TEMP/W Tutorial

1 Introduction

The objective of this example is to model ground freezing beneath a skating rink. The modeling approach is applicable to any engineering project that involves ground freezing because it demonstrates the key material properties and boundary conditions required for this class of problems.

2 Feature highlights

GeoStudio feature highlights include:

- Multiple analyses in a single file (i.e., project)
- Mesh refinement in the anticipated phase change zone
- Material properties for a 'full-thermal' material model
- Modeling phase change

3 Numerical Model

Figure 1 presents the geometry and mesh for the model domain. The ice surface extends from an x-coordinate of 0 to 1 m, where the ice rink boards are located. Outside of this area sits a walkway and spectator seating. There is little value extending the model domain further to the left because the freezing front propagation will be vertically downward beneath the ice surface. The right and left boundary locations were selected to minimize the influence on the area of interest.

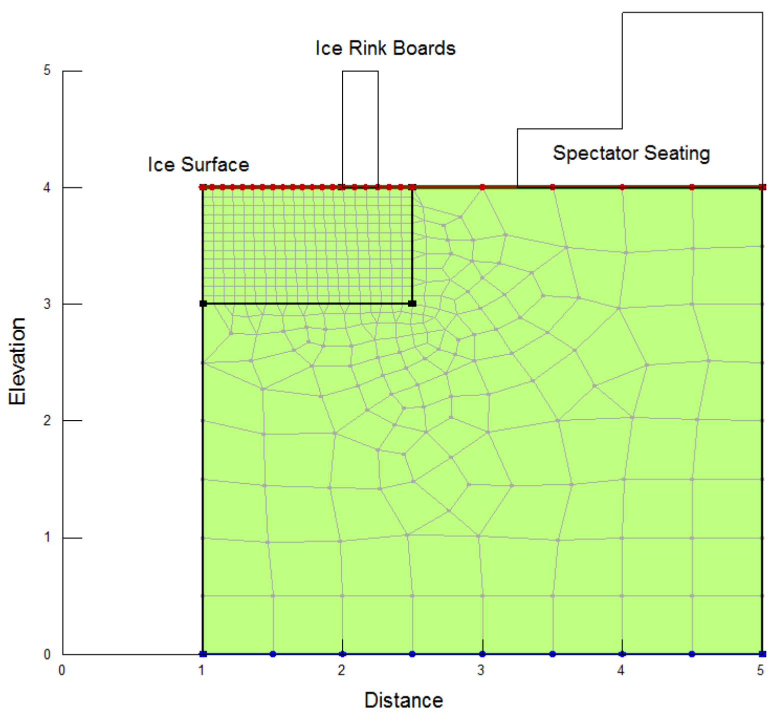

Figure 1 - Model geometry and mesh

A global element size of 0.5 m was used for the model domain. The mesh in the rectangular region beneath the ice surface was refined because: a) greater resolution is desirable in the area of interest; b) the thermal gradient is anticipated to be high in this zone; and, c) phase change will occur in this region. Mesh refinement was accomplished by clicking on Draw Mesh properties, selecting the region, and selecting 'Rectangular Grid of Quads'. Subsequently, the left and bottom lines of this region were selected and an element size of 0.075 m was specified (Figure 2).

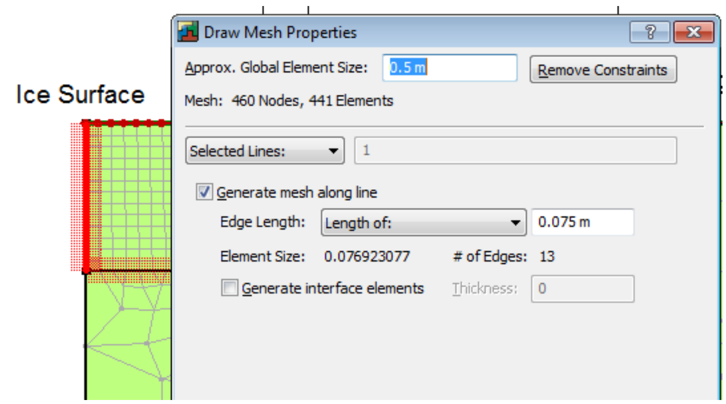

Figure 2 - Mesh properties for region beneath ice surface

Figure 3 displays the project analysis tree for this file. There are two analyses: a) a steady-state analysis used to establish the initial conditions; and, b) a transient analysis used to model the downward propagation of the freezing front. GEO-SLOPE International uses a family-tree nomenclature to describe the relationship between analyses. In this case, the steady-state analysis (Initial Condition) is the Parent and the transient analysis (1-Freezing Stage) is the Child, as indicated by the relative position in the Analysis Tree. The initial temperature conditions for the transient analysis are defined using the Parent analysis under the KeyIn Analyses settings (Figure 4).

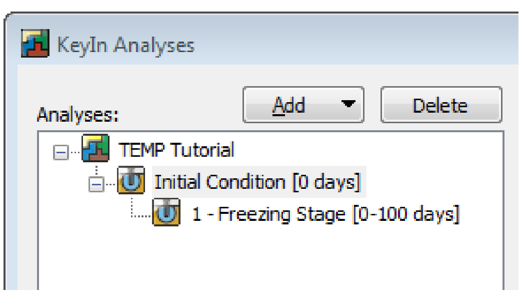

Figure 3 - Analysis tree for the GeoStudio project

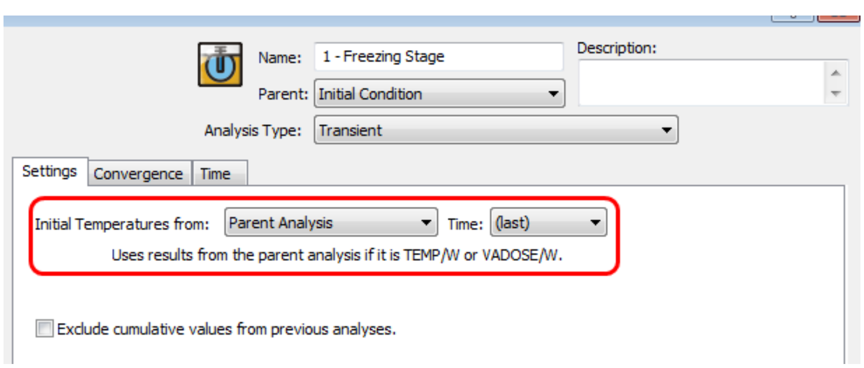

Figure 4 – Definition of the initial conditions for the Freezing Stage transient analysis

A full-thermal material model has been selected for the foundation soil (Figure 5). The fundamental difference between a full thermal and simplified thermal material model in TEMP/W is the manner in which the latent heat of fusion is included during phase change. A simplified thermal material model assumes that all of the pore-water is either frozen or unfrozen. In contrast, a full thermal model utilizes the normalized unfrozen water content function (UVWC, Figure 6). Consider a change from + 1°C to – 1 °C across a time step for the material below. The simplified thermal model would assume that 0.5 m^3 of water per m^3 of soil froze instantly. The full-thermal material model would calculate the change in UVWC using the function as 0.5 (1 – 0.2) = 0.4 m^3 of water per m^3 of soil. This may seem like an insignificant difference, but it can have a substantial effect on numerical oscillation during solution given the fact that the latent heat of fusion of water is about two orders greater than the heat capacity of a saturated soil.

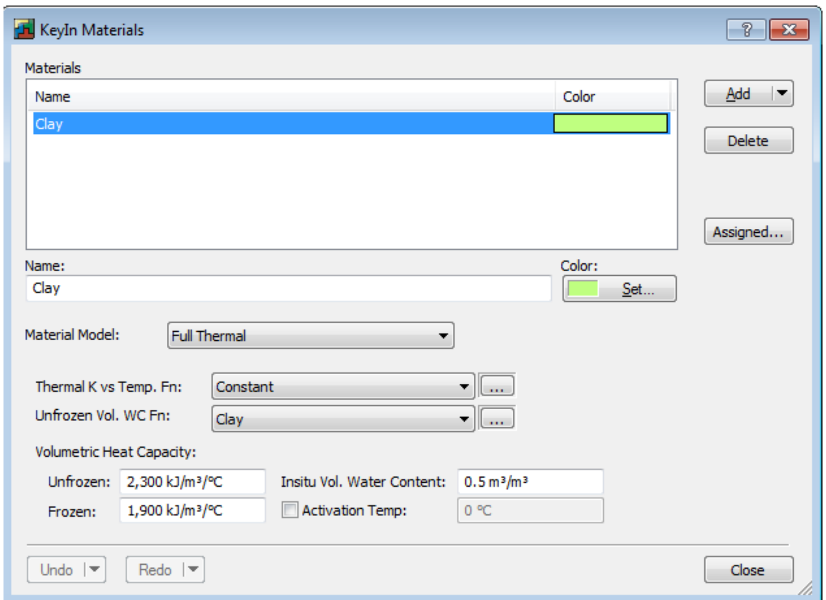

Figure 5 - Inputs for a full-thermal material model

For this example, the thermal conductivity was assumed constant with temperature at a value of 165 kJ/day/m/°C. The volumetric heat capacity of the unfrozen and frozen soil was set to 2300 kJ/m^3/°C and 1900 kJ/m^3/°C, respectively. This implies that an unfrozen soil has a greater capacity to store heat energy than a frozen soil. Stated another way, more energy must be adsorbed or released per volume of soil to change the temperature of the soil by one degree Celsius.

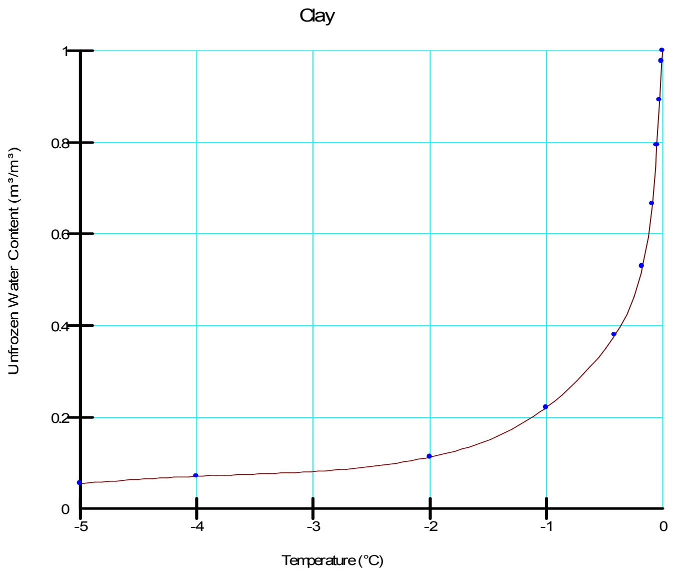

Figure 6 – Normalized unfrozen water content function for a silty sand

In the steady-state analysis, a constant temperature boundary condition of 3.1 °C and 3.0 °C has been applied to the top and bottom of the domain, respectively. In the transient analysis, the top boundary was replaced with a constant temperature of –5 °C. It should be noted that this boundary condition was applied only to the line that terminates at the inside edge of the rink boards. The left and right edges of the domain are no-flow, which is the default boundary condition in a finite element analysis (i.e. no heat flow crosses these boundaries). The ground surface outside the ice surface footprint is also set to a no-flow condition, although it could be argued that a more realistic boundary condition would be the ambient air temperature inside the building.

The duration of the analysis is set to 100 days using ten time steps and an exponential step increase. The initial increment size is set to 2 days and each time step is saved. The default convergence and under-relaxation values are used in this analysis.

4 Results and Discussion

Figure 9 presents the temperature contours and location of the freezing front in the vicinity of the ice surface on day 100 and Figure 10 presents temperature profiles for all time steps. Figure 11 displays the location of the freezing front for each time step, which was generated using the Draw Isolines command and selecting all time steps. Contour labels are added by selecting the Draw Contour Labels command. The results demonstrate the downward propagation of the freezing front with time. The thermal flux vectors are pointed upward toward the ground surface as heat flow is toward the cooling front. Naturally, the contours are tightest near the frozen zone where the gradient is the highest. The contours and thermal flux vectors in Figure 9 also demonstrate that the freezing front is propagating laterally underneath the rink boards.

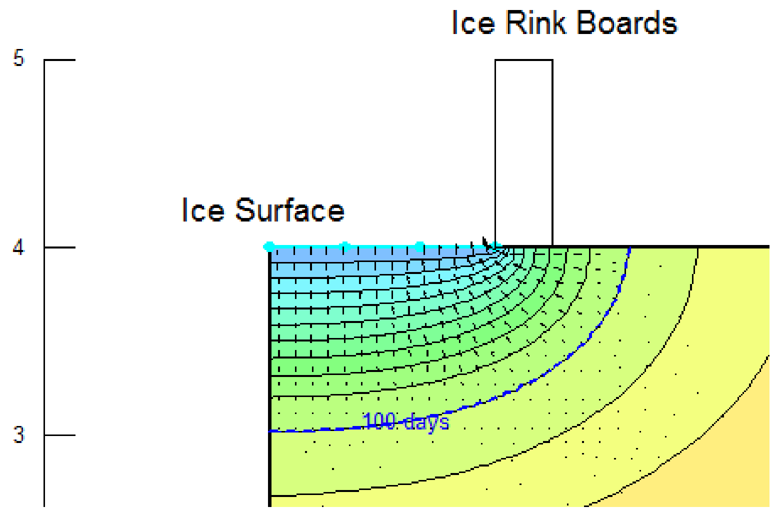

Figure 9 – Contours of temperature on Day 100

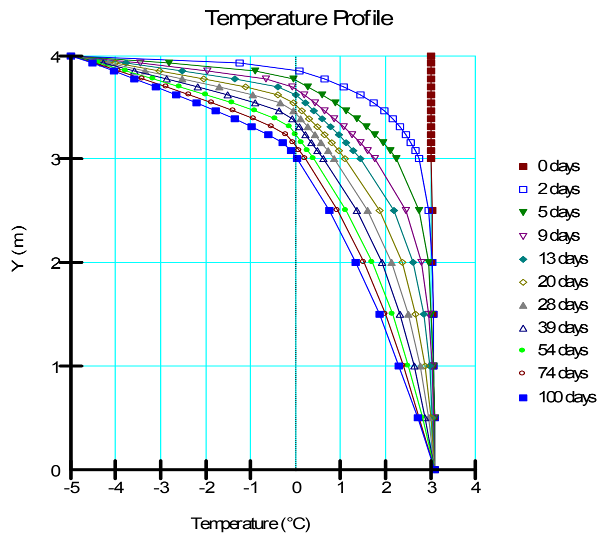

Figure 10 - Temperature profile along left edge for all time steps

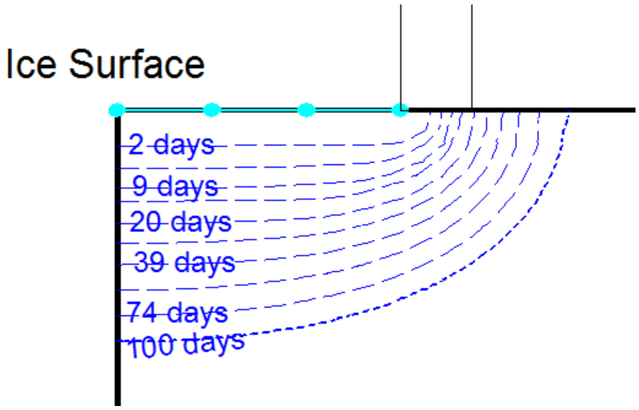

Figure 11 - Location of the freezing front at all-time steps

Figure 12 presents the cumulative energy extracted from the ice surface with time. The data at each node is summed and presented as a single value. This data could be used for sizing the refrigeration equipment or electrical power consumption for the facility. It is important to remember that a two-dimensional analysis assumes one unit in the out-of-plane direction, so this graph represents the cumulative heat flow across an area that is 1 m by 1 m in dimension.

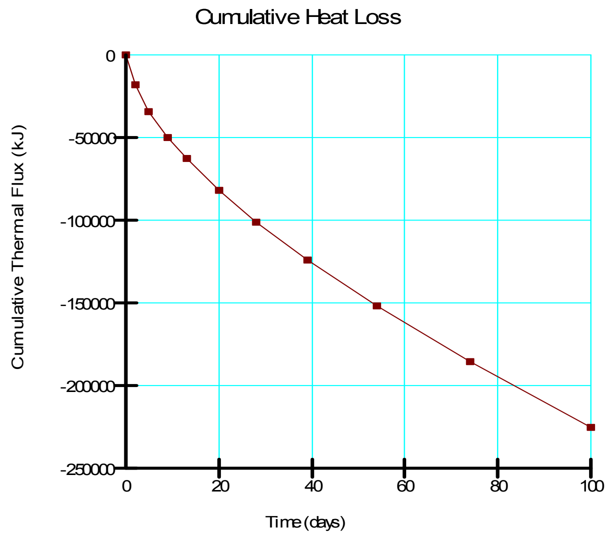

Figure 12 – Cumulative energy extraction from ice surface.

Finally, a plot of iteration count verses time step is presented in Figure 14 to demonstrate that the analysis is converged. In this analysis, the maximum iteration count is set to 100 under the KeyIn Analyses convergence tab and the convergence criterion is set to 2 significant digits. In other words, the difference in solved temperature between two successive iterations at every node in the domain must be within 1.00×10^{-1} °C (0.01 °C) before the solver terminates. It is possible to solve such numerically demanding phase change problems in TEMP/W due to the under-relaxation algorithm implemented in the software. Without under-relaxation, the solution would oscillate in perpetuity and convergence would not be achieved.

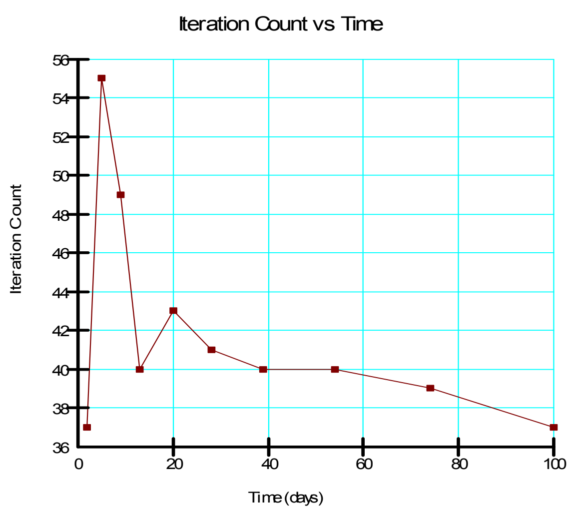

Figure 14 - Iteration count verses time

5 Summary and Conclusions

This example demonstrates the key material properties, boundary conditions, and mesh refinement required for a ground freezing analysis. A full-thermal material model is used for the soil domain to demonstrate the use of a normalized unfrozen water content function. The results show that the freezing front propagates vertically downward to a depth below ground of approximately 1 m. Moreover, the TEMP/W analysis can be used to design the refrigeration system and power requirements for a ground freezing project.