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Tunnels

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MONTREAL AT WORK

New tunnel construction starts across the city

GROUND CONTROL

Joseph Sopko, director of ground freezing for Moretrench, discusses the design of frozen Earth structure for cross passage excavation

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THE USE OF GROUND freezing to provide excavation support and groundwater control for the construction of cross passages between two tunnels has been used extensively in Europe, Asia and most recently in North America on the Port of Miami Tunnel and the Northgate Link Extension in Seattle. There are more projects in the planning phase in the United Kingdom, Los Angeles and Australia where ground freezing is being considered as the most technically appropriate method of ground improvement.

Ground freezing offers several advantages over other methods of ground improvement.

- Ground freezing systems can be installed from within the existing tunnels requiring no disruption at the ground surface. There is no impact on traffic, structures nor utilities.
- Freezing provides a structurally sound and water-tight excavation. If done properly, there is no need for any additional groundwater control measures.
- Instrumentation systems provide real-time data confirming the formation of the frozen structure to commence with a safe excavation.

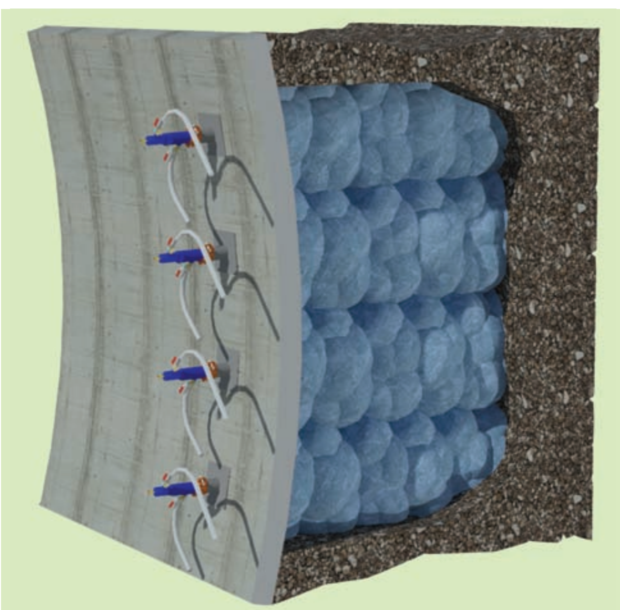
Most ground freezing applications look straightforward and simple, and in fact they are. They usually consist of refrigeration pipes drilled and installed at one meter spacing and the circulation of coolant through these pipes at -25ºC or colder (Figure 1). Freezing for cross passages however, requires considerably more evaluation, including laboratory testing of the frozen soil, strength and deformation analysis of the frozen earth structure, thermal analysis and design, and frost heave and thaw consolidation evaluation. Quite often the geometry of the cross passage relative to the main tunnels requires complex drilling angles, specialised equipment and quality assurance procedures to ensure accurate placement and continuity of the refrigeration pipes (Figure 2).

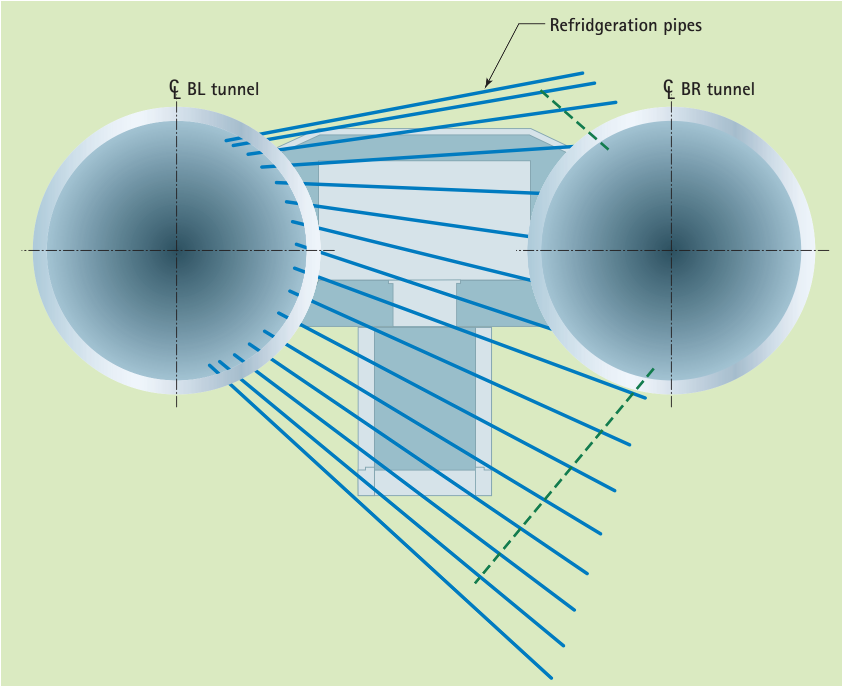
The first component of the design of a frozen cross passage is the evaluation of the material properties of the soil, both in the natural and frozen state. Ground freezing is most applicable in coarse-grained water bearing soils. Other methods such as the sequential excavation method (SEM) are typically well suited for fine grained clayey or silty clayey soils. The preliminary evaluation is typically driven by the permeability of soils. If groundwater cannot be controlled by dewatering or grouting techniques from the surface, freezing becomes an attractive option.

The permeability of the soils in the excavation zone is best evaluated by groundwater pumping tests. However, such tests are rarely available requiring evaluation of the grain size distribution curve. A few methods are typically used when determining the permeability. The Hazen (Hazen 1892) or Kozeny-Carman (Carrier 2003) methods have been used successfully. Newer techniques proposed by Chapuis (2016) are currently being evaluated.

Evaluation of the soil properties above the cross passages is required to determine the vertical loading on the frozen Earth structure. Most of these properties are presented in the Geotechnical Baseline Report (if available), and include unit weight, compressive strength as well the elastic modulus and Poisson's ratio of the unfrozen soil. The compressive strength and elastic modulus of the frozen soil are essential parameters

Right: ***Figure 1, pipes installed for ground freezing***





Above left: ***Figure 2, ground freezing for cross passages***

Above right: ***Figure 3, testing samples***

for the determination of the required thickness and temperature regime of the frozen structure.

Frozen earth exhibits time and temperature dependent rheological behaviour. In other words, the strength is based on the temperature of the soil and duration of the loading. There are two test methods used to evaluate the frozen strength. The instantaneous strength and elastic modulus are determined by a constant strain rate test (ASTM D7300-11) and the time dependent strength using creep tests (ASTM D5520-11). A series of creep tests at stresses of 0.7q, 0.5q, 0.3q and sometimes 0.1 (q= unconfined compressive strength as determined in ASTM D7300) are typically conducted in the design of shafts in fine grained soils where the excavation is open for extended periods of time.

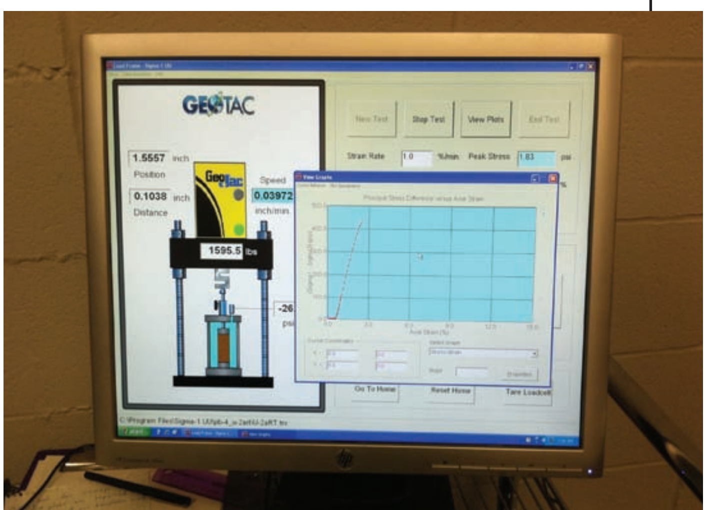
Cross passages are typically excavated using the SEM and shotcrete support in place almost immediately upon excavation. For this reason, in coarse grained soils, results of the constant strain rate test are used, using very low strain rate (0.10 per cent/min). See Figure 3.

The results of these tests are only as good as the samples tested. Since it is extremely difficult to retrieve undisturbed sand samples, it is almost always necessary to reconstitute the sample. This requires compacting the sample as close to the in-situ density as practical. Unfortunately, the most readily available method for determining the in-situ density is correlate standard penetration tests with density using a method such as described by Cubrinovski et. al, or similar. While there are other in-situ methods more reliable than the standard penetration test, these methods are not often available.

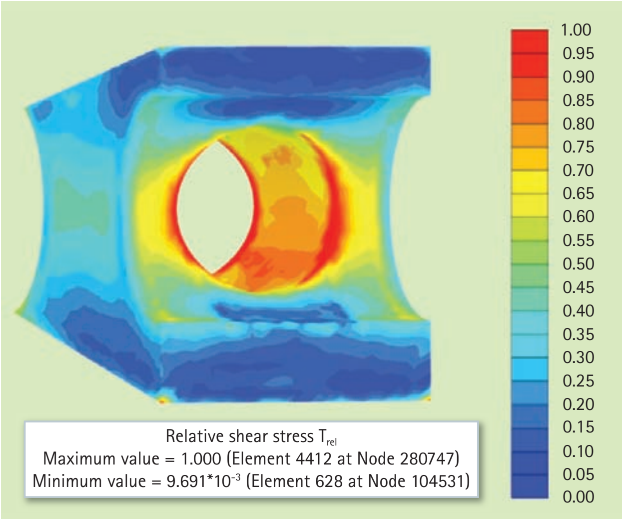
Since almost all applications of ground freezing are in saturated soils (otherwise the ground doesn't need to be frozen), it is important to ensure that the samples are fully saturated in a triaxle or similar cell prior to freezing for the compression tests. It is extremely important that the water used to saturate the samples is taken from the exploratory borehole when salinity or groundwater contamination is present. Salts, minerals or other contaminants may reduce the strength of the frozen soil in the compression tests.

It is also important to obtain accurate length and diameter measurements of the samples prior to and after freezing. These measurements are used to compute the volumetric expansion of the soils upon freezing. Values of this expansion are used in the structural analysis to evaluate stresses on the existing tunnel lining segments, underground structures and utilities, as well as heave at the ground surface.

A structural analysis is necessary to determine the required thickness of the frozen cylindrical structure. The thickness of the frozen zone is typically considered that zone between the -2°C isotherms intrados and extrados. This is



Above: ***Figure 3b, performing tests on ground samples in preparation for freezing and excavating cross passages between two tunnels***



Above: ***Figure 4, 3D finite element models as opposed to 2D are used to evaluate force on tunnel liners***

based on the common laboratory testing temperature of -10°C; however it is subject to variation based on conducting tests at multiple temperatures and a highly refined structural model.

The structural evaluation of the frozen cylinder can be accomplished using a two dimensional finite element model. The two dimension models provide evaluation of the internal stresses of the frozen mass, as well as the elastic deformation. These models however, do not permit the evaluation of the forces on the tunnel liner. For this reason, three dimensional finite element models are used as shown in Figure 4.

Left: ***A refrigeration plant at surface level***

Left: ***A smaller refrigeration plant located in the tunnel***

Left: ***A typical cross passage freeze to support excavation***

When selecting the frozen soils parameters as input values in the finite element program, the designer should consider the reliability of the laboratory testing program. Standard practice as determined by the International Symposium on Ground Freezing, (Auld et al 2002) was to reduce the laboratory values in half, considering therefore a factor of safety of two.

Current practice is to use the parameters from the testing in the model, evaluate the internal stresses of the frozen mass, and compare these stresses to the laboratory strengths to estimate a factor of safety. This method can only be used when multiple tests are conducted on quality samples in accordance with the ASTM standards.

Several iterations of the model are often necessary to determine a frozen wall thickness within the desired factor of safety. With each iteration of wall thickness, it is necessary to evaluate the frost pressures induced on the tunnel and any adjacent structures or utilities. This procedure is only used when a structural lining is installed in sequences during the excavation. It does not evaluate long term creep behaviour of the frozen ground.

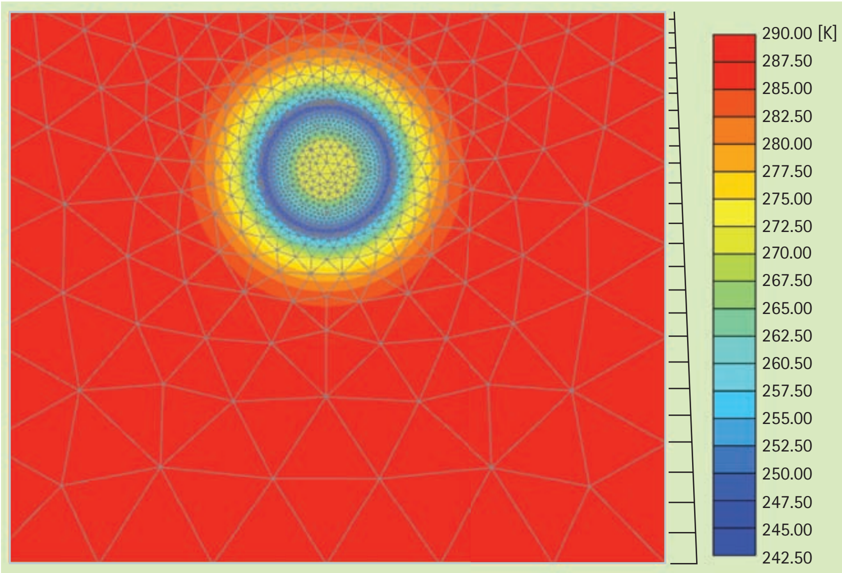
Once the dimensions of the frozen cylinder are determined, a thermal analysis must be conducted to determine; 1) the required time to freeze and form the structure; 2) the required refrigeration load; and 3) the effects of groundwater velocity on the freezing process. The thermal analysis is completed using a time dependent finite element model. The model should permit the coupling of groundwater flow around the refrigeration pipes (Sopko, 2017). A typical model is shown in Figure 5, and a model with groundwater flow in Figure 6.

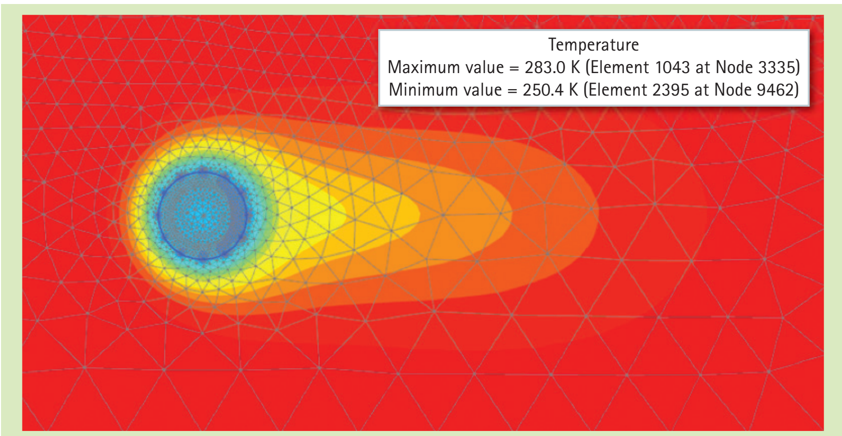
The key components of the thermal model are the thermal properties of the soil(s), initial groundwater temperature, coolant temperature and flow rates, and refrigeration pipe spacing. The spacing of the refrigeration pipes is somewhat more complicated than selecting nodes in a model at a convenient geometric spacing. Consideration must be given the size of the tunnel lining segments, segment gaskets and internal steel reinforcing. These factors often lead to variable pipe spacing which has to be used in the model.

In the event that the model includes groundwater velocity that will retard or prevent the formation of the frozen wall, modifications to the freeze process must be incorporated. These methods are explained in detail (Sopko, et al 2017) but include reduction of the groundwater gradient, closer refrigeration pipe spacing and remedial grouting.

The thermal models will evaluate the heat load and refrigeration capacity required to form and maintain the frozen cross passages. Practical consideration must be given to the selection of the refrigeration equipment. Refrigeration plants can be either at the ground surface, or in the tunnel located near the cross passages. Surface plants have the advantage of greater capacity and the use of the more efficient ammonia refrigerant. The disadvantages of these units are that they require space at the ground surface (often very limited) and the pumping requirements of long distances result in inefficiencies. They also require a water source for the cooling. An alternative and more common approach is a small refrigeration unit place in the tunnel. These units are air-cooled and do not require the use of ammonia as a primary refrigeration.

A typical system, as shown, requires approximately six to 10 weeks of refrigeration to form the frozen cross passage





***Top:* Figure 5, a typical model for a thermal analysis**

***Above:* Figure 5, a model showing groundwater flow**

support. Instrumentation should be considered during the evaluation process and included in the final design. System instrumentation should include the following:

- Coolant supply temperatures
- Coolant return temperatures for each refrigeration pipe or pipe circuit
- Coolant flow rates
- Coolant leak detection
- Refrigeration plant operating parameters and settings

Ground temperature and groundwater pressure monitoring are required to determine when the frozen structure is of sufficient thickness and temperature to initiate the excavation. The ground temperatures must be consistent with the thermal design.

Temperatures are measured in temperature monitoring pipes that are installed in a similar manner to each refrigeration pipe. Temperatures within each pipe are typically measured at one-meter intervals. Temperature sensors can be thermistors, RTDs or fibre optics and connected to a computer drive SCADA system.

Complete formation of the frozen mass however is best determined by groundwater pressure. As the frozen cylinder forms and seals against the exterior of the tunnel lining, groundwater pressure in the interior of the cross passage will begin to rise as the water freezes and expands. This pressure can be monitored with a pressure transducer drilled and installed in the centre of the cross passage. Excavation cannot begin if there is not confirmation of the pressure increase.

Once closure and formation of the frozen mass has occurred, excavation may commence. As the excavation proceeds and the temporary lining installed, it is imperative to continuously monitor and evaluate the instrumentation data. While remote monitoring of the data has become a standard operating procedure, on-site daily inspection by a qualified technician is required.

The design procedures outlined have been used successfully on several cross passages in North American. An interesting observation by an early pioneer in ground freezing was that you learn something different on each job. With this in mind, it is important to note that each project is different. Soil conditions, groundwater and project geometry vary.

The experienced designer will and should understand the effects of these variations and alter the design process accordingly.

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