Ground Freezing for Tunnel, Shafts, and Adits

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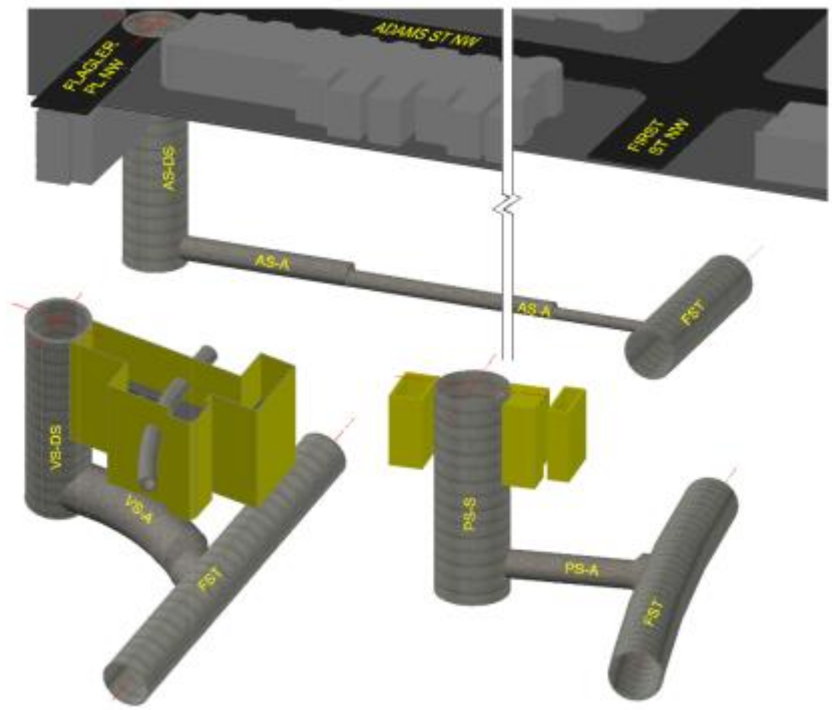
ABSTRACT

Construction of a 0.81km long, 6.1m diameter sewer tunnel, a component of D.C. Water's Clean River Project required construction of three drop shafts and connecting adits. The location of these three shafts and adits was complicated by their locations in a populated suburban neighborhood. Ground freezing from the surface was selected as the method to provide temporary earth support and groundwater control during construction. The ground freezing option was not only the most technically appropriate method, it provided significant advantages to accommodating the citizens in the neighborhood. Not only did the drilling and installation process provide a minimal equipment footprint at each site and reduce cuttings and spoils, but the refrigeration plants were located at a remote location reducing noise levels during the freezing process and construction. This paper discusses the design and implementation process of this complex freezing system that included drilling refrigeration pipes at complex angles in order to minimize traffic interruption and avoid utilities. Additionally, horizontal freeze pipes were drilled under 3 bars of pressure from the EPB tunnel in order to ensure that the adit connections were sufficiently frozen. The intricate cooling system extended over half a mile on both the surface and underground tunnel with instrumentation and monitoring along all points.

INTRODUCTION

The relatively short (0.81km) First Street Tunnel had three individual drop shafts designed to transport combined sewage from higher elevation sewers to the tunnel via small diameter (2.4-5m) adits. The three shafts and adits are shown in section in Figure 1.



Source: Rob Chamberland, MTAC

Figure 1. First Street Tunnel shafts and adits

Construction of these shafts and adits was complicated by their locations within a residential neighborhood. In selecting the support of excavation for the shafts and the required ground improvement for the adits, consideration was given to minimizing the impact on the residents as well as minimizing noise. Secant piles and slurry diaphragm walls were considered for the shafts while jet grouting was a technical feasible method of ground improvement for the Sequential Excavation Method (SEM) for the adits.

While both methods were technically and economically feasible, there were some significant disadvantages related to their compatibility with working in a residential neighborhood. Specifically there was concern that space was limited for slurry diaphragm wall construction due to the reinforcing steel on-site storage and placement. Jet grouting would result in a significant amount of cuttings and spoils that would not only create a less than pristine site, but would also result in significant traffic for disposal. Furthermore, jet grouting would require significant utility relocations to avoid angled drill holes.

Ground freezing was originally considered, however immediately ruled out due to the constant operations of the refrigeration plants at each of the three shaft and adit sites. Ground freezing, however, had several technical advantages to the methods. Specifically:

- Ground freezing could be used for groundwater control and temporary earth support for the shafts and adits requiring one equipment mobilization.
- Cuttings and spoils would be minimized.
- Freezing could be used to ensure a water-tight connection from the adits to First Street Tunnel.
- Vehicle traffic near the residential structures would be minimized.
- Construction noise and vibration would be minimized

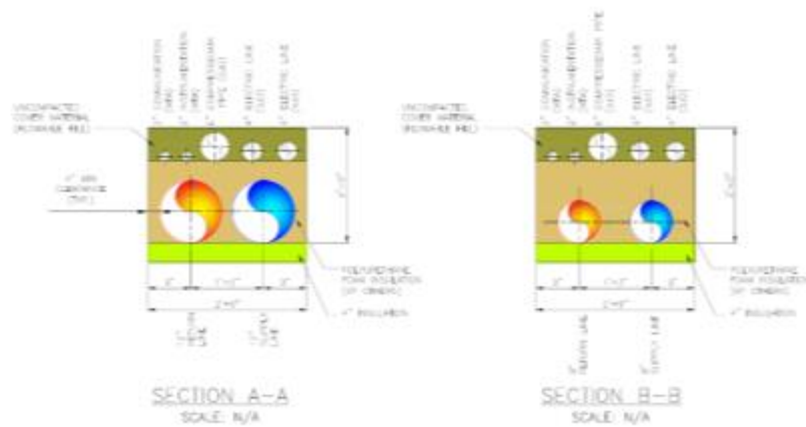
These advantages were too significant to totally discard the freezing concept. After reviewing the site plan in detail, an alternative approach was considered. The Channing Street Shaft site where the Tunnel Boring Machine (TBM) would be launched was not only relatively far from the residences, but had ample laydown room to place the refrigeration plants, pumping skid, and instrumentation trailer. This unprecedented approach was to use the Channing Street site as the lay-down area and transfer the refrigerated coolant to each of the three sites using a subsurface distribution manifold. Using this concept, the ground could be freezing at each of the sites literally unnoticeable to the residents of the community.

COOLANT DISTRIBUTION MANIFOLD

The initial design computations concluded that three electrically powered mobile refrigeration units would be required to provide sufficient cooling capacity to the shafts and adits at the required times as proposed by the original schedules. As shown in Figure 2, the plants and pumping system would be located near the Channing Street Shaft. The refrigerated calcium chloride brine would be pumped to each of the sites through a subsurface manifold system as shown in Figure 3. The Pumping Station Site was located 670 m from the plants. In addition to the hydraulic requirements as related to the pumping capacity and pipe size, heat loss through the system was also evaluated.

Source: Rob Chamberland. MTAC

Figure 2. Freeze plant and pumping system



Source: Rob Chamberland, MTAC

Figure 3. Subsurface manifold system

The manifold was buried and essentially undetected during the process. The heat loss was mitigated by backfilling the trench with polyurethane insulation. This insulation resulted in a heat gain of less than 2 ^{o}C at the Pumping Station, consistent with the thermal design requirements of providing -25 ^{o}C brine or colder through each subsurface refrigeration pipe. It should be noted that in addition to maintaining the cold brine temperature within the manifold pipes, the insulation also served to reduce or eliminate any frost effects to the sidewalks and pavements due to the freezing temperatures.

While the design of the frozen earth structures stipulated a brine temperature of -25 ^{o}C or colder, sufficient flow through each individual freeze pipe or circuit of freeze pipes is just as important to the timely and successful formation. To ensure both temperature and flow requirements, an instrumentation system specifically designed for this project was designed and fabricated. Figure 3 shows the placement of conduits, one to be used to transmit information for the shaft sites back to a centralized computer and SCADA system.

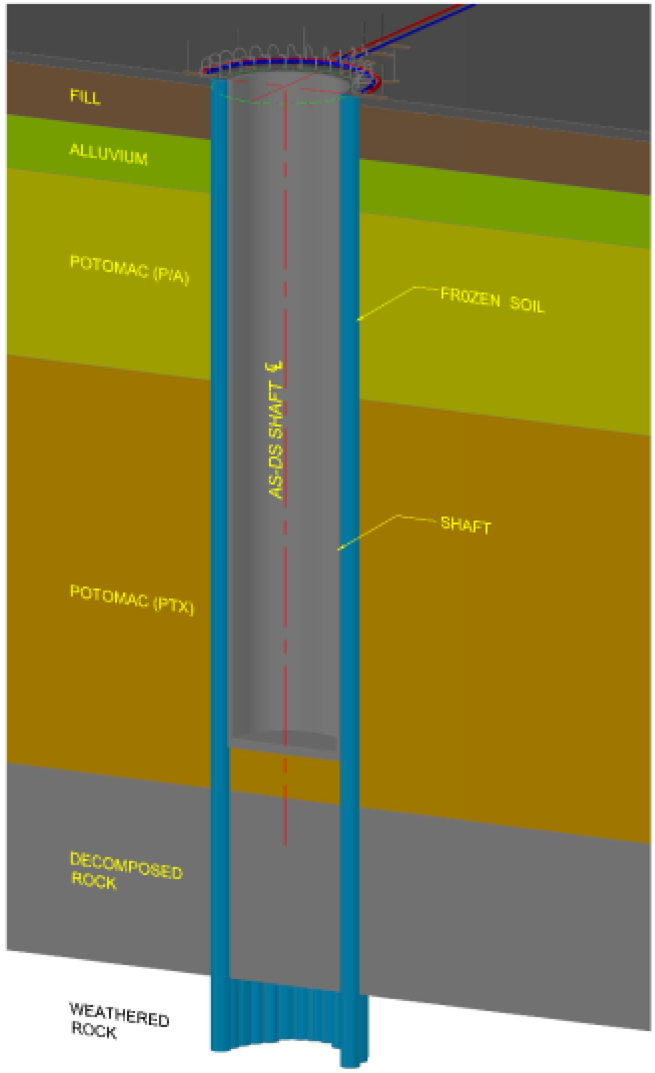
The performance of the distribution system was monitored with flow meters and also the supply and return temperatures of the circulating brine. Flow meters were used to evaluate the overall mass flow in and out of the pumping system. The brine supply and return temperature was measured at each pipe or circuits of pipes. By evaluating the difference between the supply and return temperatures it was possible to not only confirm sufficient flow, but also to balance the system across each individual structure.

FROZEN EARTH SHAFTS

The frozen earth for the shafts provided both temporary earth support and groundwater control. The three frozen shafts are described in Table 1.

Table 1. Frozen shaft dimensions (m)

Shaft	Shaft Inside Diameter	Excavated Depth	Depth to Rock
Adams Street	6.0	29.9	42.8
V Street	7.0	27.3	44.0
Pumping Station	7.0	26.8	40.0



Source: Rob Chamberland, MTAC

Figure 4. Typical shaft freeze system

Figure 4 shows the typical system for this project. To provide bottom stability of the excavation, the frozen wall was terminated in competent rock below the excavation invert. A structural evaluation of the frozen shafts prior to design was completed following a frozen soil test program completed on samples retrieved following the contract award. The analyses concluded that at 2.5 to 3.0m thick freeze wall would provide the required resistance to lateral earth and hydrostatic pressures and the time and temperature dependent creep properties of the frozen earth. A thermal analysis estimated a freezing time of approximately eight weeks, using refrigeration pipes at 1.0m spacing.

The freeze pipes were drilled with mud rotary methods and verified for verticality with an orientable inclinometer. Once the freezing process was initiated, the ground temperature data indicated freezing times compatible with the thermal model. As the frozen wall was formed, pore water within the shaft was forced to the center as a result of the expansion created as the water was converted to ice. This expansion was observed through pressure measurements in a piezometer drilled and installed in the interior of each shaft.

Following the indication of the closure of the frozen wall, an additional two to three weeks of freezing was required to achieve the required 2.5 to 3.0m thickness. Once this thickness was achieved excavation commenced.

Prior to achieving the 3.0m thickness excavation was able to begin within the upper fill area, which contained no pore water. Standard soldier piles and lagging were used in this non-frozen area to ensure ground stability. Once the 3.0m thickness of frozen wall was achieved, excavation through the frozen soil began using a Brokk hammer along with mini excavator.

As excavation progressed a 10cm thick layer of foam insulation was sprayed onto the exposed earth. Due to site noise and work hour restrictions, excavation, form, and concrete works had to be performed during weekdays and daytime hours only. Excavation of each of the three frozen shafts took approximately 2.5 months each.

Immediately after bottoming out the shaft excavation, the base slab was poured followed by the formwork for the walls of the shaft. The formwork was installed in 4.9m lifts followed by pouring of the concrete liner. Once poured the formwork was stripped and raised for the next lift. Cycle time per lift averaged approximately 1 week. Wooden block-outs within the liner were also installed at the adit connection locations.

After the entire height of shaft line was poured and cured, the freeze pipes for the shaft were shut off.

FROZEN ADITS AND TUNNEL CONNECTIONS

The frozen soil for the adit connections provided both a temporary earth support system as well as a ground water cutoff. The adits were designed as solid frozen soil masses. The dimensions of the frozen masses are outlined in the table below:

Table 2. Frozen soil mass dimensions (m)

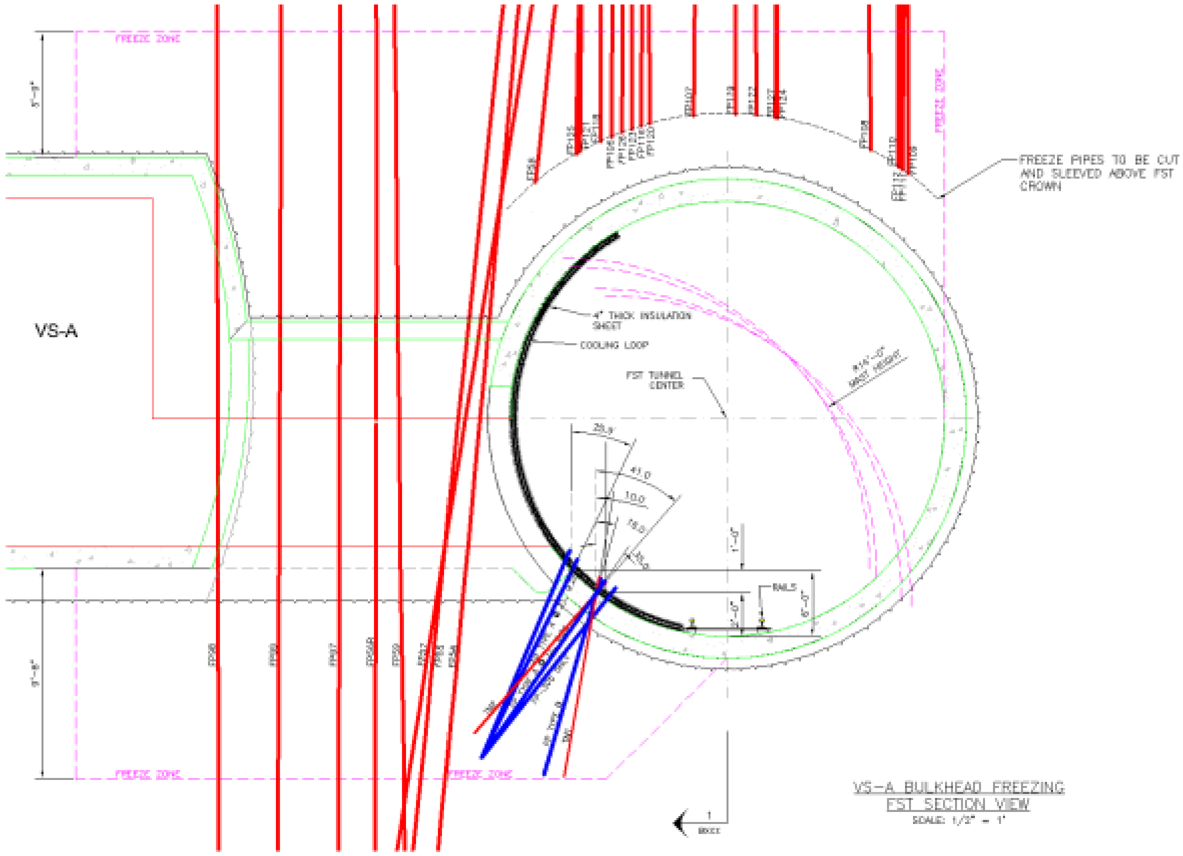
Adit Location	Length	Width	Height
Adams Street Adit	26.5	8.2	8.2
Adams Channing Tunnel Connection	8.5	7.9	8.2
V Street Adit	24.7	9.7	11
Pump Station Adit	25.9	9.1	10

At a minimum, 1.8 m. of frozen soil was required by design around the designed excavated area.

Unlike the shafts, the adits were considered sufficiently frozen when temperature monitors combined with thermal modeling indicated a complete frozen mass. As a precaution, probe drilling was performed ahead of the excavation to verify anticipated frozen soil conditions.

Excavation of the adits was performed utilizing Sequential Excavation Methods (SEM). A Brokk utilizing a roadheader type mining attachment was used to excavate the adits. Upon completion 1.2m of excavation, a lattice and girder support system was installed and 28 cm of shotcrete, installed in 2 passes, were used as additional excavation support. This was necessary due to the fact that freeze pipes were removed during excavation and thawing would occur prior to the installation of the final lining.

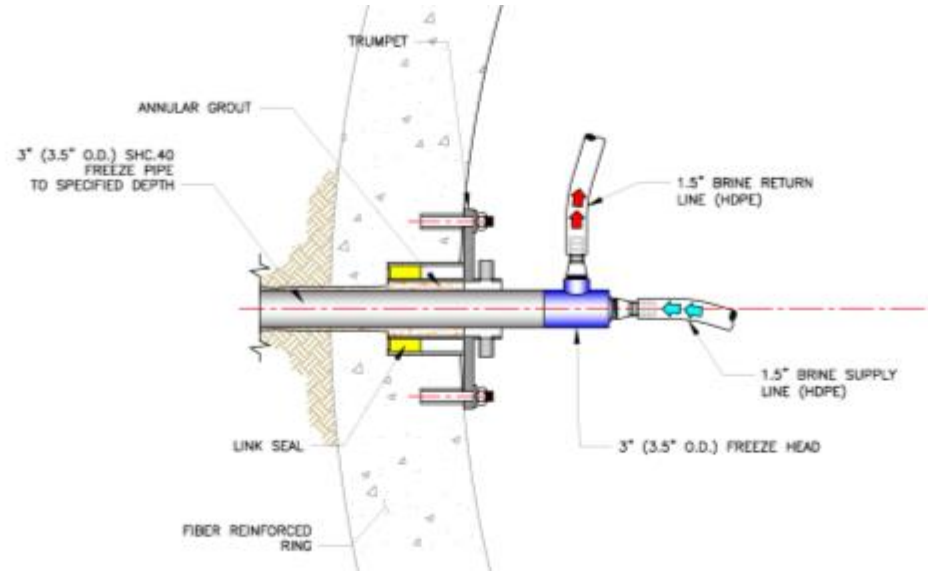
Schedule required the passing of the TBM through the adit connection areas prior to completion of the adits. As such, a latter connection between the frozen adit and the newly mined tunnel was necessary. Freeze pipes that were installed prior to the TBM mining had to be decommissioned once the main tunnel passed. To facilitate such connection, with the concerns of thawing, additional freeze pipes were installed from within the tunnel through the invert to ensure a sufficient frozen mass beneath the connection.



Source: Rob Chamberland, MTAC

Figure 5. Tunnel Connection Drawing

Trumpets were mounted on the tunnel liner and core holes were drilled though a series of valves and wiper seals to prevent excess soil loss in the event that unfrozen soil was encountered. Once the freeze pipes were installed, urethane grout was used to seal the protrusion through the tunnel liner. Additionally, cooling loops were secured to the tunnel lining along the excavation line to ensure that a sufficient seal was maintained between the concrete lining and the frozen soil.



Source: Rob Chamberland, MTAC

Figure 6. Trumpet and freeze pipe detail

HEAVE AND MITIGATION

Because of the difficulty in accurately estimating the freeze related heave and/or settlement, the approach for the First Street Tunnel was to go beyond evaluation of freeze related heave through modeling and to incorporate freeze heave mitigation as part of the project-wide protection of structures process. The protection of structures process required performing analyses to determine allowable and maximum movements or deformation limits and, if required, mitigations for any impacts during construction. During construction, information from instrumentation and monitoring of the existing utilities and structures was used in the selection and timely deployment of mitigation measures for excessive heaving. Typical mitigations that were used included installation of heat trace pipes to cut off or slow down freeze growth and modifications to the brine flow in the freeze system. Other mitigation measures included systematic isolation or shut-down of portions of the freeze system to control freeze related ground deformations and protect existing utilities and structures.

CONCLUSION

In order to accommodate the specific needs of this project all methods of work had to be evaluated. Due to the rigorous constraints relating to available area, noise, structural stability, and environmental concerns, ground freezing was proven to be the necessary method of support of excavation.

With the unique structure and layout of the First Street Tunnel project, alternate ideas and concepts of supply and install of brine were critical to the success of the project. Implementation of innovative concepts within the ground freeze technology allowed for lessened impact to the surrounding community. Accurate monitoring and survey throughout the entire process proved critical to ensuring real-time data updates for schedule progression along with mitigation of any issues within the system.