Coupled Heat Transfer and Groundwater Flow Models for Ground Freezing Design and Analysis in Construction

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ABSTRACT

Artificial ground freezing has been used for over 100 years to provide temporary earth support and groundwater control for deep excavation in both unconsolidated soils and rock. Time dependent thermal numeric models have been used to evaluate the required freezing time for ground freezing systems and to evaluate the required refrigeration loads. Groundwater velocity through the freezing system is a mechanism that introduces additional heat energy into the system that can retard or even prevent the formation of a frozen earth barrier. Recent software developments have introduced models that couple the traditional heat transfer model with groundwater flow models. These models allow the design engineer to evaluate the effects of the groundwater velocity on the freezing system. It permits the design engineer to modify the ground freezing system or to reduce the permeability of the soils with ground improvement techniques thereby reducing the groundwater velocity permitting timely ground freezing operations. This paper discusses the application of these models and compares them to actual field results on key ground freezing projects. The results of these comparisons indicate the commercially available models are reliable thereby establishing a standard method of design for ground freezing projects.

INTRODUCTION

Artificial ground freezing is a method used to provide temporary earth support and ground water control for deep excavations, typically in water bearing unconsolidated soils, but occasionally in highly fractured rock. Freezing is accomplished by drilling and installing a series of subsurface refrigeration pipes along the perimeter of the proposed excavation. A refrigerated coolant is circulated through the frozen pipes, forming a frozen earth barrier as illustrated in Figure 1.

There are different methods of drilling and installing the freeze pipes, as well as two primary methods of refrigeration. One of these methods is referred to as the direct expansion where a cryogenic liquid such as liquid nitrogen is pumped into the pipes, vaporizes and the gas is released to the atmosphere. This method is extremely expensive and typically used on small, emergency projects (Sopko, et al. 2016). A more common method is a closed circulation system where a primary refrigerant such anhydrous ammonia or R22 cools the circulating coolant in a heat exchanger.

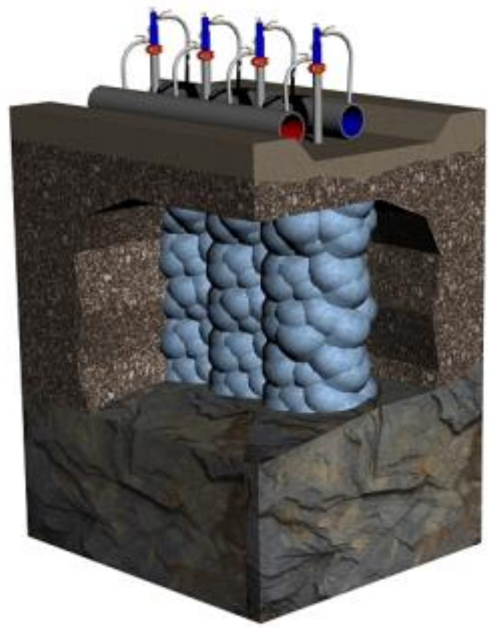


Figure 1 – Schematic of a Frozen Earth Barrier

The configuration of a typical closed system refrigeration pipe is similar to that presented in Figure 2.

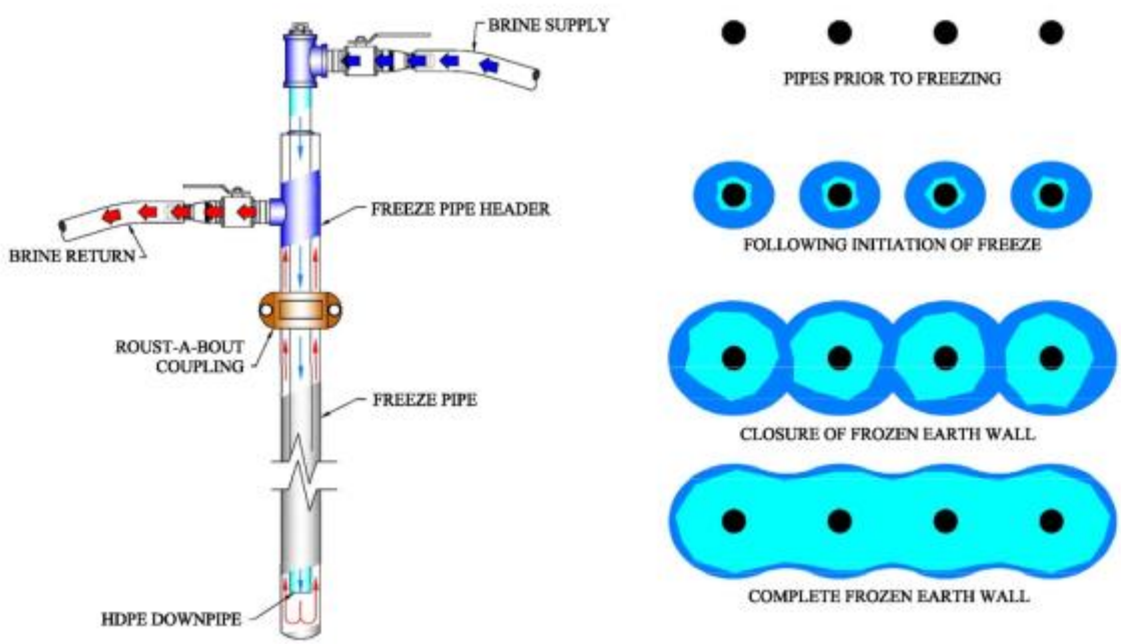


Figure 2 – Schematic of a refrigeration (freeze) pipe and typical configuration

The actual spacing of the refrigeration pipes determined by the methods presented in this paper. In practice, the spacing is determined to fulfill the design requirements to form a structurally competent frozen earth wall within a specified time frame consistent with construction schedule. Evaluating the required freezing time has evolved in the last 30 years with the introduction of time dependent heat transfer finite element computer programs. While the use of these programs is well established among ground specialists, there have been few publications available to the geotechnical engineering community to document the current standard design practices.

BACKGROUND

Figure 1 illustrates the four basic phases of ground freezing used in the thermal design:

1. Pipes prior to freezing,
2. The initiation of freezing
3. Closure of the frozen wall (occurs at time = t_I)
4. Complete frozen earth wall (occurs at time =t_{II})

During ground freezing construction, the required freezing time is crucial to the overall schedule and success of the project. The required freezing time is evaluated to plan for the construction activities and resources. Too little freezing time could result in excavating a shaft that is not completely frozen and result in catastrophic failure, while over-freezing can result in excessive energy costs and difficult excavation of frozen soil that has encroached towards the center of the excavation.

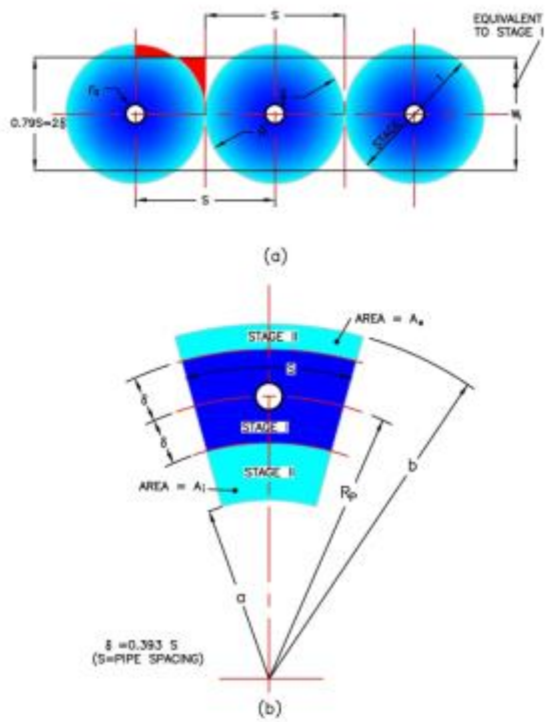
Freezing time is computed in two separate stages. Closure of the frozen earth wall, as previously illustrated occurs when there is a continuous wall of frozen (t_I), impermeable soil surrounding the excavation. In most cases, additional freezing time (t_{II}) is required to complete a much thicker frozen zone to provide the structural integrity to support the open excavation as described by Sopko (1990).

Sanger (1968) proposed a method of computing both t_I and t_{II} that was accepted and used in practice for over 30 years. Using the dimensions defined in Figure 3, the respective freezing times

$$t_1 = \frac{R^2 L_I}{4k_f v_s}\left(2\ln\frac{R}{r_o} - 1 + \frac{c_{vf} v_s}{L_1}\right)$$

Where $L_1 = L + \frac{a_r^2 - 1}{2\ln a_r} c_{vu} v_o$ and

$$t_{II} = \frac{1}{2k_f v_s} L_{II}\left[\left(R_p - \delta\right)^2 \ln\frac{R_p - \delta}{a} - \frac{\left(R_p - \delta\right)^2 - a^2}{2}\right] + \frac{c_{vf}}{2k_f}\left[\frac{\left(R_p - \delta\right)^2 - a^2}{2}\right]$$



Two stages assumed for thermal computations: (a) straight wall;
(b) curved wall

Figure 3 Definition of variables for thermal computations

k_f = thermal conductivity of the frozen soil $v_s = (T_s\text{-}T_0)$, the temperature difference between the freeze pipe surface temperature (T_s) and the freezing point of water (T_0) R = the radius to the frozen-unfrozen soil interface L = volumetric latent heat of the soil c_{vf} = volumetric heat capacity for the frozen soil c_{vu} = volumetric heat capacity for the unfrozen soil $a_r = (R_A/R)$, the radius of temperature influence of the refrigeration pipe in the unfrozen soil $v_0 = (T_g\text{-}T_0)$, the temperature difference between the ambient ground temperature (T_g) and the freezing point of water (T_0)

In practice however, these equations have two limitations:

1. The equations can become cumbersome when using multiple rows of freeze pipes.
2. The equations assume a uniform pipe spacing that is often not practical in practice.

To consider the actual freeze pipe spacing at depth, it is important to understand the process of drilling and installing freeze pipes. Even the most precise drilling procedures result in deviation of borehole as it is being drilled. The magnitude and direction of the deviation cannot be predicted with any level of certainty. After drilling and installing each individual freeze pipe, a deviation survey is completed using a gyroscopic device or orientable inclinometer.

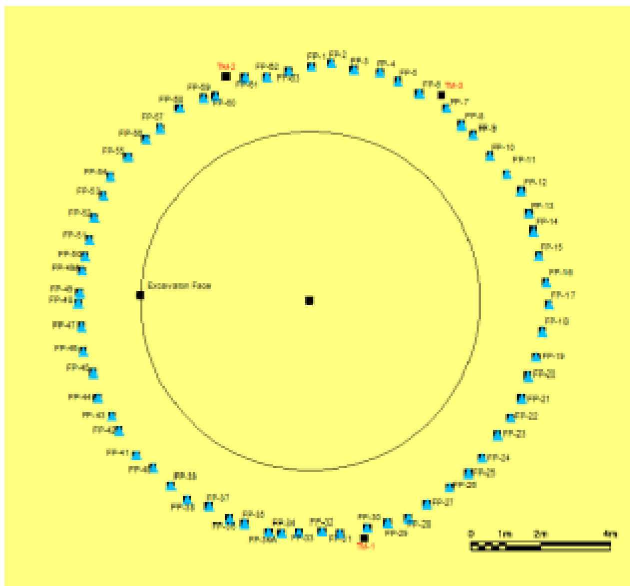


Figure 4 Typical "as-built" drawing showing freeze pipe deviations

A typical "as-built" drawing is illustrated in Figure 4. The actual locations of the deviated freeze pipes are shown at pre-defined depths. The ground freezing engineer must then use the information to evaluate the required time to form the frozen earth structure and incorporate in the construction schedule. With the variation of pipe spacing and randomness of the deviation, computing this time using the conventional equations was not possible. For this reason, ground freezing engineers have used time dependent heat transfer finite element method programs since the mid 1980's. The programs have become significantly more sophisticated since then when with the evaluation of the personal computer and of course the software.

NUMERICAL HEAT TRANSFER SOLUTIONS

The author has used several programs during the evolution of FEM heat transfer programs, but currently has limited use to two particular programs, TEMP/W produced by GeoSlope, Calgary, Alberta and PLAXIS Thermal Flow produced by PLAXIS, Delft, The Netherlands.

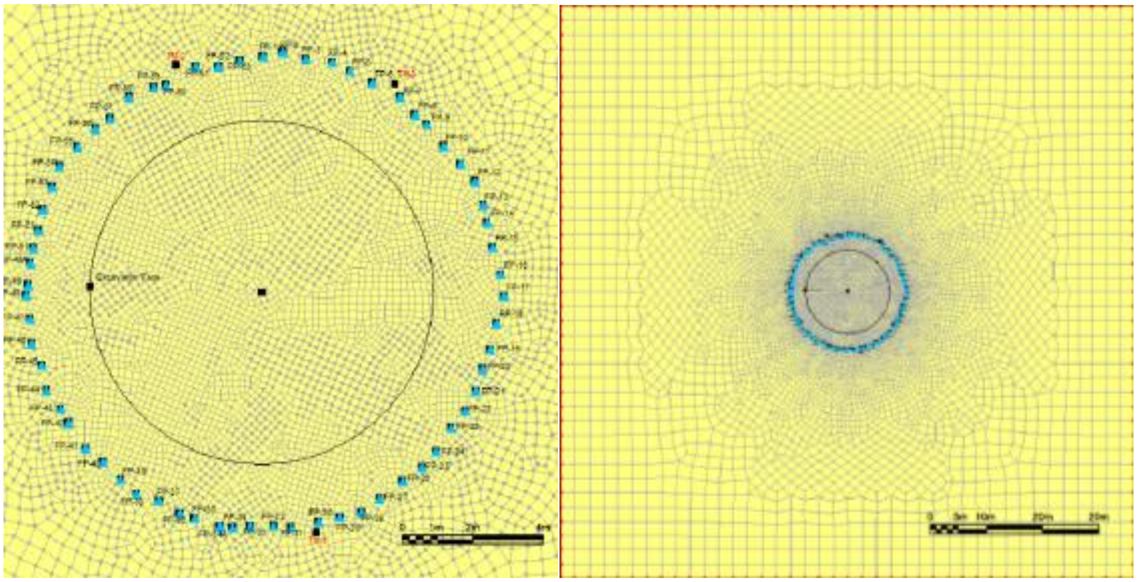


Figure 5 Incorporation of the "as-built" into a FEM mesh

The programs permit the simple incorporation of the freeze pipes coordinates into the mesh as shown in Figure 5. Figure 5 shows both the entire mesh and a close-up of the refrigeration pipes. Note that refrigeration pipes are labeled "FP-#", while the temperature monitoring pipes are labeled as "TM-##". In this paper, the location of the temperature monitoring pipes incorporated into the mesh will be used to compare actual field results with the modeled results.

In addition the geometric location of the freeze pipes, the FEM models also permit the input of the following parameters:

A. Frozen thermal conductivity of the soils (1.7 J/sec/m/^{o}C)
B. Unfrozen thermal conductivity of the soils (1.2 J/sec/m/^{o}C)
C. Frozen heat capacity of the soils (3,100,000 J/m^{3}/^{o}C)
D. Unfrozen heat capacity of the soils (1,766,000 J/m^{3}/^{o}C)
E. An unfrozen water content versus temperature function
F. Volumetric water content of the soils (0.23)

These parameters are typically measured in the field with hand-held probes that have proven to be very reliable.

In addition to the material properties of the soils, boundary conditions are established that include the initial ground temperature and the actual coolant temperature for each day of the analysis. The current software also permits defining each individual refrigeration pipe as a boundary node condition node. Definition of this nodes includes the pipe size, coolant flow rate and heat transfer coefficient as components of the input.

The most useful components of the output to the ground freezing engineer are the temperature contours and plots of the time versus temperature plots at the nodes representing the temperature monitoring pipes.

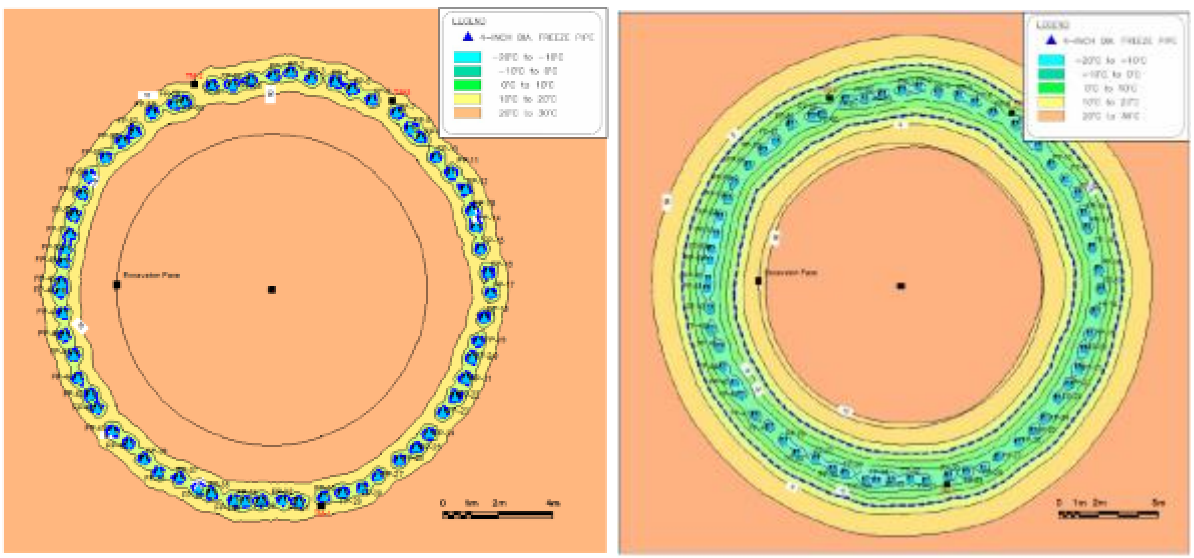


Figure 6 Temperature contours of the frozen wall at 4 and 30 days

Evaluation of the temperature contours as shown in Figure 6 indicates when the frozen earth wall has reached sufficient thickness and temperature to provide the required structural capacity to support the excavation.

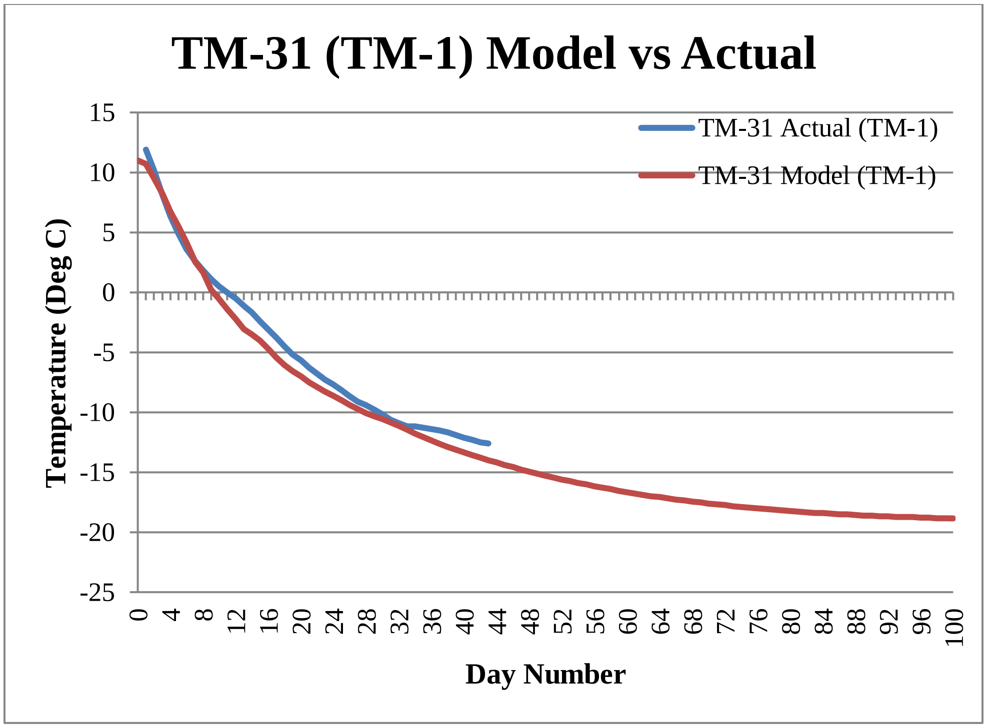


Figure 7 Modeled and actual field temperatures

Figure 7 shows the accuracy of the model as compared to what was measured in the field. This evaluation increases the level of confidence with the temperature contours permitting the excavation of the particular shaft based on the measured temperatures.

LATERAL GROUNDWATER FLOW

The configuration of refrigeration pipes, freezing time calculations and FEM models presented thus far are based on a constant heat flow from the ground and groundwater. This is not always the case in practice. Lateral groundwater flow will introduce additional heat energy into the freezing system and can retard or even prevent the formation of the frozen earth barrier. Sanger and Sayles (1979) introduced the concept of the critical groundwater velocity, u_c as defined below in m/day. The variables have been previously defined.

$$u_c = \frac{k_f}{4S\ln\left(\frac{S}{4r_o}\right)} \frac{V_s}{V_o}$$

The critical groundwater velocity is the seepage velocity at a magnitude where the frozen wall can no longer be formed given the refrigeration pipe spacing, size, ground temperature and coolant temperature.

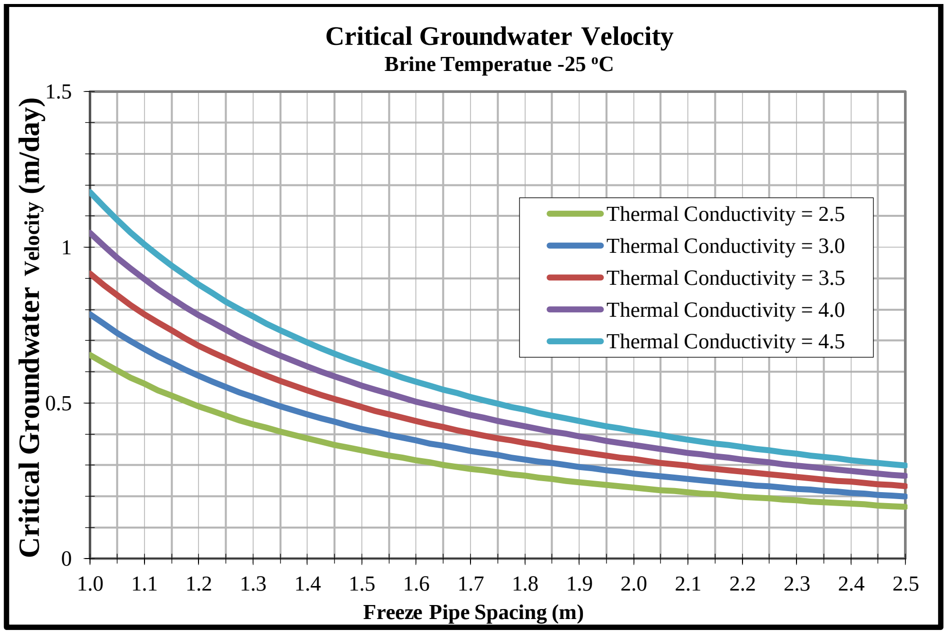


Figure 8 Effects of variables on the critical groundwater velocity

The same limitations of the static groundwater condition related to freeze pipe spacing also pertains to lateral groundwater condition. Additionally, the equation assumes that the groundwater flow is perpendicular to a line of freeze pipes. The effects of groundwater flow can also be modeled using time dependent FEM analysis.

In practice, evaluating groundwater flow in-situ is not a straightforward procedure. For most ground freezing applications, the groundwater velocity is calculated my measuring the soil permeability with pumping tests and the groundwater gradient by evaluating levels in several piezometers located across the site. Sites where groundwater velocity is too high require ground improvement to reduce permeability or increased refrigeration capacity by decreasing the spacing between pipes, adding an additional row of pipes, lowering the coolant temperature, or a combination of these. Evaluation of these modifications to the freezing system requires the coupled analyses.

The program TEMP/W accommodates the introduction of groundwater flow when coupled with the program SEEP/W. The input format using these two programs requires the input of the soil permeability and gradient resulting in calculated velocity. PLAXIS has recently introduced it's Thermal-Flow program that permits the coupled analysis in one program. A groundwater velocity and direction can readily added to the thermal model.

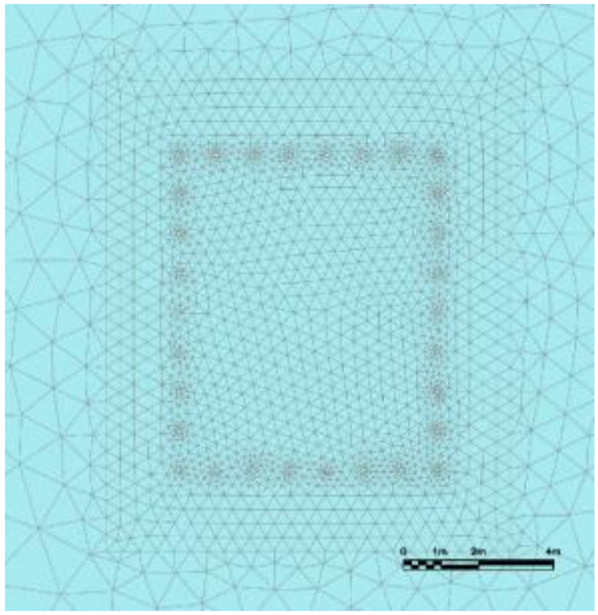


Figure 9 FEM mesh for the thermal-flow coupled model

The mesh for the PLAXIS model shown in Figure 9 represents a freezing system for a frozen tunnel crosses passage. Figure 10 illustrates the effects the groundwater flow has on the freezing time.

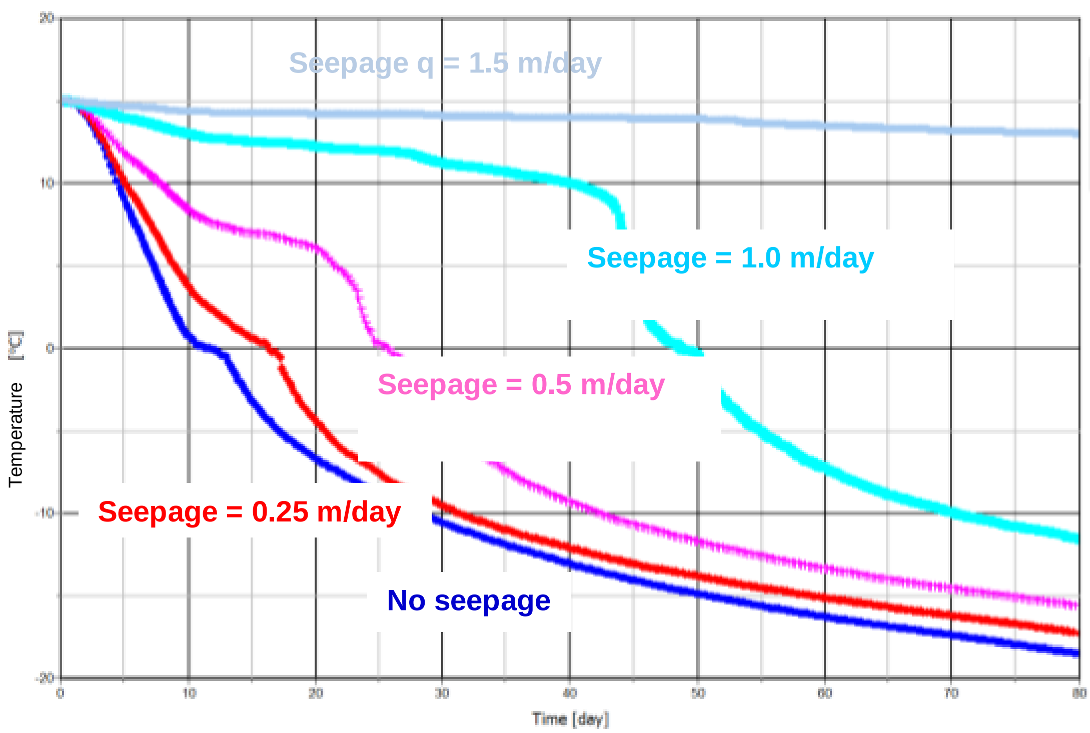


Figure 9 FEM mesh for the thermal-flow coupled model

This analysis indicates results somewhat similar to the calculated values in Figure 8, it is not possible to evaluate the as-built configuration or the addition of another row of refrigeration pipes.

The PLAXIS program has been recently introduced, and being used on several ground freezing projects in the United States. Data is being acquired in the field to compare the effects of groundwater velocity on freezing times to compare the models.

CONCLUSION

Thermal modeling of the “as-built’ configurations have shown results very close, if not identical to the actual temperatures recorded in the field. These correlations permit accurate representations of the total temperature regime within the frozen mass. The evaluation of the total dimensions and temperatures are critical to predicating the time required to achieve a structural frozen earth wall. These accurate predictions are essential to scheduling construction assets.

Recently introduced models that couple groundwater flow with the thermal analysis offer an additional tool in the design and analysis of frozen shafts and tunnels. Current on-going projects represent opportunities to evaluate the results of these models.

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