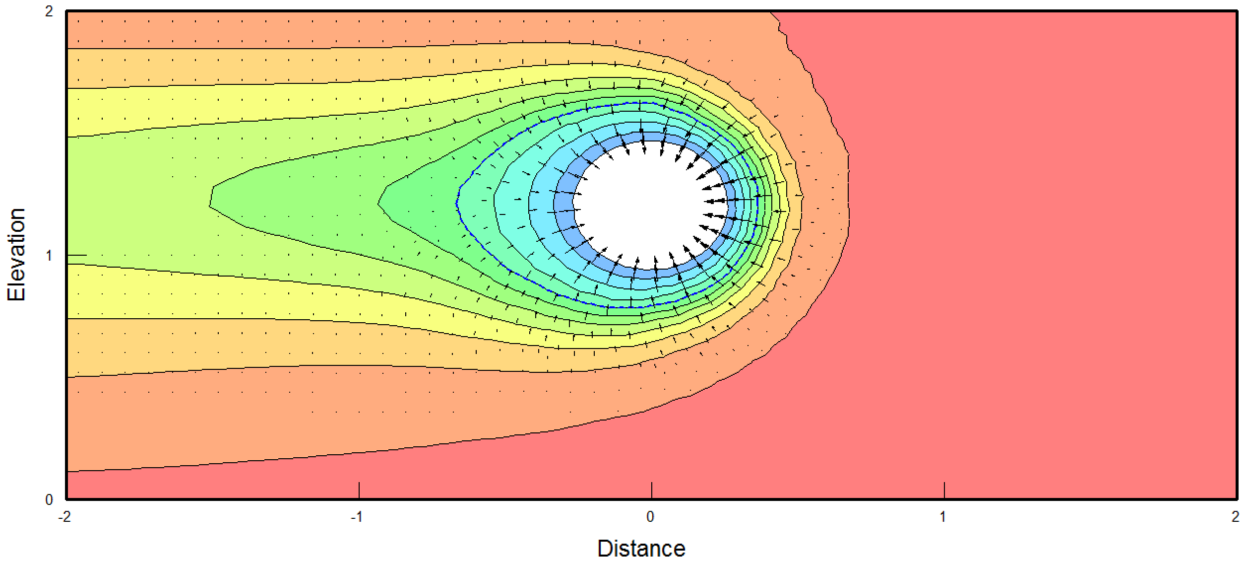


Figure 11 - Temperature contours and freezing front location for convection analysis

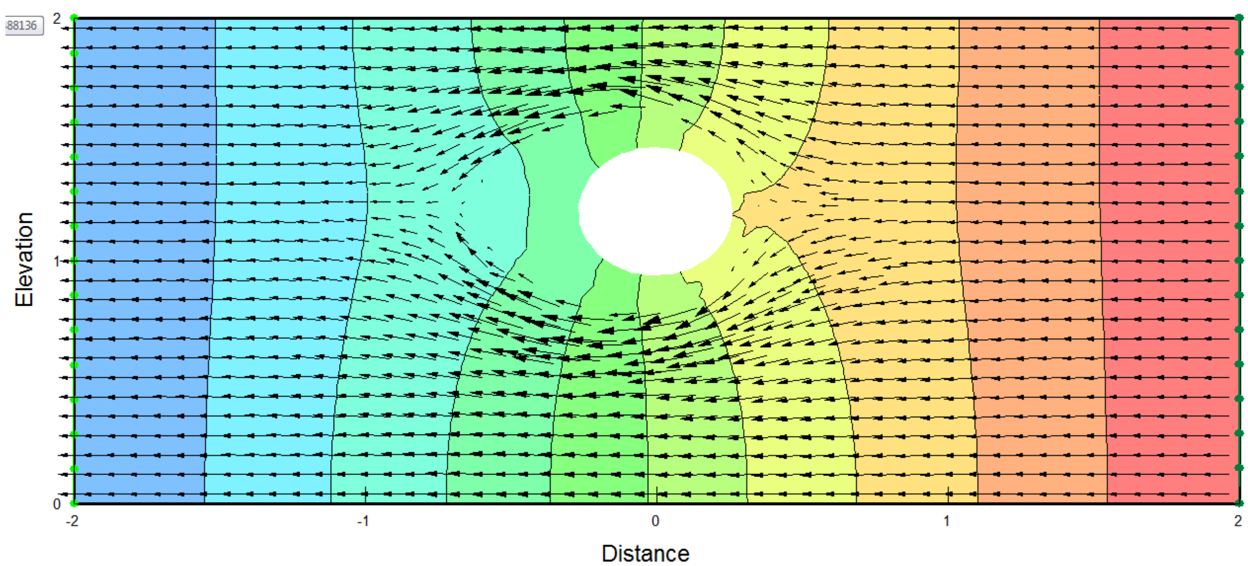


Figure 12 - Flux vectors from the transient SEEP/W analysis

A comparison between the two analyses demonstrates the significant effect of flowing water on the growth of the freezing zone. If the groundwater velocity would be even higher, the growth of the frozen zone could be completely inhibited. In other words, there would be a balance between the amount of heat being added by the flowing water and the heat being extracted by the cold pipe.

6 Summary and Conclusions

TEMP/W can be used to model convective heat flow with moving water. This type of analysis requires three key material inputs: a) a thermal conductivity verses water content function; b) a volumetric specific heat capacity verses water content function; and, c) an unfrozen water content function. The software automatically makes adjustments to the material properties for frozen and unfrozen conditions.

Adding a convective TEMP/W analysis to a GeoStudio Project automatically generates a SEEP/W file as both the heat and water transfer equations are solved using a coupled technique. This also necessitates the definition of hydraulic material properties and boundary conditions, in addition to the thermal boundary conditions.

A comparison between a conduction-only and conduction-convection analysis demonstrated that convective heat transfer via flowing water can prohibit the growth of the frozen zone. This can have substantial consequences for engineering projects that involve artificial ground freezing if the frozen zones around adjacent freeze pipes cannot grow together because of increasing water velocity in the unfrozen gap.