FEATURE ARTICLE

Ground freezing resolves complex challenges ahead of SEM tunneling

A complex soil profile and high water table, together with a below-grade active subway tunnel, an above-ground elevated railway line, and the heavily travelled Northern Boulevard all passing above the tunnel alignment, combined to make mining of New York's Northern Boulevard Crossing what is widely considered to be the most challenging portion of the multi-billion-dollar East Side Access project.

The Northern Boulevard Crossing is a vital link in this project which, when completed, will connect the Long Island Railroad to Grand Central Terminal in Manhattan. How the sequential excavation method (SEM) tunneling was successfully accomplished, despite the obstacles, was a textbook exercise in practical innovation coupled with close cooperation between the owner, the construction manager, Hatch Mott MacDonald, the designer, Parsons Brinckerhoff, the contractor, Schiavone-Kiewit, and specialty geotechnical contractor, Moretrench.

Tunnel excavation prior to the removal of internal braces.

The 38-m- (125-ft-) long tunnel was to be mined 16.7 m (55 ft) below the ground water table between two 25-m- (85-ft-) deep access shafts and through soils consisting of glacial deposits including highly sensitive Bull's Liver-like silts, sands, boulders, till and bedrock. For short tunnel reaches through soft ground, SEM tunneling is the most economical option, but a relatively long soil stand-up time is required, together with adequate ground water control if the tunnel alignment is below the water table. However, several complicating factors limited available options for ground support and ground water control. Any disruption to subway or rail traffic was prohibited, eliminating vertical drilling for ground improvement, either from the surface or from within the subway tunnel. Horizontal drilling and jet and permeation grouting were considered. Jet grouting was rejected in light of the potential difficulties of working horizontally and below the water table. Permeation grouting was eliminated because of the high fines content in the soils. Conventional dewatering was also not an option since plumes in the vicinity of the tunnel alignment precluded lowering of the ground water.

Ultimately, the project team concluded that the most viable option of meeting all the constraints was the designer's scheme to use horizontal ground freezing to create a frozen arch above the tunnel alignment. This approach would provide excavation support and ground water control in one operation and, at the same time, obviate concerns regarding disruption to subway and rail traffic. Ground freezing was also ideal for the difficult soil conditions since obstructions are simply incorporated into the frozen soil matrix, and the freeze could be implemented through pre-existing pile clusters and the soil-rock interface, providing a tight water cutoff.

Gregory T. Ziegler, Patrick Rooney and Paul C. Schmall

Gregory T. Ziegler and **Paul C. Schmall**, members UCA of SME, are vice president and project manager and vice president and chief engineer, Moretrench, and **Patrick J. Rooney**, member UCA of SME, is vice president-operations, Schiavone Construction Co. email gziegler@mtac.com, pschmall@mtac.com.

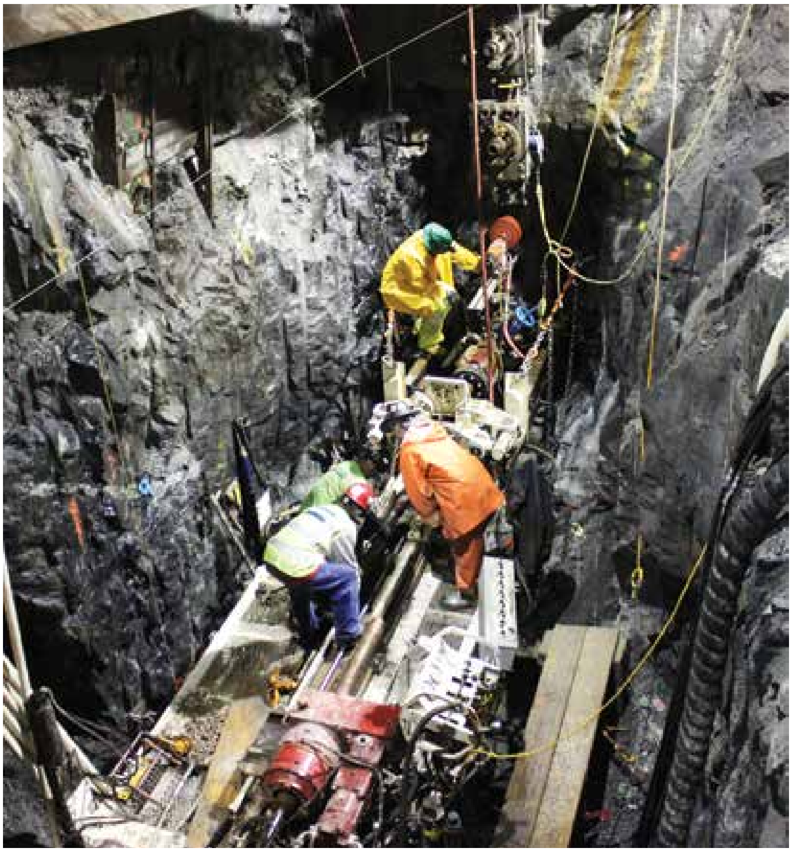
Project challenges

Freeze pipe alignment is critical to every ground freezing project. Design of the freeze is directly related to the spacing between the pipes. Any deviation greater than design tolerance can result in windows of unfrozen soil within the formation. A complicating factor for this project was that the freeze pipes had to penetrate four clusters of 304-mm (12-in.), concrete filled steel pipe piles supporting the elevated railway line, as well as cobbles, boulders and an undulating rock surface.

The pipes would also be installed from below the ground water table through a thick layer of Bull's Liver-like silty sands and silts. This material is historically very sensitive to construction-induced disturbance, likely leading to loss of ground, settlement and possible pipe movement. The Bulls Liver-like soils would also be susceptible to the formation of ice lenses and heave with the formation of the freeze. Ice lenses typically exert forces in the direction of the temperature gradient. For vertical freezes, the forces are lateral and are rarely an issue. For horizontal freezes, however, they are vertical. This would exacerbate heave of the structure, particularly at shallow depth.

And last, but by no means least, the bottom of the existing subway tunnel beneath Northern Boulevard would be within just a few feet of the top of the frozen arch. Controlling heave in this zone during the freezing operation and settlement during thawing was important to avoid any adverse effect on these structures.

Drilling of the bottom hole on each side of the frozen arch from drill pits blasted into the rock was necessary to allow a frozen seal into the bedrock.



Design

The need for such extremely close control during the ground freezing operation drove an innovative ground freezing design that included provision for heave and settlement control. Ahead of freeze pipe installation, pre-grouting with horizontal compaction grouting methods was performed in the soils beneath the subway box to improve the ground and fill any open, water-filled zones. Compensation grout pipes were also installed to mitigate any settlement of the overlying structures during freeze pipe installation. A specially formulated noncementitious grout was formulated that essentially mimicked the strength and consistency of the in situ soils but would not leave cemented obstructions for any subsequent heave control that might be required.

If heave occurred during freezing, soil extraction would be performed through casings installed between the frozen arch and the base of the subway box. Soil extraction, or underexcavation, has been used previously to correct differential settlement, albeit on only a handful of projects. But it has never been attempted below the water table. However, given Moretrench's experience of drilling and working with difficult Bull's Liver-like soils below the water table, particularly on the adjacent East Side Access section, there was every indication that this approach would be viable, should it be required. A secondary arch of heat pipes was also incorporated to control the outward growth of the freeze.

Provision was also made for compensation grouting to be performed through the preinstalled pipes to mitigate structural settlement during thawing of the frozen ground following tunnel completion.

Ground freezing

The subsurface challenges on this project, with horizontal drilling to be accomplished below the water table through the sensitive soils, added to the complexity of the project, as well as restricting drilling methodologies. The specialty geotechnical contractor, therefore, instituted considerable measures to ensure that freeze pipe installation would be within tolerances, while also preventing ground loss.

Drilling for freeze pipe installation was a multiphase operation in line with the contractor's sequence of excavation that called for the installation of large concrete bracing slabs as the excavation proceeded. Once the slabs were poured, the next level could be excavated and the next set of freeze pipes drilled. High-speed coring platform drills, tracked geotechnical rigs, and a dual head skid mounted geotechnical drill were used to overcome the changing geology as the excavation progressed. Some of the most difficult drilling proved to be through the large boulders just above the undulating bedrock surface while maintaining alignment.

The bottom hole on each side of the frozen arch needed to be drilled full-length through competent rock to allow an impenetrable frozen seal to the bedrock. Accurate horizontal drilling, under almost 25 m (80 ft) of hydrostatic head, from drill pits blasted into the rock to accommodate the rigs, was a significant challenge. The specialty contractor, therefore, cored these holes and retrieved the cores to verify the rock quality.

Completed boreholes were surveyed for borehole deviation with a gyro survey tool that can be used in a horizontal orientation. The results of these deviation plots were used to select redrill locations, if necessary, and also incorporated into the thermal modeling that assisted Moretrench in verification of the as-built design.

The specialty geotechnical contractor used a large mobile freeze plant with two 400-hp rotary screw compressors. Anhydrous ammonia refrigerant was circulated in the closed loop freeze plant. Brine (29 percent calcium chloride solution) was cooled in a freeze plant's titanium plate heat exchanger and pumped through a piping system to all freeze pipes by a distribution manifold system. This included a distribution pipe underneath Northern Boulevard to service freeze pipes on the opposite side of the street from the main early access chamber.

A heating system was installed in 14 combination compensation grout/heat pipes drilled in the secondary arch above the crown of the freeze to limit the growth of frozen ground should excessive movement of the subway structure occur during formation of the frozen arch.

Once temperatures indicated formation of the frozen arch, a drain-down test of the internal water was conducted. Results of the test and subsequent temperature verification revealed two warm spots, indicating "windows" in the frozen arch due to moving ground water. A grouting program was initiated by the specialty geotechnical contractor to address this, and sodium silicate and cement-bentonite grouts were pumped to seal off the windows. A second drain-down test was conducted following the grouting program, with further temperature profiling confirming that closure of the frozen formation had been achieved, allowing mining of the tunnel to begin.

SEM tunnel excavation

The final design of the SEM was a modified three-over-three drift plan, where the two center drifts were revised to reflect a top heading, bench and invert excavation. The final design took into consideration in situ soil conditions observed during excavation of the access chamber. Drifts 1, 2 and 5 were excavated using a top heading and bench approach.

Round lengths were limited to 1.2 m (4 ft) in the upper drifts and 2.4 m (8 ft) in the lower drifts. Concurrency of excavation in the drifts was limited because of design limitations and short tunnel length. One of the unique difficulties anticipated to be encountered during this particular SEM was the fact that the alignment passed through underpinning piles supporting the elevated subway above, as well as the existing pile clusters that the underpinning piles had replaced. As an additional step during the cycle, the existing piles had to be cut at the excavation interface, while the excavation had to work around the temporary underpinning piles until the final liner was installed.

Initial ground support consisted of an insulating layer of shotcrete 76 mm (3 in.) to address the temperature impact of the ground freeze on the initial shotcrete lining. This was followed by installation of lattice girders at 1.2 m (4 ft) spacing, matching the geometry of the drift configuration, two layers of welded wire fabric and 305 mm (12 in.) of shotcrete.

Shotcrete pumps, loaders and excavators used during the excavation were fitted to accept various attachments including the bucket, hammer and grinder. Plant-batched shotcrete was primarily used, with dry mix stored on site for emergency conditions.

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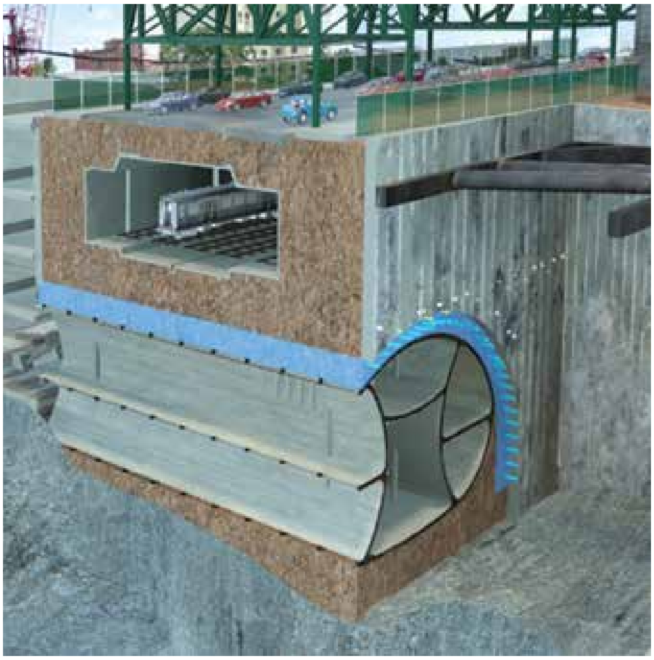

Given the proximity of the excavation to surrounding structures (subway, elevated subway, buildings and arterials), instrumentation and monitoring was critical to the operation. A combination of automated monitoring of existing structures as well as on site survey of line, grade and deflection yielded little or no movement.

After excavation was completed and the temporary interior sidewalls were removed, the final lining was installed. This consisted of 14 ring girders, necessary to support the pile clusters, #11 radial bars, #7 bars placed longitudinally, waterproofing, and a 762 mm (30-in.) pneumatically applied concrete final lining. The loads were transferred from the underpinning piles back to the original foundations after the final lining had achieved sufficient strength. Following additional monitoring to confirm stabilization and settlement, the underpinning piles were removed and the final lining was restored at the penetration points. Finish track work will be performed in future contracts.

Thawing and compensation grouting

Freezing of the protective arch was terminated in late February 2013, and a natural thaw method was selected by the owner. Settlement monitoring is in place for the roadway, underground subway and elevated train tracks. Previously installed compensation grout pipes have been profiled to determine areas of frozen soils. As of August, there is still frozen ground. This information is being used to develop a compensation grouting plan to address minor settlements that have occurred.

The rigorous controls instituted by specialty geotechnical contractor Moretrench throughout the Northern Boulevard crossing project paid dividends. Only 13 mm (0.5 in.) of heave occurred during the freeze and activation of the heat pipes, soil extraction, and pre-excavation compensation grouting were not required. ■