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GeoStudio Example File
Mine Shaft Freezing

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Introduction

Artificial ground freezing is commonly utilized in engineering projects to excavate and construct mine shafts, tunnels, or other underground structures through water-bearing, often unstable, soil formations. This technique involves installing freeze pipes at equal distances to create a frozen barrier that encircles the mine shaft, thereby stabilizing the surrounding ground. A ground freezing analysis was completed in both 2D and 3D to simulate this phenomenon. The analyses are saved as separate GeoStudio project files. The 3D simulation provides a more comprehensive understanding of the freezing process because it considers heat transfer past the bottom of the freeze wall.

Numerical Simulation

Figure 1 shows the 2D domain comprising the mine shaft with a diameter of 12 m and the freeze pipes 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. For computing and file storage efficiency, only a pie-shaped segment of the domain is simulated, which is possible because of symmetry. The total duration of the analysis is set to 60 days with 4-hour time increments. It is assumed that the groundwater velocity is not high enough to affect the closure of the freeze wall.

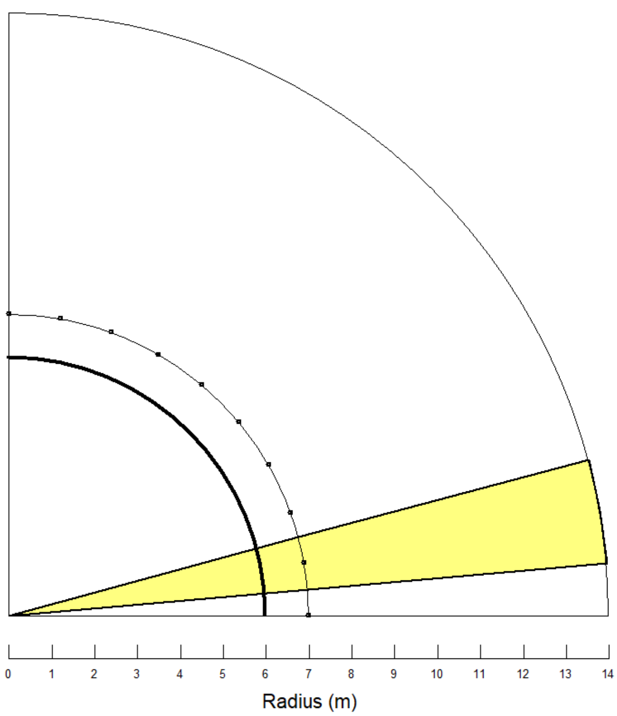

Figure 1. 2D domain configuration.

Meshing plays a critical role in soil-freezing simulations because phase change can introduce numerical oscillations during the solution process. A finer mesh is desirable in the phase change zone, where thermal gradients are steep and significant heat release or absorbtion occurs, causing abrupt temperature changes over short distances. As shown in Figure 2, the 2D mesh was refined by reducing the corresponding edge length around the freeze pipe (Draw – Mesh Properties).

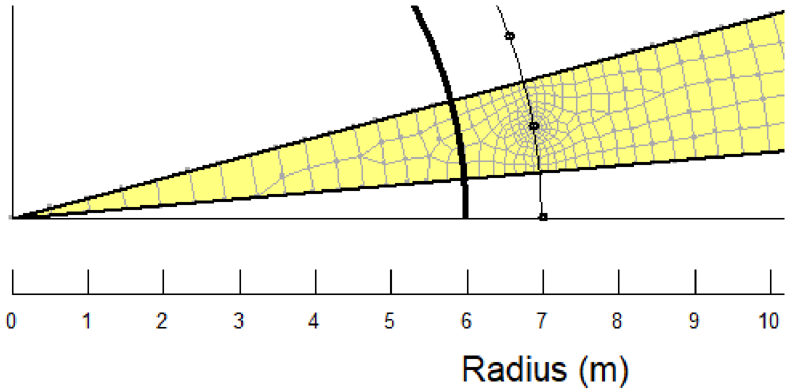

Figure 2. Mesh refinement along location of freeze pipes.

For the 3D analysis, the cross-section is extruded 10 m in the y-dimension (Figure 3). The freeze pipe extends from an elevation of 6 m to 10 m. Mesh refinement around the freeze pipe is achieved by setting a constraint and defining a refinement distance. The finite element mesh was generated with 1 m edge lengths in a tetrahedral pattern.

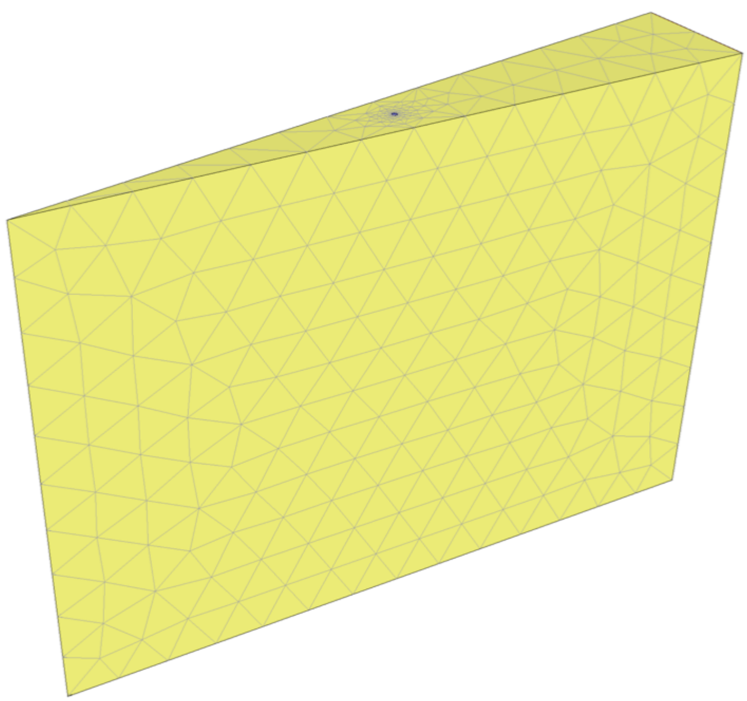

Figure 3. 3D domain and mesh configuration.

Figure 4 shows the Full Thermal Material Model of the clayey soil. The thermal conductivity function, shown in Figure 5, 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. The normalized unfrozen water content function is also estimated from the sample clay material. As shown in Figure 6, some of the pore water remains unfrozen at temperatures below the freezing temperature of pure water. The presence of this unfrozen water is mainly attributed to salinity, capillarity, and surface forces. The material activation temperature, or initial temperature, is set equal to 8°C.

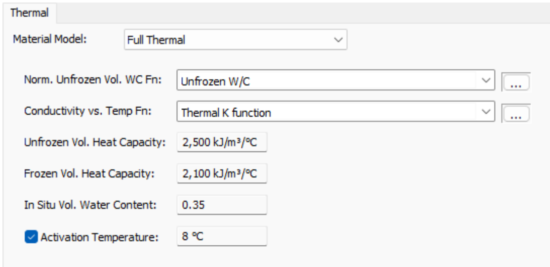

Figure 4. Full Thermal Material Model settings.

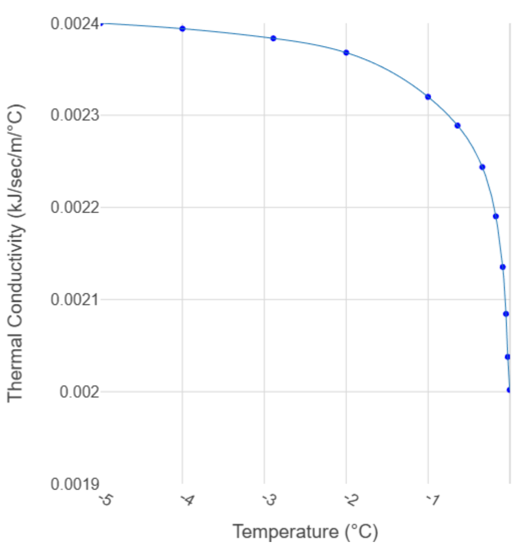

Figure 5. Thermal conductivity function.

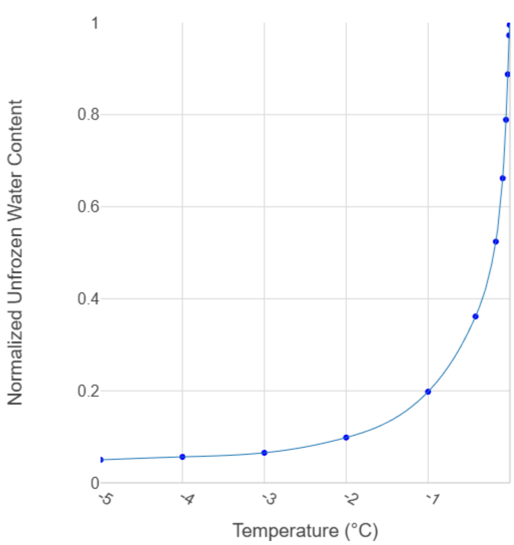

Figure 6. Normalized unfrozen volumetric water content function.

The Convective Surface is a third-type boundary condition, which is generally preferred over first-type or constant temperature boundary conditions because they more accurately represent heat transfer between the pipe surface and the brine. The Convective Surface boundary condition can be applied to a point (2D), line (3D), or surface (2D/3D). Application to a point or a line requires specification of the pipe's surface perimeter to correctly calculate the heat rate from the flux. The boundary condition is more accurately represented by applying the boundary condition to a surface because the geometry effects of the freeze pipe are represented. As such, the pipe is modeled as a circular opening in both the 2D and 3D analyses; consequently the Surface Perimeter is unspecified (Figure 7).

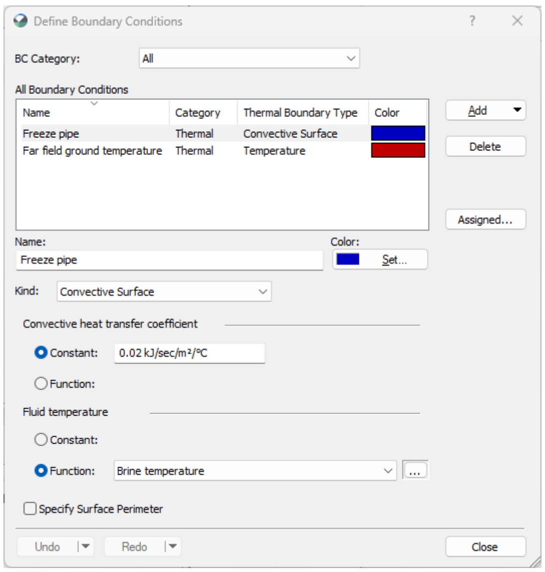

Figure 7. Required inputs for the convective surface boundary condition.

The heat flux is calculated as the product of the convective heat transfer coefficient and the temperature difference between the brine and the pipe surface. The convective heat transfer coefficient, h, is determined using the following relationship:

$$h = \frac{k_b Nu}{D_h} \qquad \text{Equation 1}$$

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 of the pipe, 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 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). For 100 mm-diameter pipes with calcium chloride (k_b = 0.497 J/sec/m/°C), the convective heat transfer coefficient is calculated as:

$$\frac{u}{-} = \frac{k_b Nu}{\frac{4(\pi D^2/4)}{\pi D}} = \frac{k_b Nu}{D} = \frac{0.497\ J/sec/m/°C\ \times\ 3.66}{0.1\ m} = 18.19\ J/sec/m^2/°C \qquad \text{Equation 2}$$

As shown in Figure 8, the brine temperature is assumed to decrease from 8°C to -25°C over a five-day period. The far-field is maintained at the initial soil temperature (8°C) using a constant temperature boundary condition.

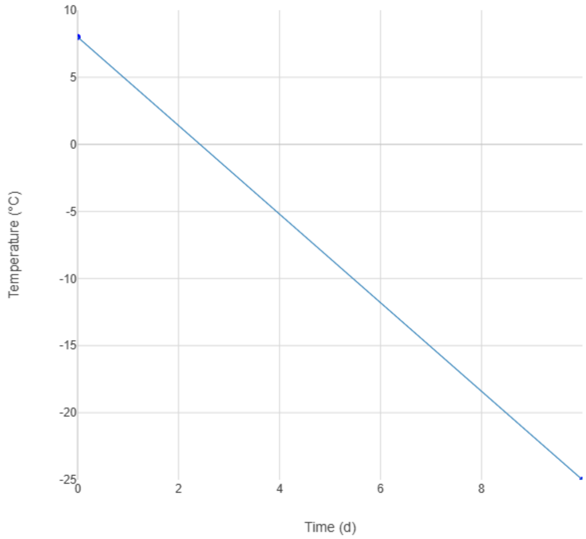

Figure 8. Brine temperature versus time.

Results and Discussion

Figure 9 and Figure 10 present the temperature contours day 10, 30, and 60 in 2D and 3D, respectively. The soil is only considered frozen once it reaches the solidus temperature, which in this case is approximately -3°C. To visualize the frozen zone, the temperature isosurface (dashed blue line in 2D) is set to -3°C. Figure 11 shows the -3°C isotherm in 3D. A small frozen zone forms around the freeze pipe by day 10 and expands over time. By day 30, the frozen zone extends halfway across the domain, and by day 60 it has closed the gap between the pipes, forming a 1.5 m thick frozen wall between the pipes and the edge of the mine shaft. The conditions near the bottom of the pipe in 3D are noticeably different.

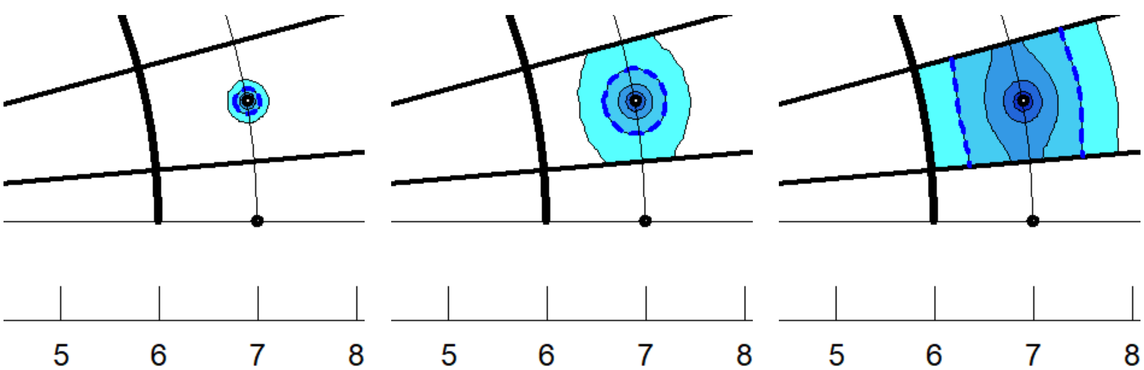

Figure 9. Temperature contours (min/max -18/0 °C) and isosurface (-3°C) on day 10, 30, and 60 of the 2D analysis.

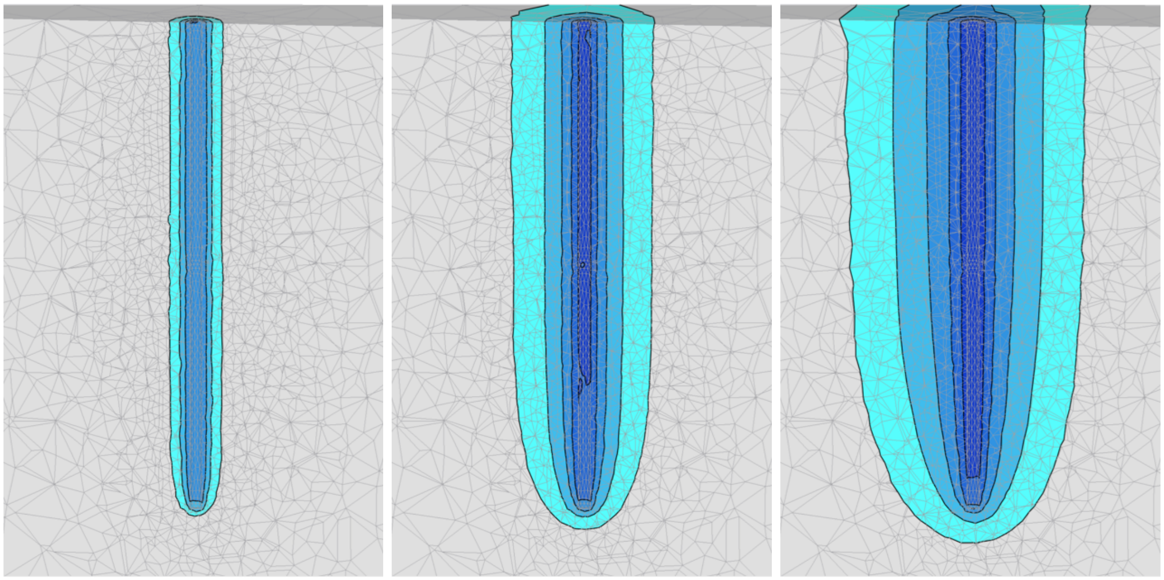

Figure 10. Temperature contours (min/max -18/0 °C) on day 10, 30, and 60 of the 3D analysis.

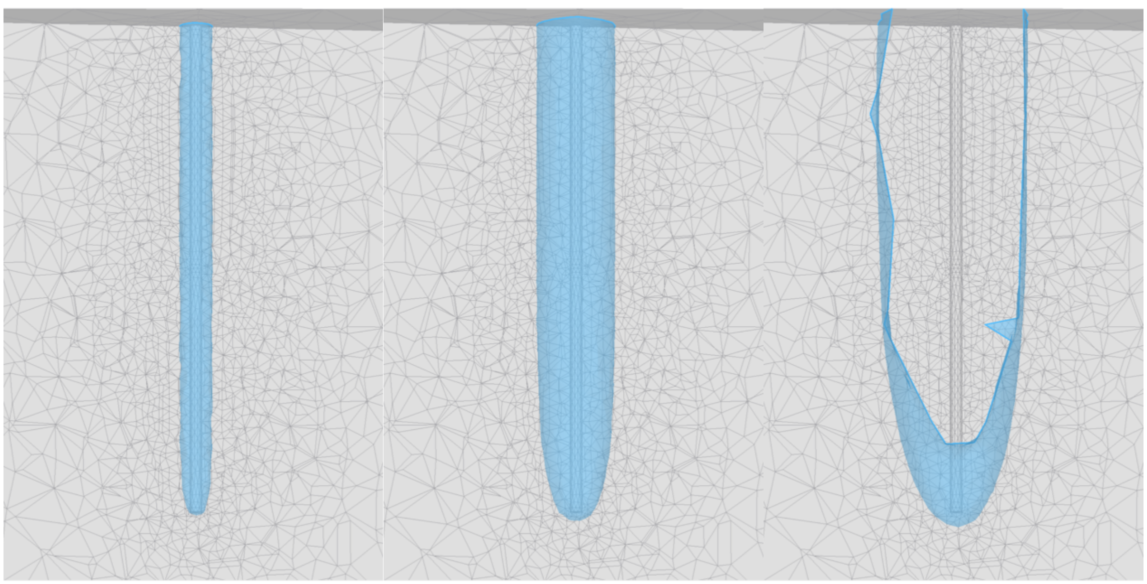

Figure 11. Temperature isosurface (-3°C) on day 10, 30, and 60 of the 3D analysis.

Figure 12 shows the temperature-time response of the 2D simulation at the midpoint between the freeze pipes. Water is often assumed to freeze at 0°C; however, factors such as salinity, capillarity, and surface forces cause freezing to occur over a range of temperatures. In this simulation, the range is controlled by the input thermal functions, and more specifically, the normalized unfrozen volumetric water content function. Cooling slows as a large amount of latent heat is extracted through the freeze pipes. Consequently, the temperature remains nearly constant between days 20 and 25. Beyond this point, latent heat extraction decreases as the temperature drops and the amount of unfrozen water decreases.

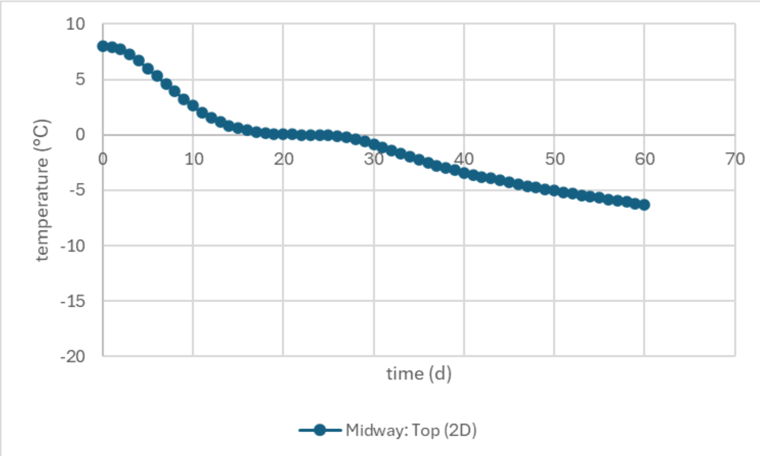

Figure 12. Temperature versus time at the midpoint between the freeze pipes in the 2D analysis.

Figure 13 presents the temperature-time response from the 3D simulation at the midpoint between the freeze pipes and the edge of the pipe. At the top of the pipe, the temperature response at the midpoint is nearly identical to the 2D results (Figure 12). The temperature at the bottom of the freeze pipe is approximately 6.5°C greater, both at the midpoint and pipe edge. This temperature difference is attributed to the three-dimensional aspect of the thermal field at the bottom of the pipe, where heat is extracted from around and below the freeze pipe. The temperature of the midway point at the bottom of the freeze pipe remains close to 0°C at the end of the analysis. To ensure that the freeze wall (temperature < -3°C) extends to the bottom of the freeze pipes, heat extraction would have to continue beyond the duration of the analysis, or alternatively, the freeze pipes would have to be installed to a greater depth.

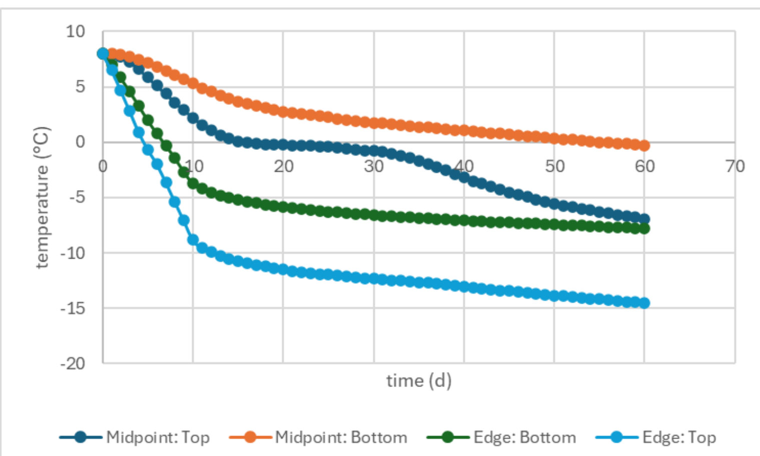

Figure 13. Temperature versus time at the midpoint between the freeze pipes and pipe edge (top and bottom of the pipe) in the 3D analysis.

Figure 14 shows the temperature profiles at the midpoint and pipe edge. The profiles confirm that there is a large lag in cooling between 20 and 30 days as a large amount of latent heat is extracted by the freeze pipe. The 3D profiles also reveal the influence of the soil below the bottom of the freeze pipe.

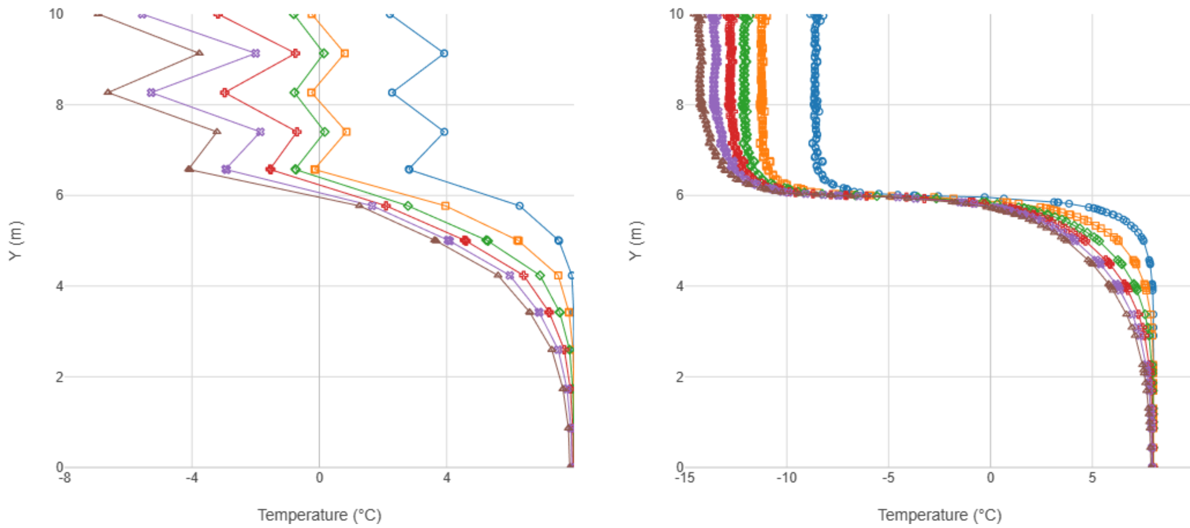

Figure 14. Temperature profiles at the midpoint between the freeze pipes (left) and pipe edge (right) at 10, 20, 30, 40, 50, and 60 days of the 3D analysis.

Figure 15 shows the temperature from the center of the shaft to the outer edge of the 2D domain. A similar graph could be generated from the 3D results at both the top and bottom of the pipe. Notice that the soil temperature is well above the brine temperature of -25°C. Even after 60 days, the soil temperature is only -14.8°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 pipe continues to cool, the pipe wall temperature will approach the brine temperature, but will never reach this temperature if there is a heat source somewhere in the ground.

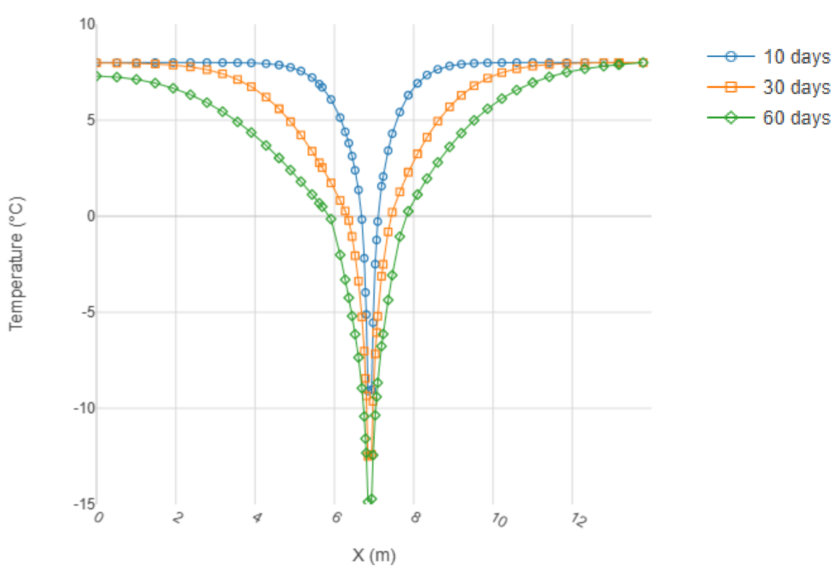

Figure 15. Temperature profile along the centerline of the domain in the 2D analysis.

Figure 16 shows the 2D heat extraction rate per unit length of pipe. Figure 17 shows the 3D heat extraction rate for the entire freeze pipe, which is approximately about 4 times greater because of the 4 m length. Figure 18 shows the heat extracted from the upper and lower halves of the freeze pipe, where the rate in the upper half is expectedly lower than in the lower half where more energy transfer occurs. The heat rate initially increases until the brine temperature reaches its minimum of -25°C (the negative sign indicates heat removal from the system). Beyond this point, the rate gradually decreases as the soil temperature continues to drop. This behavior is consistent with the convective surface boundary condition, which dictates that the extraction rate is proportional to the temperature difference between the pipe surface and the brine.

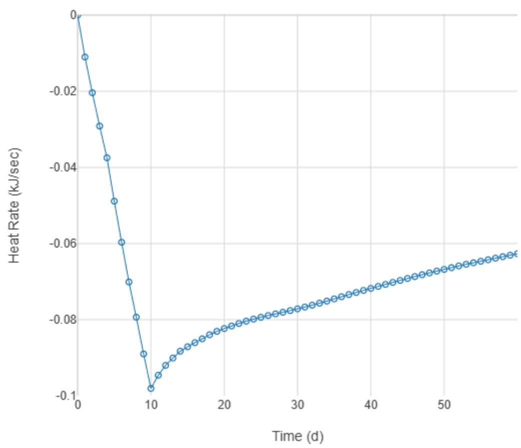

Figure 16. Heat extraction rate per unit length of pipe in the 2D analysis.

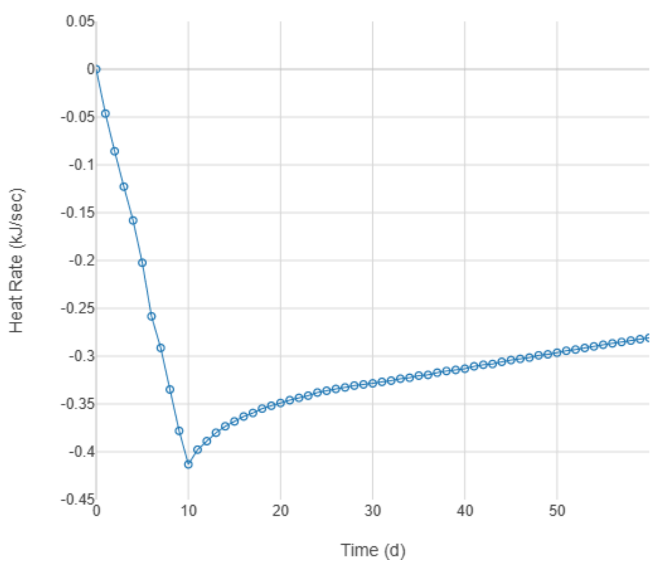

Figure 17. Heat extraction rate from the entire length of the freeze pipe in the 3D analysis.

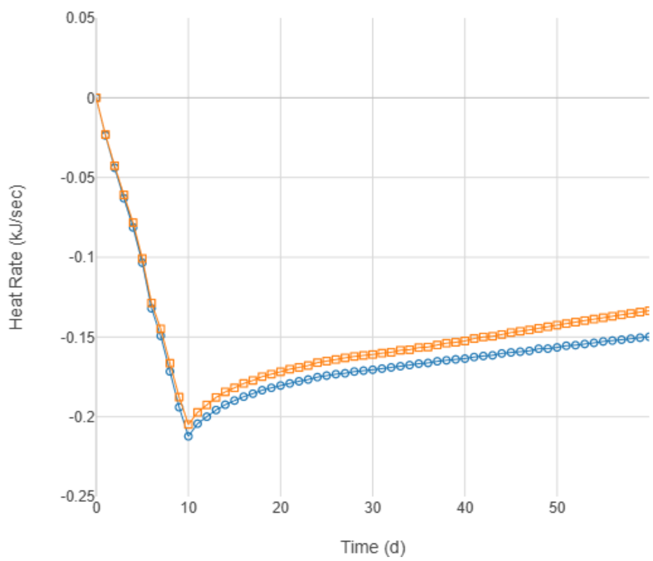

Figure 18. Heat extraction rate from the upper (orange) and lower (blue) halves of the freeze pipe in the 3D analysis.

A key aspect of designing a shaft-freezing project is estimating the time to develop a fully formed freeze wall and determining the total amount of heat that must be removed. Figure 16 indicates that the long-term heat extraction rate for a single freeze pipe is approximately -0.0627 kJ/sec/m. This value can serve as the basis for determining the required refrigeration capacity, expressed in tons of refrigeration. A ton of refrigeration represents the rate of heat removal needed to freeze one short ton (2,000 lb or 907.18 kg) of pure ice in 24 hours. Given that the latent heat of fusion/solidification of pure water is 334 kJ/kg, the heat transfer rate required to freeze one short ton of ice is:

$$\frac{334\ kJ/kg\ \times\ 907.18\ kg}{24\ h\ \times\ 60\ min/h\ \times 60\ sec/min} = 3.51\ kJ/sec \qquad \textbf{Equation 3}$$

Assuming a total of sixteen freeze pipes for this project, each 4 m in length, the minimum freeze plant capacity can be calculated as follows:

$$\frac{16 \times\ 0.0627\ kJ/sec/m\ \times 4\ m}{3.51\ kJ/sec} = 1.14\ tons\ of\ refrigeration \qquad \textbf{Equation 4}$$

To achieve the maximum heat extraction rate, the capacity would need to approximately double (around 2.5 tons of refrigeration). In practice, a freeze plant with a capacity of about 5 tons is typically selected to account for efficiency losses and operational variability. It is important to note that increasing the freeze plant capacity does not accelerate the freezing process. The heat load is governed by the rate at which the soil releases heat to the brine, not by the brine's ability to absorb heat. The only effective ways to reduce freezing time are to increase the number of pipes or lower the brine temperature. Increasing pipe diameter may offer a slight benefit during the initial freezing stage, but this effect is minimal.

Summary and Conclusion

The software can be used to simulate artificial ground freezing. In this example, the formation of a freeze wall was modeled over a 60-day period. The results provide critical input for designing the refrigeration system, estimating the time required for wall closure, and verifying that the frozen wall achieves the necessary thickness.

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.