
V. Gall, R. Blessing IV
Gall Zeidler Consultants, Ashburn, USA.

A. J. Thompson
Hatch Mott MacDonald, New York, USA.

ABSTRACT: The East Side Access project in New York City, which will provide a new connection for the Long Island Rail Road into Grand Central Terminal, recently completed the crossing under Northern Boulevard. Tunneling involved the development of a very large cross-section at a springline diameter of about 18.4 meters in soft, water-saturated soils using SEM tunneling techniques (a first for New York) under very shallow cover. To enable tunneling beneath an existing subway tunnel, the above lying road way, Northern Boulevard, and an elevated rail viaduct without any disruption to the 24/7 operation of these major traffic arteries, the Northern Boulevard Crossing tunneling used ground freezing for pre-support and ground water cut-off, compensation grouting, vacuum dewatering and partial underpinning. This paper provides a comprehensive case history for this state-of-the-art urban tunneling project.

1 INTRODUCTION

The East Side Access project is being constructed by the Metropolitan Transportation Authority Capital Construction (MTACC) in New York City to provide Long Island commuters with direct access to Manhattan’s Grand Central Terminal (GCT) and thus the east side of Manhattan. This infrastructure project, which is currently the largest in the United States, requires extensive tunneling in the highly urbanized environments of Manhattan and Queens. The entire project includes four tunneling contracts of which CQ039 Contract, Northern Boulevard Crossing (NBX), is considered the most technically challenging and is also the keystone of the project, as it links the existing 63rd St Tunnels, built in the 1970s, to the newly constructed tunnels beneath Sunnyside Yard that link into the existing Long Island Railroad mainline. The tunnel is a 36.5-meter long SEM tunnel, with an 18.4-meter wide and 11.8-meter tall excavated cross-section. The Contractor for this work was a Schiavone/Kiewit joint venture (S/K), with Moretrench American Corp. (Moretrench) serving as the specialty geotechnical contractor.

The General Engineering Consultant responsible for the design of the tunnel is a tri-venture between Parsons Brinckerhoff, STV and Parsons Transportation Group, with Gall Zeidler Consultants as tunneling sub consultant. Construction management services are being provided by URS, with Hatch Mott McAdam providing specialty tunnel services.

The NBX tunnel was excavated using sequential excavation methods beneath the existing New York City Transit (NYCT) IND subway box structure, Northern Boulevard, and an elevated three-track NYCT BMT Line (Figure 1), all of which were to remain open and operational during construction. Restricted access to the tunnel location, together with challenging geotechnical issues, have made NBX the most complex and technically challenging part of the East Side Access Project. To overcome these, state-of-the-art application of several methods, including pre-conditioning of the ground, ground freezing as a means of support and groundwater cut-off, and conventional tunneling methods provided the best solutions for the construction of the NBX tunnel (Rice 2012).
2 PROJECT ENVIRONMENT

2.1 Subway Lines and Northern Boulevard

The CQ039 tunnel passes directly beneath three major transportation arteries.

The first of these is the five-track NYCT IND subway tunnel structure, which is located approximately 12 meters below grade, and is approximately 23 meters wide and 7.6 meters tall. There is approximately 3.6 to 4.8 meters between the base of the subway box and the NBX tunnel crown. This busy subway services over 500 trains per weekday (Clark and Stummvoll, 2012).

The tunnel also runs beneath the pile-supported elevated NYCT BMT Line, which services approximately 290 trains per weekday. Concrete piers supporting this elevated structure are connected to the sidewalls of the IND subway box. Four of these piers were located within the CQ039 tunnel envelope, presenting another challenge to the construction of the tunnel.

Finally, the tunnel runs beneath Northern Boulevard, a six-lane roadway that extends from Eastern Queens to the Queensboro Bridge. This highway is one of the major east-west roadways in Queens and carries heavy traffic volumes to and from Manhattan during peak commuting hours.

All of these structures had to remain operational during the construction of the NBX tunnel. In order to achieve this, several pre-support measures, monitoring systems, and mitigation schemes were put in place to control ground movements and settlements.

2.2 Geology

The NBX tunnel is located near the physiographic province boundary between the Manhattan Prong of the New England Upland and the Atlantic Coastal Plain, and is underlain by Cambrian- and Ordovician-age (570 to 438 Ma) metamorphic rocks. The rocks consist primarily of granitic gneisses with irregular occurrences of amphibolite and granitic pegmatite. Weathering has penetrated the rock mass to depths greater than 30 meters in some areas, but at the project location, much of the softer weathered material appears to have been removed by glacial scour and depth to bedrock ranges from 12 to 27 meters below the existing ground level (MTA 2009).

Overlying the bedrock throughout the project area are Pleistocene-age (2.6 Ma to 10 ka) deposits comprised of mixed glacial, interglacial and post-glacial materials that were deposited during the last glacial advance, known as the Wisconsin Glacial Episode. These materials were deposited in extremely heterogeneous layers of sediments, with grain sizes ranging from fine silts and clays to large boulders. Meltwater from the glacier collected in the ancient glacial Lake Flushing, where varved clays and other fine sediments were deposited. Glacial outwash deposits, including the Jameco Gravel, were also deposited around this time. Because of the cyclical nature of the depositional history of these sediments, the stratification of the glacial materials in the project area is generally complex and significant variations in the thickness and location of individual occurs (MTA 2009).

The most recent glacial sediments at the project site are generally separated into three groups, Mixed Glacial Deposits, Glacial Till, and Outwash/Reworked Glacial Till Deposits. These three groups have been further categorized into 8 strata.

Fill, or Stratum 1, is composed of a heterogeneous mixtures of sands, silts, gravels, cobbles, and miscellaneous building debris, including brick fragments, wood, metal pieces, concrete and other rubble. This Fill material overlies glacial sediments throughout the project area and is on average 2.7 and 10 meters thick.

The majority of the NBX tunnel was constructed in the materials of Strata 2 through 4 (Mixed Glacial Deposits), which are predominantly non-plastic silts to clays of low plasticity containing sand and gravel. Stratum 2
has a thickness ranging between 0 and 10.6 meters, Stratum 3 is generally between 0 and 5.5 meters thick, and Stratum 4, which is the most dominant material throughout the project area, has a thickness ranging between 0 and 12.2 meters. However, the boundaries between these strata are sometimes difficult to define and interlaying of these strata is also observed.

Stratum 5 is the Outwash/Reworked Glacial Till Deposits. These till materials are poorly sorted, and consist of a highly heterogeneous mixture of sands, silts and gravels together with large isolated boulders.

Stratum 6 is composed of decomposed rock. These materials included mostly very stiff to hard silts, clays and sands up to 1.2 meters above the bedrock surface. This material is not continuous and is less than 2.4 meters thick at the project site. Directly underlying this stratum is the bedrock materials of Stratum 7, which include strong to very strong gneiss and schistose gneiss. Stratum 7 is located approximately 21 to 27 meters below ground level and was encountered in the tunnel invert (MTA 2009).

Throughout much of the tunnel cross-section, considerable thicknesses of “bulls liver soils,” also known as “rock flour,” were encountered. These soils, often mistaken for clay because of their particle size, are composed of extremely fine-grained quartz that has been ground by the abrasive activity of glaciers. These soils are susceptible to ice lensing as a result of ground freezing techniques, which can lead to substantial heave (Schmall et al, 2013). They have been known to “quake like jelly” due to vibrations brought on by construction activities and, in some cases, may even flow like a liquid. Special attention was paid to these materials as much of the horizontal drilling of compensation grout pipes, ground freezing pipes, and heating pipes was conducted through these materials (Ott et al, 2013).

2.3 Groundwater

Groundwater in the project area exists within an unconfined aquifer formed in the sediments of the Mixed Glacial Deposits (Strata 2 through 4), and lies approximately 5 meters below the ground surface. The NBX tunnel is approximately 17 meters below the groundwater table (Clark et al, 2013). The groundwater in the project site typically flows to the southwest towards Newtown Creek and, to a lesser degree, west and northwest towards the East River (MTA 2009).

The construction team was not permitted to drawdown the groundwater table during construction due to the location of contaminant plumes in the nearby Sunnyside Yard (Ott et al, 2013); groundwater was not allowed to drop more than 0.6 meters below the groundwater baseline elevation of 309 feet. Therefore, the tunnel cross-section was located entirely within the water table. Another purpose of this constraint was to ensure that the removal of groundwater from the unconsolidated glacial sediments did not result in ground settlements, which would cause damage to the surrounding subway structures, Northern Boulevard, and other buildings (Gall and O’Brien, 2013).

In order to overcome the problem of constructing the NBX tunnel deep below the groundwater table, and without violating the strict regulations in place regarding drawdown, it was determined that ground freezing was the best option to cut off the groundwater within the tunnel cross-section.

2.4 Proximity to Buildings

In addition to the proximity of the NBX tunnel to adjacent transportation arteries, the project alignment was also located close to several buildings and other structures. Great care was taken to ensure tunneling activities did not cause damage to these structures due to ground settlements by means of ground monitoring, grouting, and ground freezing.

3 PROJECT CONDITIONS

3.1 Existing Slurry Walls

Prior to the pre-conditioning and excavation of the NBX tunnel, the existing slurry wall that created the tunnel work area needed to be repaired to minimize ground water inflow through the wall and remediate poor construction undertaken by the previous defaulted contractor.

Cores were taken in the slurry wall panels and various deficiencies were found. To mitigate these issues, jet grout columns were installed on the outside of the slurry wall to cut off the groundwater inflow, as well as inside the slurry wall to assist in lateral stability of the slurry wall toe.
Because tunnel excavation was carried out during warm summer months, the freezing subcontractor chose to insulate the slurry wall around the b Rough three of the tunnel together with installing freeze hoses directly into the slurry wall, in order to maintain the interface between the slurry wall and soil in a frozen state (Clark et al, 2013).

4 PREPARATION FOR TUNNELING

Before excavation of the tunnel was able to begin, on-site geological and geotechnical conditions, earth support and groundwater control measures were needed to prepare the ground for tunneling works. However, vertical drilling from ground level and from within the existing NYCT subway structure was prohibited. Ultimately, the method chosen was the horizontal installation of a protective frozen arch above the tunnel alignment, which would extend into the bedrock for complete groundwater cut-off, as well as provide some ground support during the excavation operations (Gall and O’Brien, 2013).

4.1 Void Grouting

The first ground conditioning process undertaken was to fill any potential water-filled voids present below the subway structure. The purpose of this ground conditioning measure was also to aid in the quick correction of any future ground settlements, should they occur, by means of controlled grout injections. Because conventional cement-based grouts could render the ground unusable for future grouting operations, a specially formulated non-cementitious grout was developed that mimicked the strength and consistency of the in-situ soils (Schmall et al, 2013).

Because a large amount of void grouting was anticipated, end-of-casing grouting was selected, where grout is injected directly through the drill casing. Drill casings had a diameter of 8.9 centimeters with a nominal spacing of 3 meters. Grouting continued until pressure refusal or a total grout volume per hole—approximately 23.85 kiloliters—was reached. In order to limit the potential for uncontrolled lifting of the subway structure, the maximum allowable grouting pressure utilized at any stage was dependent on the total volume injected into the void at a given point. Grouting was performed through 10 holes, but another 10 holes were added after grouting of the initial holes was generally terminated upon the predetermined volume refusal rather than a pressure refusal, or upon movement of the subway, indicating that the filling of voids and “tightening” of the ground was not yet achieved.

The structure was closely monitored for movement during grouting. A total of approximately 220 kiloliters of grout was pumped beneath the below-grade NYCT subway structure, reflecting the extremely loose condition of the ground before commencement of the void grouting phase (Schmall et al, 2013).

4.2 Installation of Compensation Grout Pipes

After the void grouting phase and prior to the ground freeze, heat/temperature monitoring pipes and a row of horizontal compensation grouting pipes were installed beneath the NYCT subway tunnel structure in order to reverse deformations in the event of excavation induced settlements and to fill the voids after thawing the frozen ground. Heat pipes were also installed around the top of the arch in order to control the outward growth of the freeze.

In order to counteract heave of the subway structure during freeze formation and freeze maintenance, it was initially planned that soil be extracted from the zone between the frozen arch and the base of the existing subway box. Ultimately, soil was not extracted as only a few centimeters of actual heave occurred (Schmall et al, 2013).

During thawing of the frozen ground following the completion of the tunnel excavation and support, it was envisioned that compensation grouting could be performed through the pre-installed grout pipes as necessary to mitigate against settlement (Ott et al, 2013).

Compensation grouting was not performed during the freeze drilling as very limited settlement occurred. However, compensation grouting has been performed during the thaw period after completion of the final lining. Measures were put into place by Moretrench in order to install the pipes within permissible tolerances while preventing ground loss, including groundwater control devices (blow-out preventers) with design features that eliminated ground loss during drilling, as well as being able to advance multiple casings to overcome obstructions. Platform-mounted core
drills could advance a wide range of casing and tool diameters at high or low rotation speeds to address a wide range of ground and obstruction conditions. In areas where obstructions were not anticipated, casing was advanced by duplex, cased-hole, positive flush methods. All pipes were surveyed with a gyroscope immediately upon completion (Ott et al, 2013).

4.3 Ground Freezing

Ground freezing presented the best option in order to mitigate the high groundwater level in the project area while simultaneously adhering to the strict regulations regarding groundwater drawdown. Additionally, ground freezing also provided flexibility to overcome obstacles such as boulders, steel pipes and drilling misalignment that might occur as a result of the difficult ground conditions.

Horizontal drilling for the installation of the freeze pipes was accomplished below the groundwater table and through the heterogeneous sediments of the Mixed Glacial Deposits (Strata 2 through 4) from within what is referred to as the Early Access Chamber (EAC), a work area bounded by a structural slurry wall earth support system (Figure 2) (Schiavone/Kiewit, 2011).

The design of the freeze pipes was based on specific distance between the pipes, which meant that pipe deviation was of concern. Freeze pipes were spaced at 1.2-meter nominal centers, with an allowable deviation of up to 1.8 meters. The final design of the frozen arch consisted of a thickness of 1.8 meters (Schmål et al, 2013).

After the drilling of the freeze pipes, the soils were frozen by circulating brine at -32°C through 45 horizontal freeze pipes. The freeze plant operated 24 hours a day, seven days a week (Clark et al 2013). In order to control the advancement of ice lenses and heave-induced movements within the horizon between the frozen arch and the overlying subway box structure, temperature control (heat) pipes were installed above the uppermost freeze pipes of the frozen arch. Thermal modeling was performed to evaluate the effectiveness of the heat pipes, as well as to evaluate the time to closure and the structural thickness of the frozen arch (Ott et al, 2013) (Figure 3).

The closure of the frozen arch effectively isolated the excavation cross-section from the surrounding groundwater table, allowing the construction team to implement effective groundwater control methods without impacting the surrounding groundwater table; three deep longitudinal vacuum wells were installed in the lower part of the face inside the arch. The wells were used to inject water during the final stages of the freeze development in order to maintain equilibrium between the groundwater elevation inside and outside of the frozen arch. The groundwater elevation in the core inside the arch dropped below the deepest well once the freeze was fully closed and the recharge turned off (Clark et al, 2013).

Silty fine sands and silts in the lower part of the excavation would not drain properly by gravity alone, so self-drilling vacuum lances were installed to increase the standup time of the soils. A flow of less than 3.4 liters per minute from three vacuum points was sufficient.

Figure 2. Installation of compensation grouting, temperature control (heat), and ground freezing pipes from within the EAC (Schiavone/Kiewit, 2011).

Figure 3. Thermal model of as-built pipe array showing temperature distribution after 59 days of freezing (Ott et al, 2013).
to eliminate any flowing soil conditions throughout the excavation (Clark et al, 2013).

5 TUNNEL EXCAVATION

5.1 Sequential Excavation

Sequential excavation methods (SEM), in conjunction with ground freezing techniques, presented the best option for the tunneling works for the NBX tunnel project. This method included the application of initial shotcrete after initial excavation of individual drifts, utilizing the strength of the frozen arch for support. The NBX tunnel is the first tunnel to be constructed using SEM in the five Boroughs of New York (Ott et al, 2013).

5.2 A Seven Drift Approach

The tunnel cross-section was excavated in multiple drifts in order to minimize the area of the cross-section left exposed, which limited the potential for soil unraveling and settlement (Gall and O’Brien, 2013). Excavation and support of the tunnel commenced after the closure of the frozen arch. Excavation was designed to be undertaken using a six-drift scheme, although a minor change was made to split Drift 6 into two sections, one soil and one rock (Figure 4). Round lengths were 1.2 meters for all of the upper drifts and 2.4 meters for all lower drifts (Ott et al, 2013).

![Figure 4. Excavation drifts (Gall and O’Brien, 2013).](image)

The construction phase began with the excavation and support of Drift 1; as soon as excavation was 10.6 to 12.1 meters ahead of Drift 2, excavation and support of Drift 2 would begin. After Drift 2 was at least 10.6 meters ahead, the excavation of Drift 5 would proceed up to 4.8 meters and be finished with the placement of a temporary invert. Drift 3 would commence when Drift 5 had proceeded at least 4.8 meters, and, upon the completion of Drift 2, Drift 4 would commence and be staggered behind Drift 3 by 10.6 to 12.1 meters. Excavation and support of Drift 5 would commence as soon as drifts 3 and 4 were completed, and Drift 6 would commence as soon as Drift 5 was at least 10.6 meters ahead. Temporary sidewalls would be removed, and Drift 7 excavation and support would start; remaining temporary sidewalls would be removed and the invert would be placed. Finally, the excavation and support would be alternated between drifts 6 and 7 (Clark et al, 2013).

These sequences were staggered between headings and altered during construction in order to accommodate conditions encountered. For instance, flowing silty fine sands were encountered during the commencement of the excavation and support of Drift 1, which was mitigated by the installation of the vacuum wells. As a result, Drift 2 became the leading upper sidewall drift. After Drift 2 completion, the first 4.8 meters of Drift 5 was completed as per the final design plans.

Drift 4 led Drift 3 and, though the Drift 4 was started prior to the Drift 3, excavation was slowed due to hard rock excavation, and Drift 3 passed the Drift 4. The crews commenced Drift 5 after the completion of Drift 3 and before the completion of Drift 4.

Drifts 6 and 7 were completed following the original excavation sequence, apart from the demolition of the temporary sidewalls. Sidewall removal took place in 9-meter long sections after the ring closure in Drift 7; the design sequence had the temporary sidewalls removed in 2.4-meter sections before closing the Drift 7 Invert (Clark et al, 2013).

6 TUNNEL LINING

After the excavation of each drift, an initial, insulating shotcrete layer of 76 millimeters was placed against the frozen soil, followed by 300 millimeters of shotcrete reinforced with two layers of 4X4 D4XD4 Welded Wire Fabric (WWF). 3-bar lattice girders were placed with 1.2-meter centers as integral parts of the shotcrete lining to support the soil load and
subway box in conjunction with the frozen arch. Temporary sidewalls had the same reinforcement with a total shotcrete thickness of 300 millimeters. A 230-millimeter thick shotcrete initial lining was installed as a temporary invert between the upper and lower sidewall drifts, which had one layer of WWF (Clark et al., 2013). Shotcrete strength requirements were 1,800 psi (12 MPa) at 24 hours, 2,500 psi (17 MPa) at 3 days and 5,000 psi (34.5 MPa) at 28 days (Ott et al., 2013).

The application of the 76 millimeter insulating shotcrete lining, prior to lattice girder installation, created certain challenges during tunnel construction. The heat of hydration from the flasherete tended to thaw the first few centimeters of frozen soil, possibly creating delaminations. To remedy this problem, flasherete was applied in conjunction with the initial structural shotcrete layer. Additionally, the outside layer of wire mesh was stiffened with reinforcing bars to allow the shotcrete to build up without sagging due to deflection of the mesh. As a result, the inside WWF of a round was installed during the outside mesh and girder installation of the following round; the second shotcrete pass of a round was applied immediately after placing the initial pass of the following round. Using this approach, the next operation following the shotcrete was excavation and only the boom of the excavator was exposed to freshly placed shotcrete (Clark et al., 2013).

6.1 Waterproofing

Following the completion of the tunnel excavation and initial liner, a PVC waterproofing membrane was installed, followed by a 1-meter thick reinforced concrete liner. The interior dimensions of the final tunnel lining are approximately 16 meters wide by 10 meters high (Figure 5).

6.2 Pneumatically Applied Concrete (PAC)

For the final lining of the NBX tunnel arch, a freeform concrete was used. This is a method of applying concrete without using formwork, where a pneumatically applied wet mix concrete, or PAC, was installed. With PAC, the ready mixed concrete is pumped to a nozzle, where air is added to create the velocity and spray pattern needed to encase the reinforcement properly and completely for structural concrete applications. The total lining thickness for the NBX tunnel arch was 1 meter, with strength of 5,000 psi (Thompson, 2013).

7 IMPACTS ON OVERLYING STRUCTURES

7.1 Settlements to Date

An extensive real-time monitoring system was deployed across the entire alignment of the ESA project, above ground, on critical structures, and in subway tunnels. The system monitors ground conditions and critical structures 24 hours a day, seven days a week, outputting the data to a web-based data management system. The system also automatically generates email alerts to critical personnel when instruments report movements that exceed threshold values. The instruments being used include Robotic Total Stations (RSTs), manual surveying points, inclinometers, extensometers, observation wells, tiltmeters, seismographs, strain gauges, and liquid level settlement systems (LLSS) (Gall and O’Brien, 2013).

Upon completion of the excavation and support in November 2012, all deformations of the NBX tunnel, ground and the structures above remained well within the allowable and
specified limits. The tunnel modeling indicated settlement at the crown of the tunnel to be 33 millimeters and the base of the subway box to settle approximately 15 millimeters. Slight, 2.5 to 5 millimeters of movement was observed within the overlying subway structure settlement monitoring during tunnel excavation and removal of the temporary sidewalls. Following excavation of the center drift, only 7.5 to 15 millimeters of movement was observed in the crown. No further movement was observed during or after the removal of the temporary sidewalls (Ott et al, 2013).

Currently, the frozen ground is being thawed, and after five months of such activities the maximum movements observed is approaching 50 millimeters. Compensation grouting will be used to mitigate this settlement (Ott et al, 2013).

7.2 Other Considerations
An additional consideration taken into account during the design and construction of the NBX tunnel was the presence of concrete piers supporting the elevated NYCT track, which were connected to the sidewalls of the NYCT subway tunnel; four of these piers fell within the NBX tunnel alignment (Figure 6). In order to ensure stability of the elevated structure, the weight was temporarily transferred to soldier piles socketed into the bedrock. With the piles in place, the concrete piers encountered could be cut as needed to remove sections from the tunnel cross-section. Once the tunnel excavation was completed, the concrete piers were incorporated into the tunnel final lining, to which the structural stability of the piers was transferred upon the removal of the steel pilings (Gall and O’Brien, 2013).

An important aspect of this project were the daily meetings held by the Owner’s representatives and Contractor to discuss safety and quality concerns, production over the previous 24 hours, conditions that were encountered during excavation, performance of the instrumentation, and planning for the next 24 hours. During these meetings, decisions were made with regard to the alteration of the excavation sequence and additional ground support measures, as required by encountered geological and geotechnical conditions. This process provided necessary flexibility during construction and allowed for the tunnel to be excavated in the most expedient and technically correct manner (Clark et al, 2013).

8 CONCLUSIONS
Several factors were of great concern during the construction of the Northern Boulevard Crossing, including challenging geological and geotechnical conditions, groundwater and restrictions on groundwater drawdown, proximity to major traffic arteries that were to remain open and unaffected by tunneling activities during the project as well as other buildings and structures, and shallow overburden between the tunnel crown and the NYCT subway box structure that was located just meters above the alignment. These issues were remedied by extensive ground support methods, including the creation of a frozen arch for both pre-support and groundwater cut-off purposes, and void and compensation grouting. Modeling of the tunneling works and the frozen arch provided a sound approach to mitigate the various geotechnical uncertainties encountered, and SEM excavation was performed in a safe and satisfactory manner, with actual ground and structural deformations less than the numerical modeling indicated. The ground freezing installation was performed with negligible ground loss, and no compensation grouting was required during system installation. Ground heave due to ice lensing was also within acceptable limits and no soil extraction was necessary (Ott et al, 2013).
REFERENCES


