

# **Past and Present Soft Ground NATM for Tunnel and Shaft Construction for the Washington, D.C. Metro**

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**ABSTRACT:** The first application of soft ground NATM in the US was on Washington, D.C. Metro Section E5 Fort Totten Station and running tunnels. Due to its success it was subsequently applied for tunneling under Rock Creek Cemetery and Section F6b, south of Congress heights station on the Outer Branch Route. Tunneling for Section E4b also called for the construction of a large NATM oval shaft that was used to stage tunnel construction. In its final build-out it is configured as an emergency egress structure. Application of the NATM and its successes laid the ground work for the method's increased use on urban soft ground tunnels, recently the Beacon Hill station in Seattle. NATM tunneling is currently being employed in a design-build framework for the extension of Washington's Metro to Dulles International Airport. This paper provides a concise case history summary and focuses on the developments and refinements of the NATM in Washington ranging from technical, to contractual and newly risk management aspects and its use on the Dulles Corridor Metrorail project at Tysons Corner, Virginia. This project involves two shallow 520 m long single track tunnels that feature a systematic implementation of the pipe arch canopy method for pre-support for the entire length of the tunnels where settlement is critical to control. The latter is one of the examples of the many innovations that led to the method's refinements and were pioneered on the Metro system in Washington, D.C.

## **INTRODUCTION**

Soft ground NATM's first application in the US was to Section E5 Fort Totten Station and running tunnels of the Washington, D.C. Metro system in 1988. In addition, this method was applied to the Section F6b tunnels under Rock Creek Cemetery and for the tunnels and shaft of Section E4b. All three projects are significant in their own right, being the testing ground of what were innovative and novel concepts at the time. These refinements of the NATM in Washington, D.C. range from technical, to contractual and new risk management concepts. With the start of construction of the latest soft ground NATM tunnels in Tysons Corner for the metrorail extension, the concepts and the construction method itself that were once so novel have been refined further, and are now being successfully applied to the Dulles Corridor Metrorail Project.

## **FORT TOTTEN STATION AND RUNNING TUNNELS, SECTION E5**

### **Project Description**

Section E5 of the Washington Metro at Fort Totten Station in Northeast Washington, D.C. on the Green Line represents the first Washington Metro station and running tunnels to be constructed using the soft ground NATM. The underground structures of the project consisted of a station chamber, a vent shaft, twin tunnels, and a fan shaft. The station chamber measures approximately 20 m in width by 10 m in height by 91 m in length, while the twin tunnels are approximately 305 m in length. Overburden ranges from approximately 6 m at the least over the station to as much as 30.5 m over the tunnels. The construction contract was awarded in August 1988. The contractors had the option to submit bids based upon conventional construction methods, NATM, or a combination of both. The contractor, a joint venture between Mergentime and HT Construction, chose the NATM option with Hochtief providing specialized equipment as well as management personnel with prior NATM experience (Darmody 1991).

### Geologic and Hydrologic Conditions

Washington D.C. is located on the boundary between Virginia’s Piedmont and Coastal Plain physiographic provinces. This boundary is commonly referred to as the “Fall Line.” Section E5 is located east of the “Fall Line” within the Coastal Plain sediments identified collectively as the Potomac Group. More specifically, construction was within the Patuxent Formation, the lowest member of the Potomac Group, which is predominately unconsolidated sand and gravel with lesser amounts of clay. The sediments are overconsolidated and contain some irregular beds of iron-oxide cemented sand or gravel. The Potomac Group sediments at Section E5 were categorized into two primary groups: “P1” clays and “P2” sands following the general and system wide nomenclature established by WMATA’s General Soils Consultant.

The ventilation and fan shafts were excavated within interlayered sands and clays while the two single track tunnels were excavated primarily through cross-bedded, silty or clayey, fine to medium sands. The station was excavated within loose to compact interlayered sand and gravels, stiff clay, and clean to silty sand in the eastern half and interlayered clay and sandy clay in the western half. Figure 1 shows a geological profile longitudinal section and cross section from the center drift of the station as obtained from borings and field mapping.

Piezometer information obtained prior to construction indicated the static groundwater table to generally be below invert elevation of the NATM structures. Due to the lenticular nature of the Patuxent Formation sediments, subsurface water inflows and perched groundwater were more of a concern during construction. Therefore prior to the start of excavation, the contractor drilled two 24 m long, 152 mm horizontal drains at the portal wall on either side of the center drift for drainage. Initial high flow rates were attributed to the drainage of a large perched groundwater basin. The subsequent flow rate of 2.8 liters per minute from one of the two holes for the remainder of the station excavation was attributed to groundwater recharge of the basin (Darmody 1991).

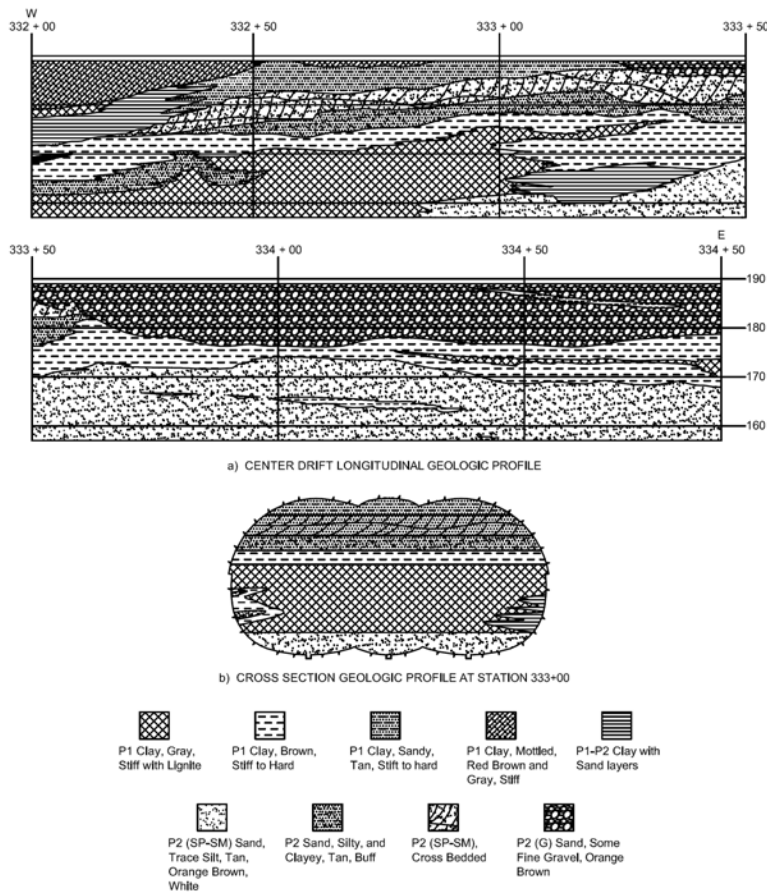
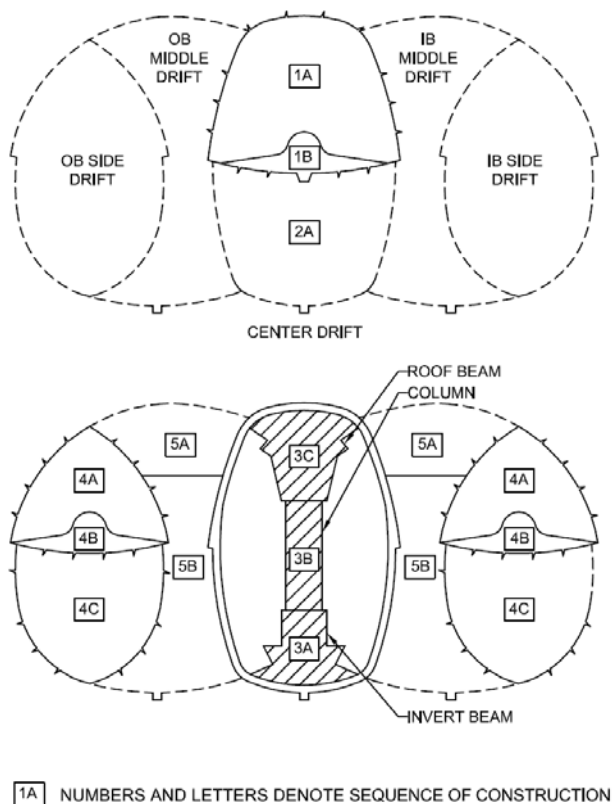


Figure 1. a) Center Drift Longitudinal Geologic Profile, b) Cross Section Geologic Profile at Station 333+00 (after Darmody 1991)

## NATM Station Tunneling

The station excavation sequence was broken down into multiple drifts. The center drift was the first to be excavated, with excavation proceeding in 0.9 m increments westward from the portal wall. The top heading was excavated in its entirety, followed by the bench. Upon completion of the center drift, station excavation activities paused for approximately 4 months while a cast-in-place concrete center drift support frame consisting of an invert beam, nine columns, and a roof beam was constructed. See Figure 2 for the excavation sequence.

Once the center drift and its support frame were completed, the contractor proceeded with simultaneous excavation of the IB and OB side drifts in 0.9 m increments, alternating between the top heading and bench. Excavation of the twin tunnels proceeded in 0.9 m increments as well, with excavation alternating between top heading, bench, and invert. The initial support for each excavation round consisted of the application of a sealing layer of shotcrete to the excavated ground, followed by installation of a lattice girder, installation of the first layer of welded wire fabric (WWF), shotcrete to the outer edge of the lattice girder, excavation and shotcrete of a temporary invert, installation of a second layer of WWF, and finally the application of a second layer of shotcrete.



**Figure 2. Excavation and Support Sequence of NATM Station**

The occasional running or raveling ground encountered during excavation was successfully controlled using pre-support means; however, only with one significant instance of ground loss. In this instance, some 38 m<sup>3</sup> of sand fell from a small hole in the IB tunnel crown. The resulting surface settlement was less than 0.5 mm and the ground loss area was stabilized with additional shotcrete and positively drained by installing drain pipes. Once excavation had progressed 4.5 m beyond the area of settlement, the contractor grouted the area of ground loss with water-cement grout to further stabilize the ground. Overlapping forepoling sheets were effectively used to control raveling ground during excavation.

Upon completion of the initial lining for all structures, the station, twin tunnels, and shafts were waterproofed using a full round or “tanked” PVC waterproofing membrane. Subsequently, the cast-in-place concrete final lining was installed.

## ROCK CREEK CEMETERY, SECTION E4B

### Project Description

Section E4b was constructed as part of WMATA's \$642 million Mid City E-Route construction that provided connection between the U Street/Shaw station and the Fort Totten Station in northeast Washington, D.C. Construction began in the mid 90's and included two cut-and-cover stations, 4.7 kilometers of single-track tunnels constructed mainly by TBMs and a series of ventilation and emergency access and egress shafts. The Farragut shaft, part of Section E4b, was the only shaft constructed by NATM. Section E4b adjoined the running tunnels of Section E5a that were constructed several years earlier by NATM. From the Farragut Shaft, which adjoined Section E5a, to the Buchanan shaft, located further south, the tunnels had to pass under the historic Rock Creek cemetery, the oldest in Washington, D.C. The tunnel alignment passes beneath the cemetery compound at a depth of approximately 15-25 meters. Prior to the start of the project, the cemetery stated that any tunneling approach under the cemetery would have to be without any "discernible settlements." WMATA's Board of Engineering Consultants (BOEC, a select group of US tunneling experts) and Design Engineers responded with an investigation into a series of tunneling and ground conditioning options. With initial hesitation mainly due to the fact that soft ground NATM was still a relatively untested technique in the US at that time, an engineering recommendation was made to apply NATM with the aid of ground improvement and pre-support measures to suit local conditions. In the end, it was concluded that only the NATM with such additional measures would be able to meet the requirement for close to negligible surface settlements, thus satisfying the restrictions imposed by the cemetery. Tunneling surface settlements were estimated to be less than 1 cm and were projected to spread over a wide surface settlement trough.

### NATM Tunneling

The two single-track tunnels, separated by approximately one tunnel diameter pillar width were about 940 meters in total length, each. The contractor, a joint venture between Kiewit and Kenny Construction, used the fully designed classical soft ground NATM excavation and support sequence with top heading and bench excavation sequencing and the top heading advance limited to a maximum of 1 meter per round. The bench excavation followed at a distance of 2 meters (Figure 3). The initial shotcrete lining was 18 cm thick and reinforced with welded wire fabric. The tunnel was waterproofed using a PVC continuous membrane and unreinforced cast-in-place 30 cm thick concrete was installed as final lining (Irshad 1995). Depending on geologic conditions, pre-support in the crown involved pipe spiling, and forepoling sheets were used to control potentially running soils such as soft silts and silty sands. Pipe spiling was used as needed in stiffer silts. Chemical-grout was specified in portions of the alignment where silty sands with occasional pockets or zones of clean sand and perched water were anticipated within the P2 materials. Installation of a chemically improved soil arch above the tunnel crown was carried out using the horizontal directional drilling technique, a novelty for tunnel pre-support installation at that time.



Figure 3. Section E4b – NATM Tunneling under Rock Creek Cemetery (Courtesy Paul Madsen, Kiewit Construction)

### **Grouted Pre-Support Arch – Horizontal Directional Drilling and Chemical Grouting**

Chemical grouting was required above both the inbound and outbound NATM tunnel crowns for about 100 meters starting from the Farragut shafts towards Ft. Totten Station, from Farragut shaft for about 250 meters towards the Buchanan shaft and from the Buchanan shaft towards the Farragut shaft for about 160 meters, for a total length of about 2 x 510 meters. The grouting subcontractor, Hayward Baker, Inc. proposed a Horizontal Directional Drilling (HDD) program for the installation of steel TAM pipes to allow unimpeded access to the heading for continuous mining, better control of the grout injections by minimizing the number of faces exposed to the grouting process. After weighing schedule and cost advantages/disadvantages of HDD vs. conventional drilling per design the joint venture of Kiewit/Kenny proposed and WMATA accepted the HDD installation of TAMs for chemical grouting.

A total of more than 8,000 m in TAM pipes was installed either from within the shafts or from grouting chambers created near the shafts. HDD use enabled NATM tunneling in silty and clean sands on Section E4b without the need for stoppages during tunneling.

In summary, use of chemical grouting and standard pre-support measure including spiling and sheeting in combination with NATM sequencing and early support installation achieved project objectives and guaranteed the tunneling performance with “no discernible” surface settlements within the cemetery.

### **SECTION F6B – PRE-SUPPORT OPTIMIZATION**

#### **Project Description**

Section F6b included the construction of Congress Heights Station using cut-and-cover techniques and two 460 m long, single track tunnels. This section is part of the Branch Avenue Route and is situated in southeastern Washington, D.C. NATM was selected for tunnel construction because of (1) the short length of tunnels, (2) short mobilization duration, and (3) the ability to mine from multiple headings. It was anticipated that with rapid mobilization and the use of multiple headings to advance through a relatively short length and comparatively homogeneous geology, the NATM tunnels could be completed during the early part of the overall project construction. The Contract for Section F6b was awarded to a joint venture of Clark/Shea with J.F. Shea being responsible for NATM tunneling which started in October 1996 and the “hole through” in the IB tunnel completing both tunnel drives was made in September 1997.

A number of pre-support measures were used to stabilize the tunnel crown in areas where saturated sand layers were known to occur and in adjacent sections where the thickness, extent and stability of firm clays over the tunnel were uncertain. These measures included pre-support grouting using directional drilling, grouted pipe spiling, and rebar spiling, in combination with dewatering in advance of the face. These measures were required to increase the stand up time and cut off groundwater. Pre-support chemical grouting of the northernmost 70 m was required to consolidate a saturated sand layer in the crown to enable successful NATM tunneling.

Per WMATA design criteria the tunnel cross section was designed as a dual lining structure comprising a shotcrete lining and cast-in-place unreinforced concrete lining. The shotcrete lining was reinforced with welded wire fabric, lattice girders, splice bars, and splice clips. The tunnel is waterproofed by a flexible plastic membrane around its entire circumference.

The tunneling of the outbound tunnel proceeded as specified in the contract documents. During mining of the inbound tunnel, however, interception of 4 unmapped sand lenses in the crown resulted in unexpected inflow of groundwater and work stoppages. With chemical grout injection primarily from inside the tunnel and installation of drain pipes ahead of the face, the contractor was able to resume safe mining below a hydrostatic pressure of up to 8 m (Gall, Zeidler, Bohlke, and Alfredson 1998).

#### **Geologic Conditions**

Based on exploratory borings along the NATM tunnels, the first approximately 70 meters of the tunnel beginning at the station in the north were mapped as a thick sequence of firm overconsolidated (P1) clays with up to 1.5 m of saturated sands (P2) in and above the tunnel crown. The presence of the P2 sand layer dictated the use of pre-support methods to stabilize the crown and prevent the inflow of flowing sands and uncontrolled loss of ground. Directional drilling, pipe spiling, and grout injection were specified to assist in stabilizing the crown of the tunnel through this particular reach. Beyond the first 70 m south of Congress Heights Station, the predominant soil type at

the face and above the tunnel was anticipated as a thick sequence of over-consolidated Cretaceous P1 clays with occasional sand lenses.

### **Pre-Support Methods**

Based on ground conditions the main types of pre-support foreseen F6b included rebar spiling, grouted pipe spiling, and installation of a chemical grouting canopy.

Rebar spiling consists of steel rebar rammed into the ground in soils where a bridging effect can be achieved between closely spaced bars. Rebar spiling was also specified in the area of the chemical grout canopy to limit over break in the tunnel arch. Experience during construction of past projects has shown that even when the P2 material is improved by chemical grouting, over break in the crown and tunnel shoulders may occur because of inhomogeneities in the ground. To limit such over break No. 8 (25 mm) rebar spiling installed at 0.3 m distances was specified on an as required basis.

Grouted pipe spiling consisted of perforated steel pipes installed above the tunnel crown at a centerline spacing of approximately 0.3 m in pre-drilled holes at a look-out angle of 5 degrees and through which grout was injected to stabilize the ground. These were installed systematically between the ground improved by chemical grouting and to a location where the P1 Clays would extend a minimum of 1.5 m above the tunnel crown.

Installation of the grout canopy was specified to ensure that ground water is prevented from draining into the tunnel section, the ground properties are improved, and the steel grouting pipes provide longitudinal reinforcement by forming a supporting arch extending into the P1 clays above the tunnel crown. The chemical grouting canopy was to consist of steel pipes installed into the ground ahead of the tunnel face for a distance of up to 100 m using directional drilling. Following placement of the pipes chemical grout was to be injected to stabilize the ground in sandy P2 materials along the perimeter of the tunnel crown.

However, shortly after award the contractor proposed to install roughly 45 m long drills from within the Congress Heights Station excavation into the arch (and saturated sand layer) above the future tunnel using conventional methods. The remaining length of this canopy was then grouted from within the tunnel during advancing northward from the south using shorter, overlapping 21 m long TAMs.

### **Dewatering/Groundwater Control**

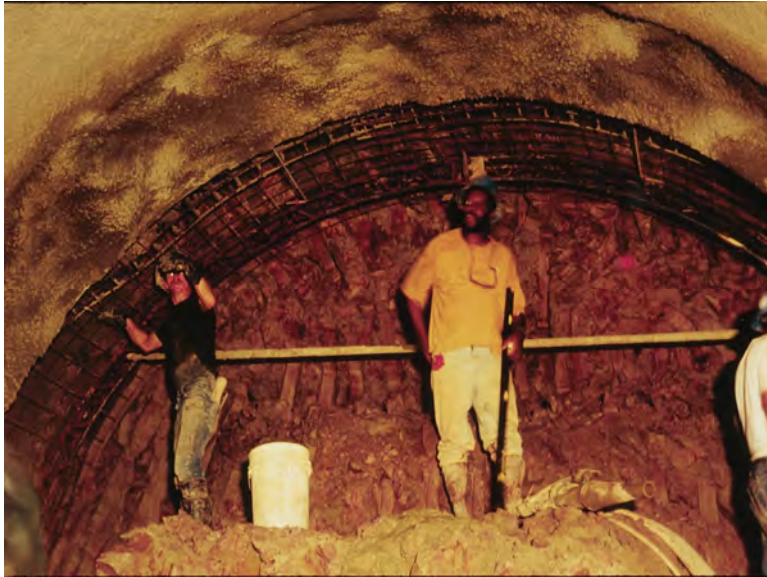
To dewater the saturated P2 sands in advance of the tunnel heading after installation of the chemical grout arch the contract foresaw drilling of horizontal dewatering pipes to lower the groundwater table for the tunnel construction in the P2 material. The groundwater table was to be lowered to the interface between the P2 and P1 material. To achieve a continuous dewatering system drilling for the horizontal dewatering pipes was also to be carried out using directional drilling.

### **Tunneling**

The tunnel excavation and support sequence followed basic considerations for soft ground NATM tunneling. The excavation face was subdivided in top heading and bench with excavation rounds of up to 1 m length in the top heading. The typical excavation sequence for tunneling in P1 clays called for a ring closure distance of maximum 5 m. The actual support installation in the top heading is shown in Figure 4. For tunneling beneath the chemically grouted sand canopy the excavation procedure was modified, calling for an earlier shotcrete ring closure, allowing a maximum distance between advancing top heading and closed shotcrete ring in the invert of only 4 m. Tunnel excavation began in October 1996 from a southern shaft at Mississippi Avenue with two headings being driven simultaneously.

Geologic conditions observed in the outbound tunnel (OB) were in overall agreement with, or better than those established in the geotechnical documents and tunneling proceeded with pre-support as specified or less. In contrast to the outbound tunnel, the inbound tunnel excavation was affected by occasional, large inflow of water at the face when the heading intercepted unmapped saturated sand layers. Tunnel advance was stopped four different times with groundwater inflow rates of 3.2 to 5.0 liters per second. In those instances tunnel excavation was halted until the water bearing P2 material affecting the tunnel was sufficiently grouted to enable tunneling beneath and through a soil improved ground with additional dewatering through drainage pipes as required. Due to the required use of probe drilling to check for presence of water saturated sand lenses known to be present in the P1 clay material, the

sand lenses were detected early on. This exploratory measure provided knowledge of ground conditions ahead of the face, and repeatedly, proved essential to assessing tunnel face stability and tunneling safety.



**Figure 4. Section F6b – Top Heading in P1 Clays**

In one instance inflows were of such magnitude resulting in ground loss estimated at 50-100 cubic meters which required the use of cement grouting to fill the void created by the loss of ground ahead of the tunnel face. This was achieved by a surface grouting program which led to an interruption of tunneling of about 2 months (Gall, Zeidler, Bohlke, and Alfredson 1998). Four work stoppages occurred during inbound tunneling and in each case, tunneling was able to resume once the crown was adequately stabilized with the use of pre-support chemical grouting in advance of the face. In summary NATM tunneling was carried out successfully for the first time under a hydrostatic head of up to about 8 m.

## **TUNNELING AT TYSONS CORNER FOR DULLES METRORAIL**

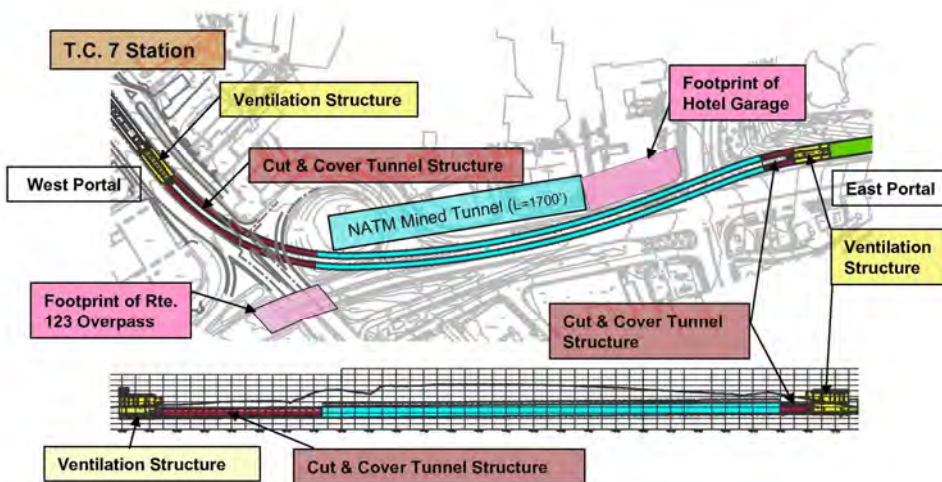
### **Project Description**

The Metropolitan Washington Airports Authority (MWAA) is currently undertaking the first major expansion of the WMATA system that reached a total rail length of 172 kilometers with the completion of the Largo Line in 2004 (Rudolf and Gall 2007). This current expansion is known as the Dulles Corridor Metrorail Extension Project (DCMP) and will significantly improve the service of WMATA's metrorail system in the Capitol Region in Northern Virginia and will connect the Washington Dulles International Airport (IAD) with Washington D.C. The expansion will add a total length of 37 kilometers of rail. Its first phase is currently being implemented in a design-build contract by Dulles Transit Partners (DTP) a joint Venture of Bechtel, Inc. and URS. This Phase 1 involves NATM tunneling as the most feasible tunneling option at Tysons Corner.

The NATM tunnel segment includes twin single-track tunnels at a length of approximately 520 m each. A short cut-and-cover section adjoins the NATM tunnels at the east portal and a longer cut-and-cover section exists at the west portal. These tunnels are being constructed in soft ground and are located adjacent to existing structures and utilities that are sensitive to ground movements (Figure 5). The alignment and elements of the short tunnels at Tysons Corner are shown in Figure 6. For this very shallow overburden alignment, a busy 4-lane thoroughfare at International Drive is located about only 4.6 m above the tunnel crown. The deepest overburden cover exists at about mid-point of the alignment with nearly 11.6 m. At the west portal and the transition to the cut-and-cover box the overburden is about 6 m.



**Figure 5. View NATM Tunnel East Portal in Relation to High-rise Buildings near the Alignment**



**Figure 6. NATM Tunnel and Tysons Corner Tunnel Alignment**

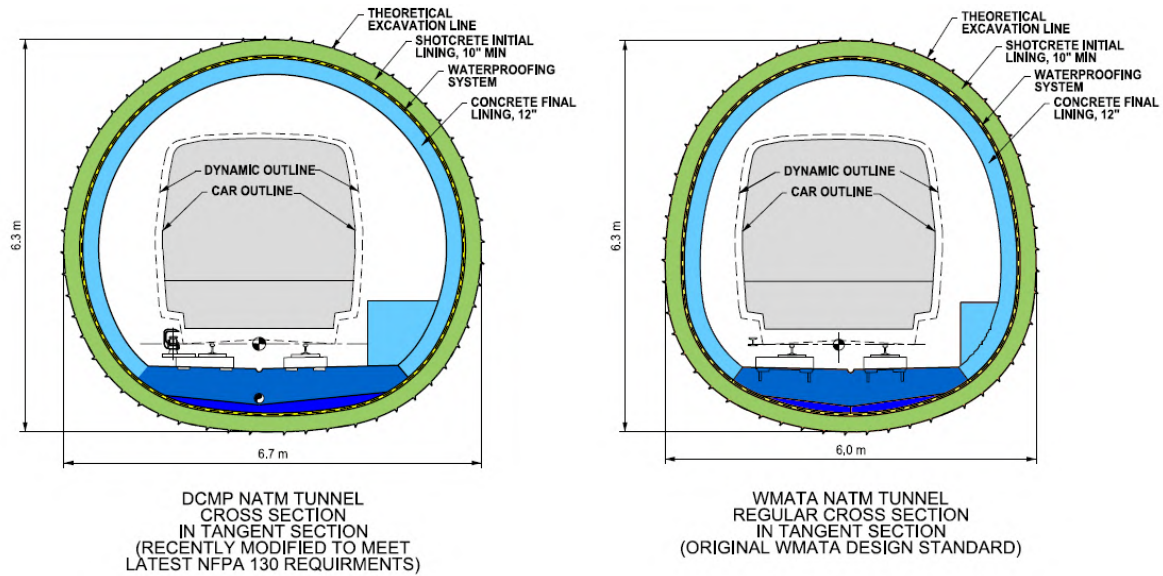
**Geologic Conditions**

The soils along the tunnel alignment include mainly residual soils and soil-like completely decomposed rock. The residual soils are the result of in-place weathering of the underlying bedrock and are typically fine sandy silts, clays and silty fine sands. According to the project classification, the residual soils are identified as Stratum S, which can be divided into two substrata (S1 and S2) based on the consistency and degree of weathering. Only to a limited extent where the tunnel is deepest will tunneling encounter decomposed rock referred to as "D1" in bench and invert. The decomposed rock is a soil-like material but has higher strength. Ground water at portal locations is generally at invert elevation, at the mid-point of the tunnel alignment it rises up to the tunnel spring line.

**Tunneling**

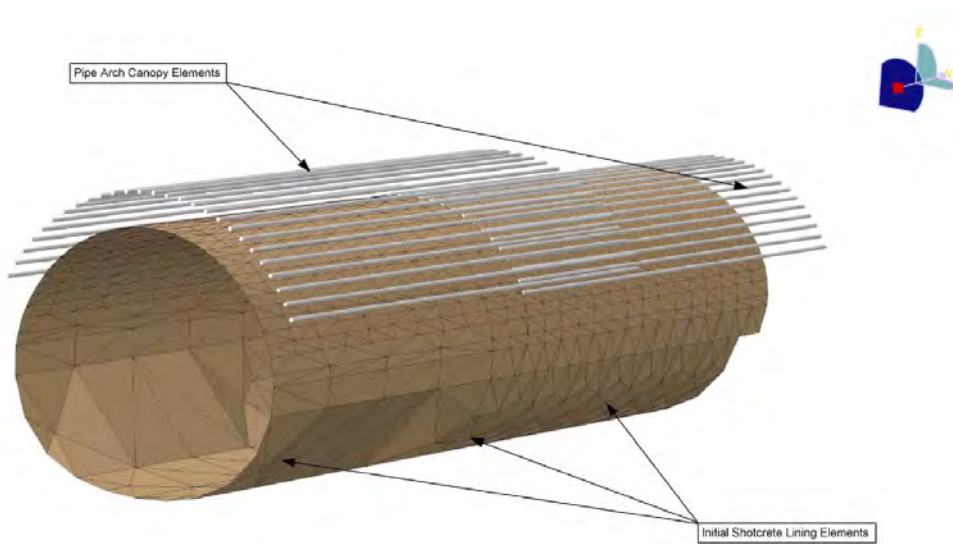
Due to WMATA's long history of tunneling the agency has developed a comprehensive and detailed set of design criteria that often impose "mandatory" design requirements on the tunnel engineers. The NATM design at Tysons Corner, however, is using a newly developed NATM tunnel cross section that is wider than the classical and previously mandatory WMATA NATM regular cross section. Just as the previous section for soft ground NATM, this section is of dual lining character and features a waterproofing wrap around system but is wider to accommodate fire-life-safety considerations called for by the National Fire Protection Association's (NFPA) 130 code requirements for walkway width (Figure 7).



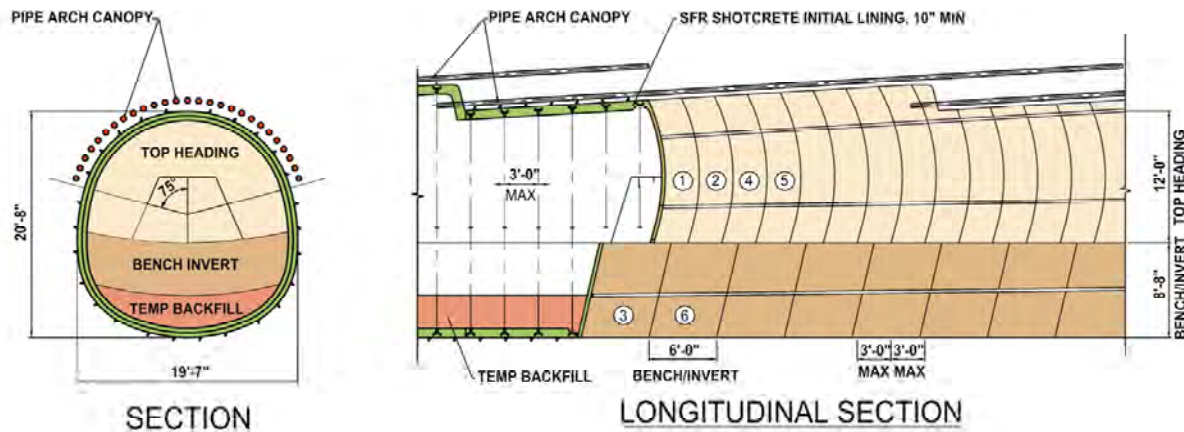


**Figure 7. DCMP New Cross Section vs. WMATA NATM Regular Cross Section**

Because of the shallow depth, the prevailing soft ground conditions, the need to control settlements, and risk mitigation issues the NATM is supplemented by a grouted pipe arch canopy for the entire length of the tunnels (Figures 8, 9 and 10a). This will be sufficient for pre-support where the overburden is greater and surface structures are less sensitive. An additional row of pipe arch umbrellas, using closely spaced, approximately 114 mm diameter grouted steel pipes will be used on the first 90 m length at the east portal where tunneling is shallow with 4.6 m overburden. The pipes will be installed at 30 cm center-to-center distances around the tunnel crown. Construction of the NATM tunnels at Tysons Corner is underway, and thus far the Pipe Arch Canopy pre-support is working as it should with no significant ground settlements observed.

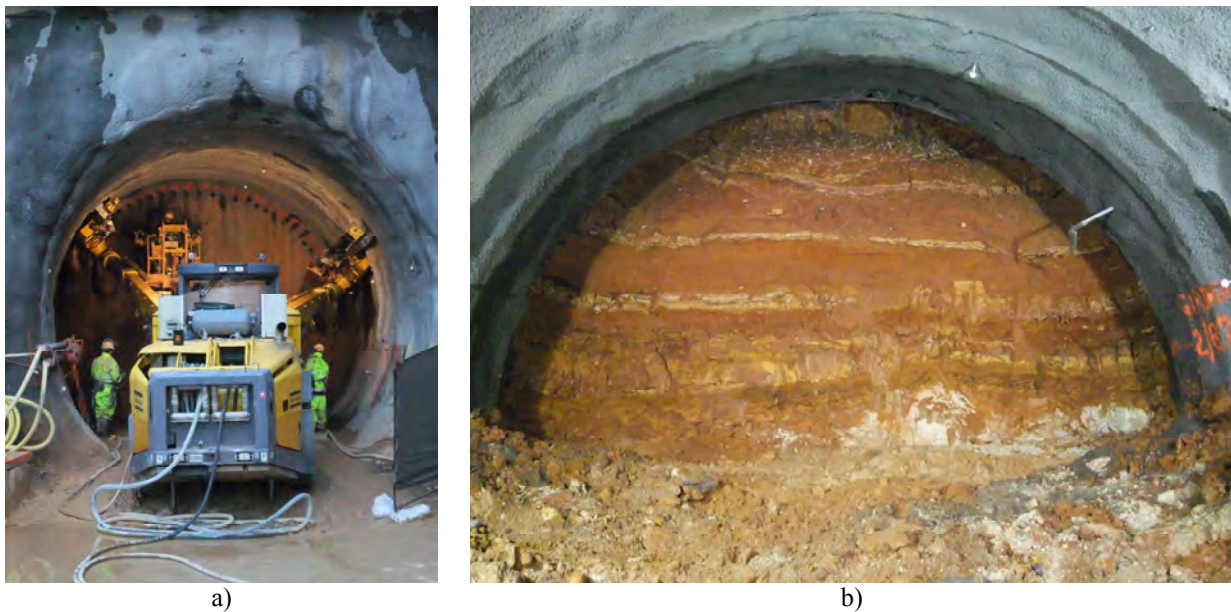


**Figure 8. 3-D View of the NATM Tunnel Pipe Arch Canopy Pre-support**



**Figure 9. NATM Tunnel with Single Pipe Arch Pre-support for Shallow Soft Ground Tunneling**

Presently, the excavation of outbound tunnel is proceeding through a combination of residual Piedmont soil, found in the bench/invert, and ancient Coastal Plain material found in the top heading (Figure 10b). The Coastal Plain material contains distinct bands of clay between layers of silty sand and gravels/cobbles. The sand and gravel/cobbles are rounded and smooth due by mechanical action of water when the layers were originally deposited. As excavation progresses, the tunnel will eventually move entirely within the residual Piedmont soils.



**Figure 10. a) View of the NATM Tunnel Pipe Arch Canopy Pre-support Installation, b) View of Coastal Plain Material in Outbound NATM Tunnel Top Heading**

#### **Design-Build Contract**

The project is being realized under a design-build contract. The design-builder, Dulles Transit Partners, was required to develop preliminary engineering for the rail project. The preliminary engineering then formed the basis to develop a fixed firm price by the design-builder. The need to maintain previously established budget resulted in design challenges and the need to optimize design and construction methods. Value Planning (VP) and Value Engineering (VE) exercises were a central activity of the design development in pursuit of the most economical approach that would impart the least impact on the surroundings. For Phase I of the project, these exercises led to a

series of changes in the underground segment at Tysons Corner. The alignment was originally envisioned as deep, 1.6 kilometer long twin TBM tunnels an approximately 24 meter deep underground station constructed by cut-and-cover methods within Route 7, a major traffic artery. However, analysis of construction cost favored implementation of the current alignment consisting of the short NATM tunnels with a quasi at-grade station within the median of Route 7 at a cost savings of roughly \$200 million.

### SUMMARY AND CONCLUSION

With the commencement of construction on the Dulles Corridor Metrorail Extension, the Washington Metro system is once again undertaking soft ground NATM tunneling through a sensitive urban area. All four of the tunnel projects discussed presented their own unique challenges, while adapting state-of-the-art pre-support techniques to meet those challenges. Table 1 summarizes the main characteristics of NATM tunneling for each of the four discussed projects.

**Table 1. Summary of Characteristics for Washington Metro NATM Tunnels**

<b>Project / Elements</b>	<b>E5 Fort Totten</b>	<b>E4b New Hampshire Ave.</b>	<b>F6b Congress Heights</b>	<b>DCMP Tysons</b>
Ground Conditions	Overconsolidated Clays and Sands	Overconsolidated Clays with Saturated Sands	Overconsolidated Clays with Saturated Sands	Coastal Plain Silty Sands & Gravels; Piedmont Residual Soil
Groundwater Elevation	Below Invert	Invert	Above Crown	Springline
Cross Section	Trinocular and Single Track Standard	Single Track Standard	Single Track WMATA Standard	Single Track Widened per NFPA 2003
Overburden	20 to 100 feet	50 to 147 feet	35 to 60 feet	8 to 35 feet
Surface Features	Park and Residential	Rock Creek Cemetery	Green Field, Apartment Building	International Drive, Rte. 123
Excavation and Support Sequence	Top Heading -Bench / Invert 3-4" Top Heading max.	Top Heading -Bench / Invert 3-4" Top Heading max.	Top Heading -Bench / Invert 3-4" Top Heading max.	Top Heading -Bench / Invert 3-0" Top Heading max.
Pre-Support	Spiles, Sheets	Spiles, Sheets, Pipe Spiling	Spiles, Pipe Spiling, Chemical Grouting	Pipe Arch Canopies: Double and Single Rows
Ground Improvement	N/A	Chemical Grouting with Directional Drilling / Dewatering by Vacuum Lances	Permeation Grouting for Differing Site Conditions	Ground Water Pressure Relief
Formal Risk Assessment	No	No	No	Yes
Contract	Design-Bid-Build	Design-Bid-Build	Design-Bid-Build	Design-Build

The use of the NATM within the Washington D.C. Metrorail system has made a significant contribution to soft ground NATM in the U.S. Construction of the Section E5, F6b, and E4b essentially used continuously updated, state-of-the-art pre-support techniques in soft ground NATM tunneling, which have now become accepted and widely used. These experiences and technologies are now being applied in the challenging task of constructing the twin soft ground tunnels through the urban Tysons Corner.

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