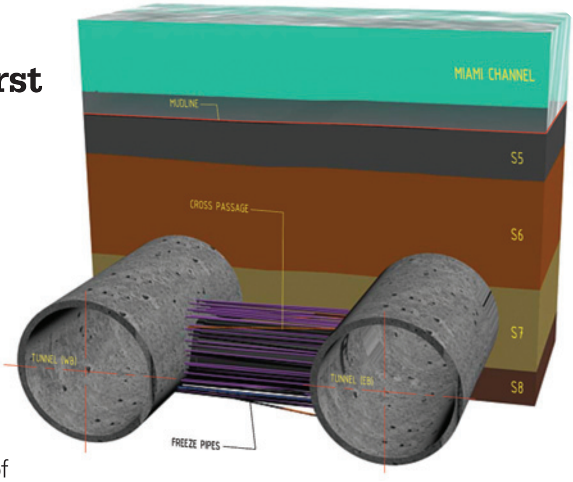
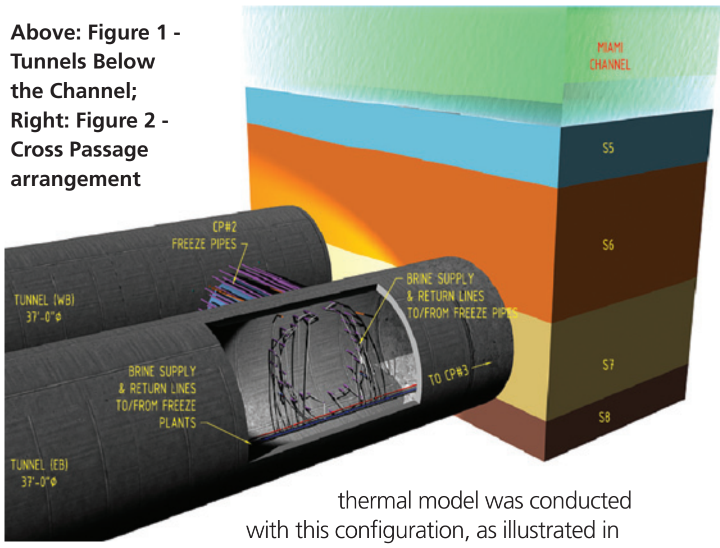
Chilling out in Florida: PORT OF MIAMI'S CROSS PASSAGES

Joseph A Sopko, PhD, PE, Director of Groundfreezing at Moretrench, describes the first use of ground freezing for cross passage construction in North America





Above: Figure 1 - Tunnels Below the Channel; Right: Figure 2 - Cross Passage arrangement

ARTIFICIAL GROUND FREEZING for cross passage construction was recently used for the first time in North America on the Port of Miami Tunnel, in Florida. The 42.9ft (13.1m) diameter twin tunnels extend from Interstate 395 on Watson Island to the Port of Miami on Dodge Island (see *NATJ*, June/July 2013, p10). The tunnels have five, 9.2ft (2.8m) diameter cross passages ranging in length from 79.7ft (24.3m) to 119ft (36.5m). Two of these cross passages required ground freezing to provide groundwater control and temporary earth support for excavation.

Cross Passages 2 and 3, were approximately 100ft (30m) below the ground water level and were mostly within the highly pervious Key Largo formation as shown in Figure 1 and Figure 2. Key Largo is a rock formation consisting of coral fragments within a cemented calcarenite matrix. An additional geotechnical investigation conducted by the contractor after the contract award showed that this formation had a very low percentage of fine materials and could become very unstable during tunneling.

The successful ground freezing projects in Europe and Asia were in either clayey or sandy soils with no significant lateral groundwater flow. The geotechnical properties of the Key Largo formation complicated its application. Conventional ground freezing systems typically use a series of pipes spaced approximately 3ft (1m) apart and circulate a -13 to -31°F (-25 to -35°C) calcium chloride solution through a closed-loop system. This calcium chloride "brine" is refrigerated with mobile, electrically powered plants specifically designed for ground freezing applications.

These freeze systems are designed to extract the heat from the ground in an approximate six to ten-week time frame. Lateral groundwater flow however, can introduce additional heat to the system, retarding or even preventing the formation of the frozen earth support system. On most conventional brine ground freezing systems, lateral ground water flow greater than 3ft (1m) per day can retard or even prevent the formation of a frozen earth wall.

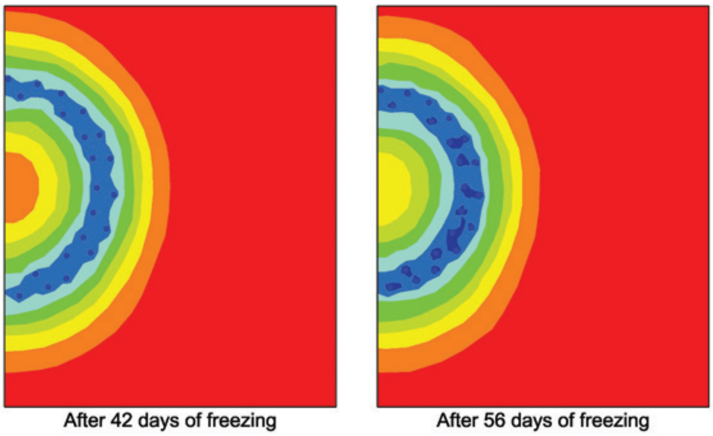
From the earliest inception of the use of ground freezing, the high permeability and the 85% porosity of the Key Largo formation coupled with subsurface water currents and tidal influence, raised concern that groundwater velocities may have an impact on the ability to freeze the ground. The most straightforward approach to reducing the groundwater velocity would be to decrease the permeability of the Key Largo formation with a comprehensive grouting program.

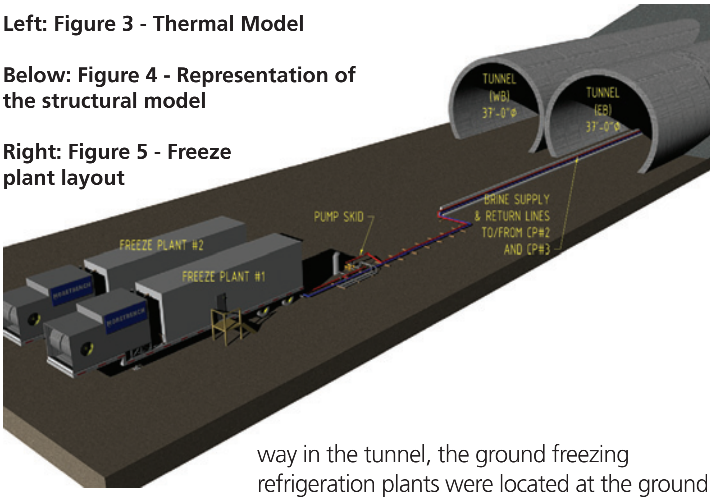
This major grouting program, instituted prior to the installation of the ground freezing system, was implemented from the ground surface[1]. A series of grout tests were performed and ultimately a final grout design was selected. A downstage grouting program was implemented both on and offshore to reduce the permeability of the soils, and subsequently the groundwater velocity.

Design of the freezing system

The design of the ground freezing system consisted of two rows of freeze pipes with centerline radii of 11ft (3.35m) and 13ft (3.96m). A time-dependent finite element thermal model was conducted with this configuration, as illustrated in Figure 3. The two rings of freeze pipes were drilled and installed from the eastbound tunnel. These pipes had an immediate contact with the tunnel lining on the exterior of the tunnel and a frozen seal could be easily attained. The situation was somewhat different westbound end of the cross passages.

The termination of each of the closed-end freeze pipes would be close to the westbound lining, but not necessarily in contact to ensure the required frozen seal. Warm air circulating through the tunnel would act as a large heat sink at the termini of the two frozen cross passages. To mitigate this consequence, two small refrigeration units were installed at each





Left: Figure 3 - Thermal Model

Below: Figure 4 - Representation of the structural model

Right: Figure 5 - Freeze plant layout

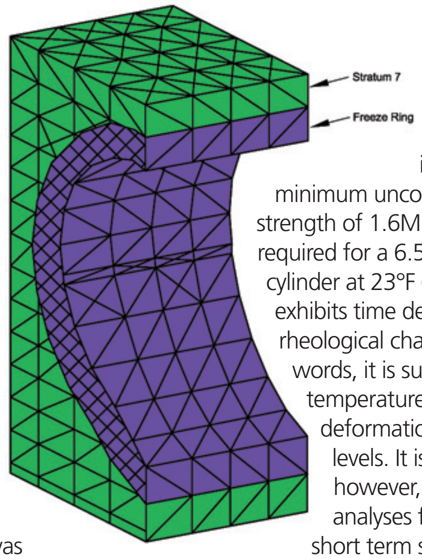
of the cross passages in the westbound tunnel, completely independent of the freezing system circulating through the series of freeze pipes from the eastbound tunnel.

These significantly smaller units would cool and circulate a --34°F (-30°C) calcium chloride solution through cooing tube matching the contour of the tunnel and mounted to the interior liner on the westbound tunnel in the area of the cross passages. These cooling tubes would be insulated to minimize any effect of the warm ambient air in the tunnel.

Design of the freezing system was based on four integrated components. These components – thermal, structural and hydraulic (lateral groundwater flow) and the mechanical system – are common to all ground freezing systems. The hydraulic design was addressed in the grouting program.

The thermal design was based on a time dependent heat transfer finite element method model, used to determine the required freezing time using two rows of refrigeration pipes. Figure 3 represents the model output, where the blue zones are frozen earth. Material properties of the modeled Key Largo formation were obtained from the index properties obtained during the additional geotechnical investigation.

A structural finite element analysis was conducted using PLAXIS. Figure 4, represents a section of a cylindrical model created using a



2D axisymmetric model. Results of this analysis indicated that a minimum unconfined compressive strength of 1.6MPa would be required for a 6.5ft (2m) thick frozen cylinder at 23°F (-5°C). Frozen soil exhibits time dependent, rheological characteristics. In other words, it is subject to time and temperature dependent deformation at high stress levels. It is common practice however, to use elastic analyses for low stress and short term structures such as the frozen cross passages.

Both the structural and thermal analyses indicated that a freezing design using two rows of freeze pipe was required, not necessarily to get the required frozen earth thickness, but to achieve the required thickness in a relatively short time frame. To ensure that the required frozen cylinder was of sufficient size, a series of temperature monitoring pipes were installed within and on the exterior of the frozen soil. Target temperatures of 14°F (-10°C) were established.

Implementation of the freeze was somewhat unusual due to the distance from the cross passages to the tunnel entrance.

Freeze implementation

Due to the construction schedule, equipment availability and maintaining a vehicle right of way in the tunnel, the ground freezing refrigeration plants were located at the ground surface, 600ft (183m) away from the tunnel entrance (Figure 5). Another consideration at the time of freezing was the use of anhydrous ammonia as a primary refrigerant. Ammonia is typically not permitted in underground structures. Other refrigerants, such as that used in the smaller units on the westbound tunnel are accepted, however refrigeration units in the eastbound tunnel would create vehicular traffic obstructions. This relatively long distance contributed to a substantial heat load on the refrigeration system.

Compared to most ground freezing projects, the total refrigeration load on this project was very low, but the distance from the freeze plants to each of the cross passages added a considerable heat load and pressure loss through the coolant distribution manifold. During the initial formation-freezing phase of the project it was necessary to increase the insulation on manifold piping and increase refrigeration capacity due to the excessive heat and humidity in Miami during the summer.

The ground freezing instrumentation system was designed to measure both ground temperatures within the frozen mass and groundwater pressures within the proposed frozen cylinders. While the temperatures are the most obvious indication of the formation of a frozen zone, the key and most significant indicator of a fully formed and closed frozen wall is the internal groundwater pressure.

On conventional vertical shafts, closure is typically indicated by a rise in the water level of an internal piezometer. As the frozen earth forms, groundwater within the structure is displaced by the ice, increasing the pressure

Figure 6: Instrumentation screen shot of the freeze system layout

Figure 7: Instrumentation screen shot of the coolant distribution manifold system data

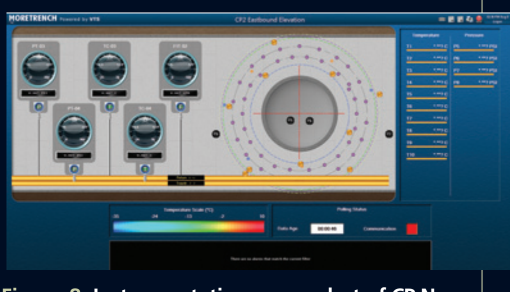


Figure 8: Instrumentation screen shot of CP No. 2 temperature and pressure acquisition

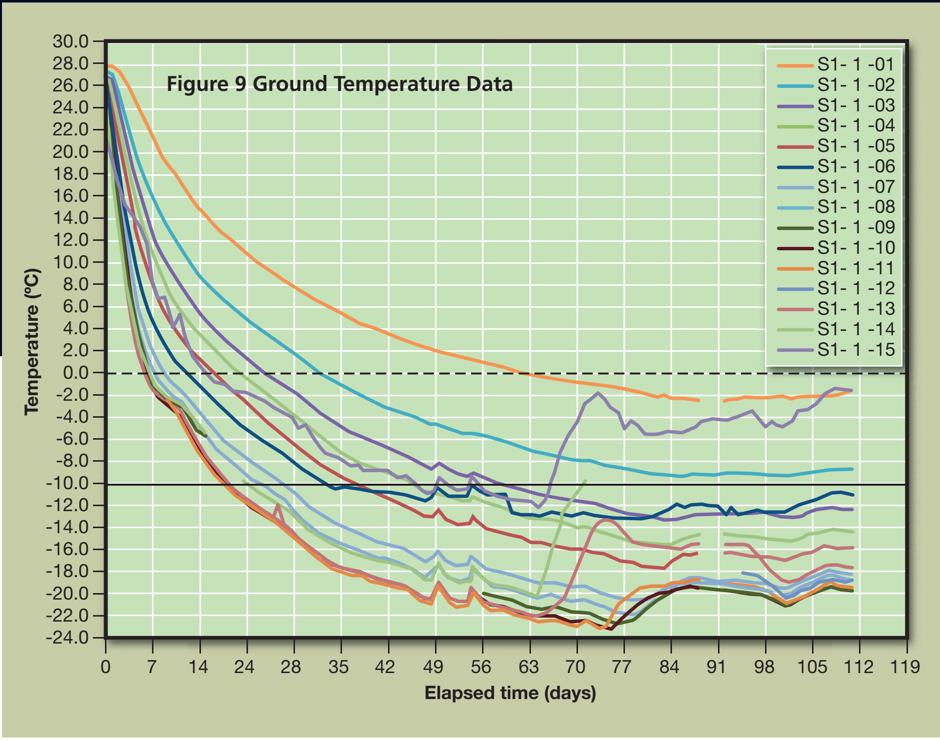



Figure 11: Cross passage excavation


Figure 12: Cross passage lining

and indicated by a noticeable rise in the piezometer. In fact, this phenomenon is so pronounced in some shafts that water can sometimes be observed flowing from the piezometer. Since the cross passages were horizontal and submerged, the increase was measured using a pressure transducer at the center of each cross passage. The groundwater pressure within each stratum was subject to tidal influences. The tidal variation was measured with the pressure transducers as well. Closure of the frozen cylinders was confirmed when tidal variation dissipated and pressures began to rise.

In addition to the temperature and groundwater pressure, the instrumentation system measured coolant flow rates and pressures as well as supply and return temperatures. Data was acquired at each of the cross passages and sent via a radio signal to a computer system above ground. The horizontal and vertical curvature of the tunnels required the use of a repeater system to relay the signal for data transmission.

The monitoring system was custom-designed for this project and resulted in screen displays not only at the ground surface, but remotely from any authorized computer, tablet, or cell phone.

The instrumentation system was designed to scan all sensors approximately every 10 seconds. Data was not only visually accessible on the screen, but stored and plotted. Additionally, alarms were incorporated into the system in the event that parameters exceeded normal ranges. In the event of an alarm condition, the project engineer and superintendent would be notified.

Figure 9 shows the temperature data acquired for one of the 10 temperature monitoring pipes. The sensors were installed in the pipe at approximately 3ft (1m) intervals. Note that at 65 days, excavation commenced and the warming was recorded.

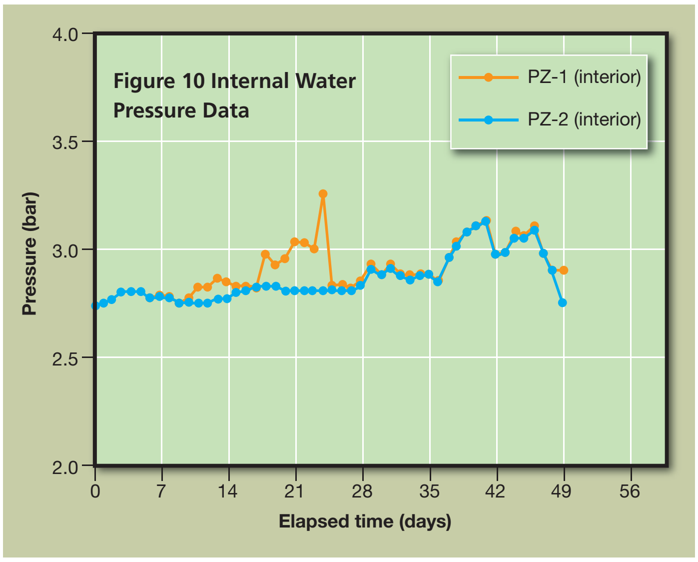


Figure 10 shows the actual water pressure measured inside the frozen cross passage. It was unclear why the two sensors did not completely track together during the early stages of the freeze, but it is likely attributed to the grout injected into the formation. After 36 days, note the dramatic increase in pressure, indicating closure of the frozen cylinder. At 41 days the pressure was relieved. At 49 days, as excavation was beginning, pressures could not longer be measured.

Prior to excavation, water-tight gates were installed at the face of each cross passage. In the event that the freeze was breached, flooding of the cross passages would result in potentially catastrophic flooding of the tunnel. Excavation and final lining proceeded as shown in Figures 11 and 12. During the excavation phase significant quantities of grout were observed. Due to the size of the grout inclusions, it is the author's opinion that the successful freeze could not have been accomplished without grouting to decrease the permeability of the Key Largo formation.

The cross passage freezing was a successful joint-effort comprising the general contractor, Bouygues Civil Works Florida, and its drilling [Nicholson Construction] and freezing [Moretrench] subcontractors. It demonstrated the successful use of ground freezing for cross passages in North America for the first time.

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