NATM AND GROUND FREEZING COMBINED AT RUSSIA WHARF

Boston's Silverline may be the way new urban transportation systems will develop in the years ahead. It combines dedicated surface bus lanes together with undergound bus tunnels and limited stops with the flexibility of special rubber tyred articulated buses, driven by low pollution fuel systems (compressed natural gas) on the surface sections transferring to 'no-pollution' electric power in the tunnel sections. The construction of one of the Silverline tunnel sections, where the underground busway has to pass only a short distance under 100 year old buildings which are in constant use, has necessitated an interesting construction technique involving NATM in conjunction with ground freezing and spiling.

The Silverline, one of the most ambitious public transport projects in recent years in Boston is often addressed as part of the Big Dig. In fact in some areas it is very close to the Central Artery (even the same Cut and Cover operation was used to build a Silverline tunnel on top of the Central Artery Highway I93 tunnel near South Station) and it uses the Ted Williams Tunnel to connect South Boston to Logan Airport. But the Silverline is a Massachusetts Bay Transportation Authority (MBTA)-operated Bus Rapid Transit Line which, once finished, will connect Logan Airport with South Boston, continue underground from D Street (Stations: World Trade Center, Court House) to South Station, Central Boston (Chinatown Station, Station Orange Line and Boylston Station, Green Line) and run surface bound from New England Medical Center to Dudley Square in Roxbury.

Right now the last and most challenging part of Silverline Phase II (Logan Airport to South Station) is under construction. This includes the crossing of the Fort Point Channel using immersed tube tunnelling. At the time of writing, two of the three prefabricated concrete tubes were still waiting in the dry-dock to be floated in and sunk in a pre-dredged trench crossing the Channel and connect in the north to an already constructed 30m cut and cover box located at the former Boston Edison Company Site (BECO) at Atlantic Avenue.

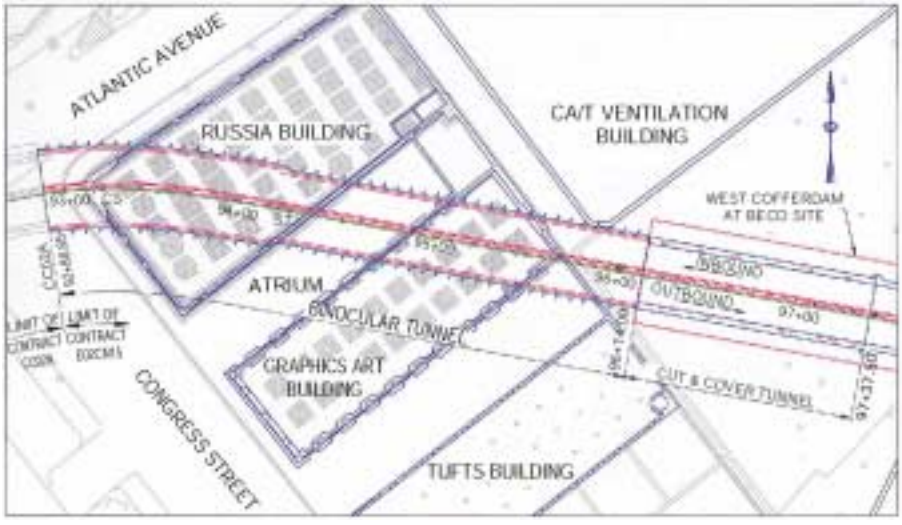
This cut and cover box provides also the starting shaft for the mining operation which crosses underneath the Russia Wharf building.

Russia Wharf

Russia Wharf is a 100 year old, three building complex, each of them seven stories high. Their structural steel columns and red brick facades are founded on granite footings which are supported on up to 14m long wooden piles. Keeping these office buildings fully operational and minimising the impacts on the tenants and these old structures while tunnelling underneath them, led the designers (DMJM+Harris and the NATM specialist subconsultant DSC, the Dr. G. Sauer Corporation of Herndon, VA) to the first use of the combination of ground freezing and NATM in the US.

Birds-eye view of the Russia Wharf buildings. One of the construction shafts is seen bottom left

DSC provided a binocular shaped tunnel design meeting various demands, such as minimising the excavation volume, as the MBTA had to purchase the right of way from the building owner (one of the biggest commercial property landlords at



Plan showing passage of Silverline bus tunnel under the Russia Wharf complex

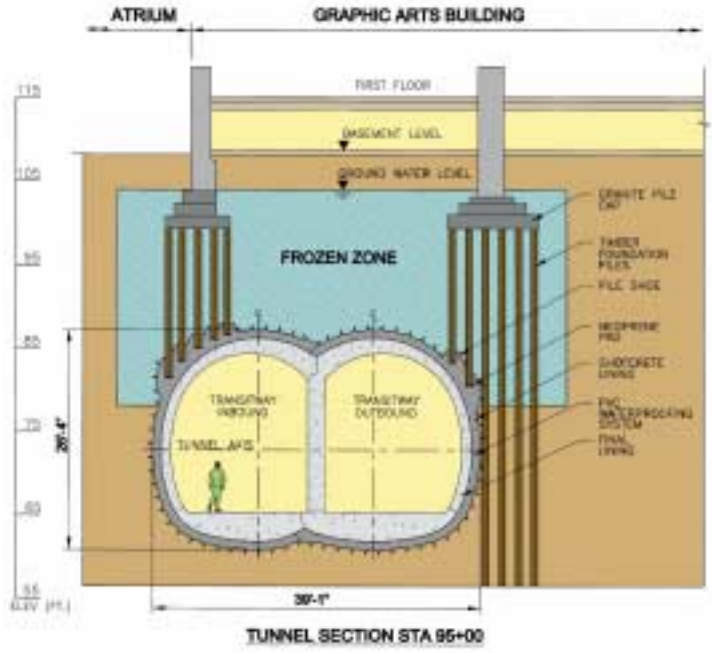
Tunnel portal view with Liebherr 900 excavator in foreground

the east coast), and reducing the height to maximise the clearance to the foundations. A continuous centrewall separates inbound and outbound lanes for safety reasons and provides refuge niches at constant distances. Settlements had to be limited to the very minimum with fully occupied buildings only a couple of metres above the NATM operation. That is why construction of the inbound part of the binocular tube started a few weeks after completion of the outbound final liner and the structural centre wall was completed for at least 1m ahead of the second excavation face.

A minimum of 300mm thickness of shotcrete, lattice girders (spacing of 76cm) and two layers of welded wire fabric were designed and constructed as primary liner. After waterproofing with a PVC membrane an additional 300mm of shotcrete has been applied as final liner from the cast in place invert slab to the centre wall.

The three buildings, Tufts, Graphic Arts and Russia Building are affected differently by the NATM operation as the alignment, rising after the Fort Point Channel Crossing at 3.5 per cent to make it over the Central Artery/Tunnel by the end of the NATM section, crosses under two of them diagonally and has its starting shaft just adjacent to the Tufts Building.

Different concepts for underpinning of the foundations, pre support and excavation sequence are used for the five sections of the 100m long tunnel.



Construction section

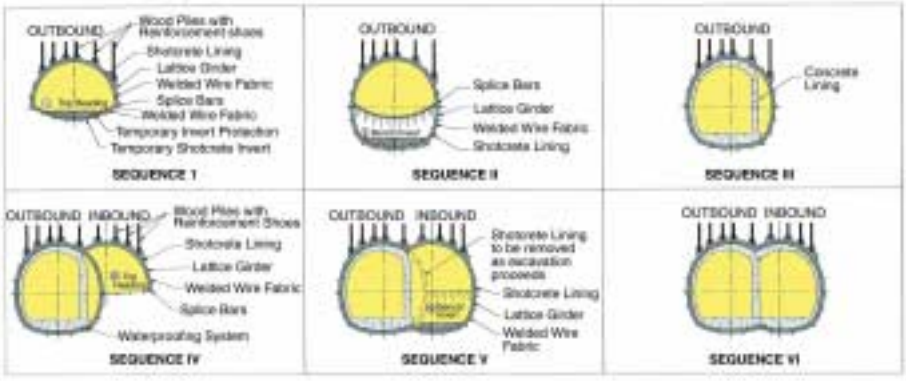
Spiling with 2.74m long grouted pipe spiles was considered sufficient to maintain safe working conditions and minimise surface impact in section E under the BECO site. For the future development of a high rise building the final liner had to be flattened in this area to provide room for the parking garage. The primary liner will be demolished from the top and only a 230mm concrete slab will divide the two structures.

An area of solid frozen (–15°C) ground (about 32.5m^2, 7.6m deep) underneath the Graphic Arts Buildings (Section D) creates not only safe face conditions for the workers (Boston's Sandhogs, Union Local 88 working for a joint venture of Modern Continental Construction and BEMO, NATM experienced Beton-und MonierBau from Austria) but supports the woodpiles of the Russia Building while they are cut in the mining operation. The load of the wood piles brought into the undisturbed soil utilising friction has to be transformed onto the primary liner as the excavation cuts at least half the length of all piles within the extent of the tunnel.

Temporary underpinning was used to disconnect the columns from their footings and place hydraulic jacks in between. The jacks allow the columns to be vertically adjusted as necessary to compensate for heave and settlement due to the impact of the different operations. The mass freeze was accompanied by heave up to 50mm. The affected columns were lowered to minimise the impact on the buildings. No adjustments were necessary during outbound tunnel construction. But once the inbound tunnel is finished and the thawing process starts, the jacks might have to be used again to raise the building.

Miners excavate around each timber foundation pile embedded into the solid frozen soil, with layers of organic clay on top, Boston's Blue and Marine Clay below, and attach a 25mm neoprene attenuation pad on each saw-cut pile, wrap it with a bond breaker and attach a "pile shoe". These are prefabricated reinforcing baskets which encase the pile and are tied to the first layer of welded wire fabric. After shotcreting, this special "pile treatment" will prevent piles from punching through or slipping off the primary liner. That way incorporated within the primary liner, the piles will transfer their load onto the tunnel, which then acts as a strip foundation once the thawing process starts.

Underneath the Atrium (Section C), an entrance area to both the Russia and Graphic Arts buildings, no mass ground freezing is performed. A combination of



Construction sequence

freeze slurry cut-off walls allows mining operations as tidal influence is present due to the close proximity to the Fort Point Channel. Again, grouted spiling was designed and has been used to improve ground conditions during NATM operation in this section.

Another about 37m^2 of ground is maintained frozen by MCC's subcontractor Layne Christensen underneath the Russia Building (Section B). Using brine that circulates from about 180 freeze pipes to the freeze plant located 100m off the furthermost pipes. The primary task of the frozen ground is to provide soil stability for the mining operation. As overburden decreases to 3.7m under the Russia Building, it was not considered sufficient to support the wood piles carrying building loads during construction, and a different approach was taken for the support of the foundations of this building. A permanent underpinning system was installed to transfer the loads of the building to steel piles which are founded 37m deep in the bedrock.

Tunnel excavation showing wooden piles in the working face

The system is composed of three layers of steel frames. The bottom layer of the steel frames spans across the tunnel and is founded on "minipiles". These steel piles (200mm to 300mm in diameter) had to be driven in 1.5m shots from the confined space of the building's basement area and were placed on either side and within the future centre wall of the tunnel.

The wooden foundation piles were cut or removed using the road header attachment of the Liebherr 900 excavator. As the excavation of the outbound tunnel includes the space of the centre wall, the steel minipiles were encountered during the mining operations. Digging between these piles, which spanned 8.2m from the crown to the invert and are loaded with up to 500t from the buildings above, was one of the most challenging parts the contractor and the MBTA's field staff had to accomplish.

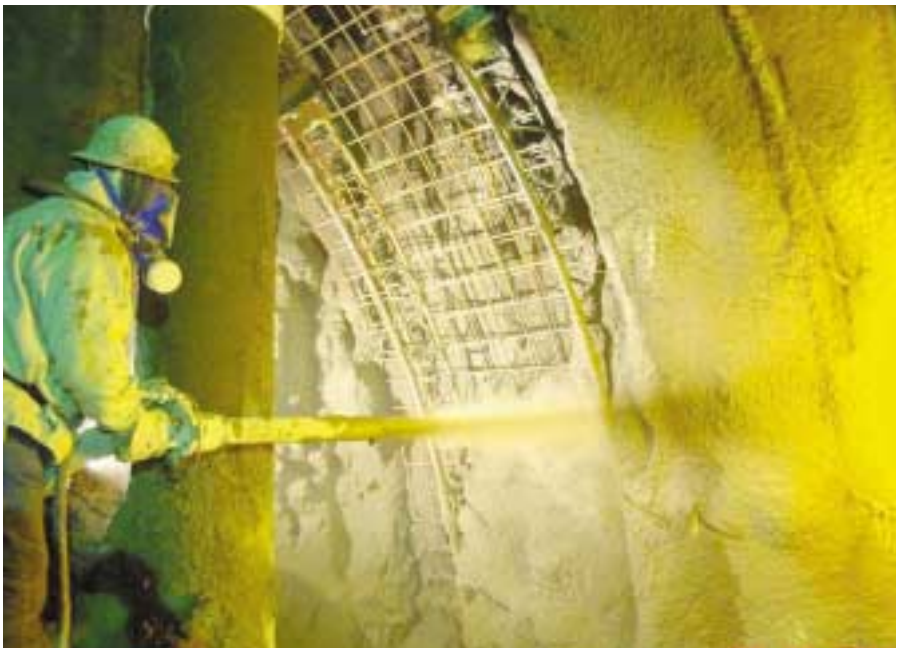
The 6m long section A, about 6m underneath the surface of the intersection of Atlantic Avenue and Congress Street connects to the cut & cover box of the CCO2A contract. This part of the Silverline going to South Station was constructed directly on top of the Central Artery northbound tunnel using the same cut & cover trench.

During construction the owner has maintained the presence of the design team, and NATM specialist DSC has been on site during mining operations full time to provide expert supervision, advise and monitoring data processing and interpretation.

The Modern Continental Construction/BEMO JV submitted several cost and time saving value engineering proposals. The most significant was the utilisation of the on-site mixed high strength dry-mix shotcrete not only for the initial lining but also for the final liner. Minimal design values for the primary liner of 17.5MPa after 24 hours, 25MPa after 7 days and 35MPa after 28 days were achieved easily. The need for this high early strength of 17.5MPa (to mitigate surface settlements) resulted in a compressive strength of 70MPa after 28 days.

Steel fibres were added to the shotcrete for the final liner to meet the residual strength performance criteria, but the concrete mix was not changed. To comply with operational surface requirements the final lining has a 50mm finish layer with smaller aggregate size and reinforced with polyfibres to avoid cracking caused by shrinkage.

Due to the achieved shotcrete strength and encountered ground conditions (the



Shotcrete application

frozen material was tougher than anticipated) lattice girder spacing was able to be increased from 0.76m to 1.1m.

A complex waterproofing system was necessary because the binocular tunnel structure will be completely submerged in ground water after the thawing process is completed. The two different excavation runs (outbound first, followed by inbound) created a need for two longitudinal connections from the inbound to the outbound tunnel, including special treatment for the minipiles, which penetrate the entire structure.

Geotextile protects the PVC membrane against the primary liner at the invert, walls and roof of the final binocular shaped structure. Waterbarriers are welded onto the PVC to create sections which can be grouted independently and on demand only if leakage is observed. The invert waterproofing was set up first reaching from the inbound side (north) of the outbound tunnel to the south wall. After the invert cast in place concrete slab was poured, the waterproofing continued from the south wall upward and to the inbound side of the future centrewall. Two special designed details enable the waterproofing system to be continued at the crown and in the invert once the centrewall inside the outbound tunnel is finished and excavation of the inbound tunnel is completed. Even more complex was the situation where minipiles of the existing buildings and steel structures for the future hotel run through the centrewall penetrating the primary as well as the final liner. Special consideration was also given to the change of final lining construction method from cast in place to shotcrete.

Mining operation started in September 2002 at the outbound tunnel. The contract limit, a slurry wall closing the adjacent CCO2A cut and cover box was encountered with the top heading beginning of March 2003 and was removed after bench and invert was finished at end of March 2003. Waterproofing and final liner construction followed.

Excavation of the inbound tunnel started on July, 21 2003 and will be finished approximately mid January 2004. Waterproofing, final lining and finishing works will follow to make the tunnel accessible for follow-on contractors applying utilities and systems, such as light, standpipes and catenaries.

Service on Phase I of the Silverline started in July 2002 connecting Roxbury surface bound to Downtown Boston and the silver buses are already well known and used by Boston's commuters. Phase II should be open in summer 2004 but delays seem unavoidable. In the meanwhile preliminary design has started for Phase III, the 1.6km long underground connection from South Station to Central Boston. The 15% design will be completed by the URS/DMJM+Harris Joint Venture, also using DSC as specialist NATM subconsultant, in early 2004. Construction for Phase III is planned to start in 2006, completing the missing link between Logan Airport, Downtown Boston and Dudley Square.

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