GeoStudio Example File
Freezing Around a Pipe with Flowing Water

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Introduction

Groundwater flow can have a significant effect on ground freezing because heat flow via forced convection is often more effective at moving energy 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 a heat transfer analysis involving groundwater flowing around a freeze pipe. The effect of pore-ice blockage on water and heat transfer is highlighted.

Background

The development of pore-ice during ground freezing impedes groundwater flow due to pore blockage. This phenomenon can be incorporated into a numerical model using an impedance factor (Lundin, 1990). Conversely, a number of researchers have found that there is a strong similarity between the volumetric water content function and the soil freezing curve (Spaans and Baker, 1996, Flerchinger et al. 2006)). Spaans and Baker (1996) indicated that the suction of frozen soil was equal to the suction in unfrozen soil at the same water content. Flerchinger et al. (2006) also noted that a drop in liquid water content and pore-water pressure during freezing was analogous to soil drying.

Laboratory testing completed by Schofield (1935) indicated a non-linear increase in suction from about 0 to 20,000 kPa at temperatures ranging from 0 to -1°C. Assuming an equivalent change in pressure within the liquid water and ice, the change in the freezing point of the liquid water can be determined from a Clausius–Clapeyron thermodynamic equilibrium equation:

$$\frac{\partial u_w}{\partial T} = \frac{\partial u_{ice}}{\partial T} = \frac{h_{sf}}{(v_w - v_{ice})T_0}$$

Equation 1

where u_w and u_{ice} are pore-pressures for water and ice, respectively, h_{sf} is the latent heat of fusion, v_w and v_{ice} are the specific volumes of water and ice, respectively, and T_0 is the normal freezing point of water at atmospheric pressure (i.e. 273.15 K). In an unsaturated soil, the changes in water and ice pressures are not equal. Assuming that the ice pressure remains at atmospheric pressure (i.e. unconstrained expansion), a simplified form of Equation 1 can be derived (Williams and Smith, 1989):

$$\frac{\partial u_w}{\partial T} = \frac{h_{sf}}{v_w T_0}$$

Equation 2

which indicates a decrease in the water pressure of about 1.2 MPa per degree Celsius. Equation 2 provided a reasonable match to Schofield’s work and is used by SEEP/W to determine the frozen soil matric suction.

Numerical Simulation

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.

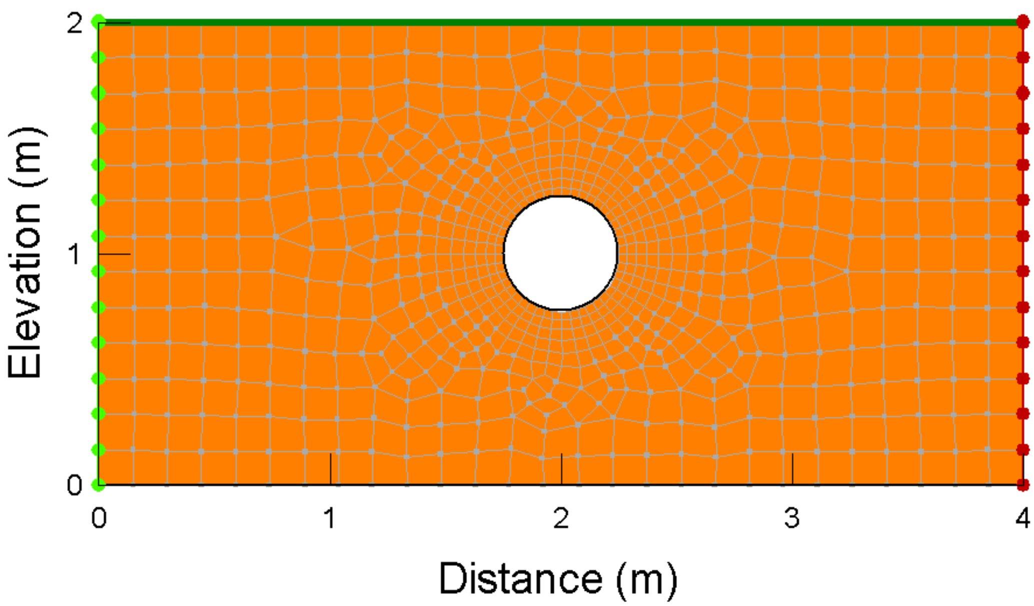

Figure 1 Model domain and mesh.

The GeoStudio analysis tree is shown in Figure 2. There are three analyses in this file, including a steady-state SEEP/W analysis. This analysis was created in order to establish initial seepage conditions for the transient forced convection analyses. A spatial function is used to define the initial temperature conditions for both TEMP/W analyses (Figure 3).

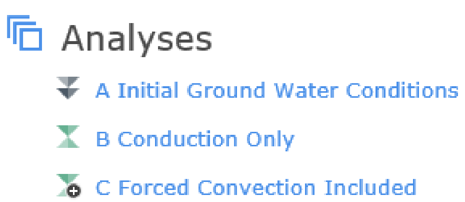

Figure 2 Analysis tree for the project.

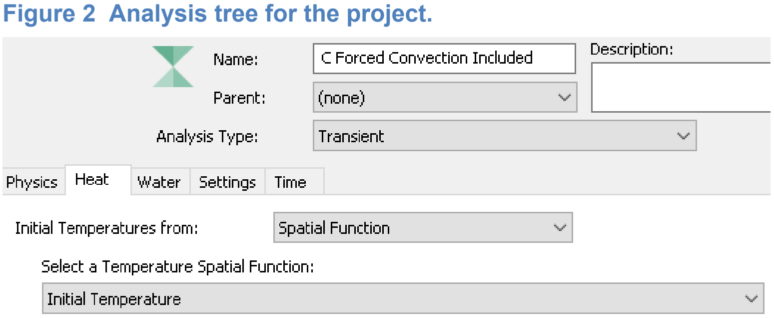

Figure 3 Example of establishing the initial conditions for a transient analysis using spatial functions.

The analysis entitled ‘B Conduction Only’ is a transient TEMP/W analysis that is not coupled with SEEP/W. It should be noted on the Physics tab of the Define Analyses dialogue box that the only physical process being solved on the domain is heat transfer.

The third analysis (C Forced Convection Included) couples TEMP/W to SEEP/W by toggling-on the Forced Convection with Water Transfer option (Figure 4). This coupling is visually indicated by the plus sign on the icon in the Analysis Tree, as seen in Figure 2. The initial pore-water pressure conditions on the Water tab are defined using the steady-state seepage analysis (Analysis A) as shown in Figure 5.

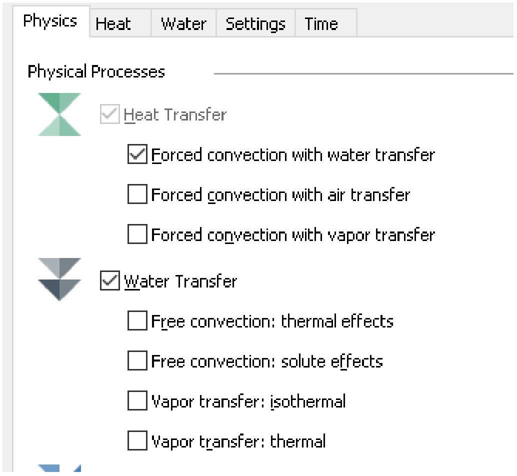

Figure 4. Example of coupling SEEP/W to TEMP/W for convective heat transfer analyses.

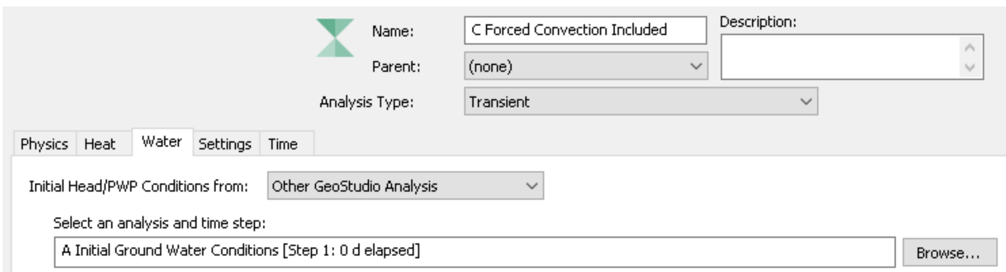

Figure 5. Setting the initial conditions from another GeoStudio Analysis.

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 versus 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 6). The temperature remains constant at – 2 °C from Day 1 onward.

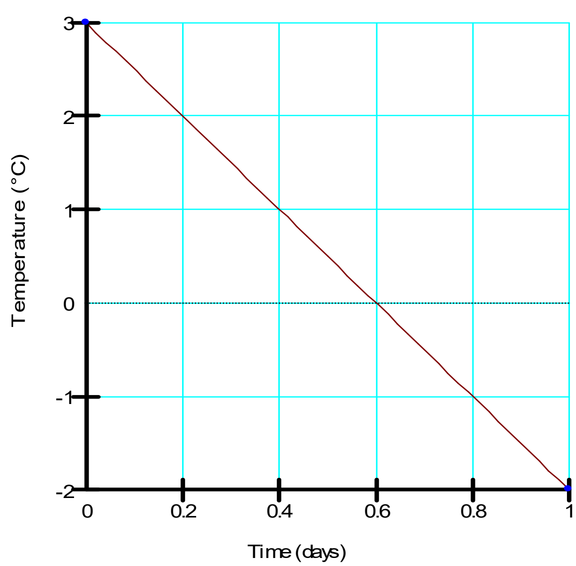

Figure 6 Temperature verses time boundary function used to model pipe cooling.

The hydraulic boundary conditions were selected in this analysis to establish a lateral groundwater flux of about 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 and coupled 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 2 years using twenty time steps with an exponential sequence and an initial time increment of 3.65 days.

The heat transfer material properties are kept the same in the conduction-only and forced convection analyses. The full-thermal material model is used for both TEMP/W analyses, which makes the thermal conductivity a function of temperature (Figure 7), while also introducing an Unfrozen Water Content function. The latter ensures that the pore-water changes phase over a temperature range (Figure 8). The water content is also entered as a constant (Figure 9). The use of a full-thermal material model highlights the fact that a coupled-convective material model is not required for a coupled heat and water transfer analysis, particularly if the water content is constant throughout the analysis.

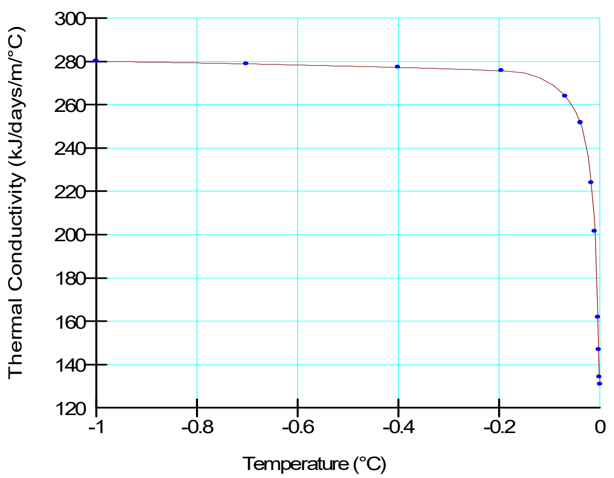

Figure 7. Thermal conductivity function for a full-thermal material model.

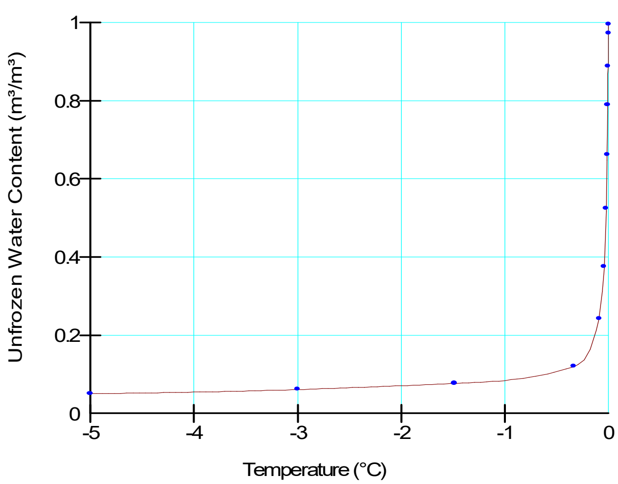

Figure 8. Unfrozen water content function for a full-thermal material model.

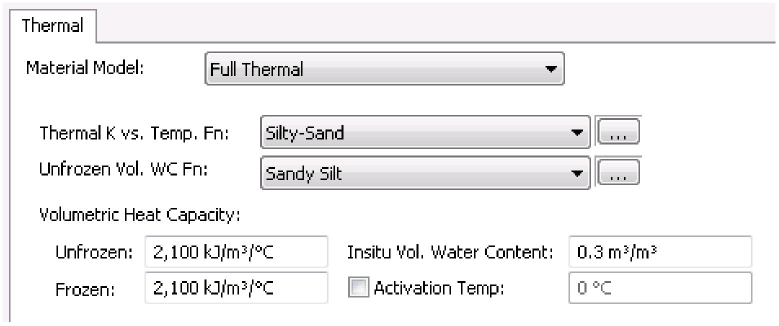

Figure 9. Material inputs for a full-thermal material model.

Figure 10 presents the hydraulic tab for the material in the forced-convection analysis. The hydraulic properties must be defined because a water transfer analysis is being solved on the same domain. More importantly, a saturated-unsaturated material model with a hydraulic conductivity function is required in order for SEEP/W to give consideration to frozen ground conditions. In a forced-convection analysis, SEEP/W computes the frozen ground matric suction according the Clausius-Clapeyron equation. This suction is then used to determine the hydraulic conductivity directly from the function.

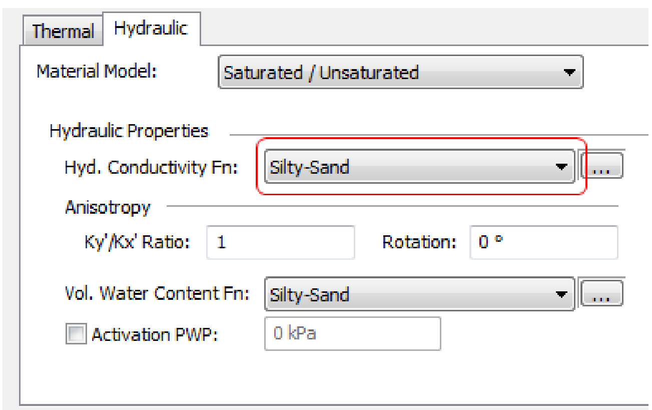

Figure 10. Hydraulic tab for the material properties.

Results and Discussion

Figure 11 presents the results for a gauss region in the steady-state seepage analysis. The x-flux rate is 8.25 x 10^{-6} m^3/sec/m^2 and the gradient is 0.00475, which is consistent with the boundary conditions and hand calculation presented above. The x-gradient and flux rate actually vary across the domain due to the presence of the pipe, which alters the total head distribution.

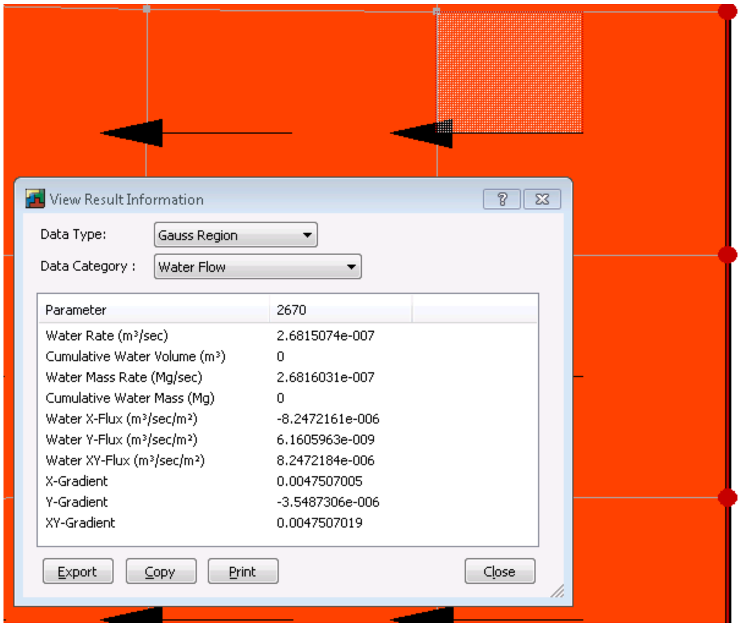

Figure 11. Gauss region results from the steady-state seepage analysis.

Figure 12 presents the temperature contours and freezing front location for the conduction-only case at year 2. 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.

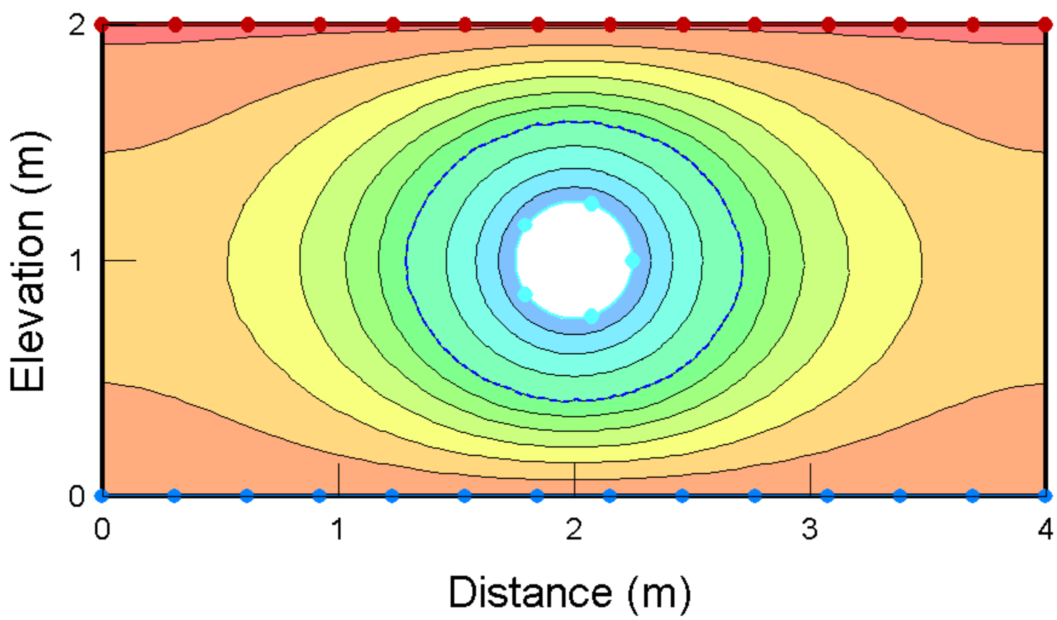

Figure 12. Temperature contours and freezing front location for conduction-only analysis.

The results for the forced convection analysis at year 2 are presented in Figure 13. The flow of heat from right to left via convection with the flowing water has mitigated the propagation of the freezing front in the upstream direction compared to the conduction-only analysis. Interestingly, the freezing front on the 'downstream' side of the pipe (left side) has expanded only as far as the conduction-only case. This occurs because of the relatively stagnant water flow within the freezing front, which implies that conduction is the dominant transport mechanism. Figure 14 presents the corresponding water flux vectors, demonstrating that water flow is impeded within the frozen zone.

A comparison between the two analyses demonstrates the significant effect of flowing water on the growth of the freezing zone and the importance of impeding water flow due to pore-ice blockage. If the groundwater velocity would be even higher, the growth of the frozen zone upstream of the pipe 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.

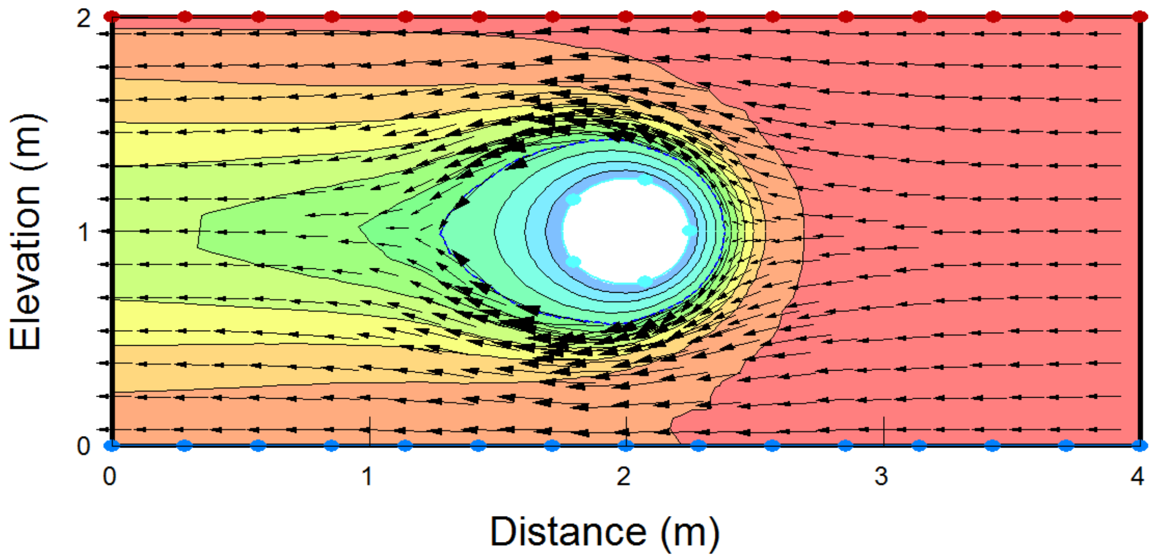

Figure 13. Temperature contours and freezing front location for forced convection analysis.

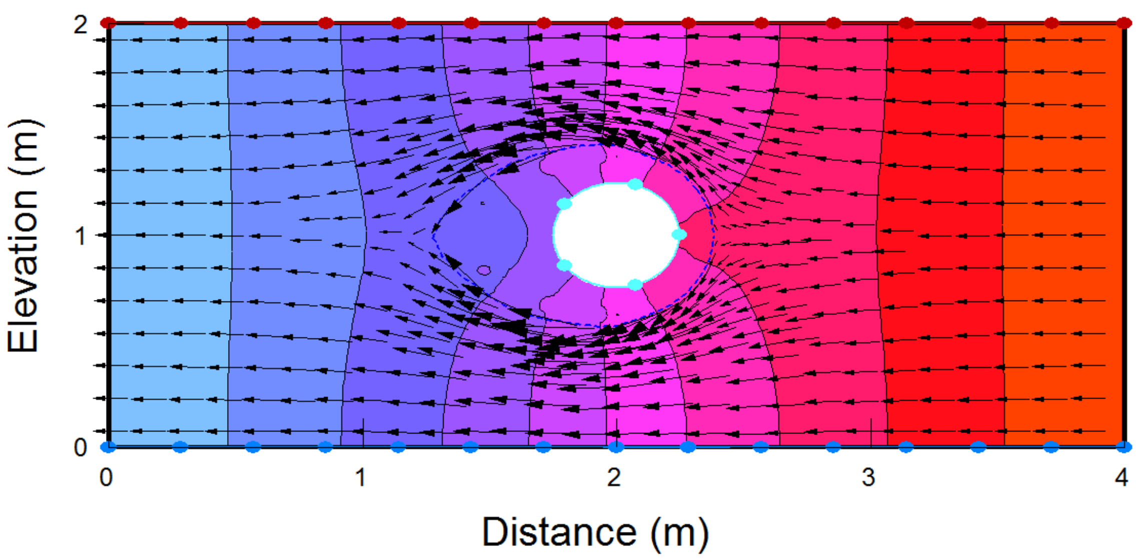

Figure 14. Flux vectors from the transient SEEP/W analysis.

Summary and Conclusions

TEMP/W can be used to model heat transfer via conduction and forced convection with moving water. In this example, the Full Thermal material model was used and required the following material inputs: a) thermal conductivity versus temperature function; b) unfrozen water content function; and c) frozen and unfrozen volumetric specific heat capacity constants. The software automatically makes adjustments to the material properties for frozen and unfrozen conditions.

A forced-convection TEMP/W analysis in which the hydraulic conductivity is reduced in the frozen zone requires that both heat and water transfer be solved on the same domain. This necessitates the definition of hydraulic material properties and boundary conditions, in addition to the thermal boundary conditions. A saturated-unsaturated material model must be used along with a hydraulic conductivity function such that the hydraulic conductivity is reduced when the ground undergoes freezing.

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.

References

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