# Ground Freezing for Tunnel Cross Passages
# First Application in North America

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Ground freezing was used for the first time in North America to freeze two 2.8m diameter cross passages for the Port of Miami Tunnel. While ground freezing has been used for similar construction in Europe and Asia, this was the first application in North America. This project was complicated by the extremely porous subsea soils. To reduce the permeability of these soils and rock, an initial grouting program was implemented from the ground and channel surfaces.

Two rows of horizontal freeze pipes were drilled and installed to form the frozen cylinders for excavation support and groundwater control for cross passage construction. The refrigeration system used to circulate the cooling medium was located at the ground surface and supplied to the cross passages via supply and return manifolds and a specially designed pumping system.

An extensive system of instrumentation was installed to monitor ground temperatures, soil and rock water pressures, coolant flow rates and pressures and process information from the refrigeration plants.

This paper will discuss the grouting approach, freezing system drilling and installation; freeze monitoring and the excavation and completion process of a very successful project. Guidelines and recommendations for frozen cross passage construction are summarized.

## DESIGN OF THE FREEZE SYSTEM

The Port of Miami Tunnel consisted of twin 13.1-m diameter tunnels to connect Interstate 395 on Watson Island to the Port of Miami on Dodge Island. The two tunnels had five, 2.8m diameter cross passages ranging in length from 24.3 to 36.5 meters. Two of these cross passages required ground freezing to provide groundwater control and temporary earth support for excavation. This was the first time ground freezing had been used for cross passage construction in North America.

Cross Passages 2 and 3, were approximately 30 m below the ground water level and were mostly within the highly pervious Key Largo formation as shown in Figure 1. The Key Largo is a rock formation consisting of coral fragments within a cemented calcarenite matrix. After the contract award, the tunneling contractor Bouygues, conducted its own geotechnical investigation and found that this formation was predominately coarse-grained soil and could become unstable during tunneling operations.

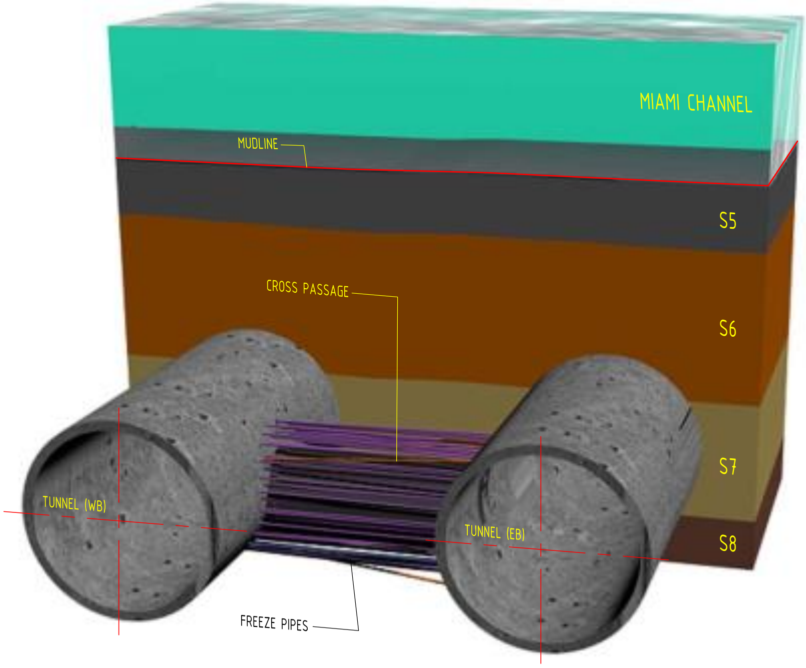

**FIGURE 1 Tunnels Below the Channel**

The initial review of the freezing application for the Port of Miami Tunnel uncovered several complications dealing with a highly porous subsurface soil matrix that had the potential for lateral groundwater flow through the freezing system. Conventional ground freezing systems typically use a series of pipes spaced approximately 1m apart and circulate a -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. Given this pipe spacing and brine temperature, closure and formation of the cross passages was anticipated in approximately six weeks. The term closure refers to the point in the freezing process when the frozen cylinder is formed to the extent that a hydraulic barrier is created. Formation refers to the point where the frozen cylinder grows in sufficient thickness to provide the required structural capacity to facilitate excavation.

These two phases are key to the successful implementation of ground freezing. Frozen ground decreases in strength, deforms and can even fail with time. This time dependent behavior must be considered when determining the freeze pipe spacing, freezing time and permissible standup time before installing the final structural lining.

The closure phase of ground freezing can be retarded or even prevented if groundwater velocity through the freeze pipes introduces more heat than the system can extract. The high permeability of the Key Largo formation, coupled with groundwater gradients induced by tides and ocean currents created the potential for high ground water velocity. Typically groundwater velocity greater than 0.5 to 1.0 m/day can create delays in the formation of the frozen cylinder.

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.

Prior to the installation of the ground freezing system, a grouting program was performed from ground surface and described by Barison 2014. A series of grout tests were performed and ultimately a final grout design was selected. This extensive grouting program was performed from the surface, both on land and on barges in the channel. The program consisted of downstage grouting using the specially designed mix.

The design of the ground freezing system consisted of two rows of freeze pipes with centerline radii of 3.35m and 3.96m. Finite element modeling was used to evaluate the required freezing time and subsequent required refrigeration load. 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 at the end of the cross passages at the westbound tunnel.

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 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 -25°C ethylene glycol solution through cooling tubes 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 within the tunnel.

The design of the frozen cross passages and freezing system had four key components:

1. Thermal design to evaluate the freezing time and required refrigeration load
2. Structural design to determine the required frozen cylinder thickness
3. Hydraulic design to determine the necessary grouting program
4. Mechanical system design to evaluate the freeze plant, distribution manifold and instrumentation system

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 -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, 183 meters away from the tunnel entrance as illustrated in 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 such as tunnels. 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.

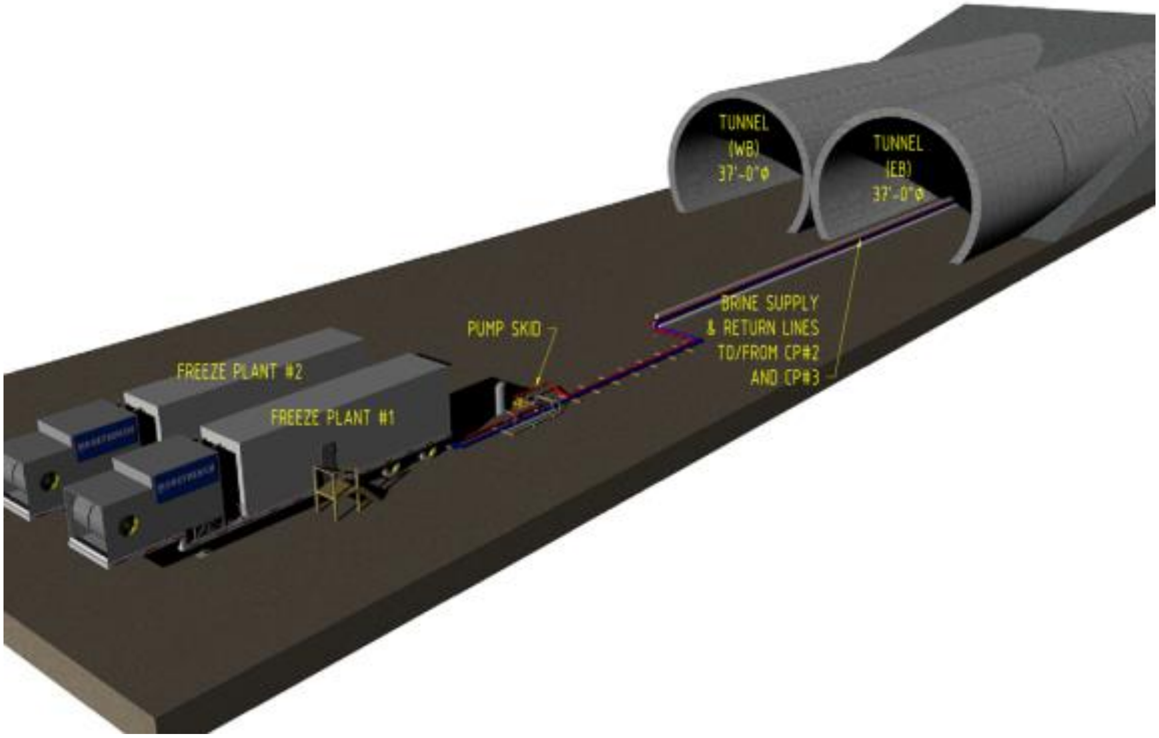

**FIGURE 2 Freeze Plant Layout**

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 months.

The ground freezing instrumentation system for this project 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 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 the 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.

FIGURE 3 Instrumentation Screen Shot of the Freeze System Layout

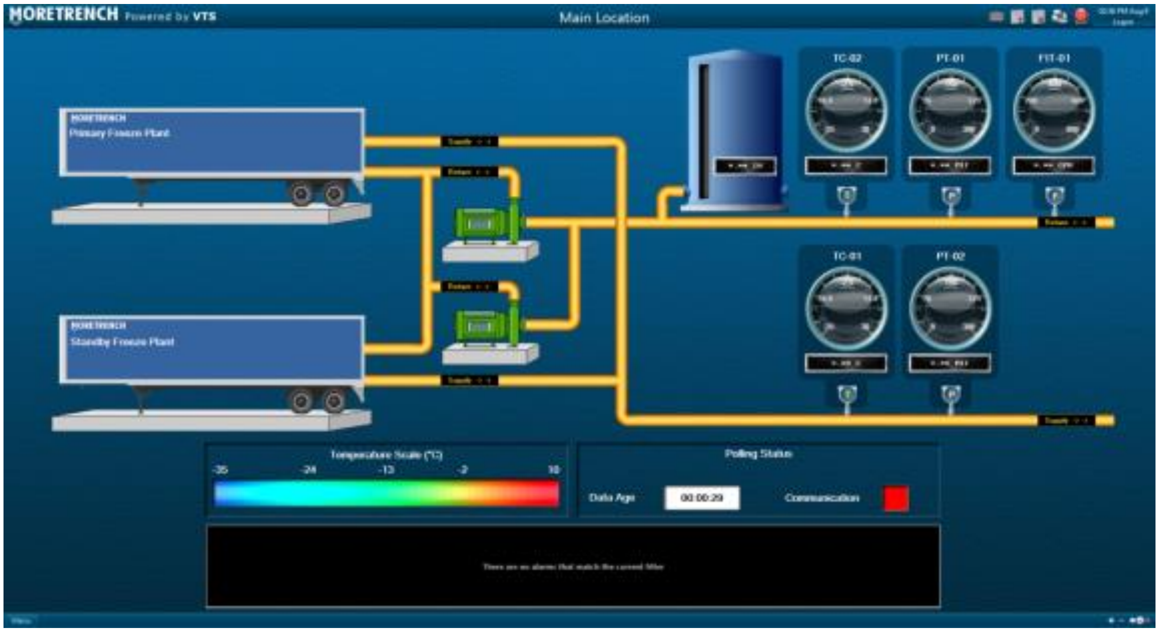

FIGURE 4 Instrumentation Screen Shot of the
Coolant Distribution Manifold System Data.

FIGURE 5 Instrumentation Screen Shot of Cross Passage No. 2
Temperature and Pressure Acquisition.

The instrumentation system was designed to scan all sensors approximately every ten 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 immediately.

Figure 6 shows the temperature data acquired for one of the ten temperature monitoring pipes. The sensors were installed in the pipe at approximately one-meter intervals. Note that at 65 days, excavation commenced and the warming was recorded.

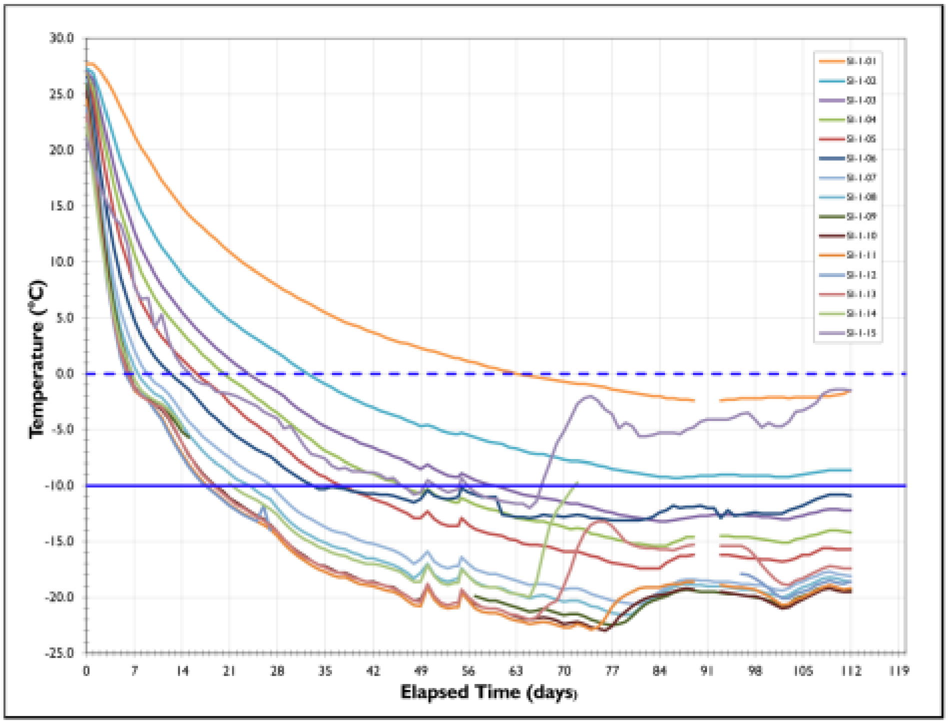

FIGURE 6 Ground Temperature Data

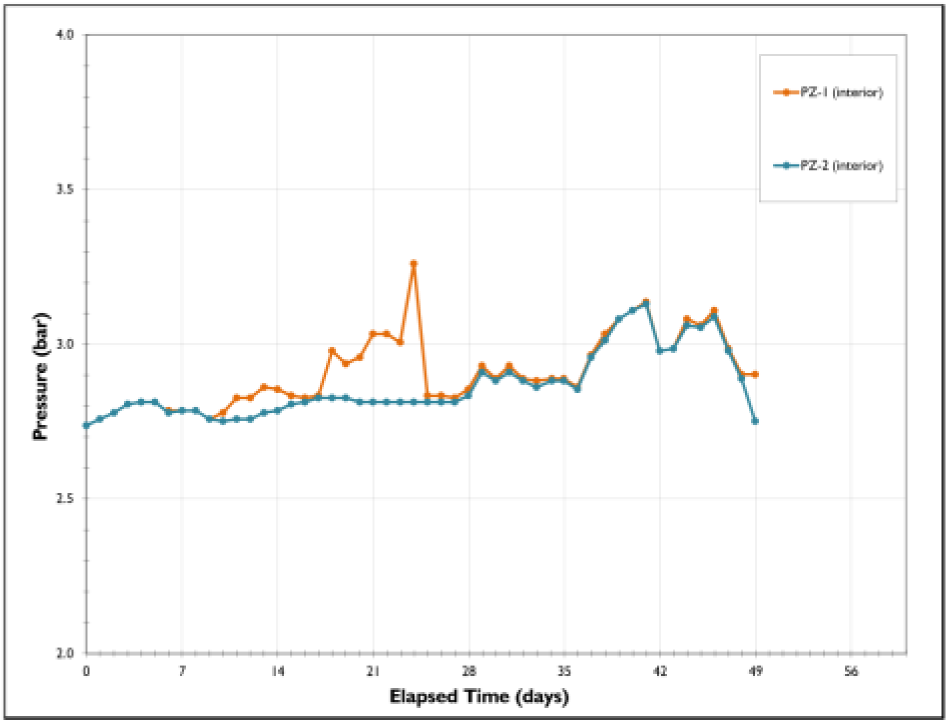

FIGURE 7 Internal Water Pressure Data

Figure 7 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 most 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 the excavation phase 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 8 and 9.

**FIGURE 8 Cross Passage Excavation**

**FIGURE 9 Cross Passage Lining**

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.

## CONCLUSION

The cross passage freezing was a successful joint-effort comprising the general contractor and drilling and freezing subcontractors. It demonstrated the successful use of ground freezing for cross passages in North America for the first time. There were several design and procedural aspects of this successful project that should be considered when using ground freezing for cross passage construction, specifically:

- Ensure sufficient geotechnical data for unfrozen and frozen soils are available and understood. Conduct frozen soil strength tests if needed.
- Complete comprehensive thermal and structural modeling analysis.
- Be aware of the potential for lateral groundwater flow prior to freezing. If necessary implement a grouting program to reduce soil permeability.
- Temperature monitors should fully represent the entire area to be frozen.
- Monitor the pressures in the cross passage interior to ensure frozen closure.
- Install the bulkheads in advance of any potential problems.
- Line the cross passage concurrently with excavation.

## REFERENCES

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