# THE DULLES CORRIDOR METRORAIL PROJECT— EXTENSION TO DULLES INTERNATIONAL AIRPORT AND ITS TUNNELING ASPECTS

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# ABSTRACT

The Virginia Department of Rail and Public Transportation and the Metropolitan Washington Airports Authority are undertaking the extension of Washington Metropolitan Area Transit Authority's Metrorail service to Washington Dulles International Airport and beyond to Route 772 in Loudoun County, Virginia. The roughly 37 kilometers long, double track alignment involves two 700 meters long single track, soft ground NATM tunnels at Tysons Corner, two 3.3 kilometers long single track rock TBM tunnels at Dulles Airport and one 25-meter deep station at the airport to be constructed by NATM in sedimentary rock. The design-build project is being implemented in a Public-Private-Partnership. A joint venture of Bechtel and Washington Group International has concluded the preliminary engineering and construction is scheduled to start in late 2007.

# INTRODUCTION

The Dulles Corridor Metrorail Project will extend Washington Metropolitan Area Transit Authority's (WMATA) rail services from the Metrorail Orange Line in Fairfax County, Virginia to Route 772 near Ashburn in eastern Loudoun County, Virginia. This corridor encompasses several activity centers including Tysons Corner, Reston, Herndon, and International Airport Dulles (IAD) as well as emerging activity centers in eastern Loudoun County. The proposed project alignment within the Dulles Corridor is displayed in Figure 1.

Rapid Transit for the Dulles Corridor was initially explored in the 1950s as part of the planning process for Dulles Airport. At that time it was decided to reserve the median of the Dulles Airport Access Highway for future transit access to the airport. Preservation of this median allows the alignment to be at grade for most of its length within the corridor. Since the initial planning, the need for transit in the Dulles Corridor had been studied and although rail transit in the corridor was not part of WMATA's originally adopted rapid transit system, rapid transit service for the corridor remained a local and regional goal (Schrag, 2006).

The strong growth of the activity centers within the corridor in particular during the1990s and 2000s that continues today has led to momentum for Metrorail in the Dulles Corridor. Current and projected, regional growth data exemplify the need for rapid transit and its timely implementation (Dulles Transit Partners, 2006):

- Tysons Corner is the largest employment center in Virginia with 115,000 jobs and close to 4 million square meters of commercial space.
- Reston/Herndon is home of 70,000 jobs and 2.7 million square meters of commercial space.



Figure 1. Dulles corridor Metrorail project

- In Fairfax County employment is expected to increase 63 percent in the next 20 years.
- Loudoun County grew by 49 percent in the last 5 years and is currently the fastest growing county in the nation.
- In the last nine years traffic on the Toll Road in Loudoun County has increased from 50,000 to 90,000 cars per day.
- Dulles International Airport employs more than 19,000 people and serves 27 million passengers per year and presently is being expanded and modernized. Modernization includes a new underground automated people mover system with multiple stations at main and mid terminals.

Regional growth and progress result however in urban and social challenges:

- The Washington, DC region has the 3rd worst congestion in the US.
- The annual delay amounts to 69 hours per traveler resulting in a "congestion cost" of US\$2.5 billion per year.
- 5 of 8 main roads in the corridor will be gridlocked by 2010.

The implementation of the project began with Preliminary Engineering in 2004 under a public private partnership agreement between Virginia Department of Rail and Transportation (DRPT) and the joint venture of Bechtel and Washington Group International referred to as Dulles Transit Partners (DTP). Other funding partners in financing the project and approving the preliminary engineering effort are the Federal Transit Administration (FTA), the Metropolitan Washington Airports Authority (MWAA), County of Fairfax, Loudoun County, the towns of Reston and Herndon and WMATA as the technical reviewer who will operate the system. At the end of 2006, ownership of the project was essentially transferred from DRPT to MWAA.

The Dulles Airport extension, to be known as the Silverline once completed, will significantly increase the length of the existing Metrorail system. The original system as conceptualized in the 1960s included 166 kilometers ("103-mile system") and was designed and built between 1969 and 2001. Additions including the Largo Line were accomplished between 2001 and 2004 extending the total system length to about 171 kilometers. The planned extension to Dulles Airport and into Loudoun County when fully completed will constitute an addition of some 23% in length.

#### Table 1. Current Metrorail system

	Double Track Length (km)	Number of Stations
System wide		
Subway Tunnels Includes cut-and-cover construction	80.55	47
Surface	70.41	32
Aerial	14.84	7
Metro System (Total in 2001) Without Largo segment	165.79	84
By Jurisdiction		
District of Columbia	61.64	40
Maryland	61.55	24
Virginia	47.43	20
TOTAL Metro System With Largo segment added in 2004	170.62	86



Figure 2. Metrorail system map

# WMATA METRORAIL SYSTEM AND TUNNELING EXPERIENCE

WMATA's existing Metrorail system is displayed in Figure 2. A summary of the existing WMATA Metrorail system components is provided in Table 1 followed by a summary of WMATA's tunneling experience of the three decades between the early 1970s through the beginning of 2000. This experience summary is based on the main author's involvement in the construction of the Washington Metrorail System for 30 years where in particular he served as the WMATA Chief Civil/Structural Engineer between 1985 and 2003.

#### **Tunneling Experience**

WMATA's more than 80 Kilometers of subway construction provides many examples of tunneling methods and types of tunnel construction and displays a continuous development of tunnel design and construction methodology spanning some 30 years.

In the 1970s WMATA had employed tunneling methods nowadays considered an "old-standard." Soft ground methods involved mandatory dewatering for tunneling with open face digger shields, breasting and temporary support by steel ribs and lagging. These soft ground tunnels were designed for loading conditions assuming a load equivalent to full overburden. Consequently, the final tunnel lining was a rigid, heavily reinforced cast-in-place concrete structure with PVC waterstops in contraction joints as the only means of positive waterproofing. Such construction was used on the Inner City A-Redline, D-Orangeline, and Outer G-Blueline. During that time there are examples of utilizing cast iron bolted segmental linings with lead waterproofed joints between the liner segments. Cast iron linings were used for the Potomac River Tunnel on the C-Orangeline and the Waterfront Tunnel on the F-Greenline. Immersed ("sunken") tube construction was used across the Washington Channel leading toward the bridge across the Potomac River (L-Yellowline to Virginia).

For tunneling in rock, drill-and-blast methods were used for excavation with steel ribs and cribbing as temporary support followed by cast-in-place reinforced concrete for final tunnel support. During this period WMATA already used a modern, gripper-type rock TBM when good bedrock conditions were present, with cast-in-place reinforced concrete lining as final tunnel support. An example of such TBM tunneling is one section on the A-Redline. For the construction of a large, approximately 20-meter wide and 16-meter high mined station vault in rock, drill-and-blast methods were used for excavation. First, a pilot tunnel was employed in the crown followed by mining of a multiple drift cavern excavation. Support was by heavy rock bolting and massive steel ribs embedded in shotcrete for both temporary and permanent support. The final structure was established as an independent architectural segmental, pre-cast concrete structure erected within the mined vault. For the design of the permanent support in rock some arching effect was considered. Tunnel construction on the A-Redline under Connecticut and Wisconsin Avenues features examples of such rock tunneling to construct station vaults.

In the 1980s soft ground tunneling was accomplished using sophisticated Earth Pressure Balance Machines (EPBM) with a single pass segmental, pre-cast concrete lining with gaskets, both fabricated with tight tolerances. The tunneling was performed under the Anacostia River in adverse ground conditions with about a 3-bar hydrostatic pressure. A very successfully waterproofed tunnel was achieved largely as a result of well-designed and tight tolerances that were required for segment construction and gasket fabrication. A finger type shape, dense (closed cell), neoprene gasket was developed and tested during construction. This EPBM tunneling was used also on two different sections under M Street, namely Sections F3a and F3c on the Greenline. Even in most difficult conditions as under the Anacostia River tunneling was successfully completed with no water leaks through the joints, which are still dry after over 20 years in service. Dry tunnel conditions depended on a proper design and tight tolerances of the pre-cast concrete segmental lining and the gaskets, including appropriate testing that was explicitly specified. Successful installation of bolted segments with a hard gasket depends on having appropriate ring erection equipment and on contact grouting within the time specified to avoid squatting and misalignment (see Considerations for One-Pass Tunnel Lining Design Under High Hydrostatic Pressure). The contractor experienced difficulty in closing the rings due to lack of an erector ring offered by the machine manufacturer, however the final result thanks to every ones effort was a successfully constructed and watertight tunnel.

On other Metro sections open face TBM tunneling was utilized. On one section with a low hydrostatic pressure compressed air was employed to control ground water inflow. On another section with an open face TBM systematic dewatering was performed. Both open face TBM drives utilized a one-pass segmental, gasketed, pre-cast concrete lining which also was successfully installed and remained fairly dry after construction. After extensive material testing soft gaskets were used for these applications.

Also in the 1980s WMATA allowed new, at that time progressive, tunneling and waterproofing approaches. Consequently, in 1984 WMATA accepted the use of NATM rock tunneling proposed by the contractor in a Value Engineering Change Proposal (VECP) framework. This was the first application of a dual lining NATM system with PVC waterproofing in the US. It was utilized for running tunnels and station construction on the B-Redline to Wheaton, MD. The design considered arching of the surrounding ground and interaction between ground and the initial lining. Un-reinforced, cast-inplace concrete lining was used for final support. The design was conducted utilizing the German DIN Code, as the ACI Code had no provision in this application for plain (un-reinforced) concrete. Tunnel and station waterproofing was by an "umbrella type" PVC membrane with fully immersed sidewall drains located in the invert and on both sides of the tunnel arch. This system resulted in completely dry tunnels and station in contrast to the A-Redline rock tunnels experiencing persistent leaks. At the end of the 1980s and at the beginning of the 1990s NATM tunneling was used again, but this time in soft ground conditions for running tunnels and complicated split station vault construction at Fort Totten on the Greenline. The Fort Totten station of Section E5a was built using five different drifts. The first center drift was excavated for the installation of a column line located in the middle of the future station platform. A heavy pre-support by 25-meter long secant jet grouted piles installed from the portal wall to form a crown arch was specified. This roof pre-support was to be followed with overlapping forepoling sheets. In lieu of the jet grouted arch the contractor provided a heavy temporary portal wall and used soil stabilization by micro-fine cement grouting in combination with overlapping sheeting driven above lattice girders using a hydraulic ram. Both, the station and adjacent NATM running tunnels were fully encased by a PVC membrane for waterproofing.

Soft ground NATM tunneling was used again in the mid-1990s to create the connection to the Fort Totten Station. This involved tunneling under the historic Rock Creek Cemetery by employing dewatering from inside the tunnel using vacuum lances, since access to the cemetery was excluded for construction purposes. A grouted arch as a crown pre-support was used to control surface settlements. The grouted pipes were installed by "directional drilling" methods for approximately 250 meters under the Rock Creek Cemetery from a shaft at New Hampshire Avenue. The tunneling operation and the results were very successful, limiting surface settlements to below 1.5 cm. This section E4b was part of the Mid-City E-Greenline.

Also in the 1990s WMATA adopted a cost effective "Two-Pass" lining system for the circular soft ground tunnels excavated by the open face digger shield method introduced by contractors through a VECP on the Outer E-Greenline tunnels (Sections E6e and E8a) which were originally designed and specified for TBM tunneling with a single pass lining and for NATM mined tunneling, respectively.

The two-pass lining system consist of 1.2 meter wide and typically 23 cm thick initial pre-cast reinforced concrete lining segments that form a ring installed within the shield tail which is then shoved out of the tail. The ring is then expanded against the ground using 100-ton capacity jacks at 10 and 2 o'clock locations. After expansion is achieved, steel struts ("Dutchman") are inserted and grouted in place to form the structural initial lining ring. Once the tunnel opening was supported by the initial lining and monitoring indicated acceptable ring stability, PVC waterproofing membrane installation followed fully encasing the tunnel. Subsequently, a plain, cast-in-place final lining is installed, typically 42 cm thick.

Apart from the need for dewatering, the digger shield method also required the use of ground modification techniques such as chemical grouting applied systematically from the surface prior to tunneling. Examples are the 14th Street tunnels and the under/over tunnels at Park Road, both part of the Mid-City E-Greenline in Washington, DC. Construction of these tunnels started in 1994. The roughly 35 meter deep under/over tunnels were first partially dewatered following the owner's designed drawdown system using deep wells. This system was only partially effective above the tunnel invert and was followed by an extensive chemical grouting program using sodium silicate to stabilize mainly sandy ground that existed across the tunnel profile and above the tunnels. Following this grouting program, although costly, tunneling was accomplished very successfully in this urban setting.

The design of the two-pass lining system utilizing an expanded pre-cast initial liner in soft ground at that time generally assumed the initial liner to be sacrificial or "throwaway" and temporary in nature. However, WMATA changed the design philosophy and accounted for the structural capacity of the initial lining in the design of the final lining support system. The premise for this assumption and adaptation of design philosophy was that the initial support created a solid, closed concrete ring. This consequently excluded the use of wooden wedges between segments. Further, the pre-cast lining was required to be fully stabilized before the final concrete lining was cast in place. The final liner was designed taking the combined support of both liners into consideration. Using soil-structure interaction and assuming flexibility of the initial lining the liners were designed for "Short Term Loading" and all WMATA loading combinations including full hydrostatic pressure acting on the final lining for "Long Term Loading." Using these assumptions the initial pre-cast and the final cast-in-place linings share the longterm loading combination. This allowed the use of an un-reinforced, cast-in-place final concrete lining. For the initial liner segments installed as expanded rings, success depended upon dewatering, chemical pre-grouting, and immediate expansion by jacking of the segments against the ground.

Depending on the nature of the soils, the ground water level and the difficulty in dewatering, such as from aquifers of artesian nature, it was necessary to use EPBM technology again. In such instance the initial liner was of a non-expansion type, consisting of lightly bolted segments similar to those in single-pass installations but with temporary, soft gaskets designed for partially dewatered conditions. Upon initial lining installation, a PVC waterproofing system was installed followed by an un-reinforced cast-in-place concrete lining. This method was referred to as "Modified Two-Pass" system. Such systems were used on the Outer F-Greenline, Sections F6a and F6c at Suitland Parkway Line to Branch Avenue. Here, the two-pass lining system was used for the first time with the EPBM tunneling method on the WMATA system. In this application the usual rings of four (4) reinforced concrete segments with a key segment are only lightly bolted in the longitudinal joints. Sponge type gaskets in joints and the initial liner are designed for temporary hydrostatic pressure as the final waterproofing is achieved by the PVC membrane installed around the entire lining circumference. This system is obviously more costly, but was necessary to overcome the most adverse ground and water conditions where full dewatering was not allowed due to environmental concerns. For the initial lining installation success depended upon water control, proper erection systems, and accomplishing contact grouting immediately behind a sealed tail of the TBM shield (Rudolf, 1997).

# Considerations for One-Pass Tunnel Lining Design Under High Hydrostatic Pressure

From the lessons learned on the WMATA system in the past three decades a number of important considerations for the design of one-pass tunnel linings for soft ground under high hydrostatic pressure can be derived. These are equally applicable to designbid-build and design-build type project delivery methods and applicable regardless whether the specifications are of a method or performance type and summarized below.

Segment Considerations. Apart from proper selection of segment geometry with regard to the shape (rectangular or trapezoidal), the number of segments in a ring with key segments at crown level, tapering and thickness, adequate strength for ground and construction loadings leading to segment thickness and being able to accommodate gasket pockets, grooves, bolts and packing materials it is important to:

- Specify tight tolerances for segments and very tight tolerances for gasket pockets. The British Tunneling Society's recommendations for tolerances for the fabrications of special segments are suggested (British Tunneling Society, 2000).
- For pre-cast concrete segments specify high strength and high performance concrete, typically 42 MPa (6,000 psi) to 50 MPa (7,000 psi) concrete reinforced to withstand temporary and long-term loadings and appropriate loading combinations depending on type of soil and overburden as well as construction loading from longitudinal and circumferential forces including handling and bolting.
- To assure a high quality product and the tunnel's longevity all aspects of the fabrication and installation must be rigorously controlled prior to and during construction.

# **Gaskets and Packing Considerations**

- Select a high quality gasket material with high permanent resilience (stress relaxation) and specify a thorough material testing. Note that the "finger shaped," closed cell-hard 17/8" wide neoprene gasket and 30-mil neoprene pack-ing on each segment are still performing well in the Anacostia River Tunnel, although the industry nowadays prefers EPDM materials.
- Specify minimum gasket width considering possible segment offset due to installation. A width of 45 millimeters (1¾") is preferred for a 13 millimeter (0.5") offset. To prevent overfill specify that for any condition the total cross sectional area of a "hard" gasket shall not exceed 95% of the total area of the pocket between segments, calculated when the faces of the segments (including the neoprene packers) are in a full contact.
- Specify a Minimum Working Pressure (hydrostatic pressure × safety factor) and a Maximum Pressure to fully compress the gasket in the confined pocket. For the Anacostia River Tunnel the working pressure was 1.4 MPa (200 psi) and the maximum pressure was 2.8 MPa (400 psi).

## Liner and Gasket System Testing

- Specify Stability Testing for water tightness to withstand the minimum working pressure without leaks.
- Specify Load Deflection Testing to measure force closure required to fully compress the gasket confined in the pocket.

Note that prior to the design of the first single-pass WMATA tunnel with reinforced concrete pre-cast segmental tunnel linings an extensive testing of segments for strength in conjunction with the gaskets was performed by Prof. S.L. Paul for WMATA's General Engineering Consultant, DeLeuw, Cather and Company (Paul, 1978 and 1984).

It is recommended that a few gaskets be pre-fabricated to the detailed dimensions with minimum and maximum tolerances. Both types should be tested in the specified pockets (between steel plates separated by packing). This should be done in a laboratory environment similar to the Stress Relaxation Test. These requirements should be specified to verify minimum and maximum compression pressures.

These tests carried out in a laboratory environment should determine the maximum and minimum pressures obtained for the extreme values of specified tolerances so they are not exceeded in either direction. The larger gasket, i.e., maximum tolerance, should be placed in the smallest pocket with the minimum tolerance and load tested by a Load Deflection Test to verify the maximum pressure at closure. The gasket with the minimum tolerance shall be placed in the largest pocket with the maximum tolerance and tested for leakage by a Leak Test performed by squeezing to closure at the minimum pressure specified. This test shall include the compression packing material. This test should further consider an offset of 10 millimeters (0.4") to 13 millimeters (0.5") in horizontal direction.

# **Erection of Ring and Segment Bolting Considerations**

The lining erector shall be composed of a full erector ring and erector arm capable of squeezing the gaskets with a packer in the gap between segment faces without fully relying on bolts. The segments and erection ring and erection arm must be compatible with the TBM and the liner system to ensure safe and efficient segment installation and ring closing.

## **Contact Grouting Considerations**

- Require immediate grouting behind the wire brush seal in the shield tail.
- Require grout sufficiently stiff to provide immediate passive reaction to limit liner ring squatting.
- Require full grouting of each ring after ejection from the shield tail before the next excavation cycle begins.
- Specify the allowed over excavation and maximum annular space between the outside surface of the segments and the excavated ground surface.

## **Other Considerations**

- Require the contractor to lay out corrective methods due to misalignment which would involve bolting to the adjacent ring.
- Specify the allowed over excavation and maximum annular space between the outside surface of the segments and the excavated ground surface.
- Require a jacking ring or shoes with pads that will equally distribute the jacking force to the liner.
- Specify the maximum jacking force that can be applied to the liner without damaging it.
- Specify requirements for installation and instrumentation and monitoring.

These considerations and suggested requirements are to ensure that the contractor can achieve the specified structural performance of the tunnel over its design life and beyond and in particular its water tightness without costly changes during construction and/or costly repairs and post construction grouting to restore the tunnel water tightness. These also facilitate use of adequate construction techniques to prevent excessive ground loosening, development of voids, inadequate backfill grouting, and excessive liner distortion. Construction methods must facilitate a quick development of a passive reaction with the ground to limit displacement as otherwise the liner can distort beyond the design limit (Kaneshiro & Navin, 1996).

# **DULLES CORRIDOR METRORAIL PROJECT**

The roughly 37 kilometers long guideway alignment will be constructed in two phases. The Phase I segment is 19 kilometers long and involves five stations (two at grade and three elevated) and is scheduled to be operational by 2012. Phase II will extend rail to Dulles International Airport and beyond to a terminus station in Ashburn, Virginia. This alignment is mainly located at grade and on aerial structures within the median of the Dulles Access Road and the Greenway, a six lane highway. The airport area alignment segment and the metro station in front of the Airport Terminal will run deep underground in fairly competent rock conditions and will be constructed using TBM tunneling and NATM station mining. This second Phase is scheduled for completion in 2015. This description concentrates on the tunneling aspects of the project at Tysons Corner (Phase I) and at Dulles Airport (Phase II). The preliminary engineering of Phase I essentially followed the general plans of the Locally Preferred Alternative (LPA) selected by WMATA and approved by other Agencies out of many alternate alignments studied including a long tunnel at Tysons Corner with underground stations. The LPA as portrayed in the approved Final Environmental Impact Statement (FEIS) is designed mainly as an aerial guideway with a short tunnel through Tysons Corner.

Late in the preliminary engineering of Phase I WMATA, in conjunction with a Spanish contractor and an Austrian design group strongly supported by a local developer, proposed an all-underground option for the roughly 6.0 kilometers long segment at Tysons Corner. The envisioned tunnel would have been a large bore, 12 meter diameter or more TBM driven tunnel to accommodate two over/under tracks and stacked station platforms. It was based on a deep tunneling experience gained at the Barcelona Light Rail system recently constructed (Della Valle, 2002 and 2005). Despite support of an underground option by many parties involved, its realization was found to cost from US\$250 to over \$800 million more, based on various estimates, than the mostly elevated and partially at-grade alignment including the 700 meter long twin single track NATM soft ground tunnels. In reality, the large bore is four times larger in volume than one single track tunnel and two times larger than two single track Metro tunnels. There would be even a higher factor than two when comparing the concrete volume installed in the large bore vs. two single track tunnels. The large bore presents more risk than the excavation of two significantly smaller single bores, particularly when driven through mixed ground conditions with shallow soft ground cover. At several locations the proposed alignment indicated less than 1/2 tunnel diameter of mainly weak soil or fill cover. With the large bore extensive and deep excavations still would be needed for station entrances, ventilation and emergency access/egress. The large tunnel bore alone would have required handling of approximately 2.2 million cubic yards of excavated material. These facts indicate the trend towards much higher cost of the tunnel, which would be difficult to compare with an aerial and at-grade alignment.

Furthermore the large diameter tunnel option proposed throughout the entire Tysons Corner segment would have significantly deviated from the NEPA selected and approved alignment as portrayed in the FEIS and the preliminary engineering documents. This new tunnel concept would have therefore involved another environmental approval process, and additional geotechnical studies to be followed by a new preliminary engineering. This in turn would have resulted in a project delay of some 2.5 to 3 years. The additional projected cost for the tunnel alternative would have practically led to the loss of funding by the Federal Transit Administration (FTA) and substantially delayed the project. These factors and the fact that traffic congestion relief would have been postponed by another up to three years made the decision to move forward on the all-tunnel scheme very problematic. Supported by federal officials and local congressmen Virginia's Governor Timothy M. Kaine reaffirmed the Commonwealth's

selection of the aerial alignments through Tysons (MacGillis, 2006), and DTP resumed design work on the original Phase 1 project alignment.

#### Soft Ground NATM Tunneling for Phase I

The mined tunnel segment includes twin single track NATM tunnels at a length of 700 meters each and an emergency cross-passage. Short cut-and-cover sections will be utilized at the portals. These tunnels will be constructed in soft ground and will be located adjacent to existing structures and utilities that are sensitive to ground movements.

The soils encountered 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 and clays, and silty fine sands. According to project classification the residual soils are identified as Stratum S which can be divided into two substrata based on the consistency and the degree of weathering. The upper substratum, S1, typically exhibits lower N-values (averaging 16 bpf or less) and has higher fines content. Typical USCS classifications are ML, CL, and/or SM. Within the tunnel alignment, the thickness of substratum S1 varies considerably, from 0-2 feet to almost 30 feet. The lower substratum, S2, is similar to S1, but typically exhibits higher N-values (averaging 16 bph or greater) and is made up of more granular particles. Its thickness within the tunnel alignment ranges from 4 feet to 60 feet. Substrata S1 and S2 will be the predominant soil types encountered during tunnel construction with tunneling within the S1 stratum mainly near the portals and stratum S2 where the tunnel is located deeper in the mid portion of the alignment. 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 blow counts with N-values between 60 bpf and 100 bpf. Ground water at portal locations is generally at invert elevation, in mid-point of the tunnel alignment it rises up to the tunnel spring line.

Prominent building and infrastructure elements located in the tunnel's vicinity include an underground parking garage at a distance of some 8 meters from the outbound tunnel wall and bridge piers of the Route 123/Route 7 overpass, at a clear distance of approximately 15 meters from the inbound tunnel, as well as International Drive, a six-lane divided highway located about 4.5 meters above the future tunnel crowns. Deepest overburden cover exists at about mid-point of the alignment with nearly 12 meters. At the west portal and in the center of Route 7 the overburden cover is just 4 meters. A section indicating geology, arrangement of tunnels near the parking garage and local roadway is shown in Figure 3.

Because of the shallow depth, the prevailing soft ground conditions, the relatively short tunnel length, and the need to control settlements the NATM has been chosen as the preferred tunneling method. To enhance stand-up time of the soils and minimize settlements a single row of a grouted pipe arch umbrella will be utilized for the entire length of the tunnels. 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 150 mm diameter sleeved steel pipes (tube-a-manchette) will be used on the first 100 meter length at both portals where tunneling is shallow with less overburden. The pipes will be installed at 30-cm centers around the tunnel crown. Figure 4 displays the double row pipe arch umbrella above a typical single track NATM tunnel with shotcrete initial lining, closed PVC membrane waterproofing system and a cast-in-place concrete final lining.



Figure 3. Arrangement of soft ground NATM tunnels



Figure 4. NATM tunnel with pipe arch pre-support

## **Rock TBM and NATM Tunneling for Phase II**

The underground segment of Phase II lies within Dulles International Airport property with the metro station referred to as Dulles Airport Station just north and in front of the main terminal. The main terminal has considerable traffic and existing infrastructure with much of the project area having a high concentration of existing utilities. The underground structures include twin single-track TBM tunnels, emergency cross passages, shafts and two mined caverns for the Dulles Airport underground station. These underground openings will be located below existing structures and utilities that are sensitive to ground movements. The host geologic formation for tunneling will be generally competent bedrock whereas the over burden includes fill, residual soils, and decomposed rock.

The principal bedrock unit at the project site is the Balls Bluff Formation, which generally consists of interbedded mudstone and siltstone with lesser amounts of claystone and sandstone. These lithologies are described as micaceous or calcareous, with varying degrees of weathering and alteration. Where present, the bedding of this



Figure 5. Typical TBM tunnel section

formation is generally well developed, ranging from laminar (beds less than 15 mm thick) to medium bedded (beds from 20 cm to 60 cm thick).

The bedrock is occasionally to moderately jointed and the prevailing bedding planes dip at an angle of about 15° to 30° to predominantly the west. Occasional zones of highly fractured rock intercept the rock mass. While the siltstone bedrock represents a favorable tunneling medium for both TBM and road header excavation ground control and support measures have to account for the jointing and bedding planes that, if left unsupported, may develop blocks and wedges with the tendency to fall-out or slide into the excavation.

The TBM tunnels have an approximately 6 meter outside diameter and are about 3.3 kilometers long each. The tunnels will be constructed by either a shielded rock TBM using a single pass, pre-cast concrete, gasketed lining or a rock gripper type TBM with an initial rock support followed by installation of a PVC membrane waterproofing and a final cast-in-place concrete lining. Figure 5 displays a typical, single pass lining cross section for the TBM tunneling.

The mined portions of Dulles Airport Station will be constructed using NATM techniques with excavation to be carried out by road headers. Initial support will consist of rock reinforcement and shotcrete lining. All mined station and associated structures will be waterproofed using an open, "umbrella type" waterproofing system with sidewall drain pipes. The station platform is about 25 meters below the ground surface. To allow for a twin station tunnel configuration, where there are two parallel station vaults, the centerline track-to-track distance is 28 meters. Both station platform tunnels are 183 meters (600 feet) long and unobstructed by vertical circulation. The station platforms are connected with cross-passages between the station tunnels. Access to the platforms is provided by a central access structure located between the two station vaults. Figure 6 displays a typical station tunnel configuration at the central cross passage with 5.2 meters wide platforms.

All station construction will be mined except for the mezzanine and ancillary rooms, which will be constructed using cut-and-cover techniques. Mined station construction has been selected to minimize disruption to airport activities. Surface disruptions will therefore generally be limited to Mezzanine and ancillary room construction using shallow (±8 meters) cut-and-cover excavation while maintaining airport pedestrian circulation above, except for the time period when the mezzanine box will be connected to an existing pedestrian tunnel "Node" that will provide Metrorail



Figure 6. Station typical structural cross section



Figure 7. Dulles Airport Metrorail station at Dulles International Airport

Station access. Figure 7 displays a composite section of the main terminal, walkways and Metrorail underground station.

An architectural rendering for the station tunnel configuration is shown in Figure 8. Figure 9 displays the underground alignment at Dulles Airport.

## IMPLEMENTATION

## Public Private Partnership (PPP)

The project is being implemented in a Public-Private-Partnership under the Public Private Transportation Act (PPTA) an innovative project delivery framework as established by the Virginia Department of Transportation (VDOT) in 1995. Its implementation is in accordance with the guidelines as amended by the General Assembly in 2005 (The Commonwealth of Virginia, 2005). The essential goals of the PPTA are to encourage investment in the Commonwealth by creating a more stable investment climate and increasing transparency in a competitive environment and public involvement in the procurement process. According to the guidelines the private entity charged with project implementation is required to provide certain commitments or guarantees and enters into a negotiated risk sharing. Development of the Dulles Corridor Rapid Transit Project is an example of a PPP, where a private consortium facilitates public financing for the project and provides its full development in exchange for a negotiated Design-Build contract of the facilities. Per the terms and conditions of the comprehensive agreement, a firm fixed price (FFP) for construction is submitted to the client. This FFP is a detailed (bottom-up contractor's estimate) Design-Build proposal, which is then



Figure 8. Station tunnel rendering (by diDomenico+Partners, architectural design consultant)



Figure 9. Underground alignment at Dulles International Airport

negotiated on an open book basis before Final Design and Construction starts. (Martinez, 2006).

## **Design and Construction**

The project is being realized under a design-build contract. The proposed designbuilder, Dulles Transit Partners is required to initially develop preliminary engineering for the rail project. The cost for the preliminary engineering is shared between the design-builder and the project partners, DRPT, FTA, MWAA and the counties of Fairfax and Loudoun. The preliminary engineering then forms the basis to develop a fixed firm price by the design-builder. To maintain previously established budget limits this results in design challenges and the need to optimize design and construction methods to build to budget. Consequently, many design iterations are required during preliminary engineering. The design and construction team constantly weighs the benefits of underground space to keep everyday routines undisrupted versus its increased cost when compared to at grade and above ground construction.

Value Planning (VP) and Value Engineering (VE) exercises are a central activity of the design development in pursuit of the most economical approach with least impact

on the surroundings. In Phase I these exercises led to a series of transformations of the underground segment at Tysons Corner. This alignment was initially envisioned as a deep, 1.6-kilometer long twin TBM tunnel scheme in mixed ground conditions with high hydrostatic head and a roughly 24 meter deep underground station constructed by cut-and-cover methods within the Route 7 road lanes, a busy traffic artery. As a result of Fairfax County requirements the alignment was moved to the median of Route 7. During the cost reduction process that was mandated by the client a rigorous analysis of construction cost on alternate alignments was performed. This analysis favored the implementation of the short NATM tunnels with a quasi at-grade station within the median of Route 7 at a cost saving of roughly US\$200 million. In Phase II the VP exercises led to selection of a deep TBM tunneling and NATM station construction in rock instead of a cut-and-cover excavation for station and running tunnel construction originally depicted in the FEIS. Since the rock formation at the Airport is close to the surface this selection resulted in considerable cost and schedule savings. This construction will also considerably reduce impacts on the Airport operation. VE exercises, which are to follow, will search for further cost reductions; if successful these will become a new basis for construction.

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