# Grouting for Freezing

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## ABSTRACT

Ground freezing as a method to provide temporary earth support and groundwater control for deep excavations has been in use for well over one hundred years. Details on the structural and thermal properties and behavior of frozen earth as well as design methods for frozen earth structures are well documented in the literature. Dynamic groundwater conditions caused by a combination of a localized gradient and high permeability can prevent the freezing process in small, isolated zones of the frozen mass. These unfrozen zones are detrimental to completion of the excavation. Subsurface grouting is often used as a remedial technique to reduce the permeability of these zones and subsequently reducing the groundwater velocity thereby facilitating the completion of the freeze. This paper details the field procedures used to locate the zones, numeric modeling techniques to verify the effect of the groundwater velocity on the freezing process and the grouting procedures used to reduce the permeability. Methods of drilling and installing the grout pipes as well as grout mixtures against frozen ground are discussed.

## INTRODUCTION

Ground freezing has been used to provide temporary earth support and groundwater control for deep excavations since the late 1800's. Current applications include drop and access shafts for sewer and tunnel projects, mining ventilation shafts, tunnels and even large groundwater barrier walls several kilometers longe. Most conventional systems rely on a series of subsurface refrigeration pipes typically spaced between one and two meters apart. A refrigerated coolant such as calcium chloride brine is circulated through these pipes, extracting heat from the ground and forming a water-tight, structurally sound frozen earth barrier. The required time to form the frozen barrier is dependent on the following parameters:

- Thermal properties of the soil
- Initial groundwater temperature
- Refrigeration pipe spacing
- Coolant temperature
- Coolant flow rate

When these parameters are evaluated and incorporated into the design of a ground freezing system, the frozen barrier is typically formed in six to ten weeks. These systems are designed, however assuming that there is a static groundwater velocity. Moving groundwater introduces heat into the system and can retard, or even prevent the formation of the frozen earth wall. The following illustrates the effect of varying groundwater velocity through a series of refrigeration pipes spaced one meter apart with a coolant temperature of -25 °C (see Figure 1). The curves were generated using a coupled finite element method model with heat transfer and groundwater flow capability.

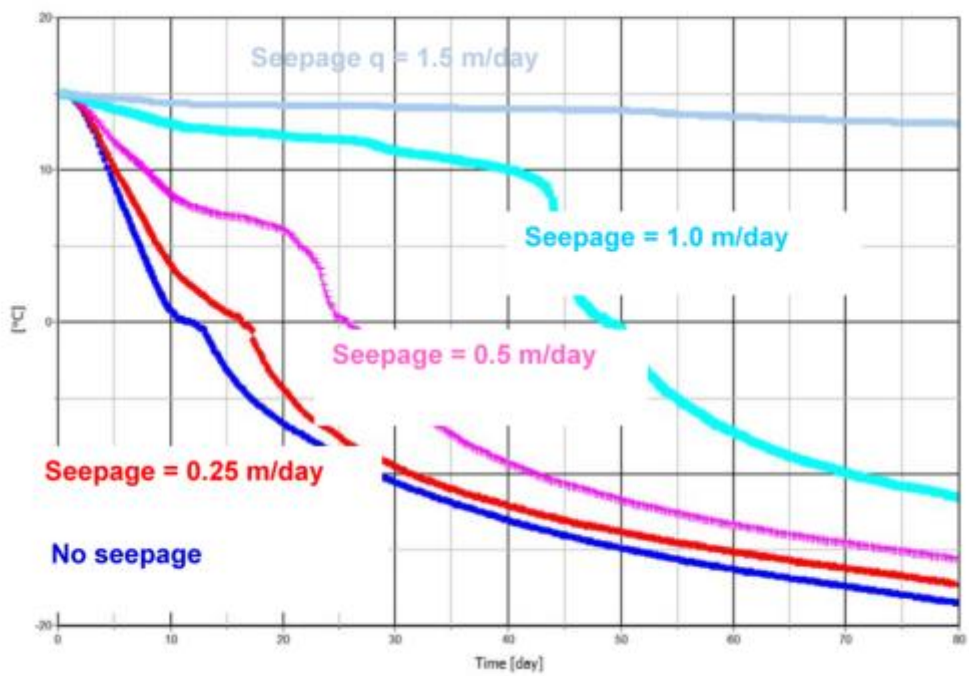


**Figure 1. Effects of groundwater velocity on freezing time**

In cases where this condition is present, it is necessary to identify the problem and take remedial action to reduce the groundwater velocity or modify the freezing system. Ground freezing contractors have developed investigative approaches to locate these unfrozen areas caused typically by small, localized zones of high groundwater velocity.

High groundwater velocity is caused by two components, a hydraulic gradient and ground permeability high enough to permit flow caused by the gradient. In order for the freezing process to be successful, either the gradient or the permeability must be reduced. In some cases, reducing the gradient and subsequently the velocity is as simple as turning off groundwater pumping wells in the vicinity of the project. In cases where there is a natural gradient causing the higher velocity, it is necessary to reduce the permeability of the soils. This reduction is accomplished by grouting.

While this paper discusses remedial grouting approaches on projects where a ground freezing system has been installed and operated and the froze wall does not form, there have been projects where ground freezing is the only feasible method of groundwater control and temporary earth support where groundwater velocities have been detected prior to construction. In cases like these often times the zones of highly permeable soils are grouted in advance of the drilling and installation of refrigeration pipes. In some cases the grout pipe drilling is done in the same boreholes used for the installation of the refrigeration pipes.

It is important to note the purpose of grouting. Grouting is used to accomplish closure of the frozen earth by reducing the permeability of the soil and hence the groundwater velocity. ***It is not used to plug a hole in a frozen earth wall***. There are two reasons for this. First, it is almost impossible to locate and place grout in the exact area required. Second, most grouting products will impede the freezing process or not have enough strength to support the excavation.

## IDENTIFICATION OF THE PROBLEM

In a typical ground freezing system, there is approximately one temperature monitoring pipes for every ten refrigeration pipes. In addition to temperature data, hydraulic confirmation is required. On most shafts where freezing is used, a system of piezometers is installed during the drilling phase of the project. Piezometers are installed in the most permeable strata, both on the interior and the exterior of the proposed shaft (see Figure 2). Full formation of the frozen wall is confirmed when there is hydraulic isolation between the interior and exterior.

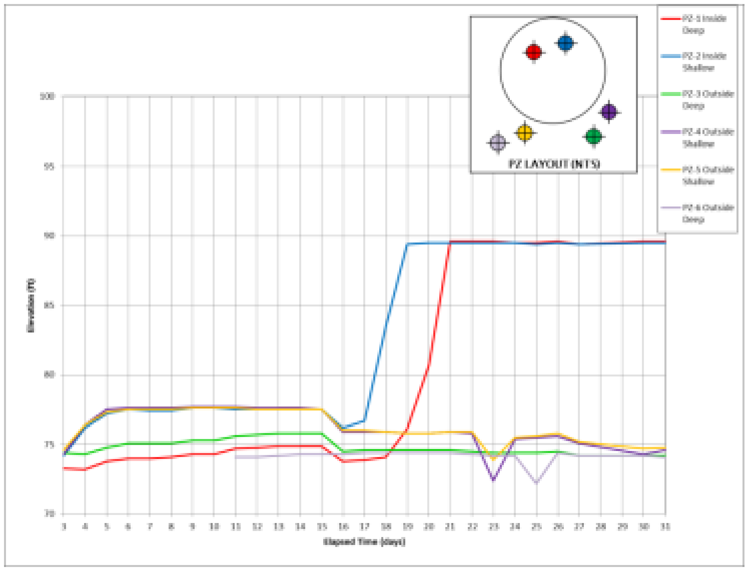


**Figure 2. Effects of groundwater velocity on freezing time**

One method of confirming the hydraulic isolation is to observe the piezometers in the interior of the shaft. Once there is complete formation of the frozen wall, the freeze continues to increase in thickness, both on the interior and exterior of the proposed shaft. As the groundwater on the interior of shaft freezes, it expands in volume and forces the unfrozen water to shaft center. As the ice volume increases, the water pressure is relieved through the piezometers as shown in Figure 2. This phenomenon is typically what ground freezing contractors prefer to observe before initiating the excavation. An alternative approach is to pump from within the shaft to create a large gradient across the frozen wall and observe the outside piezometers for changes. If there is no effect on these piezometers, a complete cutoff is indicated and excavation can begin. In cases where it is not observed, investigative procedures are necessary to locate the zone that is not frozen.

Since the ground temperature monitoring points are only located in limited zones, a refrigeration pipe profile is conducted to measure the temperature to measure the ground temperatures of the entire perimeter of the shaft.

A refrigeration pipe profile is conducted using the following steps:

- Turn off the circulating coolant through the refrigeration pipes
- Insert a temperature probe into each pipe and measure and record the temperature at two-foot intervals
- Move to the adjacent pipe and repeat the procedure
- Conduct the profile again in four hours

It is important to ensure that there are enough instruments available on site to maintain a four-hour interval before profiling the pipes for a second or third time. This four-hour interval is critical.

Once the data has been measured and recorded, individual plots of each pipe are generated showing each sequence (see Figure 3). The three graphs on the top of Figure 3 show normal profiles where there is slight, uniform warming of each pipes between the four-hour intervals. The bottom three graphs show refrigeration pipes where moving groundwater is present at a depth of approximately 150 feet. These graphs were from an actual project where the unfrozen zone was present in approximately six pipes.

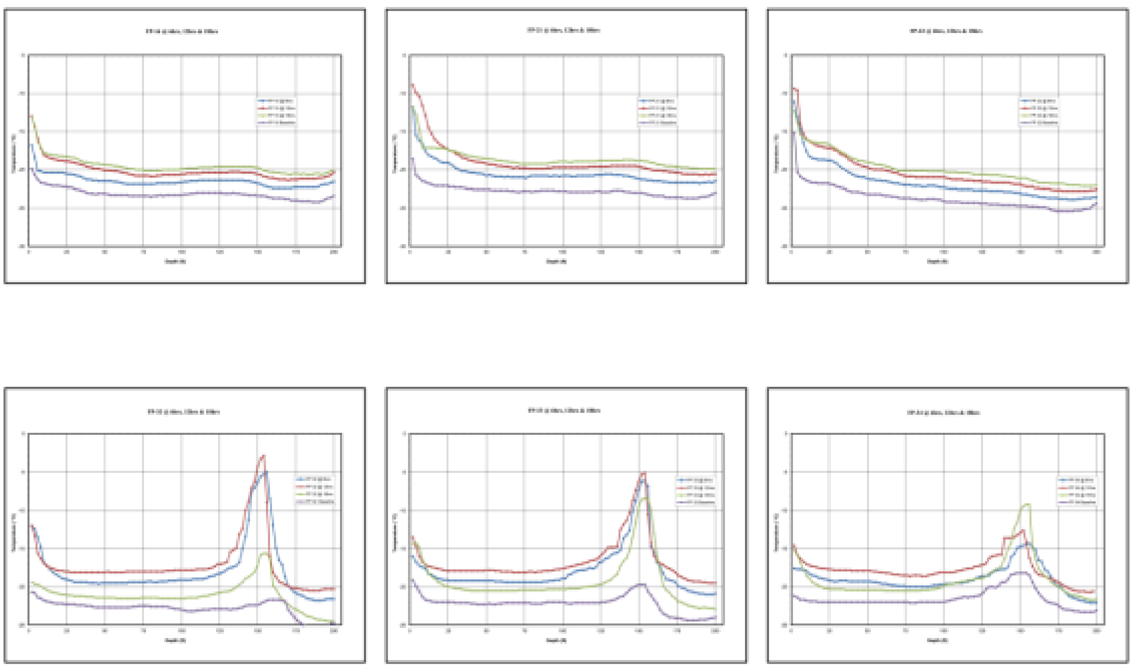

**Figure 3. Temperature profile results**

## REMEDIAL GROUTING

After locating the zone of high groundwater velocity, and exhausting all attempts to reduce the gradient, a grouting program should be implemented. Grouting pipes should be drilled and installed as close to the refrigeration pipes as logistically possible. Grout pipes are typically spaced between 1 and 3m.

The most commonly used approach for locating the grouting pipes in the zone of high groundwater velocity is illustrated below (see Figure 4), followed with the drilling and grouting sequence (see Figure 5).

Grout mix design are typically proprietary with the specialized subcontractors. Mixes consisting of sand, silt or fly ash, as well as cement-bentonite (conventional or micro fine) or sodium silicate are typically used. The use of the sleeve pipes (TAMs) permit the ability to repeatedly inject grout.

There is often consideration to grout selection based on the low temperatures of the frozen wall. In some cases, where soils types are coarse to medium gravel, a bulk mixture such as sand, fine-grained soils or fly can be pumped into the formation simply to reduce permeability. These mixes are temperature independent. Typically temperature is not considered in the other mixes because as previously mentioned, the intent of the grouting program is to reduce the permeability of soil by injecting a viscous material into soil matrix. There were several attempts on projects in Seattle and Milwaukee to use urethane based grout to fill voids within a frozen wall. The theory was that the urethane would permeate the breach and then expand. Different accelerators were used in the urethane to account for the temperature to enable expansion near the frozen wall. This expansion would then "plug" the hole in the dam. As it turned out, expanded urethane was observed in places never intended.

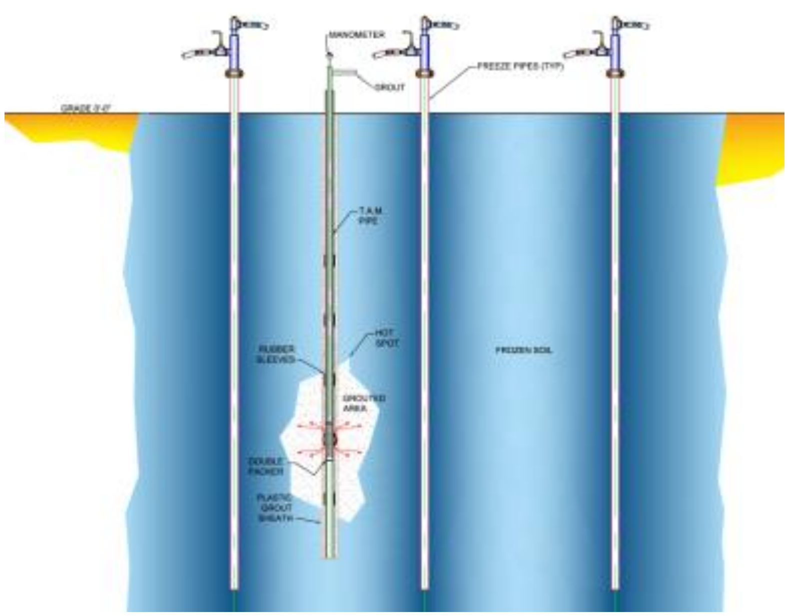


**Figure 4. Location of remedial grouting pipes**

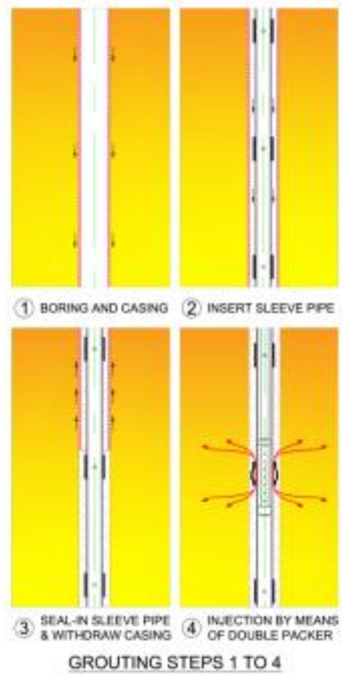


**Figure 5. Sequence of grouting procedure**

This injection should not be limited to the exact zone identified in the profile procedure but rather to a larger zone on both sides of the zone relative to the frozen shaft. To reduce the permeability, grouting often begins with a viscous mix that is gradually reduced in viscosity to permeate the finer grained soils. It is not uncommon to use a variety of mix designs. Experience has shown that it is not possible to get the grout exactly where the contractor would ideally choose. A classic example of this was a shaft near San Diego. The theory on this project was to initiate pumping from inside the shaft while injecting grout at several locations around the perimeter of the shaft.

The grout contained a fluorescent dye. It was assumed that the pumping activity would draw the grout through the breaches in the frozen wall, therefore filling the unfrozen zone. Unfortunately, after several days of pumping and grouting, at no time was the dye observed in the pump discharge, indicating that the grout had gone in an unanticipated direction.

Successful remedial grouting attempts have occurred only when a systematic and sustained injection approach has been used to reduce the permeability of the soil and thereby reducing the groundwater velocity. In these cases, freezing is still considered the primary groundwater control method. Once the velocity is reduced, it can still take several weeks to form the frozen wall.

During this freezing time however, additional temperature profiling can be conducted. Comparing these profiles with the previous profile will readily indicate the success of the grouting program, or the need to continue.

## LIQUID NITROGEN FREEZING

Liquid nitrogen has been used in some cases to close a breach in a frozen wall. Contractors should approach this application with caution, as it can be very expensive and not always successful. It has been the author's experience that under static groundwater conditions, liquid nitrogen can be used to reduce the freezing time as much as 75 percent. This assumes that there is enough liquid nitrogen product available for uninterrupted delivery. However, if a groundwater velocity prevents freezing with a conventional brine system, it is unlikely that the liquid nitrogen will be successful without remedial grouting.

There have been several projects where additional refrigeration pipes, suited for liquid nitrogen use have been installed concurrently with the grouting program. In these cases freezing the breach is accelerated.

## CONCLUSION

The procedures outlined in this paper have been successfully used on projects where isolated zones of high groundwater velocity were detected. Obviously, in these cases the projects encountered delays. Hindsight has shown that emphasis on hydraulic factors during the initial geotechnical investigation can eliminate these project delays. This investigation can result in pro-active procedures such as eliminating pumping activities or pre-grouting the soils. Often a grouting program completed during the drilling of the refrigeration pipes can save both time and money.

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