Pre-Support Measures for Shallow NATM Tunneling in Urban Settings

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ABSTRACT: Pre-support measures for urban tunneling have seen a substantial development in the recent past. Ground improvement techniques, pipe-arch and spiling methods now allow for non-disruptive tunneling at very shallow depths under sensitive structures, rail tracks and roadways. The paper presents experience gained on national and international projects built over the past decade that represent case histories and therefore may be used as guidance for the development of similar solutions for future tunneling projects at shallow depths. Reference projects include tunnels for the Washington, DC Metro, London Underground, Dulles International Airport, Busway tunnels in Boston and the Ft. Canning Tunnel in Singapore.

INTRODUCTION

Construction of underground space in urban settings is nowadays more frequently faced with the need to avoid disruption to the surface activities. This requirement often contrasts the need to situate the underground structure at shallow depth to limit vertical circulation lengths. This is true for both vehicular and mass transit schemes. The underground construction industry has reacted to this situation by refining ground improvement methods, pre-support methods and tunneling techniques. Ground improvement including jet grouting, ground freezing, and pipe arch pre-support systems are nowadays frequently applied. Compensation grouting for settlement mitigation often complements settlement limiting tunneling methods. At the same time NATM tunneling has proven its place as a tunneling method with unsurpassed flexibility in adaptation to ground conditions and geometry. For example the integral support element shotcrete has seen advances in the areas of material quality in terms of homogeneity of the lining shell and ability to achieve a very high early strength by means of additives (Zeidler et al., 2007). Due to the fact that more and more tunnels are built using this method more experience has been gained and skill of those carrying out the actual work has been increased.

The paper selects six NATM tunneling projects that have been successfully carried out over the past decade, are currently in construction or in the planning stage to demonstrate application of pre-support measures for shallow NATM tunneling.

PRE-SUPPORT FOR SHALLOW NATM TUNNELING—SELECTED CASE HISTORIES

NATM Tunneling for the Dulles Metrorail Corridor Project

The Dulles Corridor Metro Rail Project will build a roughly 11 mile long extension from a point on the existing Orange Line to Wiehle Avenue near Reston in Northern Virginia. The project is described in detail by Rudolf et al. (2007). The alignment is generally at grade or elevated at Tysons Corner, in McLean, Virginia. Only at a location near the Route 123 / Route 7 interchange it has to pass through a local rise. Just east of the rise it is elevated and to the west it is at grade. Consequently tunneling through the rise has to occur at a very shallow depth. The tunnel segment includes mined twin single-track NATM tunnels at a length of approximately 520 meters (1,700 feet) each. These tunnels will be constructed in soft ground and will be located adjacent to existing structures and utilities that are sensitive to ground movements and under International Drive a six-lane divided highway located about 4.6 meters (15 feet) above the future tunnel crowns. The soils encountered along the tunnel alignment include mainly residual soils and soil like, completely decomposed rock. The residual soils are typically fine sandy silts and clays, and silty fine sands and grouped into what is referred to as Stratum S. This is divided into two substrata based on the consistency and the degree of weathering. The upper

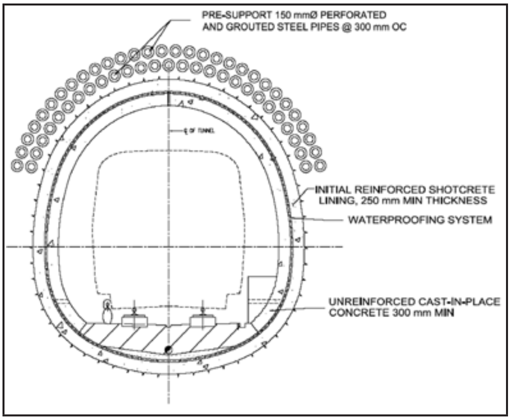


Figure 1. Double pipe arch pre-support for shallow tunneling at International Drive

substratum, S1, typically exhibits lower N-values (averaging 16 bpf or less) and has higher fines content. The lower substratum, S2, is similar to S1, but typically exhibits higher N-values (averaging 16 bpf or greater) and is made up of more granular particles. 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. Ground water at portal locations is generally at or below invert elevation and in mid-point of the tunnel alignment it rises up to the tunnel spring line. Maximum overburden cover exists at about mid-point of the alignment with nearly 12 meters (38 feet). At the west portal and the transition to the cut-and-cover box the overburden is about 6 meters (20 feet).

Because of the shallow depth, the prevailing soft ground conditions, and the need to control settlements NATM tunneling will be under the protection of a single row of a grouted pipe arch umbrella for the entire length of the tunnels. This is viewed sufficient for pre-support where the overburden is greater and surface structures are less sensitive. However an additional row of pipe arch umbrellas, using closely spaced approximately 114 mm (4.5 inch) diameter grouted steel pipes will be used on the first 90 meters (300 feet) length at the east portal where tunneling is shallow with some 4.6 meters (15 feet) of overburden and under International Drive. The pipes will be installed at 300 mm (one foot) centers around the tunnel crown. Figure 1 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.

During preliminary engineering the NATM tunnels initially continued for about another 120 meters

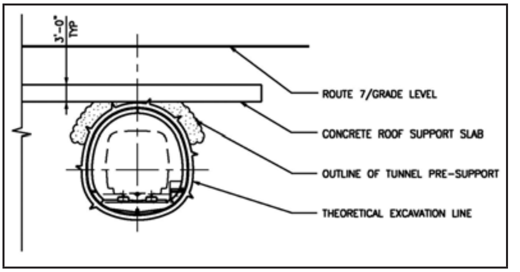


Figure 2. Top-down slab tunnel pre-support concept for shallow tunneling

(400 feet) to the west and under very shallow overburden of some 3 meters (10 feet) underneath State Route 7 and pre-support for this very shallow tunneling was foreseen to be by a double pipe arch canopy as shown for the International Drive in Figure 1. Risk concerns by the pre-selected tunneling contractor and the project insurer led to consideration of a top-down type pre-support installation for NATM tunneling. The envisioned concept using a concrete slab constructed by cut-and-cover methods prior to tunneling is shown schematically in Figure 2. Installation for this slab however, posed traffic maintenance problems that could not be resolved to the satisfaction of the Virginia Department of Transportation. This fact and tunneling cost considerations led to the implementation of two single track cut-and-cover tunnels that replaced the NATM tunneling at the western end of the tunnel alignment. The transition from cut-and-cover tunneling to mined tunneling occurs at a depth where the overburden is about one tunnel diameter and mined tunneling is more economical than cut-and-cover construction.

The project alignment that involves the shallow tunneling described above is a result of many alignment considerations that involved various tunneling technologies including large bore tunneling, single-track EPBM tunnels, use of NATM, and cut-and-cover construction. It proved that the alignment chosen with the short NATM tunnels represented the most feasible and economic configuration. A number of ground improvement methods were considered for the NATM tunneling including jet grouting, permeation grouting, and utilization of pipe arch canopies installed by directional drilling. Based on ground conditions, ability not to disrupt surface activities and utilities at all the pipe arch canopy that will be installed in short segments of lengths not to exceed 18 meters (60 feet) and overlapping by not less than 4.6 meters (15 feet) has become the method of choice. Tunneling will be by top-heading and bench / invert sequences not to exceed 0.9 meter (3.0 feet) rounds in the top heading and 1.8 meters (6.0 feet) rounds in bench / invert with fast ring closure.

London's Victoria Underground Station Upgrade

At the crossing point of two underground lines, the Victoria Line, the District & Circle Line and a railway at grade, three busy stations are in operation. The Victoria Railway Station opened in 1862 followed by the opening of the first underground station for the Metropolitan District Railway in 1868 (in 1949 the Circle Line was added to this station). The underground station was built in the Terrace Gravels and Alluvium deposits using cut-and-cover techniques and a brick lining. In 1968, a new underground station at a deeper level was opened then forming the terminus of the Victoria Line, which was extended further at a later stage. The low level station was entirely built in London Clay using open face shields, hand excavation and cast iron segmental linings. The connection tunnels to the existing stations were constructed in gravels using timber breasting, cast iron segmental lining and hand excavation.

Used by over 75 million passengers every year combined with the need for modernized interchange facilities between the three stations, frequent severe congestion problems are battering the station scheme. London Underground Ltd. (LUL) decided to initiate a major upgrade program. This program will entail, among others, a series of new passenger underground connection tunnels, new escalators and lifts for passengers with limited mobility as well as a ticket hall extension in the south and a new northern ticket hall. The majority of the new connection tunnels is planned to be mined using sprayed concrete lining (SCL, commonly referred to as NATM) techniques. The ticket halls will be built using cut-and-cover techniques. The new passenger transfer tunnels and escalators will provide improved interchange services between the underground lines and the railway and bus lines at the surface. The program is estimated to cost on the order of US$ 1 billion. The new scheme is currently in its detailed design stage and is expected to be operational by 2013.

The area around Victoria Station is very busy with traffic at the surface and features numerous historic and modern buildings (Figure 3). The sub-surface environment is crowded with structures of the existing underground lines, basements, building foundations and utilities. Any new underground structure must avoid these existing facilities. Alignment options deeper than the deep level Victoria Line station were ruled out for passenger flow and evacuation reasons. It was decided to locate the majority of new tunnels in the Thames Gravels at shallow depths above the existing Victoria Line underground station. The deepest part of the tunnels will intersect London Clay. Only the new escalator tunnel that will lead down into the existing deep level Victoria Line Station will be excavated in the more competent London Clay in its deeper sections.

Figure 3. Congested surface area in front of Victoria Station above one of the planned passenger tunnels

Locating the new tunnels in the non-cohesive Thames Gravels at shallow depths below existing foundations, streets and utilities poses a series of challenges. The Thames Gravel, which consists of gravels with varying, but generally high sand content needs to be improved prior to tunnel construction. The groundwater table is generally at about springline elevation of the planned tunnels. However, frequent utility leakage will potentially lead to locally higher groundwater elevations and increased inflow into the tunnel when under construction. The goal of the ground improvement is to introduce cohesion for sufficient stand-up time of the ground as well as to prevent the groundwater from flowing into the tunnel during excavation.

In view of the limited groutability of the Terrace Gravels due to their generally high sand contents in the project area, permeation grouting was ruled out, because it was viewed as not sufficiently reliable for the intended purpose. Two collapses occurred during underground construction works in the project area in the late 1960s that had used permeation grouting techniques. These incidents contributed to the decision to rule out permeation grouting as prime means of ground improvement.

Jet grouting from the surface was therefore selected as the prime means to achieve a reliable pre-stabilization of the soils. It is currently planned to install jet grout columns vertically or at angles from the street surface avoiding utilities and foundations. For concealed areas with limited or no surface access, alternative ground improvement methods such as ground freezing and chemical grouting are currently being investigated.

The treated area shall form a minimum of 2 meter (6.5 feet) thick layer of improved soil around the tunnel roof and sidewalls and tie approximately 1 meter (3.3 feet) into the London Clay. Compressive strengths of 1 to 2 MPa (145 to 290 psi) and permeabilities in the order of 10^{-7} m/sec shall be achieved within the treated soil area. Jet grouting will be particularly challenging in the vicinity of the numerous utilities. Minimum clearance requirements imposed by the utility owners as well as high concentration of utilities in locations will require intensive work preparations and may lead to localized lower qualities of the treated ground. With the soil sufficiently 'cemented,' the tunnel construction could be carried out without further improvements. However, past experience showed that pockets of fines (silt or clay) can lead to imperfections in the jet-grouted soil that may result in increased groundwater inflow and instabilities.

Taking into account the reported presence of such pockets, the shallowness of the tunnels and the presence of sensitive utilities and foundations above or adjacent to the alignment, it was decided to enhance the ground pre-stabilization by the systematic application of grouted steel pipe arches. 15 meter (60 feet) long, grouted steel pipe arches will be installed into the treated ground above the tunnels over their entire length. Installing the steel pipes will also provide important information on the ground conditions ahead of the tunnel excavation. Systematic grouting of the steel pipes will facilitate the treatment of any imperfections in the jet-grouted soil above the tunnel roof and shoulders and yield proper bond between the steel pipes and the ground. In addition, it is expected that the grouted steel pipe arch will contribute to limiting the ground movements and hence settlements of any utilities or foundations above the tunnel alignment.

Excavation of the tunnels below the pipe arch pre-support will be carried out in a top heading and bench/invert sequence with the 200 to 300 mm (8 to 12 inch) thick shotcrete initial lining being installed immediately after excavation of each maximum 1 meter (3 feet-4 inch) long increment. The invert closure follows in a short distance behind the top heading. In specific situations, a temporary top heading invert will be installed to allow completion of the top heading over the entire length of a tunnel section before the final invert closure will be provided. The example shown in Figure 4 depicts the construction of an escalator machine room where space constraints require a locally limited flattened invert.

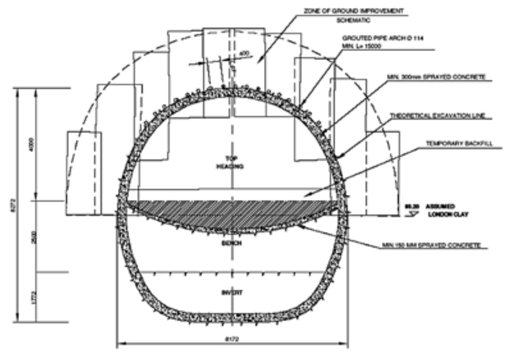


Figure 4. Schematic excavation cross section with secant jet grout columns and grouted steel pipe arch

King's Cross Redevelopment

The first underground station at King's Cross opened in 1863 followed by two more underground stations in 1907 and 1968. These stations currently serve three underground lines (Northern Line, Piccadilly Line and Victoria Line). The District, Circle and Hammersmith & City Line underground station is located slightly offset under the St. Pancras Station. King's Cross and St. Pancras Station is a busy interchange point between the London underground lines and two at-grade railway stations being frequented by about 71.5 million passengers every year. With the new terminal for the Channel Tunnel Rail Link, a significant increase of this number is expected. Due to severe station congestion problems, London Underground Ltd. decided to initiate a redevelopment program for the Victoria, Northern, and Piccadilly Line stations.

The King's Cross Station Redevelopment, Phase 2 includes the construction of a series of new passenger tunnels to improve the station's capacity and safety features. The new tunnels will provide passengers with improved facilities to connect between the existing Victoria (VLA), Piccadilly (PLA) and Northern (NLA) underground lines as well as the railway terminals of the new Channel Tunnel Rail Link (St. Pancras) and King's Cross Station. The new PLA comprises a high level passageway tunnel, upper concourse tunnel, an inclined escalator tunnel to the existing Piccadilly Line platform tunnels, a lower concourse tunnel, new cross passages and a temporary passageway tunnel and a MIP lift shaft. The new NLA comprises two inclined escalator tunnels, a passageway tunnel and a MIP lift shaft. The new VLA includes staircase and access tunnels and a shaft that houses a lift for passengers with limited mobility and parts of the staircase. Figure 5 shows project elements and plan view of the King's Cross Station and Figure 6 displays a longitudinal section underneath the train shed.

After many years of design development and safety considerations, the owner decided to construct the tunnels using sprayed concrete lining (SCL) commonly referred to as NATM for the initial tunnel support and segmental cast iron (SGI) rings for the secondary tunnel lining. The tunnel construction work for the upgrade program is currently underway and expected to be completed by mid 2009.

The majority of the new tunnels for the Piccadilly Line Access are located below the train shed of the King's Cross Train Station (Figure 6) under a ground cover of approximately 12 meters (40 feet) to 20 meters (66 feet). The Northern Line Access tunnels lead under an existing hotel complex (The

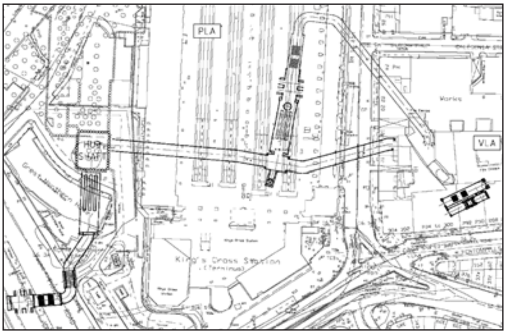


Figure 5. Plan view of the King's Cross station project

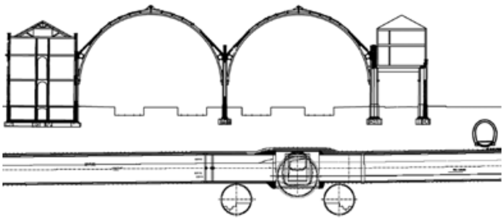


Figure 6. Longitudinal section underneath the King's Cross train shed

Great Northern) with a minimum vertical clearance between the foundations and tunnel crown of only 2 meters (6.6 feet). The Victoria Line Access tunnels are at approximately similar depths as the Piccadilly Line Access tunnels.

Most of the tunneling is in London Clay with made ground located just above the London Clay. Only in the deeper sections, the sediments of the Lambeth Beds that are over-consolidated clays with the potential for the presence of water bearing sand lenses were intersected.

The Contractor opted to use the LaserShell™ Method to construct the tunnels using NATM for the initial support. All tunnels are excavated and supported in a sequential construction approach. For tunnels larger than 5 meters (16 feet) in diameter, a pilot tunnel is constructed from which the enlargement to the full section size progresses. The pilot tunnels are constructed in the roof area of the future tunnel such that they slightly reach beyond the future tunnel roof. This additional headroom is used to install a reinforced, sprayed concrete roof beam that provides head protection during the enlargement operation. During the subsequent step, the pilot tunnel is enlarged to top heading size of the full tunnel profile. For tunnels larger than 6 meters (20 feet) diameter, a temporary invert is installed after the enlargement to top heading size ("Cod's Mouth,"

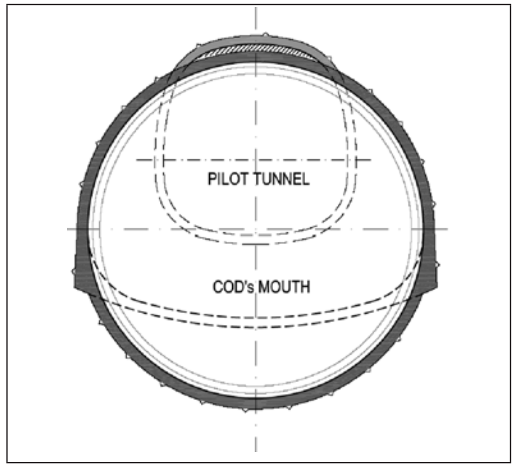


Figure 7. Tunnel cross section with pilot tunnel and "Cod's Mouth" profile

Figure 7). Subsequently, the bench and invert of the final tunnel cross section is excavated and supported. A short ring closure distance is an integral part of the design, whether it is provided by the temporary top heading or by the final tunnel invert. Steel fiber reinforced shotcrete is used for the initial support lining (Zeidler et al., 2007).

The SGI final lining is installed inside the completed shotcrete tunnel at a practical distance from the construction face. The annular gap between the shotcrete lining and SGI rings is grouted.

To protect the railway station and hotel structure above the various tunnels for the new Piccadilly Line Access, a compensation grouting system was installed that allows the neutralization of undue ground settlements caused by tunneling. Three rows of heavy gage steel pipes were installed in the area of compensation grouting. The upper and lower rows are passive rows providing stiffening of the ground and additional means for ground conditioning.

As part of the access tunnel works for the Northern Line construction of a 9 meter (30 feet) diameter escalator shaft beneath the existing historic Great Northern Hotel is required with minimum clearance between the buildings foundations and the tunnel roof. In order to protect the hotel structure from undue settlements a compensation grouting array was installed between the tunnel roof and the building foundation (Figure 8).

For the crossing underneath an existing brick railway tunnel (Maidenlane Tunnel) with a very shallow cover of only 1 meter (3.3 feet), a grouted steel pipe arch was installed (Figure 9). There was concern that there may be loosened soil or poorly compacted backfill underneath the invert of the brick structure. This grouted pipe arch offers soil improvement and

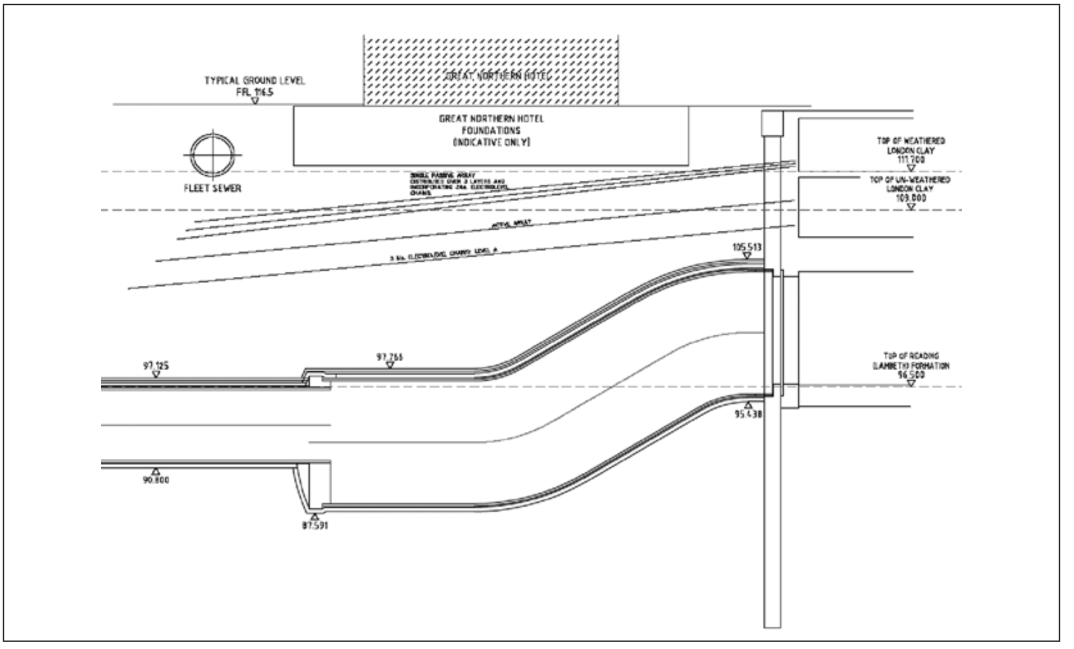


Figure 8. Longitudinal section with compensation grouting pipes at NLA

Figure 9. Grouted steel pipe arch installed underneath the Maidenlane Tunnel (Courtesy A. Reinhart)

structural soil reinforcement and contributes to tunneling safety and helps in controlling the settlements during tunnel excavation beneath.

Fort Canning Tunnel

The Fort Canning Tunnel forms a part of the project "Contract PE101A—Design and Construction of Fort Canning Tunnel and Realignment of Stamford Road," sponsored by the Land Transport Authority (LTA) of Singapore and was constructed in design-build framework. The tunnel is approximately 15 meters (50 feet) wide to accommodate three-lane vehicular traffic and has a total length of 350 meters (1,150 feet). Its 180 meters (600 feet) mined section has been constructed according to the NATM. Within close proximity of the tunnel are several man-made and natural features of great historical importance that demanded the selection of this mined construction approach that would produce the least possible amount of disturbance. The tunnel was constructed in residual soils that are underlain by the Fort Canning Boulder Beds and Jurong Formation. The boulder beds consist of boulders in a hard sandy silt or sandy silty clay matrix. The boulders show varying degrees of weathering and range from very hard to friable. The tunnel's shallow location, large cross section, soft ground conditions combined with high ground water level posed challenges that were met by constructing the tunnel in multiple drifts with a systematic pipe arch tunnel pre-support. This pipe arch support consisted of a grouted steel pipe (AGF—"All Ground Fastened") pre-support installed over the entire length of the tunnel. Tunnel construction utilized a top heading, bench and invert excavation sequence. The top heading was equipped with a temporary invert and progressed approximately 20 meter (65 feet) ahead of the bench and invert excavation face. The 300-mm-thick shotcrete initial lining was installed after each round of excavation and prior to commencement of any further excavation in sequence. The AGF was installed from within the tunnel and consisted of a single row of

Figure 10. Fort Canning tunnel construction

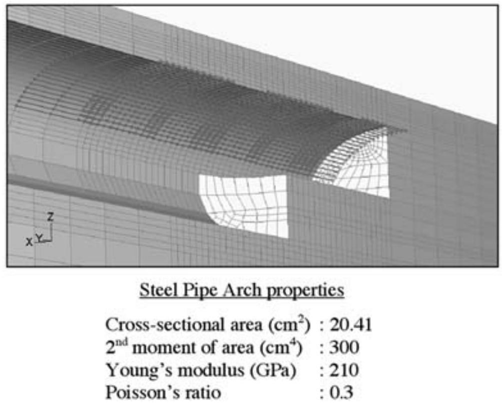


Figure 11. Fort Canning tunnel beam elements for Pipe Arch 3-D analyses

steel pipes drilled at 400 mm (15 inch) spacing in the crown of the tunnel top heading. The outer diameter of the 12.5 meter (41 feet) long steel pipes is 114mm (4.5 inch) and the pipe wall thickness was 6 mm (0.27 inch). The steel pipes were installed at a 7-degree outwards angle with an overlap of 3.5 meters (12 feet) between pipe arch sections. After excavating a 9 meter (30 feet) long tunnel section the next grouted steel pipe arch in sequence was installed (Figure 10). Upon completion of the initial shotcrete lining the waterproofing system and the cast-in-place concrete lining was installed to complete the tunnel structure.

Due to the size of the tunnel and very shallow overburden of only about 3 meters (10 feet) near the portal rigorous finite element calculations were carried out in both two (2-D) and three dimensions (3-D). The main reason for the 3-D calculations was the need to investigate function and anticipated performance of the grouted steel pipe pre-support in its longitudinal direction, a characteristic that cannot be captured in 2-D analyses.

The 3-D calculations were carried out using the finite element code ABAQUS v6.4, with a pore pressure degree of freedom, hybrid formulation and reduced integration to represent the soil (Zeidler et al., 2007). The grouted steel pipe arches were modeled as separate beams arranged in horizontal over-lapping segments as shown in Figure 11.

As an integral part of the construction, an extensive monitoring scheme was established to monitor tunneling performance. The analyzed values were compared to in-situ monitoring data. Surface settlements typically started to occur 3 to 5 meters (10 to 16 feet) ahead of the progressing top heading; deformations increased to approximately 8 to 13mm (0.3–0.5 inch) once the excavation face reached the location of a monitoring cross section. Surface settlements continued to increase as the excavation face passed the monitored section and ceased once the progressing top heading excavation face was approximately 20m beyond the monitoring location. During the combined bench and invert excavation, surface settlements resumed and increased by an additional 5 mm (0.2 inch) to 7 mm (0.3 inch). Overall it was observed that due to the generally very shallow soil cover (between 20% to 30% of the tunnel diameter), the surface settlements increased with increasing overburden thickness.

Russia Wharf Tunnel

A segment of MBTA's (Massachusetts Bay Transit Authority) new bus way to south Boston traverses underneath two buildings at the Russia Wharf complex. To enable tunneling in soft ground conditions and through existing timber pile building foundations specialty tunneling and pre-support methods were utilized. The tunneling was carried out using NATM with ground freezing for tunnel pre-support and in parts for building underpinning. The buildings remained in service during the entire construction period (Zeidler et al., 2007).

The tunnel structure enters the Russia Wharf complex at the west corner near the Congress Street/ Atlantic Avenue intersection and passes easterly toward Fort Point Channel. The Russia Wharf complex consists of three buildings, the Russia, Graphic Arts and Tufts building, of which the first two were affected by the tunnel construction (Figure 12). The buildings are founded on wooden piles. There are pile groups of typically about 30 piles per group that support pile caps made up by granite blocks. Each pile cap supports columns of the steel frame brick veneer buildings.

In the upper portion of the cross section the tunnels are located in organic and fill deposits that are

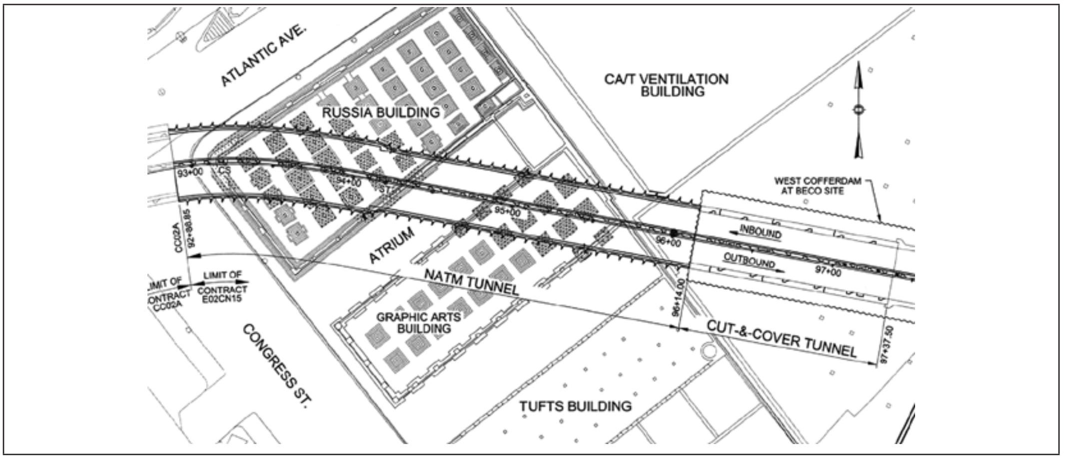


Figure 12. NATM tunnel at Russia Wharf

composed of water saturated very soft silts, sands and clays with minimal stand-up time. These deposits are underlain by soft to stiff clay often referred to as Boston Blue Clay. Tunnel construction in the soft organic deposits and fills with ground water close to the surface required systematic ground improvement to enable a safe excavation and initial support installation. The need to preserve the historical buildings above the tunnel alignment and the fact that these were founded on wooden piles located within the footprint and tunnel cross section posed further design challenges. The clearance between the tunnel roof and the base of the pile caps was only between 0.5 meter (2 feet) and 3 meters (10 feet) at the Russia Building and 3 meter (10 feet) to 4.5 meter (15 feet) under the Graphic Arts Building.

Many tunnel construction methods were considered during the planning and design phase but NATM tunneling in combination with ground freezing for pre-support and building underpinning was selected as the only alternative that preserved the buildings and allowed them to remain operational during construction. While ground freezing in the very shallow conditions at the Russia Building served tunnel pre-support only, ground freezing under the Graphic Arts Building was used for tunnel pre-support and as the sole means of temporary building support as the tunnel excavation cut through the existing timber pile supports.

Ground freezing was limited to the organic sediments and tied to only several feet into the top of the clay (Figure 13). The frozen soil encapsulated the timber piles, formed a foundation for the pile caps and acted as a supporting structure for the building loads until the piles were integrated into the tunnel shotcrete lining. The cut-off pile ends were encapsulated in reinforcing cages and were fully integrated into the initial tunnel lining. After thawing of the frozen soil the tunnel structure forms the permanent underpinning scheme for the historical buildings.

Due to clearance limitations a binocular tunnel cross section was developed to allow space for two bus lanes (Figure 14). The first tunnel was excavated and fully supported with a final lining before the excavation and support of the second tunnel could commence. The excavation and support installation followed a top heading, bench and invert sequence. After completion of excavation and initial support of the first tunnel, the waterproofing system was installed followed by placement of a permanent lining and a common center wall. Similar to the first tunnel the second tunnel was excavated in a top heading bench/invert sequence whereas its shotcrete initial lining rested on the common center wall. Following shotcrete lining installation the waterproofing was completed the permanent lining placed. After completion of the lining for the entire tunnel structured the frozen soil was allowed to thaw.

Airside Pedestrian Tunnel

The airside pedestrian tunnel at Washington, DC Dulles International Airport connects the airport's main terminal and Terminal B (Hirsch et al., 2003). Construction of the tunnel began in early 2000 and the tunnel was opened to traffic in 2004. Due to circulation requirements the tunnel structure had to remain shallow and the tunnel at an excavated springline diameter of about 12.5 meters (41 feet) and 8.3 meters (27 feet) height was excavated using NATM under an overburden cover of merely 4.6 meters (15 feet) which is about half of the tunnel height and just a third of the tunnel springline diameter. Figure 15 displays the tunnel cross section.

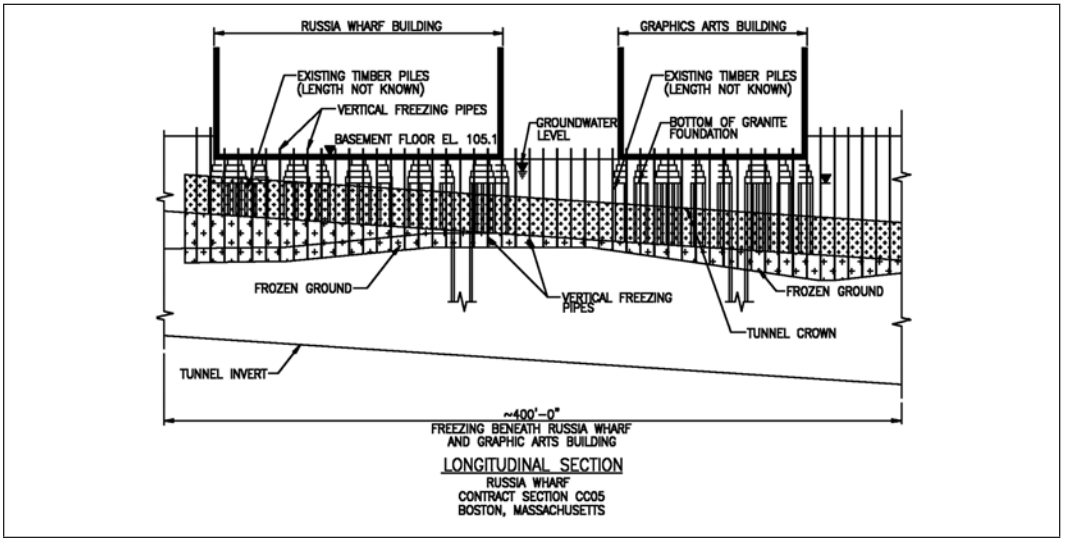


Figure 13. Tunneling at Russia Wharf longitudinal section

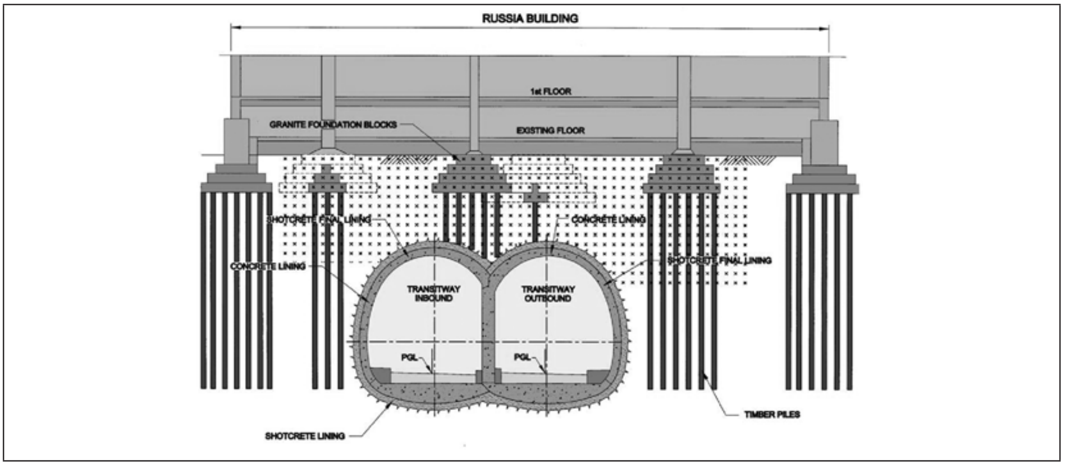


Figure 14. Typical binocular tunnel cross section

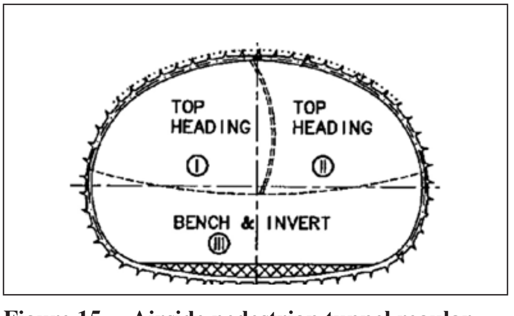
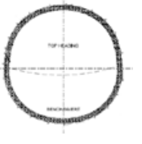
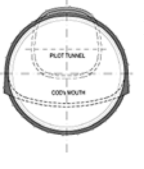
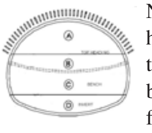
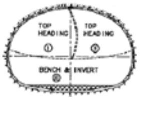


Figure 15. Airside pedestrian tunnel regular cross section

The majority of the tunnel cross section is situated in competent siltstone rock of generally good rock mass quality with an average intact uniaxial compressive strength of 42 to 52 MPa (6,000 to 8,000 psi) a material easily excavated using roadheader technologies. Only to an extent of several feet the tunnel crown is located within weathered siltstone and residual soils. Due to the shallow cover and the weathered rock and weak soil conditions in the crown the tunnel was designed using NATM soft ground principles. Moreover excavation sequencing and initial support had to accommodate high surface loads imposed by airplanes traveling on the taxi lanes. The top heading was subdivided

Table 1. Shallow tunnel case histories

Project Name Status	Geology (at tunnel elevation)	Overburden/ % of Tunnel Width	Pre-Support	Tunnel Size	Tunnel Shape	Excavation and Support
Tysons Corner Tunnel, Detailed Design; Construction 2008	Residual soils (mainly dense silts, low clay content, some sand); varying groundwater table below invert up to spring line	4.6 m (15-ft) to 12 m (38-ft) 60 to 160%	Systematic grouted steel pipe arch over the entire length	2 tunnels 7.6 m (25-ft) wide, 8 m (26-ft) high		NATM, top heading, bench/ invert; early invert closure; shotcrete thickness: 250 mm (10-in.)
Victoria Station, Upgrade Detailed Design; Construction 2009	Alluvial gravels, London Clay (over-consolidated, hard clay) in invert; groundwater table at tunnel springline level.	Typ. 6m (20-ft)/ 60 to 100%	Soil improvement with systematic jet grouting; systematic grouted steel pipe arch over entire length	6 m (20-ft) to 10 m (30-ft) wide, 6 m (20-ft) to 9.7 m (32-ft) high		NATM, top heading—bench—invert; early invert closure; shotcrete thickness: 200 mm (8-in.) to 300 mm (12-in.)
Kings Cross Station Redevelopment; The relevant section completed 2007	London Clay (over-consolidated, hard clay)	12 m (39-ft) to 20 m (66-ft)/ 170 to 290%; 1 m (3-ft) below railway tunnel/14%	Grouted steel pipe arch when crossing underneath historic brick lined railway tunnel	7 m (23-ft)		NATM, Lasershell, pilot tunnel with subsequent enlargement, inclined full face excavation with early invert closure; shotcrete thickness: 225 mm (8.8-in.)
Fort Canning Tunnel; Completed 2006	Residual soils (dense clayey silt, clay, sand lenses) and boulders (about 70% soil matrix); groundwater table at surface elevation.	3 m (9-ft) to 5 m (15-ft)/ 20 to 30%	Systematic grouted steel pipe arch over the entire length	15 m (49-ft) wide, 11 m (36-ft) high		NATM, top heading with temporary invert, bench and invert following about 20 m behind; shotcrete thickness: 300 mm (12-in.)
Russia Wharf Segment; Completed 2004	Water saturated, soft organic silts, invert in blue clay; timber pile foundation for historic building above the tunnel	3 m (10-ft) to 4.5 m (15-ft)/ 25 to 60%	Ground freezing of organic silts	Binocular tunnel 11.9 m (39-ft) wide, 7.9 m (25.9-ft) high		NATM, top heading—bench—invert, early invert closure; shotcrete thickness: 300 mm (12-in.)
Pedestrian Tunnel; Completed 2004	Residual soils (silt, clay and clayey sand) in crown, cross section generally in weathered siltstone; groundwater table above rock surface.	4.6 m (15-ft)/ 40%	Systematic grouted pipe spiling	12.5 m (41-ft) wide, 8.25 m (27-ft) high		NATM, top heading—bench—invert; shotcrete thickness: 200 mm (8-in.)

into two individual drifts followed by a bench/invert excavation and shotcrete lining ring closure. The excavation rounds in the top heading were not to exceed 1.6 meters (5 feet-2 inches) in Support Type 2 and 1 meter (3 feet-4 inches) in Support Type 1. Application of a sealing layer of 50 mm (2 inch) directly following excavation was specified in the contract documents. Primarily for the control of raveling of the weathered rock and soils in the tunnel roof the tunnel pre-support included a systematic pre-spiling using 25.4 mm (#8) diameter, 3.7 meter (12 feet) long grouted bars at 300 mm (1 foot) centers around the tunnel crown and installed for the entire tunnel drive. Tunnel excavation generally produced not more than about 20 mm (0.8 inches) of settlement at the surface with a relatively shallow wide reaching settlement trough. Tunneling occurred underneath taxi lanes with structural concrete pavement. Surface and Subsurface settlements were monitored to detect any adverse movements on the pavements and to detect any gaps that could have opened between the stiff pavement slabs and the ground directly below. Any such voids would have been grouted for proper contact. Mainly due to the wide and shallow trough a grouting program was not necessary. This tunnel project demonstrated the success of controlling settlements by the excavation and support sequencing prescribed. Tunnel pre-support was used merely to prevent raveling in the crown.

SUMMARY AND CONCLUSION

The use of various pre-support techniques in combination with NATM for shallow tunneling was demonstrated using case histories taken from urban or urban-like settings. Table 1 provides a project summary and lists characteristic project data such as ground conditions, tunnel size, overburden depths and pre-support selected.

In all of the projects listed, tunneling was enabled using pre-supports adapted to prevailing ground conditions. These ranged from the use of complete ground modification by means of ground freezing in running ground through systematic cementing of the generally cohesionless soil by means of jet grouting, to the use of steel pipe arches and forepoling elements which are grouted in place. In the case of steel pipe arches the ground must have a certain amount of in situ strength. The pipe arch acts as soil reinforcement, enhances standup time, provides a structural system that longitudinally bridges over the round being excavated and arches radially around the tunnel opening. It limits over break and settlements and is a further element of risk control. If the ground conditions are suitable the settlement and risk control properties of grouted steel pipe arch systems can be achieved at an economic cost. Table 1 provides a summary overview and thus guidance for the type of tunneling and pre-support for tunneling at shallow depths.

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