TEMP Tutorial – Getting Started

GEO-SLOPE International Ltd. | www.geo-slope.com

1200, 700 - 6th Ave SW, Calgary, AB, Canada T2P 0T8
Main: +1 403 269 2002 | Fax: +1 888 463 2239

Introduction

Artificial hockey and skating ice surfaces are currently created with a refrigeration system. This makes it possible to keep the ice in place for extended periods of time, which in turn can lead to extended ground freezing beneath the ice surface. To prevent the ground freezing, the ice surface is often constructed on top of insulation. In this illustrative example, the objective is to demonstrate the effect of the refrigeration system on an underlying soil region if this insulation is not present.

The primary purpose of the example is to illustrate the steps and procedures required for a heat transfer analysis with phase change using TEMP/W. The soil properties and boundary conditions have been selected for illustrative purposes only.

Numerical Simulation

Figure 1 presents the problem configuration. The ice surface extends from an x-coordinate of 1 to 2 m, where the ice rink boards are located. Outside of this area is a walkway and spectator seating. Beneath the ice is a concrete layer with the refrigeration pipes, which is not included in the thermal analysis. There is little value in 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.

There are two analyses in the GeoStudio Project (Figure 2). The first analysis is set as the Parent for the transient analysis (Figure 3). The Parent is a steady-state analysis and is used to establish the initial temperature conditions for the 'Child' transient analysis, which is used to simulate the downward propagation of the freezing front.

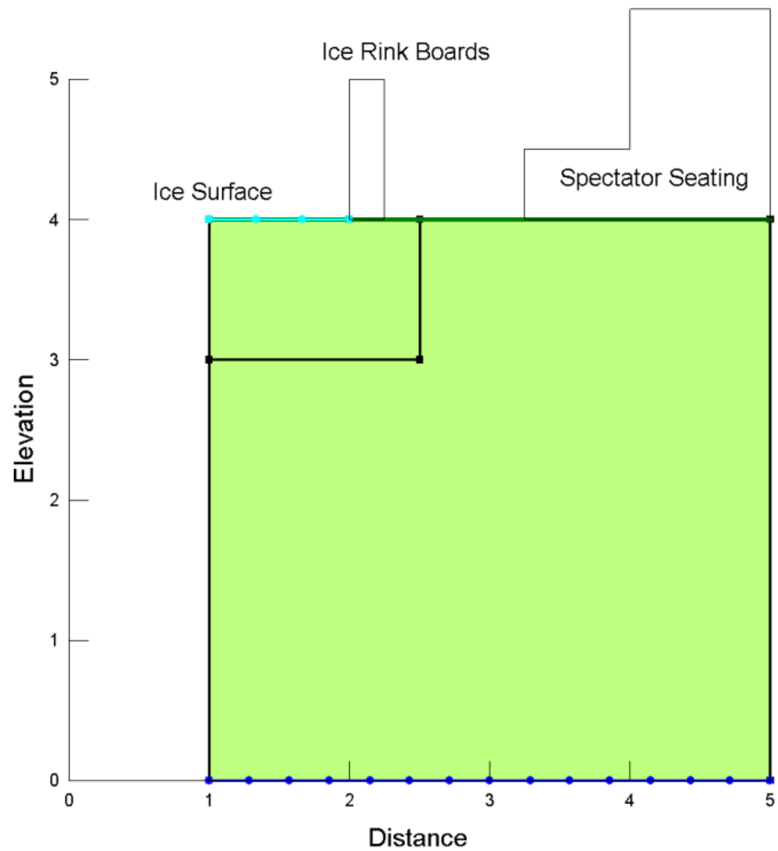

Figure 1. Problem configuration.

Figure 2. Analysis Tree for the project.

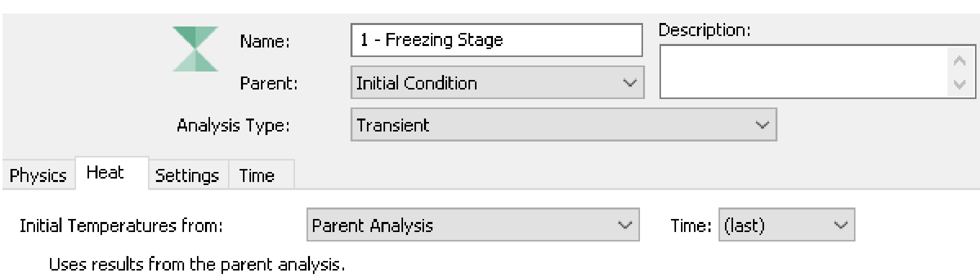

Figure 3. Initial temperatures used from the Parent analysis in the Heat tab.

A full-thermal material model has been selected for the soil (Figure 4). 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 (Figure 5). For example, 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.

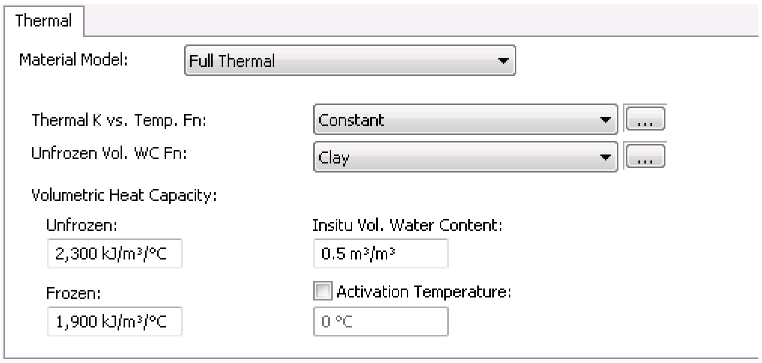

Figure 4. Specified material properties.

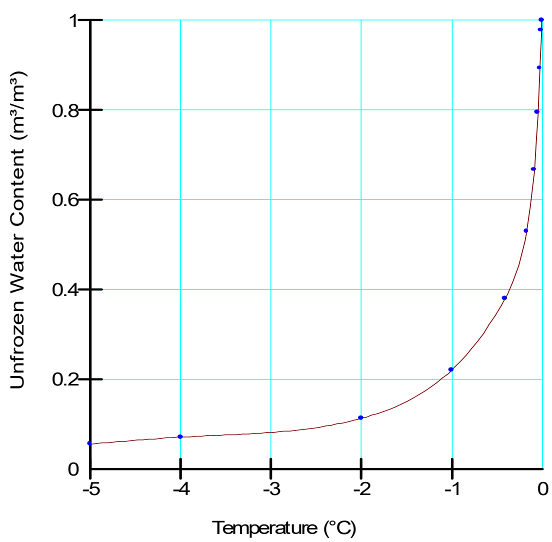

Figure 5. Unfrozen water content function.

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.

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 to represent the temperature of the ice. 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 bottom boundary is kept at the same constant 3.0°C temperature as the steady-state analysis. The temperature at the bottom boundary was assumed constant for illustrative purposes; however, a more realistic boundary condition would have been a heat flux corresponding to the geothermal gradient. Moreover, the bottom boundary should likely be moved further far-field.

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 global element size has been set to 0.5 m. In order to more accurately simulate the phase change front propagation into the soil, the region below the ice surface has been changed from the default Quads and Triangles mesh pattern to a Rectangular Grid of Quads pattern. The mesh within this region was also refined using the line segments on the lower and left boundaries and an element length of 0.075 m (Figure 6).

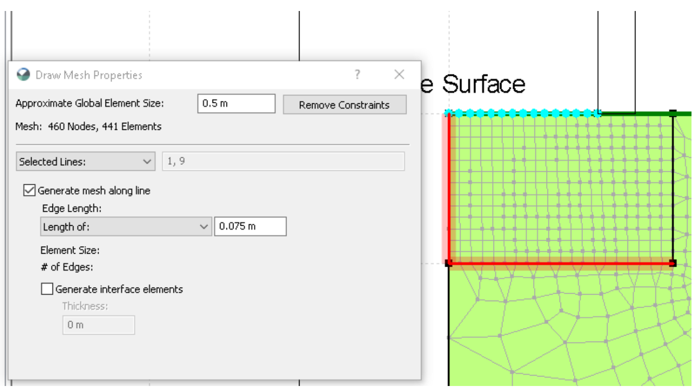

Figure 6. Mesh refinement of the soil region directly below the ice.

Computing the correct temperatures requires an iterative procedure since some of the material properties, like the conductivity for example, are functions of the computed results. Controlling the iterative process necessitates defining two parameters in the Heat tab (Figure 7). For this case, the the temperatures at each node for two successive iterations must be within 2 significant digits for convergence, while the difference in temperature is no more than 0.01 degrees. Moreover, establishing the position of the freezing front requires an under-relaxation scheme. In this case, the under-relaxation rate is 0.1 (10%).

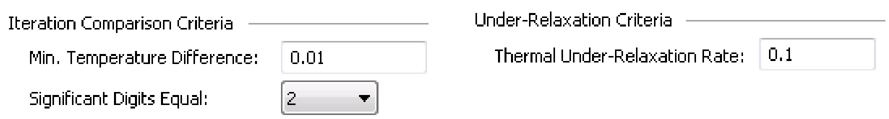

Figure 7. Convergence specifications.

Results and Discussion

The thermal regime and location of the freezing front at the end of 100 days is given in Figure 8. Figure 9 displays the location of the freezing front for each time step, which was generated using the Draw Isolines command and selecting all time steps. 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 moving 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 also demonstrate that the freezing front is propagating laterally underneath the rink boards.

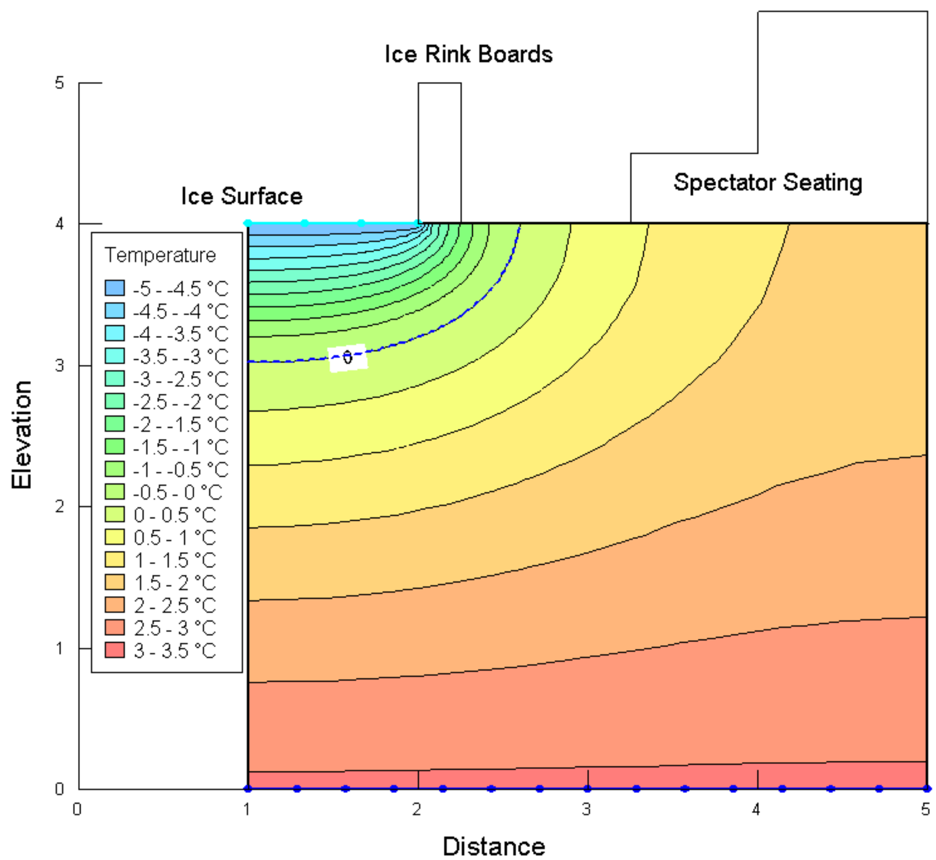

Figure 8. Freezing front location after 100 days.

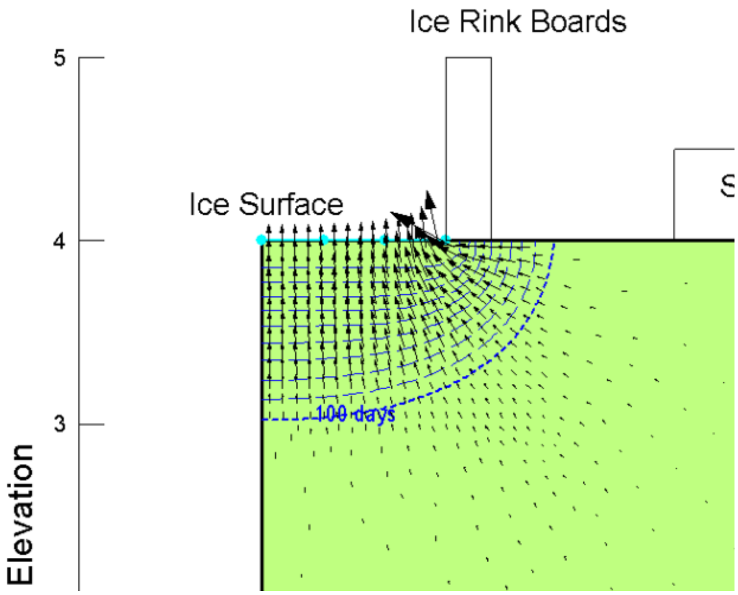

Figure 9. Freezing front location with each time step.

The temperature profile with depth is given in Figure 10. The propagation of the freezing front can also be seen in this figure for each time step along the 0°C temperature line.

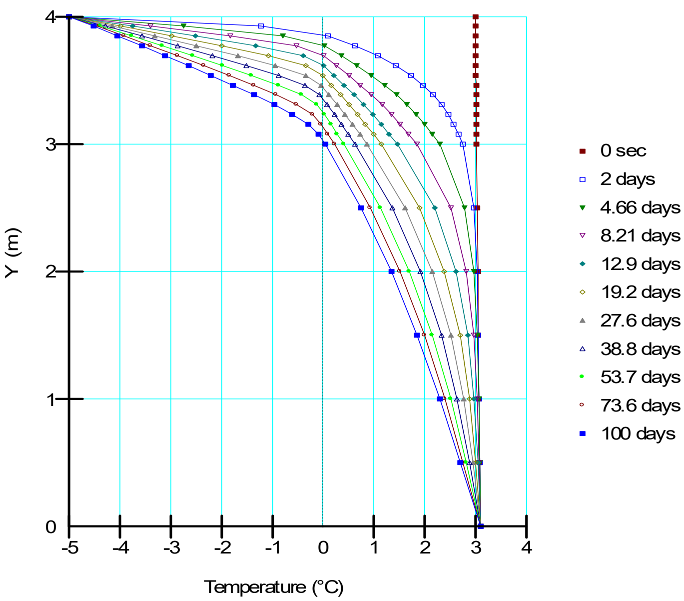

Figure 10. Ground temperature profiles at the left edge of the domain.

Figure 11 presents the cumulative energy extracted from the ice surface with time, where a negative value indicates that heat is being removed from the domain. 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.

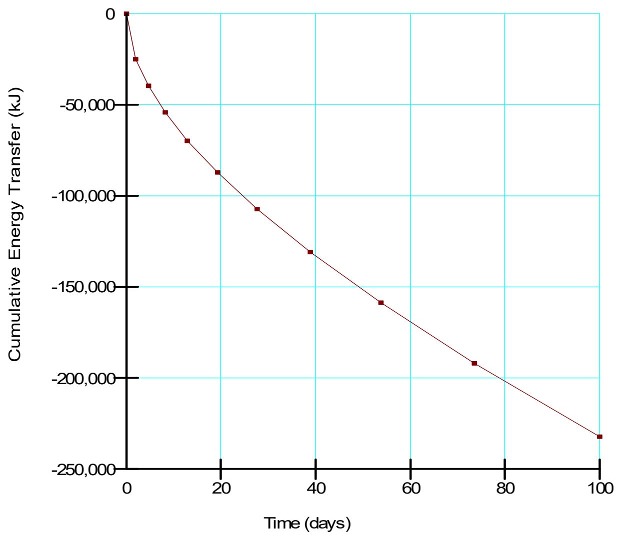

Figure 11. Cumulative energy transfer out of the domain.

Finally, a plot of iteration count versus unconverged temperature nodes is presented in Figure 12 to demonstrate that the analysis is converged. In this analysis, the maximum iteration count was set to 75. Without the under-relaxation, the solution would oscillate in perpetuity and convergence would not be achieved. In the event that the solution does not meet the convergence criteria, symbols will be drawn at the unconverged nodes provided the View Preferences option is activated (Figure 13).

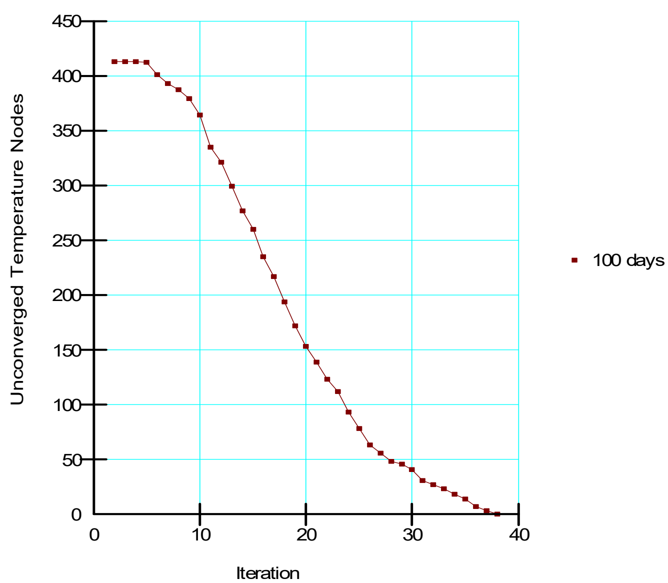

Figure 12. Unconverged temperature node counts at each iteration.

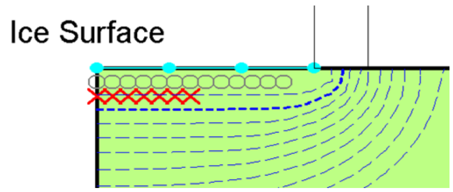

Figure 13. Illustration of flagged nodes where the solution does not meet the specified criteria.

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.