Mine Shaft Freezing

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 soil freezing is used in many engineering projects to excavate and construct mine shafts, tunnels or other underground structures through water bearing, often unstable, soil formations. This example demonstrates a procedure for modeling the freeze wall growth for a mine shaft project. It is assumed that the groundwater velocity is not high enough to affect the closure of the freeze wall.

Numerical Simulation

The intention is to create a frozen barrier that encircles a mine shaft using a series of equally spaced freeze pipes. As shown in Figure 1, the mine shaft has a diameter of 12 m, and the pipes are located 1 m from the shaft wall at a 10-degree central angle spacing. For the sake of clarity, the location of the mine shaft boundary is highlighted by a thick black arc. Due to symmetry, only a pie-shaped segment of the domain is simulated for computing and file storage efficiency. The total duration of the analysis is set to 90 days with 6 hour time increments.

Figure 2 shows the Full Thermal Material Model settings used to describe the native clayey soil. The thermal conductivity function was estimated using the sample clay material with a frozen thermal conductivity of 2.4 J/sec/m/°C and an unfrozen thermal conductivity of 2.0 J/sec/m/°C (Figure 3). The unfrozen water content function is also estimated from the sample clay material. As shown in Figure 4, some of the pore water remains unfrozen at temperatures below the freezing temperature of pure water. The presence of this unfrozen water is mainly ascribed to salinity, capillarity, and surface forces. It must be noted that the material activation temperature, or initial temperature, is set equal to 8°C.

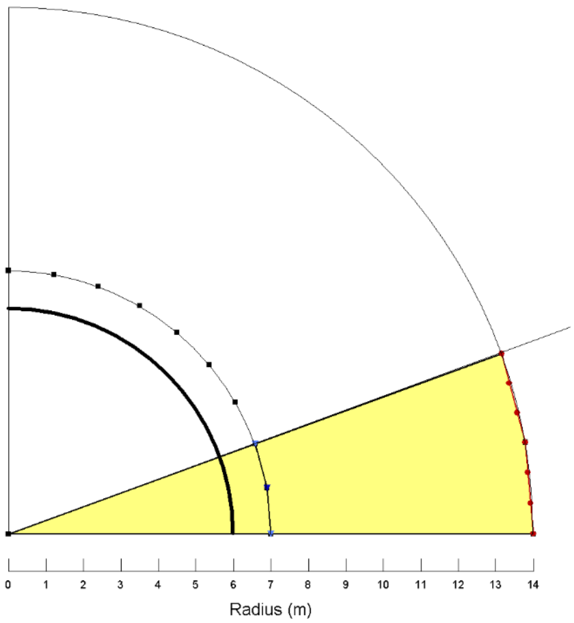

Figure 1. Problem configuration.

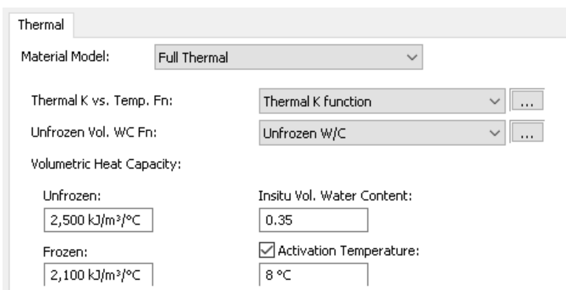

Figure 2. Full Thermal Material Model settings.

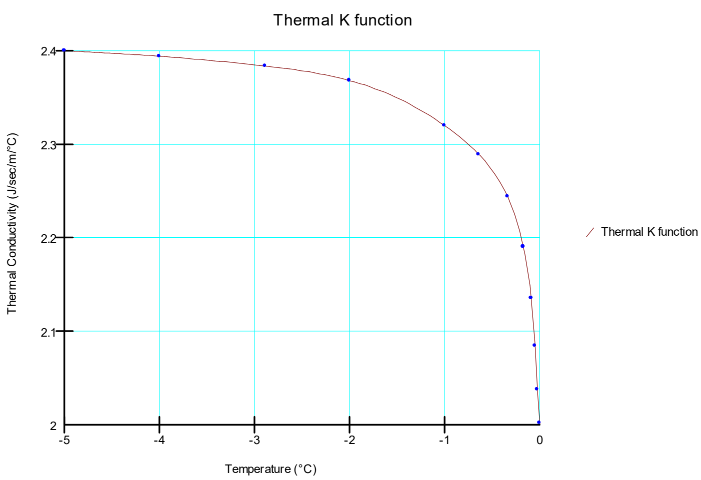

Figure 3. Thermal conductivity versus temperature.

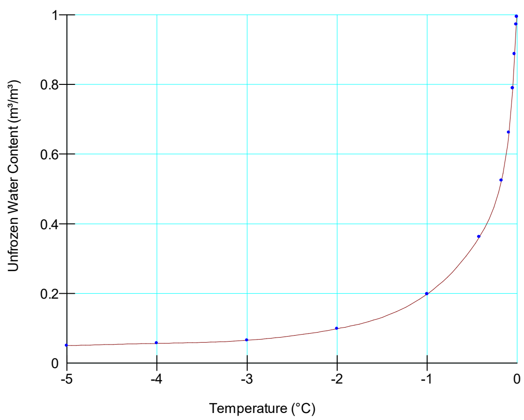

Figure 4. Normalized unfrozen volumetric water content versus temperature.

It can be difficult to create a physical opening in the finite element mesh to represent the relatively small freeze pipes. To circumvent this difficulty, points are defined at the locations of the freeze pipes, and the pipe size is specified within the Convective Surface boundary condition (Figure 5). This boundary condition is chosen over a constant temperature condition because it correctly accounts for heat transfer between the pipe wall and the flowing brine. The heat transfer coefficient, h, is computed as follows

$$h = \frac{k_b \mathrm{Nu}}{D_h}$$ **Equation 1**

where k_b is the thermal conductivity of the brine, Nu is the dimensionless Nusselt number, $D_h = 4A/P$ is the hydraulic diameter, A is the cross-sectional area, and P is the wetted perimeter. The Nusselt number depends on the pipe geometry, the flow regime, and the boundary condition at the pipe surface. In the specific case of a circular pipe with fully-developed laminar flow and constant pipe surface temperature, the Nusselt number is equal to 3.66 [Bergman et al., 2011]. Considering that the freeze pipes are 100 mm in diameter and filled with calcium chloride, k_b = 0.497 J/sec/m/°C, the heat transfer coefficient is equal to

$$h = \frac{k_b \mathrm{Nu}}{D_h} = \frac{k_b \mathrm{Nu}}{\frac{4\left(\pi D^2/4\right)}{\pi D}} = \frac{k_b \mathrm{Nu}}{D} = \frac{0.497\ \mathrm{J/sec/m/°C} \times 3.66}{0.1\mathrm{m}} = 18.19\ \mathrm{J/sec/m^2/°C}$$ **Equation 2**

It is important to note that the effective perimeter of the pipes on the edges of the domain is equal to half of the pipe perimeter. Distinct boundary conditions are therefore specified for the full pipe and the two half pipes.

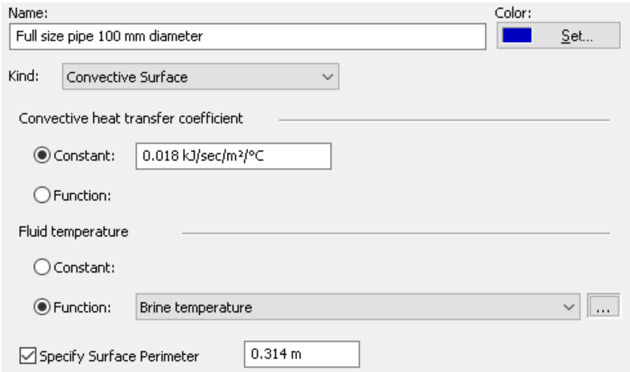

Figure 5. Required inputs for the convective surface boundary condition.

As shown in Figure 6, the brine temperature is assumed to cool down from -5 to -25°C over a period of five days. The far-field boundary is defined as the original soil temperature (8°C) using a constant temperature boundary condition.

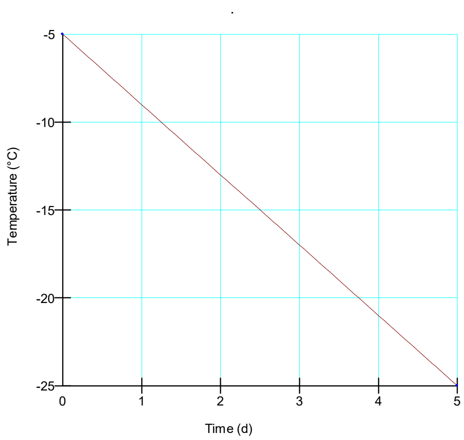

Figure 6. Brine temperature versus time.

Meshing for soil freezing problems is important because phase change can be the source of numerical oscillation in a heat transfer analysis. It is thus desirable to have a finer mesh in the phase change region where the thermal gradients are very steep and the amount of heat released or absorbed is significant, leading to abrupt changes in temperature over short distances. In this analysis, the mesh is refined near the points representing the freeze pipes, and the Split Region tool is used to create a geometry line along the freeze pipe locations (Figure 7). The mesh refinement is defined using the "ratio of default size" option in the Draw Mesh Properties window with the points chosen.

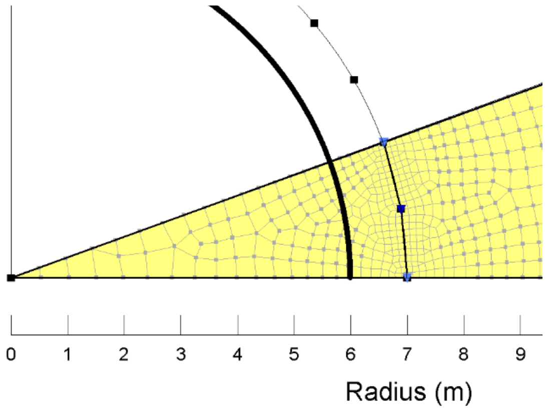

Figure 7. Mesh refinement along location of freeze pipes.

Results and Discussion

Figure 8 (a) shows the temperature contour plot as time approaches 20 days. Although the blue contours extend to a temperature of 0°C, the soil can only be considered frozen when the temperature reaches the solidus temperature, which in this case, is approximately -3°C. In order to visualize the frozen zone, the temperature isoline (dashed blue line) was herein set equal to -3°C. As expected, small frozen zones have developed around the freeze pipes. Figure 8 (b) shows that the frozen zones become large enough to close the gap between the pipes as time reaches 60 days. As shown in Figure 8 (c), a 1.5 m thick frozen wall has formed between the pipes and the edge of the mine shaft on the final simulation day.

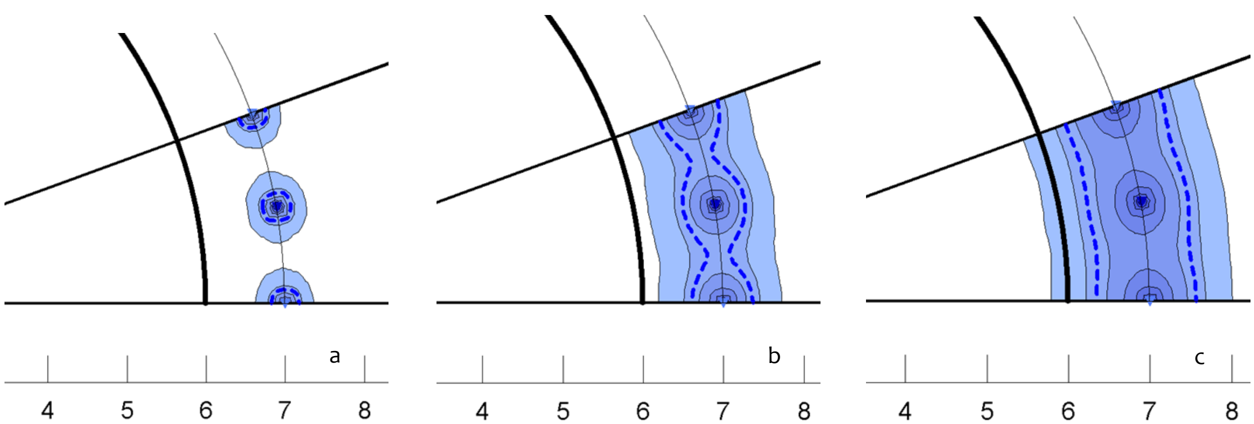

Figure 8. Extent of frozen soil. (a) Day 19.8. (b) Day 60.1. (c) Day 90.

Figure 9 presents the soil temperature versus time at a node between two freeze pipes. Although it is often assumed that water freezes at 0°C, this is not the case in soils. Due to various factors, such as salinity, capillarity and surface forces, water freezes over a range of temperatures. The range used in the model is determined from the input thermal functions, and more specifically, the unfrozen volumetric water content function. The end result is that the cooling temperatures will "lag" as a large amount of latent heat is extracted via the freeze pipes. Accordingly, the temperature remains nearly constant between 20 and 30 days. Beyond this point, the extraction of latent heat decreases as the temperature drops, and the amount of unfrozen water decreases.

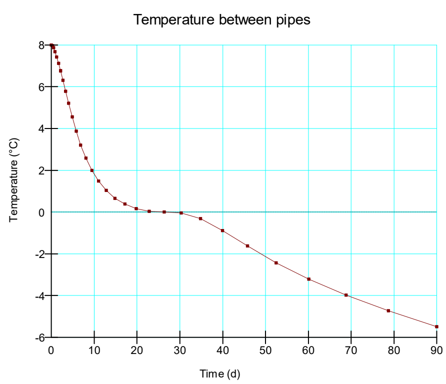

Figure 9. Temperature versus time at a node between two freeze pipes.

Figure 10 shows a cut line graph from the center of the shaft to the outer edge of the analysis domain. Notice that the soil temperature is well above the brine temperature of -25°C. Even after 90 days, the soil temperature is only -16.5°C. The pipe surface temperature does not reach the brine temperature because of the thermal gradient across the pipe wall. If the wall temperature equaled the brine temperature, there would be no temperature difference across the pipe wall and no heat transfer. As the soil around the pipes continues to cool, the pipe wall temperature will approach the brine temperature, but will never reach this temperature as long as there is a heat source somewhere in the ground.

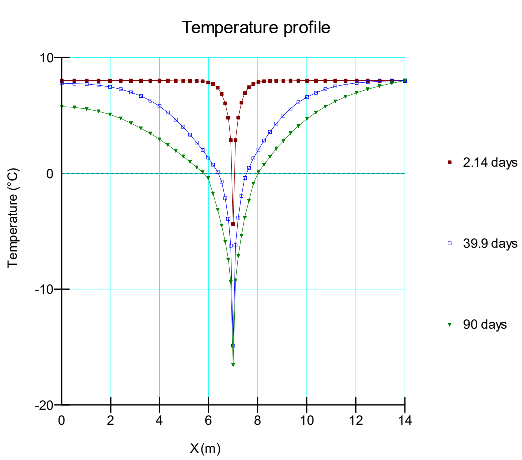

Figure 10. Temperature profile alone the outer edge of the analysis domain.

Figure 11 shows the heat extraction rate per unit length of pipe. The rate initially increases until the brine temperature reaches its minimum value of -25°C (the negative sign means that heat is being extracted from the system). After this point, the rate slowly decreases as the soil temperature drops. This is in complete agreement with the convective surface boundary condition which dictates that the extraction rate is proportional to the temperature difference between the brine and the soil.

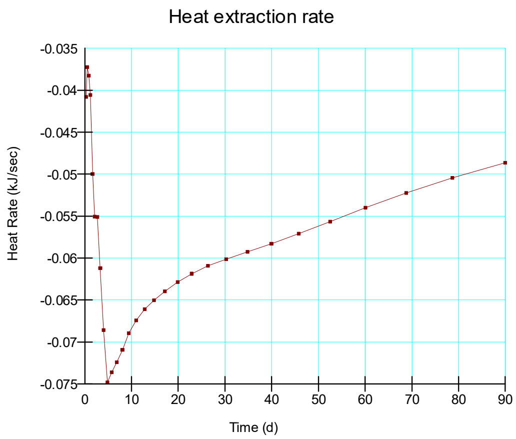

Figure 11. The rate of heat extraction per unit length of pipe.

Part of the design stage of a shaft freezing project is to determine how long it will take to develop a freeze wall, and to compute how much heat will have to be removed. Figure 11 shows that the long-term heat extraction rate for a single pipe is approximately -0.0486 kJ/sec/m. This value can be used to determine the required tons of refrigeration, which is the rate of heat transfer that results in melting one short ton (2000 lb or 907.18 kg) of pure ice in a 24 hour period. Given that the latent heat of fusion/solidification of water is 334 kJ/kg, one ton of refrigeration is equal to

$$\frac{334\ \text{kJ/kg} \times 907.18\ \text{kg}}{24\ \text{h} \times 60\ \text{min/h} \times 60\ \text{sec/min}} = 3.5\ \text{kJ/sec}$$

Equation 3

Assuming a total of sixteen freeze pipes for this project, each 100 m in length, results in a minimum freeze plant capacity of

$$\frac{16 \times 0.0486\ \text{kJ/sec/m} \times 100\ \text{m}}{3.5\ \text{kJ/sec}} = 22.2\ \text{tons of refrigeration}$$

Equation 4

If we want to meet the maximum heat extraction rate, the capacity would need to double (~ 40 tons of refrigeration). Ideally, a 100 ton freeze plant capacity would likely be selected to account for efficiency losses. It is important to realize that doubling the freeze plant capacity would not increase the freezing rate. The heat load is based on what the soil will give up to the brine, not what the brine extracts from the soil. The only way to decrease the cooling time is to add more pipes or lower the brine temperature. There may be a small benefit to increasing the diameter of the pipes, but this is a nominal gain during early freezing only.

Summary and Conclusion

TEMP/W can be used to model artificial soil freezing. In this example, the development of a freeze wall was modeled over a period of 90 days for the construction of a mine shaft. The results from the analysis can be used to design the refrigeration system, determine the time for closure, and ensure that the thickness of the frozen wall is adequate.

References

Bergman, T.L., Lavine, A.S., Incropera, F.P., and DeWitt, D.P. 2011. Fundamentals of heat and mass transfer. Seventh Edition, John Wiley & Sons, Inc.