Soft Ground to Hard Rock – Versatile Tunnelling Methods in Urban Areas

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**SUMMARY:**
The implementation of modern tunnelling techniques in urban areas provides a way to expand infrastructure with little disturbance to the surface and existing structures. When tunnelling through hard rock, pre-support measures are not often required. However, pre-support measures, such as ground freezing, jet-grouting, systematic pipe arch canopies, and grouted spiling, are essential to soft ground tunnelling at shallow depths. The projects described in this paper show that conventional tunnelling can be applied in different urban settings safely, for example in London’s soft ground or New York City’s hard rock.

1. **INTRODUCTION**

Urban infrastructure developed over 100 years ago is becoming obsolete with the continuous increase in city and urban area population. Often, the cities and urban areas are crowded with buildings and other infrastructure that makes improvement or expansion of existing roadways impractical. This has led to city planners turning to the underground as a viable way to improve infrastructure in urban areas.

There are a few methods to create underground space, each with their respective positive and negative aspects. In the past, cut and cover techniques were utilized, but today, conventional as well as mechanized tunnelling is more prevalent because it allows for improvement of infrastructure while minimizing surface disruption. This applies for shallow or deep tunnels in soft ground and hard rock.

Generally, underground access is provided from shafts built on site areas or from open cut areas where space is more readily available. While mechanized tunnelling has made vast advances over the past decades it remains limited to the construction of line structures, albeit at very large cross sections.

Likewise, conventional tunnelling has been advanced in its applications mainly due to the developments in ground improvement, pre-support measures and its main supporting element, shotcrete. Application of conventional tunnelling has been pushed to include very large openings of complex geometries constructed under overbuilt areas at shallow cover. Its successful application is worldwide. It is the intent of this paper to illustrate implementation of conventional tunnelling on selected tunnelling projects ranging from soft ground to hard rock tunnels covering not only a wide range of ground conditions, but complexity of construction in urban environments. The projects selected are located in areas where minimal impact to the existing urban infrastructure both above and below ground including commuter roadways and railways is required.

2. **CONVENTIONAL TUNNELLING**

The Conventional Tunnelling method, also commonly referred to as the New Austrian Tunnelling Method (NATM) or the Sequential Excavation Method (SEM), is a concept based on the understanding of the behaviour of the ground as it reacts to the creation of an underground opening [1],[2]. Initially, conventional tunnelling was applied to rock tunnel-
Total Stations (RTS), manual surveying points, inclinometers, extensometers, observation wells, tiltmeters, seismographs, strain gauges, stress cells, and liquid level settlement systems (LLSS). It is imperative to begin baseline monitoring well in advance to gain sufficient background information ahead of the commencement of tunnelling works. Depending on project characteristics it is generally recommended that the baseline readings encompass an entire seasonal cycle prior to start of tunnelling.

### 3. THE BOND STREET STATION UPGRADE PROJECT

#### 3.1 Project Description and Objectives

Located in the heart of London’s West End, Bond Street Station is one of London Underground’s busiest stations. The entrances to the station are on Oxford Street, which houses local residencies and businesses. Currently, both the Central Line and Jubilee Line are connected to the station. The station is at capacity with roughly 175,000 passengers per day [3]. With the future construction of the connecting Crossrail station, the daily passengers travelling through Bond Street Station is expected to increase.

![Figure 1. Overview of existing and new (light color) underground structures (3)](image-url)
Bond Street Station opened in 1900 as part of the Central London Railway. Since its opening, Bond Street Station experienced two upgrades, one in 1920’s and the later in the 1970’s. The first was to enlarge the ticket hall under Oxford Street and connect the ticket hall to the concourse level through a new escalator tunnel. About 50 years later, the Jubilee Line was constructed. This required the construction connection to the previously upgraded ticket hall.

With the construction of the Crossrail Line, another upgrade is required for Bond Street Station. This Bond Street Station Upgrade project includes the underpinning of buildings, the construction of tunnels and deep shafts, connections to the Central Line and Jubilee Line, near-surface excavations, and deep piling. This paper will focus on the tunnel and shaft construction.

### 3.2 Geology

The stratum in the site location consists of Made Ground, River Terrace Deposits, London Clay Formations, and the Lambeth Group. The majority of the tunnelling operations are through the London Clay. The Made Ground is a granular and cohesive material typically comprising of sand, clay, gravel, clayey gravelly sand, demolition waste, and ash. The River Terrace Deposits can vary from gravel-dominated beds, to tabular crossbedded gravelly sand in fining upwards units [4].

The London Clay formation has been subdivided into five lithological units, denoted Divisions A to E according to the fossil fauna and partly on the sand and silt contents. The works will be excavated mainly within the units of A2 and A3, with unit B occasionally encountered. Unit A2 consists of alternating sandy clays and silty clays, but with no presence of claystones [3]. Meanwhile, unit A3 has a base layer of homogenous silty clay, followed by silty clay. It is expected that the A3 strata contains three or four layers of claystones.

Finally, beneath the London Clay is the Lambeth Group. The stratum includes the Upper Mottled Beds, Lower Mottled Bend and Upnor Formation. The Lambeth Group is a complex, mixed sequence of clays, silts, sands, and gravel with potentially pressurized groundwater.

Two major aquifers exist within the vicinity of the site: the Upper Aquifer, within the Made Ground, Alluvium and River Terrace Gravels; and the Lower Aquifer, comprising the strata of the Lambeth Group, the Thanet Sand and Upper Chalk. The two aquifers are separated by the relatively impermeable London Clay and cohesive units of the Lambeth group [3]. The subsurface investigation revealed that the groundwater level in the Upper Aquifer ranges between 5.0 and 6.0 meters below the surface.

### 3.3 Project Challenges and Constraints

In order to gain access to the new underground tunnels, London Underground Limited purchased an existing building adjacent to the site. After the building had been demolished, the site was excavated down to the lowest level of the future ticket hall. From here, the access shafts were constructed. Even with a limited amount of space within the site, a strategic plan was in place to accommodate a crane for material and muck handling. Furthermore, shotcrete batching facilities will be present within the worksite.

The shafts and tunnels for the Bond Street Station Upgrade are to be constructed with little impact on the building along Oxford Street, Stratford Place and the surrounding areas, and with minimal effect on the London Underground Limited lines and station operations. As a result of construction, it is important to manage the vertical and lateral settlement. Many buildings within this part of London are considered Grade I, II and II* listed historical buildings. Structures such as these are very susceptible to damage with little movement. Just below the street surface, the project area houses many utilities for London. Utilities include brick-lined and composite sewers, water mains, gas mains, and telephone and power cabling.

### 3.4 Excavation and Support

Generally, the tunnel excavation and support sequence follows a staggered full-face approach. For the staggered full-face, two rounds of the top heading excavation and support are immediately fol-
owed by the bench/invert ring closure. The larger tunnels are separated to have a top heading, bench and then invert excavation rounds.

After completion of the excavation round, all exposed ground is immediately supported with a 75 millimeter thick initial layer. Upon completion of the initial layer, the shotcrete primary lining is sprayed. Shotcrete lining thickness ranges from 250 to 450 millimeters, depending on the size and shape of the tunnel or shaft. The larger tunnels with a three level excavation sequence generally use a 150 millimeter thick temporary invert after the top heading excavation. Tunnel junctions will receive local reinforcement and an increased shotcrete thickness.

Tunnelling for the Bond Street Station Upgrade will include pre-support measures at three locations to serve as ground movement mitigation measures. At the first two locations, pipe arches are under existing operational barrels, while the final location is beneath a brick sewer built in the 1930’s.

In addition to the pre-support, tube-a-manchet (TAM) arrays for compensation grouting were incorporated into the design. The TAM’s were installed from three temporary grouting shafts. Compensation grouting will be used to control tunnelling induced ground movements on overhead buildings and utilities.

3.5 Instrumentation and Monitoring

Induced ground movements are inevitable with any tunnelling method. For this project, a real-time monitoring plan is in place to determine the movements of the ground surface, existing above ground and below ground structures and utilities throughout the excavation zone of influence. The scheme includes baseline monitoring at least 12 months in advance of the commencement of tunnelling works. The lead time for the baseline monitoring will provide sufficient information on the seasonal temperature induced movements.

3.6 Project Status

The Bond Street Station Upgrade Project is underway. The implementation works within the existing station commenced in November 2010 with modifications to an existing station entrance from Oxford Street. The demolition of the Oxford Street building has been completed and the main access shaft, as well as some of the pedestrian tunnels, have been excavated to date. Tunnelling works are expected to continue into 2017.

4. THE VICTORIA STATION UPGRADE PROJECT

4.1 Project Description and Objectives

Part of the London Underground network, the London Victoria Station conveys approximately 80 million passengers every year, which contribute to passenger congestions and station close downs. In order to improve the passenger flow and emergency response facilities, a major upgrade program is being implemented that entails the construction of a new ticket hall, new access shafts, new escalator tunnels and passenger transfer tunnels between the underground stations and the surface.

The new, 5 meter wide, shallow passenger tunnels must consider surface structures as the tunnels are located underneath major central London roads, Grade II listed buildings and the busy main railway terminal. The principles of conventional tunnelling will be used in constructing the new shallow passenger tunnels.

4.2 Geology

As the new tunnels are shallow in depth, majority of the planned tunnels encounter water-saturated Ter-
Gravels. The Terrace Gravels consist of a gravel and sand mixture. Groundwater levels are expected to be at about springline level of the shallow new tunnels [5]. Intermittent layers of Alluvium (silt, peat, clay) were found above the Terrace Gravels. Deep tunnels such as the lower escalator machine room, concourse tunnel, and majority of the tunnel inverted encounter London Clay.

4.3 Project Challenges and Constraints

The Victoria Station Upgrade Project faces many of the same challenges presented from urban tunneling. Similar to the other projects discussed in this paper. However, there is one particular challenge that is unique to this project, groundwater inflow from the Terrace Gravels at a shallow depth. In order to limit the amount of groundwater inflow, the design incorporated a continuous ground improvement scheme via jet-grouting.

Jet-grouting provides ground stabilization and settlement limitation, as well as groundwater cut-off. The jet-grouting scheme consists of 2,700 columns, of up to a maximum of 13 meters long [5]. The Terrace Gravels is to be fully grouted, thus providing support for the entire tunnel face.

However, jet-grouting may cause a serious threat such as grout ingress to existing underground structures. With the project in an urban setting, installation of jet-grouting causes potential issues. The limited working areas, angular variations of the columns, and varying ground conditions make the accuracy of setting the drill rig and the predictability of the grouting column size a challenge in itself during installation.

Additionally, spoil blockage risks are considered during the grouting process. Blockages may cause the grout to build up excessive pressure and potentially hydro-fracture the grout downwards through the clays and migrate to the tunnels below. Nevertheless, with real-time monitoring in place throughout all stages of the jet-grouting procedure, the risk for spoil blockages that lead to hydro-fractures has been managed.

4.4 Excavation and Support

Tunnelling is carried out following the principles of conventional tunnelling. Two rounds of the top heading excavation and support are immediately followed by the bench excavation. In the shallow tunnels, the invert is located in London Clay, which requires rapid ring closure to avoid undue ground deformation. Steel fiber reinforced shotcrete, ranging between 200 and 300 millimeters, provides sufficient initial support.

4.5 Project Status

Station upgrade works are on-going. Jet-grouting trials were conducted and the jet-grouting scheme has been completed prior to the commencement of tunnelling. With minimal incidents where grout spillage was reported, the jet grout installation has been successful. The Victoria Station Upgrade Project is scheduled to be finished in 2018.

5. GREEN PARK STATION STEP FREE ACCESS

5.1 Project Description

Green Park Station is a main junction of the Victoria, Jubilee, and Piccadilly Lines. The Green Park Step Free Access (SFA) project’s main goal was to provide a step-free access from street level to all operational platforms via the ticket hall and between platforms for interchange purposes.
Green Park Station is located within the Royal Park and Conservation Area. The shaft and connection tunnels are located underneath a ticket hall, in close vicinity to an active escalator and between two operational platform tunnels.

The shaft was divided into three parts: 1) the upper shaft with a smaller ovoid cross section extended over 10.5 meter depth; 2) the transitional cross section with a length of 0.5 meter connects the upper shaft with lower shaft; and 3) the lower shaft with largest oval cross section has its deepest point at about 32.1 meter depth from ground level.

The upper shaft excavation passed the existing escalator barrel in less than 1 m distance. The escalator remained operational during excavation of the shaft. The lower section of the shaft fit closely between the two existing Victoria Line platform tunnels and the connecting cross passage. Excavation for the shaft consisted of 1 meter lifts. A total of 400 millimeters of steel fiber reinforced shotcrete was applied after every lift. The 13 meter high and 9 meter wide lift lobby breaking out from the shaft at the bottom elevation was excavated in sidewall drifts with a temporary middle wall, which was removed after completion of the full tunnel. The shaft and lift lobby were constructed entirely in London Clay. Extensive monitoring was implemented during construction to ensure that London Underground’s network could remain in operation safely. Particular attention was paid to the existing escalators adjacent to the new shaft construction as their continued operation was crucial for the station operation. An elaborate monitoring scheme with a series of very tight trigger levels were developed to observe the escalator’s movements. For example, Figure 5 shows the results from tiltmeter readings of an instrument installed inside the escalator barrel. Reading results fell below the amber trigger level throughout construction.

The Step Free Access at Green Park Station has been successfully completed with little influence on the existing structures or listed buildings. The successful construction of the large-size lift shaft in vicinity of an existing escalator with no disruption to the escalator operation was a key achievement used as reference project for a series of later London Underground upgrade projects.

6. THE DULLES CORRIDOR METRORAIL PROJECT

6.1 Project Description and Objectives

The Dulles Corridor Metrorail Project (DCMP) consists of a new 37 kilometer line extending the metro service from an existing line at the East Falls Church Station in Fairfax County to Route 772 in Loudoun County, Virginia. The project is divided into two phases. Phase 1 includes 18.7 kilometers, both above and below grade, five new stations, and twin underground conventional tunnels, which will be discussed in this paper. Phase 2 of the DCMP extends the service to Washington Dulles International Airport.

The final alignment chosen for the extension was a result of limited real estate in Fairfax County for...
site access, cost saving exercises and alignment optimization. The tunnel alignment calls for excavation under highly trafficked roadways, within close proximity to bridge abutment piles, near a deep underground parking garage, and around a high concentration of existing and planned utilities. At the East Portal, soil cover above the tunnels is approximately 4.6 meters. The soil cover increases to nearly 12.2 meters as excavation progresses to the west. However, the cover decreases to roughly 6.1 meters as the alignment reaches the West Portal. The minimum cover encountered when tunneling under the roadway access ramps at International Drive was only 2.5 meters.

6.2 Geology

The geologic conditions for the underground portion of the alignment ranged from Decomposed Rock to Residual Soils, the primary medium for the conventional tunnels. Fill and Terrance Gravels were also present, but were generally located near the East Portal. Due to the shallow soil cover and low quality of the residual soils, a systematic pre-support was required along the entire alignment.

Fill, comprising of poorly graded clayey/silty sand and sand silts, with occasional traces of clayey silts, crushed stone, rock fragments and organic material, was typically present at the surface along the alignment. Terrace Gravels, fine to coarse gravels and rock fragments, are found below the Fill. The Residual Soil is divided into two substrata, S1 and S2, based on the consistency and the degree of weathering. The upper substratum, S1, exhibits N-values averaging lower than 16, while the S2 lower substratum results in N-values averaging above 16. Both the S1 and S2 strata are similar in color and composition.

The groundwater levels along the alignment were typically 7.6 to 14.6 meters below the ground surface, which is just above the Decomposed Rock layer. The groundwater level however, generally follows the topography and rises into the Residual Soil stratum as the ground surface elevation rises.

6.3 Project Challenges and Constraints

Tunnelling under active roadways, near piles and an underground parking garage, as well as around existing utilities presented a challenge for the DCMP. It was a requirement that these elements remain operational and experience little disturbance from construction activities.

The existing utilities were of particular concern over the first 100 meters of the alignment, because excavation for this distance provided shallow cover. As indicated above, the underground Marriott Hotel parking garage, Route 123 overpass bridge piers, Route 123, and International Drive were also considered during construction. These elements in relation to the twin mined tunnels are shown in Fig 2. The overpass bridge piers and underground parking garage are about 15.0 and roughly 7.5 meters, respectively, from the tunnels [6].

6.4 Excavation and Support

The low ground quality and limited soil cover above the tunnels required a systemic pre-support, referred to as the Pipe Arch Canopy, ahead of the progressing excavation face. The standard tunnel pre-support consisted of thick-walled, 144 millimeter diameter steel grouting pipes arranged around the tunnel arch 305 millimeters on center. Each pipe was 18.0 meters long. In order to allow for the installation of the Pipe Arch Canopy over the entire length of the tunnel, the cross section had to gradually increase as the excavation progressed. This enlargement was typically repeated 12.8 meters, creating as “sawtooth” effect as shown in Figure 7. The overlap between consecutive canopies was roughly 5 meters.
Over the first 100 meters of the alignment, hourly measurements of monitoring points on the ground surface were carried out. Real-time monitoring was accomplished with the Total Station Method (TSM). The TSM uses a robotic theodolite equipped with a Direct Reflection (DR) Electronic Distance Meter (EDM) to locate “virtual points” on the ground surface. This system allowed the input of as many virtual points needed for the project.

Physical measurements were also incorporated in the scheme. In-tunnel deformation monitoring involved convergence bolt (CB) measurements once per day. CB arrays were designed to include 5 bolts spaced every 10 meters along the alignment. For the DCMP, a total of 40 convergence monitoring cross sections was required per tunnel by the instrumentation and monitoring program.

### 6.6 Project Status

Construction for Phase 1 of the Dulles Corridor Metrorail Project has been complete as of the writing of this paper. Excavation of the Tysons Corner tunnels was a success, with no exceedance of the threshold limit values, no disruption of traffic on International Drive and Route 123, and no impact on the existing underground parking garage and Route 123 overpass bridge piers [6]. The conventionally mined tunnels at Tysons Corner earned an Excellence in Automation Award from the American Society of Civil Engineers (ASCE) and were a finalist for the International Tunneling Awards in 2011. Service for the line will be open in the summer of 2014.

### 7. EAST SIDE ACCESS

#### 7.1 Project Description and Objectives

The East Side Access project is the largest underground rail project in New York City (NYC) and one of the most complex, ongoing transportation projects in the United States. The project is being constructed by the Metropolitan Transit Authority Capital Construction (MTACC) and Long Island Railroad (LIRR) and when complete, will connect the LIRR’s Main and Port Washington lines in Queens to a new LIRR terminal beneath the historic Grand Central Station.
Terminal (GCT). The new connection will increase the LIRR's capacity into Manhattan and dramatically shorten travel time for Long Island and eastern Queens commuters traveling to the East Side of Manhattan. Additionally, the new 8-track terminal station will alleviate congestion at New York Penn Station, currently LIRR's only terminal station in NYC. On the Queens side, the open cuts and tunnels are being constructed in glacial deposits (soft ground). Meanwhile, the shafts, escalator tunnels, access tunnels, and caverns on the Manhattan side are excavated predominantly in Manhattan Schist (hard rock).

As shown in Figure 8, East Side Access incorporated the existing 63rd Street Tunnel, which was completed in the early 1970’s. A combination of soft ground Tunnel Boring Machine (TBM), cut-and-cover construction, and conventional tunnelling was used to connect the LIRR mainline with the east end of the existing 63rd Street Tunnel. Part of the Queens area work includes tunnelling underneath Northern Boulevard. The Northern Boulevard Crossing (NBX) is considered the most technically challenging and is also the keystone of the East Side Access project. This portion of the projects falls under Construction Contract CQ039.

Contrary to the Queens pressurized face TBM, the Manhattan running tunnels were excavated using open shield and main frame rock TBMs. The hard rock TBMs were launched from the assembly chamber built at the end of the existing tunnel to the east along 63rd Street and eventually south along Park Avenue, with a termination at 37th Street and Park Avenue. The vast majority of the Manhattan structures followed conventional tunnelling techniques using drill and blast followed by rock reinforcement and shotcrete supports. Roadheader excavation was utilized for profiling and trimming. The excavation for the Manhattan structures was split into multiple contracts, with the main contracts being Contract CM009 and Contract CM019.

7.2 Geology

The Northern Boulevard Crossing site is comprised of Pleistocene glacial and interglacial deposits and post-glacial deposits, which is underlain by Ordovician/Cambrian Age metamorphic bedrock. In total, seven strata layers are defined. The subsurface strata in [the CQ039] area in sequence are Fill (Stratum 1), Mixed Glacial Deposits (Strata 2, 3 and 4), Glacial Till/Reworked Till/Outwash (Stratum 5), Decomposed Rock (Stratum 6) and Bedrock (Stratum 7) [8].

The Fill at NBX is similar to that found in most urban areas consisting of a heterogeneous mixture of sands, with silts, gravels, cobbles, and miscellaneous debris and rubble. The thickness of the Fill layer ranges from 2.7 to 10.0 meters. Beneath the Fill is the Mixed Glacial Deposits. The Mixed Glacial Deposits is inclusive of Strata 2, 3 and 4 which range from 0.0 to 10.7, 0.0 to 5.5 and 0.0 to 12.2 meters.
thick, respectively. It is through these glacial deposits, lacustrine deposits and glaciofluvial deposits that the NBX was excavated, as shown in Figure 9. The subsurface investigation revealed that Stratum 2 through 4 was often intermixed. Stratum 5 was generally between 0.0 and 7.6 meters thick and consists of a heterogeneous mixture of sand, silt, and gravel, and is considered mostly non-cohesive. The presence of boulders was anticipated in this stratum based on previous excavation experience in the NBX area. The final two layers are the Decomposed Rock and Bedrock. At the project site, Stratum 6 was less than 2.4 meters thick which was built from very stiff to hard silts, clays and sands. Lastly, the Bedrock is predominantly fine to coarse grained, unweathered to moderately weathered, storing to very strong gneiss and schistose gneiss of the Hartland Formation and is approximately 21 to 27 meters below ground level. The groundwater table is approximately 5 meters below the ground surface.

Meanwhile, the Manhattan structures site belongs to the New England Upland rock formation. This formation is locally known as the Manhattan Prong rock formation. The rocks in the project area belong to the Hartland Formation of Lower Cambrian to Middle Ordovician in age and overlie the Manhattan Schist of Lower Cambrian in age. The Hartland Formation lies in thrust contact with the underlying Manhattan Schist on a regional strike-slip thrust fault known as Cameron's Line [9]. Soils are found above the rock and its thickness varies depending on the location in Manhattan. The overburden deposits include glacial till, modified glacial drift, sands and gravels, some glacial lakebed silts and clays, and artificial fills.

The Manhattan rock is considered to have at least four major joint sets. The most prominent joint set, Set No. 1, lies parallel to the plane of weakness formed by foliation and strikes N30° to 35°E with a 70° to 80° SE or 60° to 70° NW dip. Set Nos. 2 and 4 generally strike perpendicular to the foliation jointing with dips in the range of 70° to 80° SW for Set No. 2 and about 75° NE for Set No. 4. Set No. 3 appears to run parallel to the foliation, but dips 60° to 70° in a direction opposite to Set No.1 and has been termed its conjugate [9]. Foliation shear zones and transverse fault zones are also present in the area. The water level is approximately 5.0 meters below the ground surface.

7.3 Project Challenges and Constraints

Both the Queens and Manhattan site locations had to consider the impacts of construction on the nearby utilities, existing buildings, New York City Transit (NYCT) lines, and other structures during the design development. The conventional tunnelling for CQ039 accounted for three critical and sensitive structures: 1) the NYCT subway line, 2) Northern Boulevard, and 3) the NYCT elevated line concrete piers [6]. Figure 10 displays the relationship between the existing structures and the NBX tunnel. The NYCT IND subway tunnel is approximately 23.0 meters wide by 7.6 meters high. Considering the thickness of the ground freezing arch, there is only 2.7 meters between the top of the frozen arch and the invert of the subway structure. The NYCT BMT elevated structure concrete piers are connected to the sidewalls of the IND structure, four of which intersect with the NBX alignment. Lastly, the NBX tunnel is excavated beneath Northern Boulevard. Northern Boulevard is a six-lane roadway that connects Eastern Queens with the Queensboro Bridge and it carries heavy traffic volumes to and from Manhattan. Each of these structures was required to remain operational, with minimal construction impact, during the life of the project.
In addition to the limited impact on existing structures, the groundwater table baseline could not drop more than 0.6 meters. This restriction was in place for two main reasons. The first reason was the existence of contaminant plumes in the nearby Sunnyside Yard. Secondly, groundwater removal from the unconsolidated glacial sediments could result in ground settlements that exceeded the allowable limits of the overhead structures. This is challenging to accomplish because the NBX tunnel has about 17 meters of groundwater head.

Across the East River, the construction of the Manhattan structures similarly required little impact on the utilities, building and structures within the zone of influence. However, the drawdown of the groundwater table was not as restrictive. Privately owned properties, Grand Central Terminal, Metro North Railroad facilities, the Park Avenue Tunnel, the Park Avenue Viaduct, and a total of five NYCT lines were within the zone of influence for construction. The NYCT lines include the 63rd Street Line, the 60th Street Line, the Lexington Avenue Line (at 59th Street and from 38th to 42nd Street), the 53rd Street Line, and the Flushing Line. When conventional tunnelling with drill and blast methods are in use, carefully designed and controlled blasting methods were required to minimize the noise and ground vibrations.

7.4 Excavation and Support

7.4.1 Northern Boulevard Crossing Tunnel

Prior to excavation, a 1.8 meter thick frozen ground arch was installed. Ground freezing was accomplished with the installation of freeze pipes spaced around the NBX Tunnel spaced at 1.2 meters on center. The pre-support was designed to reach down to

Figure 10. CQ039 cross section showing relationship to existing structures and pre-support system and piles [6]

Figure 11. Multi-Drift Excavation Sequence [6]
the bedrock. The design provided groundwater cut-off and a stable opening during tunnelling.

Tunnel excavation was accomplished with a seven-drift excavation sequence (Figure 11). Round lengths were limited to 1.2 meters for Drifts 1, 2 and 5. The remaining drifts were excavated in 2.4 meter round lengths. The excavation sequence commenced with Drift 1, followed by Drift 2, 3, 4, and then Drift 5. After Drift 5 at least 10.6 meters in, Drifts 6 and 7 followed in sequence.

7.4.2 Manhattan Structures

The design philosophy for the tunnel rock support is based on reinforcing the rock and creating a ‘rock support arch’ around the opening. Rock reinforcement was provided by means of rock bolts and rock dowels. Locally, and in connection with this rock arch concept, rock dowels/bolts will stabilize rock wedges. A reinforced shotcrete layer is applied to the exposed rock surface along the entire perimeter. Excavation sequencing followed conventional tunnelling principles using controlled blasting techniques. Techniques used at East Side Access followed the guidelines of the International Tunneling Association’s (ITA) Working Group 19 [2].

The two terminal caverns for East Side Access each have a cross section of approximately, 20.3 meters high by 17.8 meters wide. This cross section spans roughly 345 meters, which is about equivalent to about five city blocks. The ground support includes 6.0 meter long rock dowels spaced along the arch at 1.2x1.8 meters on center. The spacing on the sidewalls is increased to 1.8x2.4 meters. The steel fiber reinforced shotcrete is 100 millimeters. The distance between the east and west cavern is approximately 12.0 meters.

Directly below Grand Central Terminal, dual, three level cross over caverns were constructed. The distance between the foundation of GCT and the crown of the cross over cavern is, at its thinnest, 9 meters (Figure 12). Typical ground support for the cross over cavern consists of 100 millimeters of steel fiber reinforced shotcrete with an arch rock dowel spacing of 1.2x1.2 meters. Each cavern is 84 meters long, roughly the length of two city avenues, 17.3 meters high and 19.1 meters wide. The distance between the two cross over caverns is only 11 meters.

7.5 Instrumentation and Monitoring

An extensive real-time monitoring program was incorporated for East Side Access. Instruments were placed along the entire alignment above ground, on critical structures, in subway tunnels, and within Grand Central Terminal. The 24/7 monitoring system automatically generated email alerts to critical personnel when an instrument exceeded its threshold value. Additionally, each blast was coordinated with Metro North personnel in Grand Central Terminal. This was a preventive measure to ensure trains were not running at the time of the blast.

7.6 Project Status

Excavation for the Queens CQ039 NBX Tunnel resulted in tunnel deformations and movements of the structures above the tunnel well within the allowable limits set during the design phase. The installation of the frozen arch was performed with negligible ground loss. Ground heave was within the acceptable levels, eliminating the need for soil extraction. After excavation of the center drift, only 7.5 to 15 millimeters of movement was observed in the tunnel crown, with about 2.5 to 5.0 millimeters of settlement recorded within the overlying subway structure. After thawing of the frozen arch, movements of up to 50 millimeters were measured. This settlement was recovered through compensation...
grouting. The tunnel permanent support has also been installed.

Manhattan’s CM009-CM019 works have also been excavated with little influence on the existing infrastructure. Currently, interior permanent support is being installed within the caverns, shafts, cross passages, escalator tunnels, and running tunnels. East Side Access is scheduled to be completed and open for revenue services early in the next decade.

8. ACCESS TO THE REGION’S CORE

8.1 Project Description and Objectives

The Access to the Region’s Core (ARC) Project’s main goal was to provide increased commuter rail capacity from northern New Jersey to Manhattan. The project included new railway terminals, both in New Jersey and New York, and caverns under 34th Street in Manhattan between 6th and 8th Avenues, shafts at Dyer Avenue, 33rd Street and 35th Street, ventilation shafts and caverns, utility tunnels to connect the shafts and caverns, and escalator tunnels to provide access from the surface to the station platforms. The project was separated into different contracts, but the main Manhattan excavation contract which is the main focus of this discussion, involved excavation and support for the New York Penn Station Expansion (NYPSE) cavern along with its adjoining cross adits, access and utility tunnels, escalator tunnels and shafts, Cross Passages 1 and 2, the Dyer Avenue Cavern, and the Warrington Interlocking Caverns. These structures, along with running tunnels, comprised the Manhattan portion of the ARC Project. This Manhattan portion was also referred to the Trans-Hudson Express Tunnel Project (THE Project).

The design called for conventional tunnelling with drill and blast techniques. Blast vibration analysis was conducted to determine and set limits of Peak Particle Velocity (PPV) for the structures.

During design progression to final design for the Manhattan Cavern Structure New Jersey’s Governor Christie decided to cancel the project. It is anticipated, however, that due to the need for a passenger transport capacity between New Jersey and Manhattan the proposed tunnel connection will resurface in the coming years.

8.2 Geology

Similar to the ESA project described above, the NYPSE cavern and tunnels fall within the Manhattan Prong rock formation. The west side of Manhattan’s topography and drainage shows stream channels trending generally north-south or northwest-southeast. These former stream channels developed along weaknesses in the underlying bedrock and are manifested by depressed bedrock surfaces, as well as by weathered discontinuities in the rock below. Most of these channels, which formerly drained upland areas, were filled during Manhattan’s urban development [10].

The bedrock in THE Project area generally consists of interbedded schist, schistose gneiss and amphibolite, along with pegmatite intrusions. Other rock types include granite, migmatite, talk schist, chlorite schist, marble, mylonite, and serpentinite, but are expected to be found in smaller amounts. The top of rock is considered to be, in average, about 15.2 meters below the ground surface. There are, however, areas where the rock surface is about 30.5 meters blow the ground surface. Such a case is for the Warrington Interlocking Cavern, located about 110.0 meters east of the Hudson River. Three rock classifications were defined according to the characteristics of joints and other discontinuities and engineering properties for the project. The subsurface investigation revealed two frequently occurring joint sets. One joint set is subparallel to foliation in the mica schist, generally striking north to north-east and dipping west, and is present regardless of rock type. The other joint set is nearly horizontal, with an undulatory dip angle less than about 20°. These low-angle joints persist for more than 30.5 meters [10]. Additional joint sets were observed, but were limited to a specific work zone. In total, the project was split into nine work zones.

Above the bedrock, Fill, Silty Sand Deposits, Estuarine Deposits, and Glacial Deposits are found. The Fill is comprised of a heterogeneous mixture of clay, silt, sand, and gravel. Meanwhile, the Silt Sand Deposits consist of brown to red brown, inorganic silt, silty sand and sand. Estuarine Deposits are found to
have silt, clayey silt to clay with trace fine sand, shell fragments, sandy silt, and silty to clayey sand. Lastly, the Glacial Deposits are described as silt, sand and clayey silt with gravel, and containing cobbles and boulders.

Groundwater levels measured in observation wells installed across THE Project’s Cavern and Shaft Excavation area ranged between 1.5 and 7.6 meters below ground surface for wells sealed in overburden and between 1.2 and 13.1 meters below ground surface for wells sealed in rock [10]. West of about 11th Avenue, groundwater levels are within 3.0 meters of the ground surface and correspond with the water level in the Hudson River, indicating tidal fluctuation. Going to the east of about 11th Avenue, groundwater levels range between 3.0 and 13.1 meters below the ground surface.

8.3 Project Challenges and Constraints

As with most underground construction in Manhattan, excavation adjacent to existing utilities, underground structures and at-grade and below-grade foundations are inevitable. This is no different for THE Project structures. The proposed underground structures interfaced with two NYCT IRT (No. 7 Subway Line and the 7th Avenue Subway), a NYCT IND Subway Line (8th Avenue Subway), Amtrak North River and North Access Tunnels, the High Line, 10th and 11th Avenue Viaducts, NYCDEP City Water Tunnel No. 1 and Water Tunnel No. 3, Pennsylvania Station New York, LIRR West Side Storage Yard, and Herald Square, which provides a connection NCT IND and BMT Subway Lines with the NJ PATH Line. Important buildings in the vicinity of the project included One Penn Plaza, The Macy’s Building, Metropolitan Center Theater, The New Yoker Hotel, Nelson Tower, and the Church of St. Michael.

8.4 Excavation and Support

The approach for constructing the elements of THE Project was similar to that of the East Side Access Project. Excavation was envisioned to be by controlled blasting with ground support consisting of a systematic rock dowel/bolt installation supplemented with a shotcrete layer.

The design for the Dyer Avenue Cavern and NYPSE Cavern highlight the project. The Dyer Avenue Cavern has a cross section of approximately, 60 meters high by 20 meters wide. This cross section extended for roughly 60 meters. The ground support included 4.6 meter long rock dowels spaced at 1.8x1.8 meters on center. The steel fiber reinforced shotcrete is 100 millimeters.

The NYSPE cavern, while not as tall as the Dyer Avenue Cavern, presented different issues as this area in Manhattan can present abrupt changes in rock quality. Typical ground support for the NYPSE cavern consisted of 150 millimeters of steel fiber reinforced shotcrete with a rock dowel spacing of 1.5x1.5 meters. The rock dowels in the arch were 7.6 meters long, while the dowels in the sidewalls are 6.0 meters. The cavern was 490 meters long, roughly the length of two city avenues, 30 meters high and 30 meters wide.

Due to the large sizes of these caverns, multiple excavation drifts and benches were required for construction. The stability of the NYSPE Cavern, following the multi-drift excavation sequence and using
the support described above, was verified with a three-dimensional model (see Figure 14).

8.5 Instrumentation and Monitoring

Structural instrumentation was to be installed on the surface and in the subsurface, tunnels, shafts and caverns. Instruments included in the monitoring scheme include multiple position borehole extensometers, seismographs, deep borehole geophones, dynamic strain gauges, grid crack gauges, inclinometers, vibrating wire piezometers, utility monitoring point, tiltmeters, and load cells. Tunnel convergence monitoring is performed by using combinations of portable Total Stations and laser distance meters. Automated, continuous monitoring was to be performed with automatic total stations on critical structural elements.

8.6 Project Status

Although the Trans-Hudson Express Tunnel Project was not constructed, the design concept following conventional tunnelling proved that a large underground cavern can be built in a major urban area. Furthermore, the cavern and adjoining tunnels and shafts could be excavated with little impact on the nearby infrastructure.

9. NO. 7-LINE EXTENSION PROJECT

9.1 Project Description

The No. 7 Subway Line Extension project continues NYCT service beyond its current end point at Times Square. The design extends the service towards the west along 41st Street and then south along 11th Avenue terminating in the vicinity of 25th Street & 11th Avenue.

The project includes twin running tunnels with five cross passages, a 34th Street station cavern, three shafts, and numerous ancillary structures. Additionally, the construction of three shafts, a TBM assembly chamber, two interlocking caverns, a station cavern, and eight ancillary adits is part of the No. 7 Subway Line Extension projects. The shafts range from 12.2 to 15.2 meters in diameter, while the main station cavern is 18.3 meters tall by 21.3 meters wide. The interlocking caverns were approximately 18.3 meters wide by 9.2 meters high. The combination of the station cavern and the interlocking caverns totals to 0.5 kilometers. The cavern areas – and lower levels of the shafts – were excavated through hard rock consisting of granite and Manhattan schist.

Meanwhile, the running tunnels were excavated by TBMs, while the other structures employed tunnel excavation by conventional tunnelling methods using drill and blast for excavation. The No. 7 Line project is the first double-shielded TBM to tunnel under New York City while placing pre-cast concrete segments to form the tunnel support. The 6.9 meter diameter TBMs were used to excavate the approximately 2.4 kilometers of running tunnels.

The No. 7 Subway Line Extension project deals with many of the same constraints as THE Project, being that it is in close proximity to many existing surface and subsurface structures and utilities. This project also has similarities to the ESA CQ039 project described above in that ground freezing was used at a location along the running tunnels. Ground freezing methods were incorporated at the south end of the running tunnel alignment to stabilize the ground prior to the launch of the TBMs.

Roughly 90% of the construction was completed as of the end of 2013. The No. 7 Line Extension is scheduled to open in 2015.

10. CONCLUSIONS

Combining the ground support and pre-support
measures with an extensive real-time monitoring scheme, surface settlements in urban areas can be controlled. Often times, excess settlements are avoided because construction sequences are adjusted in the field according to the recorded monitoring data. Conventional tunnelling involves practical experience, understanding of the geotechnical properties of the tunnelling medium and skilled execution of the design. The projects discussed in this paper are examples of successful conventional tunnelling to create a wide range of large and complex mined openings in urban environments, both through soft ground and hard rock.

11. REFERENCES