Artificial ground freezing is a method of providing temporary earth support and ground water control for deep excavations and tunnels. The technique has been used for over 100 years in the mining and civil tunneling industries. It is established practice for specialty contractors to prepare a detailed design and then drill and install freeze pipes at approximately one-meter centers around the perimeter of proposed excavations, finally connecting to mobile refrigeration plants. Case histories regarding the design, installation, and operation of freezing systems for shafts and tunnels are well documented, but little has been said about the constraints and difficulties encountered when ground freezing is required in heavily congested urban areas with adjacent structures, utilities, surface streets, and pedestrian traffic.

The recently completed Northern Boulevard Crossing, part of the Long Island Railroad in New York City, is a great example. Here, ground freezing was the only technically feasible method to provide groundwater control for mining of a Sequential Excavation Method (SEM) tunnel in a congested urban area.

Safe Operations

This project is located in the borough of Queens. When complete, it will provide commuter rail service from communities on Long Island to Grand Central Terminal in the heart of Manhattan. A 40-m section of that tunnel crosses under the existing, heavily traveled Northern Boulevard and an active subway structure leading into a nearby station. The subsurface geometry is further complicated by the presence of pile foundations bearing the load of overhead elevated rail tracks.

With the presence of vehicular and rail traffic as well as thousands of pedestrians daily, every aspect of the project considered the priority of public safety as well as completing the tunnel with minimal impact to adjacent and overlying structures.

Unlike mining projects, where the shafts are typically located in remote areas and short tunnels can be readily open cut, projects such as this in congested cities leave no option for relocation of the tunnel alignment or alternate excavation methods. Work from Northern Boulevard or from inside of the subway structure was prohibited. After evaluating many options, a horizontally installed, frozen earth arch (Figure 1) was selected as the most technically feasible approach, offering the surest protection of the excavation and adjacent structures.

The crossing was only 40 m long, but the space available in which to construct the frozen arch was very constrained. The tunnel alignment crossed beneath a 5-track subway structure, with only a few meters of cover. The frozen arch would have to be formed through four clusters of 16 pipe piles supporting an elevated rail line. Four large-diameter piles were required through the arch to temporarily underpin the elevated rail line. Additionally, excavation support from the original subway construction would likely be encountered during horizontal drilling.

Although a challenge for the installation of the freeze pipes, these man-made obstructions would be easily incorporated within the frozen arch itself. Because the frozen ground improvement propagates itself thermally rather than by soil displacement or hydraulic erosion, a substantially thick frozen wall could be constructed through the obstructions simply by installing small diameter steel pipes spaced every 1-2 m.

The frozen arch would be formed through a wide range of natural ground conditions. The upper half of the arch would lie within finer grained glacial soils consisting mostly of highly sensitive silt. Beneath the finer grained soil is a glacial till containing cobbles and boulders overlying an undulating rock surface. With ground freezing in general, the thermal conductivity of the different soils does not vary widely; the ground freezing process is relatively insensitive to soil type. Thus, the freeze would conform perfectly through the cobbles, boulders, and geological transitions.
Design of the Frozen Arch

Design of any frozen earth structure is composed of two separate, but integrated analyses. A structural analysis is completed to evaluate the required thickness of the frozen arch both at the time of initial excavation and subsequently for the long-term duration of the project. A thermal analysis is then completed to determine the required freeze pipe spacing, freezing time, and required refrigeration capacity. In both the structural and thermal analyses, finite element models are required to fully evaluate the complexity of the soil-structure interaction.

Frozen soil exhibits time-dependent rheological properties. Unlike other construction materials, frozen strengths are dependent on both time and temperature. A laboratory testing program was required to fully evaluate the strength properties of the frozen ground. The program included uniaxial and triaxial compression testing at -10 and -15°C.

Two types of compression tests were required to obtain the necessary parameters to use in the analysis. A constant strain rate test was conducted at both temperatures to evaluate the unconfined compression strengths and the elastic moduli. Following these tests, long-term compression creep tests were run at stress levels of 0.25, 0.50, and 0.75 of the unconfined compression strength. The test results were used in evaluating the long-term deformation and stress redistribution of the frozen arch used in the structural analysis.

A two-dimensional (2D) structural analysis of the frozen arch was completed using PLAXIS to determine the required thickness of the frozen arch. Based on the parameters from the laboratory testing program, the analysis yielded a required frozen arch thickness of approximately two meters at an average temperature of -10°C.

To determine the required freeze pipe spacing, time needed to freeze, and refrigeration capacity, a 2D finite element method thermal model was developed using the program TEMP/W (Figure 2). In addition to the spacing, time, and refrigeration capacity, the model also indicated the extents of the frozen zone. The frozen soil zone (area below 0°C) actually extended further than the -10°C average zone. The effect of this extended frozen zone had to be carefully evaluated since it could impact the structures directly above the frozen arch.

Protection of Structures

As with most construction projects in large cities, preserving the integrity of existing structures must be considered in both the design and construction phases of the project. At Northern Boulevard, protection of the overlying subway structure during the work was of paramount importance. The behavior of the predominant silt stratum presented several unique concerns. Drilling of tiebacks below the water table on an adjoining contract and the corresponding ground loss revealed the
potential instability of these soils. In light of this potential ground instability, compensation grouting was required in the thin soil horizon between the top of the frozen arch and the base of the subway structure to mitigate ground loss that was anticipated with the installation of horizontal freeze pipes under as much as 20 m of groundwater pressure.

When soils are frozen, two types of expansion occur. Immediately upon freezing, the pore water increases in volume as it becomes ice. In most soils, the pore water is displaced as it expands, and there is no increase in the soil volume (heave). In a frost heave susceptible soil, ice lenses can form at the interface of the frozen/unfrozen soil boundary with continued freezing. As a result of these two mechanisms, ground heave may occur with freezing; however, at the Northern Boulevard Crossing, the frost heave susceptibility of the silts and the horizontal orientation of the pipes were potentially problematic. For vertical freezes, lateral heave forces from ice lens formation are rarely an issue because they are counteracted by greater lateral earth pressures at depth. But for horizontal freezes, the lenses exert forces vertically, which may exacerbate heave of the structure, particularly at shallower depths.

Heave of the 5-track subway structure was a concern. Under the best scenario, with minimal deviation of the drilled freeze pipes, there still would be only 2 m between the top of the frozen arch

The ground freezing process is relatively insensitive to soil type. Thus, the freeze conforms perfectly through the cobbles, boulders, and geological transitions.
A Challenging System Installation

Subsurface construction in large metropolitan areas almost always has the constraints of minimal and difficult access to the tunnel location. On this project, the majority of the horizontal drilling was initiated from an internally braced, 25-m-deep, slurry wall supported shaft.

The freeze design allowed for a specific pipe installation tolerance. Maintaining drill alignment while penetrating through old sheeting, concrete-filled pipe pile clusters, cobbles and boulders, and an undulating rock surface was challenging in and of itself. Drilling from below the water table, for the most part through very sensitive soils, compounded the complexity of the work as well as significantly restricted drilling methodologies. Significant measures were put into place to install the pipes within permissible tolerances while preventing ground loss.

Drilling of freeze and compensation grout pipes was accomplished in stages as excavation within the slurry wall structure progressed down to final elevation. Core drilling, with the capability to advance multiple casings, was the primary drilling method where obstructions were anticipated. Because of the higher rotation speeds, this method is typically better suited for drilling straighter holes through obstructions. The core drilling tools also allowed for multiple reductions in casing size to telescope them as necessary to permit casing and bit changes. In areas anticipated to be free of obstructions, pipes were advanced by duplex, positive flush methods. Sonic drilling was the contingency method to be utilized should any borehole meet a refusal condition during core drilling. However, this was not required.

The horizontal holes were drilled with positive flush methods, lost bits, and wipers to prevent an inrush of ground as the casing was being pulled. Blow-out preventers with redundant design features virtually eliminated uncontrolled soil and groundwater inflows during the drilling. The blow-out preventers enabled telescoping of casings while core drilling.

Upon completion, all pipes were surveyed with a gyroscope. Freeze formation time was verified by modeling the as-built freeze pipe array. Accuracy of compensation grout pipe installation was critical because the target zone between the top of the frozen arch and the underside of the subway box structure was very limited, and compensation grouting too close to a structure can be harmful.

Compensation grout pipes were the first pipes installed so that ground loss with any subsequent installations could be addressed, and to compensate for any thaw settlement upon completion of the work. They were installed just above the arch in the narrow space between the subway structure and the top of the frozen arch, and also served as the heat pipes to limit growth of the freeze.

An on-site compensation grouting trial verified the ability of the grouting to induce sustained heave of the subway box structure. Because of very loose ground conditions beneath the subway box, an appreciable amount of grout was injected. The goal was to ensure that any voids beneath the existing subway box were filled, thereby providing a more uniform surface against which the subsequent ground treatments would act. Preconditioning or “pre-tightening” of the balance of the area was then performed with end-of-casing methods akin to horizontal compaction grouting. Using this method, greater productivity was achieved without concern for damaging the grout pipes. A total of 220,000 liters of grout was pumped beneath the subway structure during this preconditioning phase — approximately 200 liters of grout per square meter of subway box overlying the arch.

Because conventional cement-based grouts could render the soils unworkable for heave-control soil extraction (which could occur later), a non-cementitious grout was developed. The grout mix consisted of a fine sand/coarse silt base plus additives to provide a minimum strength bulk fill material that

With the minimum design thickness of frozen ground at -10°C, the extremities of the frozen arch extended well into the tunnel excavation. This provided tremendous ground stability, but required cutting of the frozen ground with an excavator-mounted milling head.
had sufficient stability to permit injection through sleeve port
gROUT pipes, but with an intentionally high pressure filtration
coefficient. Thus, water would bleed from the in-place grout,
and it would revert to a soil-like material with the strength
and consistency of the in-situ finer glacial soils. The rigorous
controls implemented during drilling eliminated the need for
any compensation grouting during the horizontal drilling phase.

The freeze was activated utilizing a large mobile freeze plant
with two 400 HP compressors. Once horizontal temperature
monitors indicated formation of the frozen arch, a drain-down
test of the internal water was conducted. Results of the test and
subsequent temperature profiling of the freeze pipes revealed
two warm spots, indicating “windows” in the frozen arch.
Grouting and equalization of groundwater pressures across the
arch closed the windows. A second drain-down test and further
temperature profiling confirmed closure of the freeze.

SEM Tunnel Excavation

The original design consisted of three over three drifts.
During construction, the two center drifts were split into a top
heading, bench, and invert. Round lengths were 1.2 m for all
the upper drifts and 2.4 m for all lower drifts. Figure 3 shows
the SEM mining with the center drifts in progress.

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-10°C, the extremities of the frozen arch extended well into the
tunnel excavation. This provided tremendous ground stability,
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mounted milling head (Figure 4).

The original SEM support design required a 75-mm
flashcrete layer to be applied immediately after excavation
and prior to lattice girder installation to control any raveling
ground and provide a degree of insulation for the subsequent
300 mm thickness of shotcrete reinforced with welded wire
fabric. Studies of concreting against frozen ground indicate
the heat of hydration of a typical wall or liner will temporarily
thaw one or two centimeters of frozen ground which re-freezes
quickly following the temperature spike. This behavior resulted
in occasional localized delamination of the thin flashcrete
layer. To avoid this problem, the flashcrete and shotcrete
application was combined into a single pass.

After excavation was completed and the temporary interior
sidewalls were removed, the final lining was installed. This lining
included 14 massive ring girders at the locations of the elevated
railroad support piles, and a 750-mm pneumatically applied,
reinforced concrete final lining. The loads were transferred from
the underpinning piles back to the original foundations after the
final lining had achieved sufficient strength and the underpinning
piles were removed. Although no movement occurred with the
mining of the tunnel drifts, the subway box settled approximately
4 cm with the load transfer and partial thaw of the freeze.

The actual heave observed was less than anticipated (typically
2 cm); therefore, heave mitigation procedures were not required.
Compensation grouting was successfully performed during the
thaw period to correct for slight differential settlements of the
subway box. The non-cementitious grout provided lifting of the
structure in a controlled linear fashion over several weeks, with
numerous repeat injections through the same grout pipes.

Conclusion

As shown by this case study, the horizontal application
of ground freezing sometimes requires additional provisions
when the surrounding environment is a tight urban setting.
They proved effective to assure the safety and integrity of the
overlying structures during the ground freezing process, and
mitigated the risk of adverse impacts due to settlement and
heave. By making numerous behind-the-scenes provisions, the
tunneling team was able to provide excellent ground stability
and protection for the structures surrounding the site.

Although this article reflects only the views of the authors,
the success of this challenging project can be attributed to
a team effort comprised of the owner, the designer, a joint
venture of Parsons Brinckerhoff and STV; the program manager
Hatch Mott MacDonald; general contractor Schiavone/Kiewit;
and geotechnical contractor Moretrench.

Figure 4. Photograph of the frozen ground during excavation.

AUTHORS

Paul C. Schmall, PhD, PE, D.GE, FASCE, is vice president and chief engineer at Moretrench. He can be reached at pschmall@mtac.com

Joseph A. Sopko, PhD, PE, M.ASCE, is the director of ground freezing at Moretrench. He can be reached at jasopko@mtac.com

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