INNOVATIVE SOLUTIONS AND SPECIAL PROBLEMS DURING THE CONSTRUCTION OF THE CENTRAL ARTERY/THIRD HARBOR TUNNEL HIGHWAY PROJECT IN BOSTON

by - James R. Lambrechts, P.E., Professor of Civil Engineering Technology
Wentworth Institute of Technology, Boston, Massachusetts, USA; Member ASCE

ABSTRACT

Major civil engineering projects inevitably present the designers and constructors with challenges, and this was especially true for the Central Artery/Third Harbor Tunnel (CA/T) Project in Boston. Furthermore, the particular subsurface/geologic conditions around Boston's inner harbor and the existing structures made the CA/T Project a fertile site for many innovative solutions to major challenges. Several examples are presented that highlight geotechnical construction technologies that were new to the U.S. construction scene in either their application or magnitude of use. These technologies include deep soil mixing; free-standing 76m-diameter circular concrete cofferdam; post-tensioned T-shaped concrete diaphragm wall panels; full-section jacked tunnels; stacked drift mining for underpinning a subway station; concrete immersed tube tunnels; and construction of the new tunnel beneath the old elevated highway viaduct using 30m- to 37m-deep concrete slurry walls installed under low (6m max.) headroom conditions.

INTRODUCTION

The Central Artery/Third Harbor Tunnel (CA/T) Project currently being completed in Boston, Massachusetts, is the largest, most complex highway project ever attempted in the U.S. The “Big Dig,” as it is known locally, has lived up to its nickname. More than 12 million cubic meters (m^3) of soil were excavated from very congested downtown and surrounding project areas. The downtown tunnel has replaced the 50-year-old and traffic-clogged elevated Central Artery (highway I-93) in the same alignment around the edge of the city’s major financial area and nearly 3,800,000m^3 of concrete placed. Also built in this project is an extension of Massachusetts Turnpike (I-90) to Logan International Airport via the South Boston Seaport Access highway and the Ted Williams Tunnel under Boston Harbor, see Figure 1. The final cost of the CA/T Project is about $14.6 billion, of which about 55% was for the I-93 reconstruction and widening.

In replacing the old, downtown elevated highway structure, the construction of the new tunnel had to done under low headroom conditions beneath the existing six-lane structure and very near to several tall buildings. Crossings over two subway tunnels and under a subway station also had to be made. During the 13 years of construction, traffic flow on city streets and the existing I-93 highway structure was maintained. The rebuilding of the interchange between I-93 and I-90 at the southern edge of downtown had the added complications of the busy commuter railroad terminal at Boston's South Station (400 train movements per day) and the Fort Point Channel (with its 3m tide cycle, very soft bottom mud, 35m-thick marine clay, and four bridges).

Presented at the STUVA Conference on Underground Transport and Construction, November 2005, Leipzig, Germany, Proceedings Volume on Research and Practice, pp. 44 - 50.

The extension of I-90 through South Boston and under Boston Harbor had to cross under the Fort Point Channel without interrupting the subway line below, and traverse under Boston Harbor, with 20m deep excavations required on both sides for connections with the new, 1,250m-long four-lane immersed tube tunnel. Finally, just north of downtown, the signature structure for CA/T Project, a 10-lane-wide cable-stayed bridge was built over the Charles River, with legs that straddle another subway tunnel. The location of each of these challenging situations is indicated on Figure 1. Challenges that each of these areas presented to both the design engineers and the constructors are each briefly discussed below; references to earlier interesting detailed articles are given for the reader to obtain further detailed descriptions.

Challenge No. 1 - Deep Excavations Using Soil Mixing at Logan Airport, East Boston

For the construction of the deep cut-and-cover tunnels that lead I-90 through Logan International Airport to the new Third Harbor Tunnel, excavations as deep as 20m were required in soft Boston blue clay. Total width excavated was from 60 to 87m. The contractor in 1992 selected the deep soil mixing method to construct the excavation support wall system, with five levels of tieback anchors to restrain lateral earth loads. The deep soil mix walls were installed with wide-flange beams placed in each alternating column to provide the wall with necessary bending moment resistance.

The wet process of deep soil mixing was used with a triple shaft mixing machine having auger-type cutting tools on the bottoms to penetrate the ground while injecting cement grout through ports at the bottom of the auger heads. The slow, steady rate of auger advance cut into the soil at 3 to 8cm per revolution, with rotation speed of about 25 rpm. Mixing paddles or discontinuous auger sections positioned further up the shafts were used to disperse and mix the soil and cement grout, creating the soil-cement mixture.

The tieback anchors were installed as the wide excavation progressed downward. However, at about 11m depth, large lateral wall displacements occurred (>25mm/day) along more than 100m-long area of deepest Boston blue clay. The lateral displacements were believed to have been the beginning of a massive global instability deep within the marine clay stratum, the mass of which included the zone of the tieback anchors (O'Rourke and O'Donnell, 1997a). The onset of movement was attributed to lowering of clay shear strength due to dissipation of negative pore pressures in the clay, allowing it to revert from undrained to a somewhat drained, and therefore a weaker condition (McGinn and O’Rourke, 2000).

To permit the excavation to be made to the necessary depth without deep global instability, deeply founded and "floating" buttresses of soil-cement were installed by the deep soil mixing method to bolster passive restraint at the toe of the excavation support walls. Deep soil mixing buttresses were extended out about 20m from the excavation support walls. Jet grout was used in the tight space between the buttresses and the excavation support wall. These deep soil mix buttresses were used for 175m of the alignment. Figure 2 illustrates the depth and extent of the deep buttress, which was successful in resisting further excessive lateral movements (O'Rourke and O'Donnell, 1997b and O'Rourke et al., 1998), and shows the width and depth of the tunnel.

Challenge No. 2 – Deep 76m-diameter Concrete Cofferdam at South Boston Vent Building

At the South Boston side of Third Harbor Tunnel, the connection between the immersed tube tunnel and the cut-and-cover land-side tunnel was originally designed to use a rectangular, internally braced excavation support system. Depth of excavation was approximately 25m, penetrating through as much as 15m of miscellaneous fill, building debris and old pier structures, 7.5m of Boston blue clay, and 3m of glacial till before reaching the weathered argillite bedrock. The contractor decided instead to construct a 76m-diameter self-supporting concrete cofferdam using reinforced concrete diaphragm (slurry) walls supported by a continuous series of compression ring beams cast inside of the slurry wall as the excavation progressed downward. This option eliminated the need for internal bracing within what otherwise would have been a congested rectangular braced excavation. Figure 3 shows the cofferdam, as initially excavated, at the time of immersed tube connection (one of several loading conditions) and later when tunnel construction was being completed.

The slurry walls were socketed into bedrock. The ring beam system made the cofferdam walls into a stiff cylinder. With this combined system, the unbalanced lateral loading caused by the need to dredge out on one side for the immersed tube tunnel connection could be adequately resisted. The ring beams varied in thickness depending on the horizontal bending stresses produced by the unbalanced lateral earth loads. Exterior buttresses were also needed on either side of the cofferdam where tunnel connections required large (14m by 27m) opening to be cut through the cofferdam. Design required extensive finite element analysis for a variety of loading conditions caused by the many stages of excavation, and for variable bedrock support. During construction, a considerable amount of instrumentation was used to measure deformations and determine stresses in the cofferdam, which is described by Kirmani and Highfill (1996).

In preparation for this construction, the contractor pre-shattered the bedrock by detonating two large multiple-delay explosions, the larger being more than a 120Mg of high-explosive. For the larger 'big blast', more than 200 blast holes were drilled down 38m below grade into the argillite, and loaded for sequenced detonation. The resulting blast heaved the ground as much as 8.5m, and was quite successful in making the contractor's excavation for the immersed tube tunnel and the cut-and-cover section within the cofferdam much easier (see McKown and Dobbels, 1993).

Challenge No. 3 – Concrete Immersed Tube Tunnels for the Fort Point Channel Crossing

The six-lane-wide I-90 alignment traverses more than 1.7km of cut-and-cover tunnels and boat section in South Boston from the Third Harbor Tunnel to the Fort Point Channel, where it passes below this historic, 91m-wide navigable body of water. However, running beneath the axis of the channel are the twin subway tunnels of unreinforced concrete, each 6m diameter, constructed through glacial till and Boston blue clay in the 1912-14 era. For the new I-90 tunnels to cross over the subway tunnels and stay below the channel mudline, rectangular concrete immersed tube tunnels were required. Six sections were constructed in a huge casting basin immediately east of the channel. Four of the six tunnel sections were constructed in the first phase, and then floated out with two going to their permanent positions and the other two “parked” for 18 months. After the final two segments were built, these and the two that had been parked were moved to their permanent positions. Figure 4 indicates the final positions of the six tunnel segments, and shows the casting basin with four of the tunnel sections under construction. All were founded on concrete drilled shafts which extend 30 to 50m deep into bedrock. The tops of these shafts match up with recesses in the bottom of each tunnel (Boston Globe, 2000).

The casting basin was a huge excavation, approximately 305m long, 91m wide and 20m deep. Because the base was 18m below groundwater level, a special depressurization system was required to prevent inflow and uplift from the granular glacial till soils. However, depressurization was not allowed to occur at an adjacent manufacturing plant to prevent differential settlement because it has both shallow friction piles and some deep end bearing piles for foundations. An extensive recharging system was therefore installed and operated between the excavation and the plant to maintain piezometric levels within 0.6m of the pre-construction groundwater levels.

The dredged excavation for the immersed tube tunnels below Fort Point Channel had to be within 1.5m of the crown of the old subway tunnels. This required careful excavation of 10m soil cover from over the 80-year-old tunnels. The effect of this stress unloading on the unreinforced concrete subway tunnels was extensively analyzed during design, and then monitored during construction to confirm that movements and changes in stresses in the old structures remained in acceptable ranges (see Buechel, 1999).

Challenge No. 4 – Deep Soil Mixing at the I-93 NB/I-90 Interchange

One of the largest applications of an innovation for U.S. construction on CA/T was the use of deep soil mixing for tunnel foundations in the area between the Fort Point Channel immersed tube tunnels and the existing I-93. Here, a new multi-level interchange between I-90 and I-93 was constructed adjacent to, over, and beneath the six railroad tracks that are the only access to busy South Station. The alignment of roadways in the I-93NB/I-90 portion of the interchange is complex, as shown diagrammatically on Figure 5.

Throughout the interchange, more than 420,000m^3 of deep soil mixing was installed for several purposes, including as a 12m-thick by 38m-wide berm to resist unbalanced lateral load for nearly 200m length of tunnel in Area A, and as 40m-deep buttress/foundation structures for permanent tunnel foundations and to resist large, unsupported lateral loads in Areas B and C.

In Area A, the Ramp L tunnel that supports columns of new viaduct structures is positioned along the western side of the Fort Point Channel, as indicated on Figure 5. As the tunnel descends from 4m to 16m depth, it is subjected to increasingly larger unbalanced lateral earth loading condition (ground on the west side is about 10m higher than at the tidal Fort Point Channel to its east). Deep soil mixing was used to change the 38m width of fill and soft organic soil stratum at the east side of the tunnel into a berm of stiff soil-cement. This restrains the tunnel against unbalanced earth loading and prevents lateral movement of the tunnel, its drilled shaft foundations, and the viaducts supported on the tunnel roof. The 12m-thick soil-cement berm along Ramp L was designed to develop full sliding resistance with less than 12mm of horizontal displacement, which mobilizes about half of the clay stratum shear resistance. The deep soil mixing achieved the required minimum compressive strength of 485 kPa. During tunnel construction, the excavation into the soil-cement berm did not require laeral support for the full 11m depth. The deep soil mixing for the Ramp L berm encountered many obstructions, which were remnants from historical waterfront uses. Wood piles for foundations, timber platforms and wharf decks, and granite blocks for pile caps and building stones often obstructed the deep mixing. All had to be removed on an as-needed basis.

In the 350m length of Areas B and C (see Figure 5), ground stabilization using deep mixing was used to: provide basal stability for wide, deep excavations; form deep buttress-like transverse retaining elements to hold back 9m to 17m of lateral earth and water loads; and provide permanent foundations for the several contiguous highway tunnels. The latter is a first for U.S. highway tunnel construction. The most acute, unbalanced lateral earth load condition was at the east end where the Ramp D cut-and-cover tunnel links with the Immersed Tube Tunnels (ITT) of the Fort Point Channel crossing. The large, unbalanced lateral earth load on the Ramp D tunnel occurs because the adjacent ITT cannot support unbalanced lateral loads (see cross-section in Figure 5). At Ramp D, the 17m unbalanced earth load is resisted by both the rock-socketed T-shaped slurry wall (which includes heavy post-tensioning in the 3.5m-deep stem) and Ramp D tunnel that is integral with the underlying soil-cement buttress, which, in turn, develops base sliding resistance on the glacial till. The soil-cement buttress design in Area C required the entire area adjacent to Ramp D to be treated with deep mixing to a minimum soil-cement strength of 2070kPa.

For Area B, the greater overall width allowed the design layout of deep soil-cement buttress structures to use intermittent shear walls, formed by overlapping three rows of the interconnected soil-cement elements. For Area B, 4.5m wide soil-cement shear wall panels were used to form 38 percent overall area coverage across the tunnel width. The proportioning of soil-cement shear wall panels was based on analysis of internal stresses generated in the stiff soil-cement by earth pressures, tunnel loads and hydrostatic pressures, and base shear resistances developed in bearing on glacial till.

Installation of deep soil mixing in the crowded Fort Point Channel was very difficult because the channel is narrow and very shallow at low tide and has two important bridges in the middle of the deep buttress area that could not be closed. These restrictions created the need for a multi-staged approach to overwater deep mixing. Also, the heavy deep mixing equipment needed adequate “working platforms” that were made by first ‘shallow mixing’ the soft organic soils and channel bottom 'mud' with cement grout to create a stabilized layer of weak soil-cement over the 35m-thick marine clay stratum. The shallow mixing was done within perimeters of steel sheet piling, which also constrained granular fill placed to raise the areas above high tide. Even with deep mixing using cement grout, the low water content (35 to 40 percent) of the deep marine clay necessitated injecting only water on the downstroke mixing to “fluidize” the clay. Cement grout was injected only during auger withdrawal. Some difficulties were encountered in the deep mixing, as reported by Lambrechts and Nagel (2003) and Maswoswe (2001).

Challenge No. 5 – Jacked Tunnels Under Railroad Tracks at South Station

The Massachusetts Turnpike (I-90) formerly had its eastern terminus at I-93 in a congested north or south interchange. The eastward extension of I-90 to the Fort Point Channel and beyond to Logan Airport began with three, full cross-section jacked tunnels constructed beneath the five mainline tracks of the commuter and inter-city railroad. The tunnel widths were approximately 24.5m, heights were nearly 12.5m, and lengths of 48 to 107m, as described by Lambrechts, Roy and Winsor (1997) and Winsor and Taylor (1998). The tunnels were advanced through a stratigraphy of fill, organic silt, outwash sand, and Boston blue clay, as shown on Figure 6. The contractor used ground-freezing, with approximately 1,400 freeze pipes installed between the railroad tracks to stabilize the ground ahead of tunneling rather than use the combination of dewatering, grouting (both permeation grouting in the granular fill and jet grouting in organic silt), and soil nailing in the clay contained in the original design. The freezing was successful, although some ground heave did occur (15 to 25cm) along the rail tracks.

The frozen ground was readily excavated using road-header tunnel excavators. The contract-required shield was redesigned by the Contractor to provide two excavation work platforms (see Figure 6). These machines gnawed away the frozen ground at the shield face. As each 30 to 50cm of frozen soil was removed, the tunnel was pushed ahead with huge hydraulic jacks. Over the past 200 years, the area through which the tunnels were jacked had been harbor wharves, and then filled ground with wood pile supported structures that had brick masonry substructures. These were readily excavated by the road-header; however, granite blocks of former foundations had to be removed separately.

The tunnels had either one or two intermediate jacking stations so the length of tunnel that had to be jacked ahead at any one time was limited to reduce overall jacking loads. The contractor also used anti-drag wire ropes along both the top and bottom of the tunnel box to minimize friction and prevent the tunnel's forward movement from dragging the overlying soil along, which could have caused horizontal displacement of the railroad tracks. During the jacking, bentonite grout was also injected through ports in the sides of the tunnels to provide lubrication between the concrete walls and ground.

After a tunnel was installed to final position, grout was pumped through holes in the roof slab to fill voids that remained due to some overexcavation of frozen ground by the road-headers. Details of the tunnel shield, temporary excavation support systems for the thrust pit, and the jacking process are given in papers by van Dijk et al. (2001) and Donohoe et al. (2001).

Challenge No. 6 – Underpinning of a Subway Station for the Deep I-93 NB Tunnel

The I-93 northbound tunnel is in a new alignment beneath Atlantic Avenue; this is two city blocks east of the previous I-93 NB-SB Central Artery tunnel in the Chinatown area of Boston. The former two, three-lane tunnels (NB and SB) of the 45-year-old South Station tunnel have been converted to one, four-lane southbound-only tunnel. However, in building the new I-93 NB tunnel, excavations as deep as 36.5m were needed so the new, four-lane tunnel could be constructed beneath the existing subway station. The underpinning scheme, described in detail by Dobbels et al. (1996), applied a stacked-drift mined tunnels system to form the walls of the new I-93 NB tunnel and the new girder beams that are the roof of the I-93 tunnel beneath the 85-year-old concrete subway station. The final construction section is shown in Figure 7 and the steps of construction are presented below.

After installing instrumentation in the subway station, two access shafts were excavated at the underpinning wall locations north of the subway. Grouting gallery tunnels 4.5m wide were then excavated beneath the subway, each within 3m of the bottom of the subway station tunnel. From these two access tunnels, the granular glacial till and fractured argillite bedrock below were permeation grouted using tube-a-machett grout pipes drilled into the underlying strata, and multiple grouting stages with cement-bentonite and sodium silicate. The grouting was to reduce soil permeability and solidify the ground through which the stacked drifts were next to be mined (see Droof et al., 1999).

The lowest drift was then mined through, with excavation conditions varying from full face rock to full face grouted, granular glacial till soil. This bottom drift was sized to bear the weight of both the subway station and underpinning structure on the bedrock or grouted till soil. The lowest mined drifts were supported with steel ribs and a combination of timber lagging and liner plate and then backfilled with concrete to form the foundation for the underpinning. The middle drift was excavated next, again with ribs and lagging support, followed by backfilling with concrete. Finally the upper drift was excavated, but it had the overlying grouting gallery as its roof. The upper drift tunnels were backfilled with concrete to complete the stacked drift walls.

To finish the underpinning, 13 post-tensioned box girders were installed between the tops of the stacked drift walls to directly support the overlying subway station base slab. At seven locations, precast box segments were jacked through the stiff, cohesive glacial till, then backfilled with concrete, and finally post-tensioned. The six spaces between these initial seven post-tensioned girders were then excavated, backfilled with concrete, and post-tensioned. With all 13 girders completed, the soil below was mined to open the full roadway tunnel cross-section, after which the 4.5m-thick tunnel invert slab was placed to form the final lateral buttress to the stacked drifts.

Further challenges were present in the vicinity of the subway underpinning in the form of existing buildings. The approaching 36.5m cut-and-cover excavation beneath Atlantic Avenue came within 6m horizontally of the mat foundation of the One Financial Center office tower, a 46-story tower with a mat foundation bearing only 8m below ground surface. It was imperative to have solid lateral support against the soil over this 27m depth from tower mat level down to tunnel excavation bottom. A very rigid excavation support wall system was created using steel soldier piles (915mm deep wide flange beams in pairs) at 2.5 to 3m centers embedded in 1.2m-thick tremie concrete. Similar concern existed across the street, where the Federal Reserve Bank tower also has a mat foundation that was about 26m above tunnel excavation level. Throughout construction, building movements were frequently measured and did not exceed 40mm (Edgers et al., 2001).

Challenge No. 7 – Building the New I-93 Tunnel Beneath the Old I-93 Viaduct

The 1.2km-long I-93 tunnel was constructed directly beneath the old six-lane steel frame viaduct while maintaining traffic on both the highway and the city streets at ground surface. To minimize tunnel width, the excavation support system was integrated into the final tunnel walls. The walls used tremie concrete and steel soldier piles. The main tunnel is four to five lanes wide in both the north and the south directions. There is a center wall throughout the entire 1.2km length of the dual tunnels. The tunnels diverge for their southern 0.7km lengths and are two blocks apart in the South Station/Chinatown area.

During tunnel construction, the old viaduct had to be temporarily supported on the new tunnel walls so the foundation piles for the original viaduct could be removed and the new tunnels constructed. The general sequence of tunnel construction is shown for three stages on Figure 8, along with an aerial view of the old viaduct. Most of the new tunnel walls had to be installed under low headroom (6m height) conditions beneath the existing viaduct. The 0.9 to 1.2m-thick diaphragm wall panels were dug down to depths of 30 to 45m below ground surface using special low-headroom slurry wall excavator machines. The soldier piles were generally 915mm deep wide flange beams that could only be installed in 6m to 8m lengths. Therefore, three to five bolted splices were commonly needed to install each beam in the slurry trench. As many as 240 high-strength steel bolts were needed for many of the splices. Steel reinforcement was also placed in the slurry trench to reinforce the tremie concrete through the 10m height of the tunnels where the slurry walls are the permanent tunnel.

The tunnel is designed to develop its full support on these deep walls, so the tunnel invert slab was designed to span the full four to five lanes width. This, in part, was done to permit future expansion, for either a proposed railroad line or possibly for additional highway lanes. All walls were taken down to depths needed to develop side friction and end bearing in/on glacial till and argillite bedrock. The tunnel roof uses steel beams attached to the soldier piles that span from side walls to the center wall, and a concrete slab that is generally less than 35cm thick.

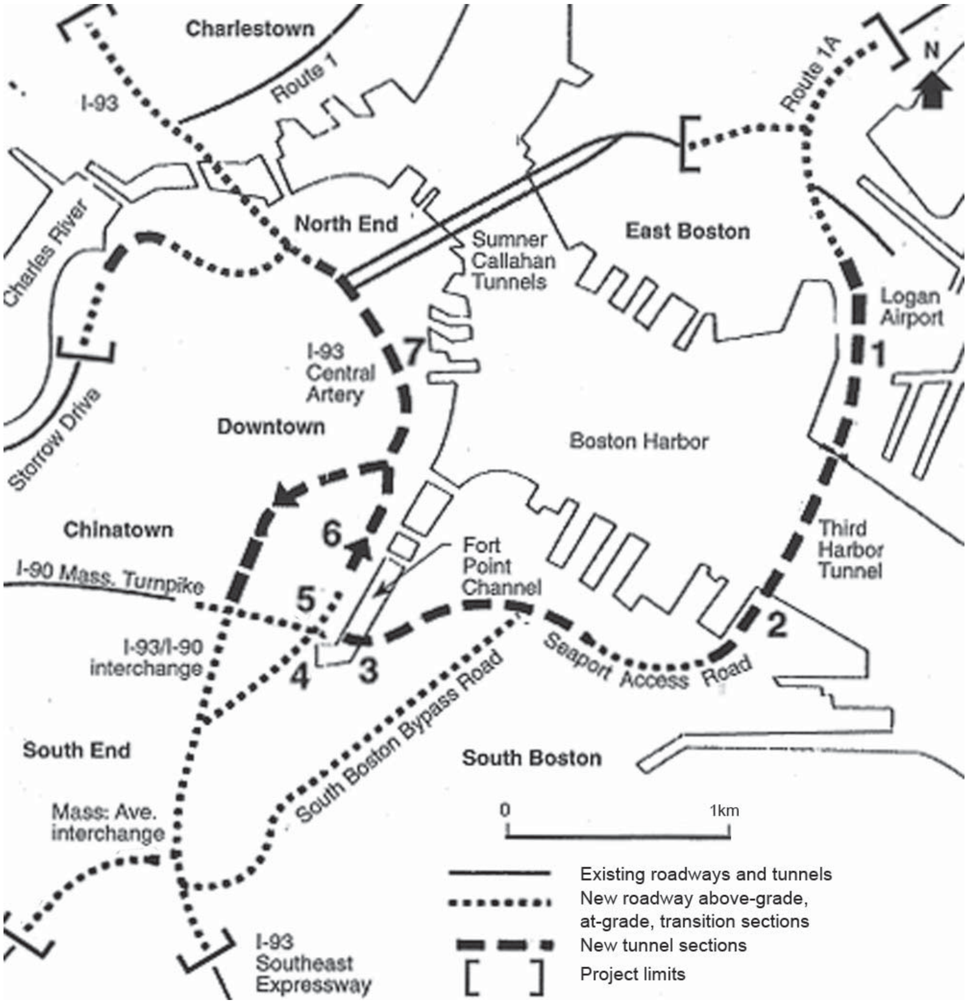
Groundwater levels along the tunnels were generally within 1.5m of ground surface, and the Boston Harbor is in some areas within 100m of the nearest wall. The tunnels were designed to resist hydrostatic uplift by dead weight, which caused some invert slabs to be more than 3.5m thick. Water leakage into the tunnel did grab headlines in September 2004, and investigations since have identified a number of areas in about 5 percent of the 2,000 wall panels that have soil inclusions that require remedial construction. Some ongoing grouting work is continuing to seal the joint between the walls and the roof slab.

SUMMARY

Every major infrastructure construction project in urban areas will have geotechnical challenges. Boston’s unusual subsurface and geologic setting have sparked many innovative applications of ground improvement, soft ground tunneling, excavation support systems, dewatering and recharging, and deep foundation construction in overcoming the challenges of this massive CA/T Project. The seven innovative approaches presented are a few of the more challenging situations that were overcome in the nearly 20 years of design and construction. Both the design engineers and contractors have made significant contributions to subsurface construction with these and other innovations on the Central Artery/Tunnel Project.

The Massachusetts Highway Department led the design and early construction efforts. The Massachusetts Turnpike Authority has since assumed project leadership to complete the construction effort. References noted can be found in a forthcoming paper that will appear in the journal, ***Civil Engineering Practice***, published by the Boston Society of Civil Engineers Section of ASCE.

Figure 1 Location Plan, Boston Central Artery/Tunnel Project, indicating areas discussed.



1. Deep soil mix walls and buttresses for excavation support
2. Large concrete circular cofferdam
3. Concrete immersed tube tunnels and casting basin
4. Deep soil mix berms, buttresses and tunnel foundation
5. Full-selection jacked highway tunnels under railroad tracks
6. Underpinning of a subway station
7. Building Tunnels under I-93 viaduct

Figure 2 Deep soil mixing for Excavation Support and Buttress for Toe of Wall, at Logan Airport Approach to Third Harbor Tunnel.

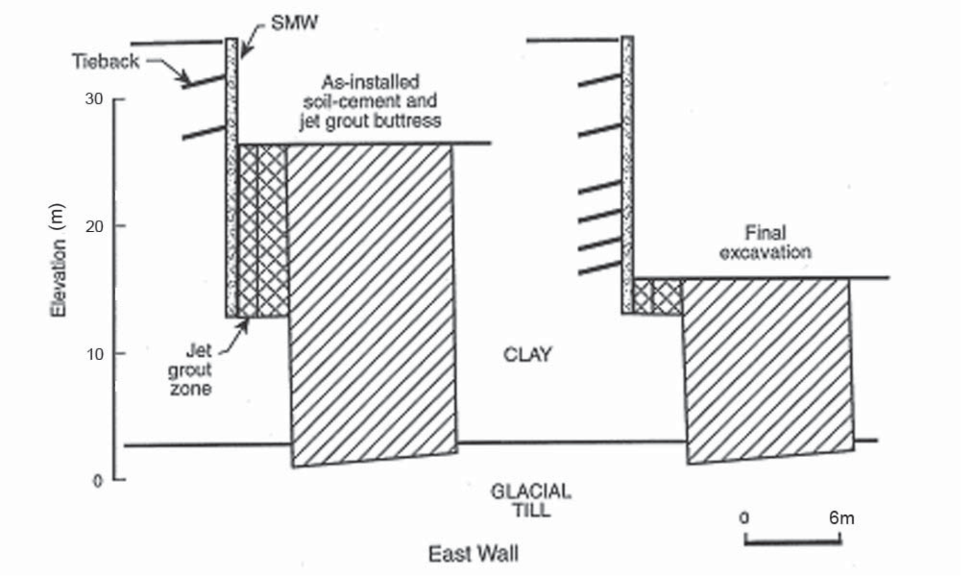


Figure 3 Large Circular Concrete Cofferdam for Connecting Immersed Tube Tunnel of Harbor Crossing to Land-Side Cut and Cover Tunnel.

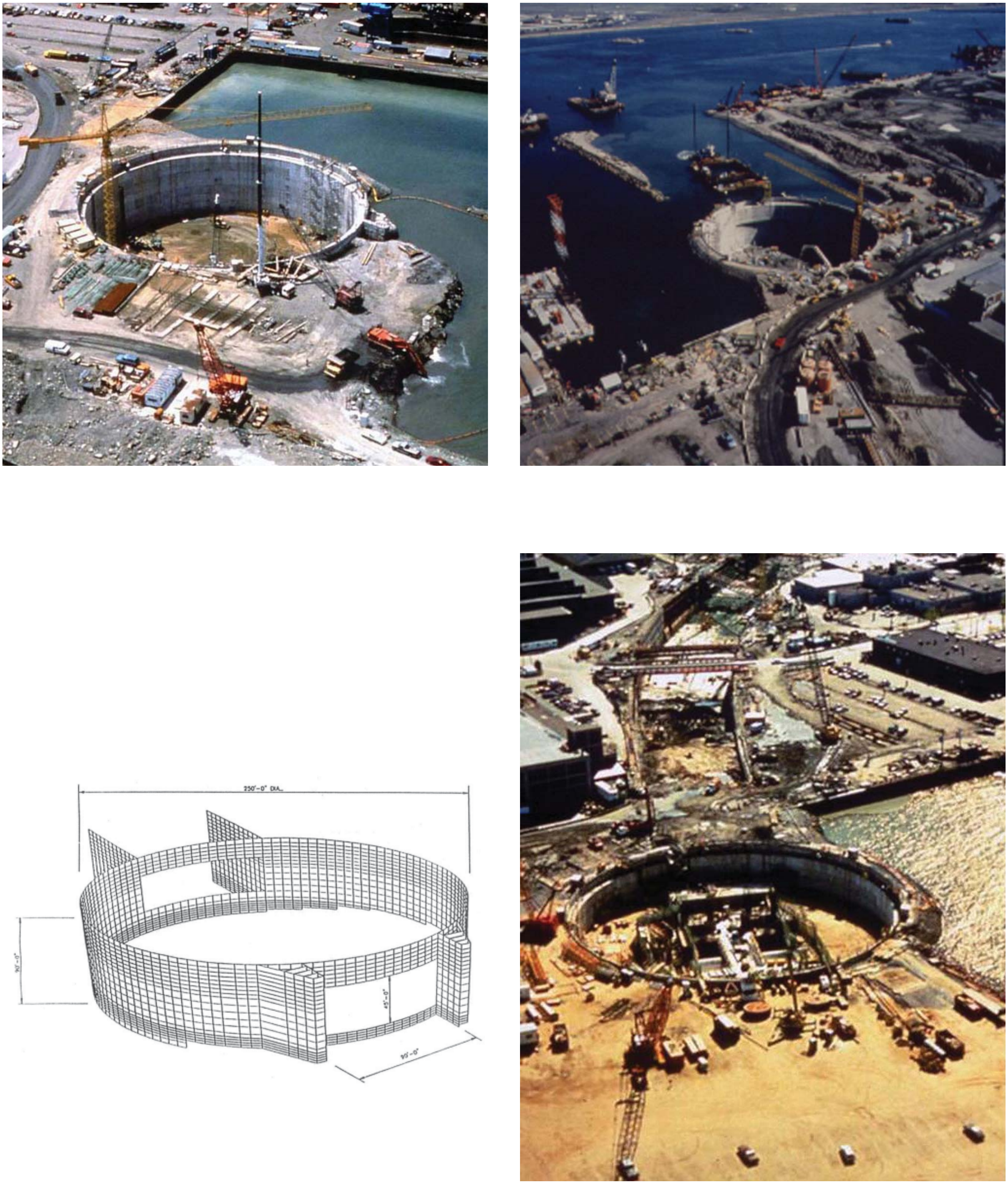


Figure 4 Concrete Immerse Tube Tunnels and Casting Basin for Fort Point Channel Crossing

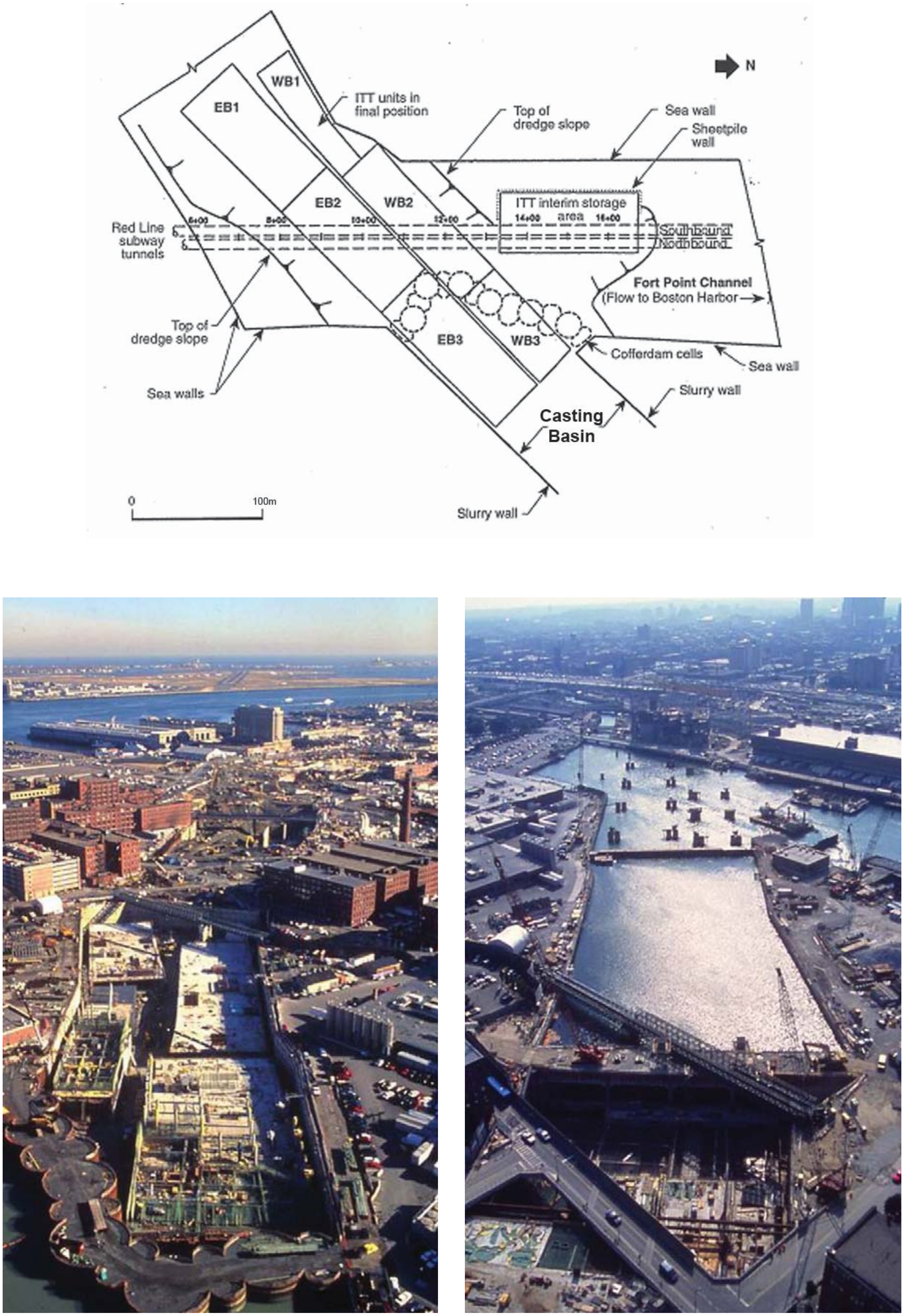
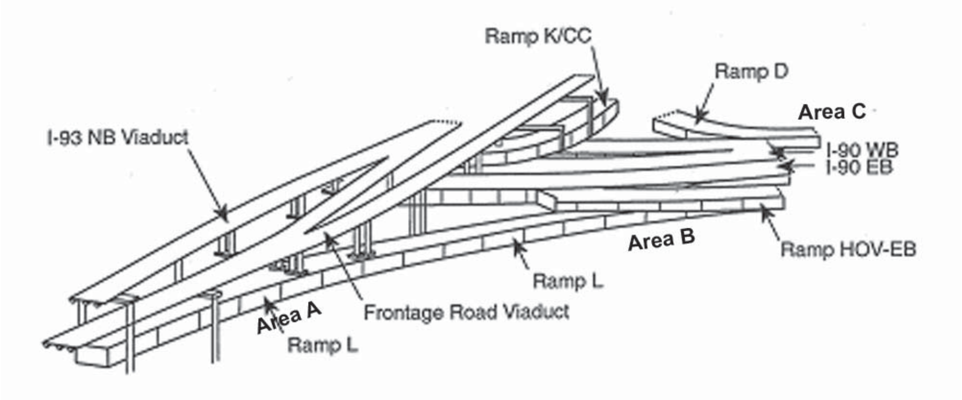
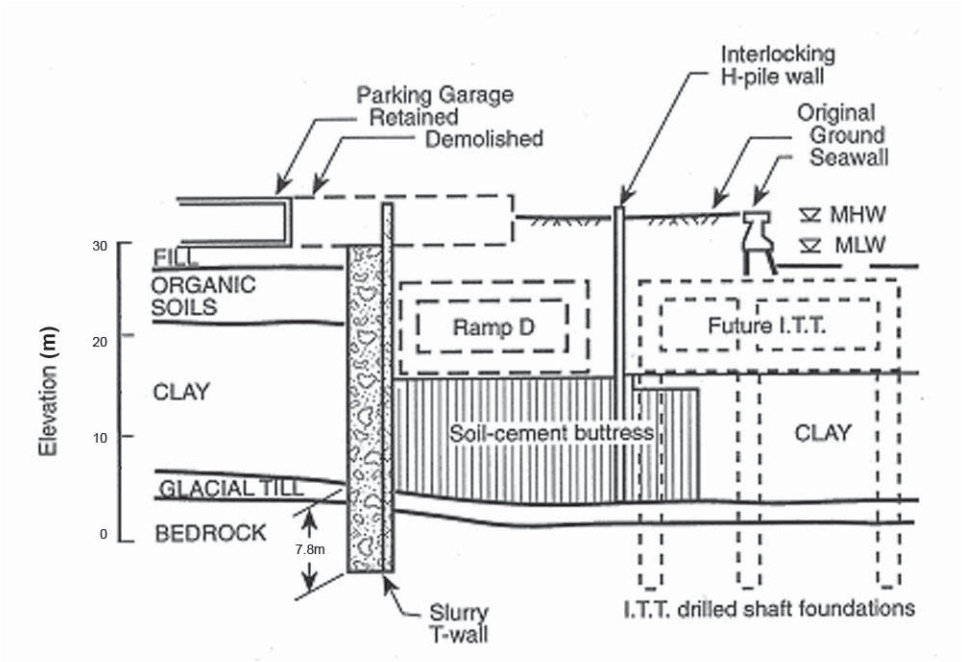


Figure 5 Areas of Deep Soil Mixing in Fort Point Channel showing Tunnels and one of the Critical Sections.





Deep Soil-Cement Buttress and Foundation for Ramp D, at Area C

Figure 6 Jacked Full-Sized HighwayTunnels Beneath Railroad Tracks at Boston's South Station.

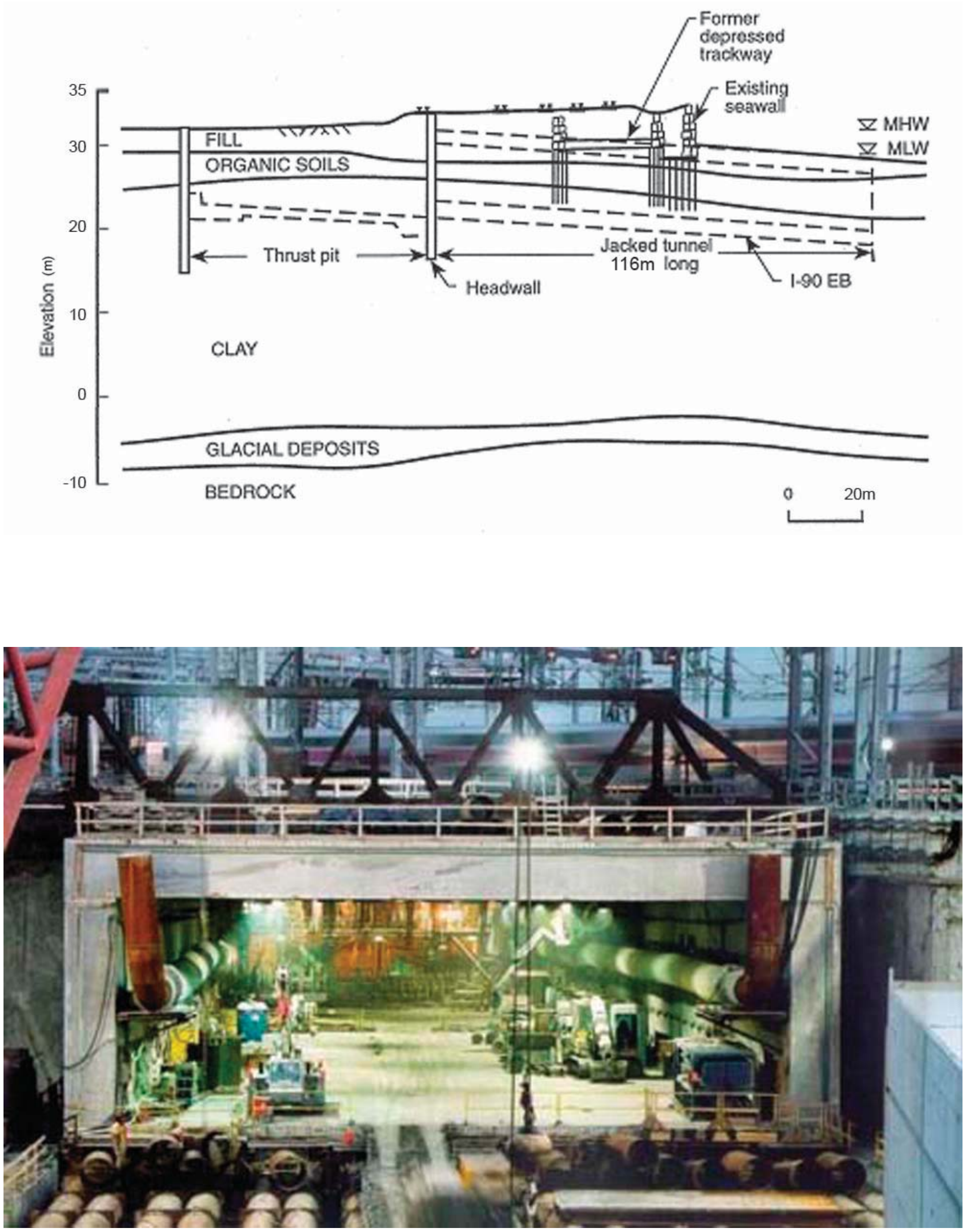


Figure 7 Underpinning Subway Station for I-93 NB Tunnel.

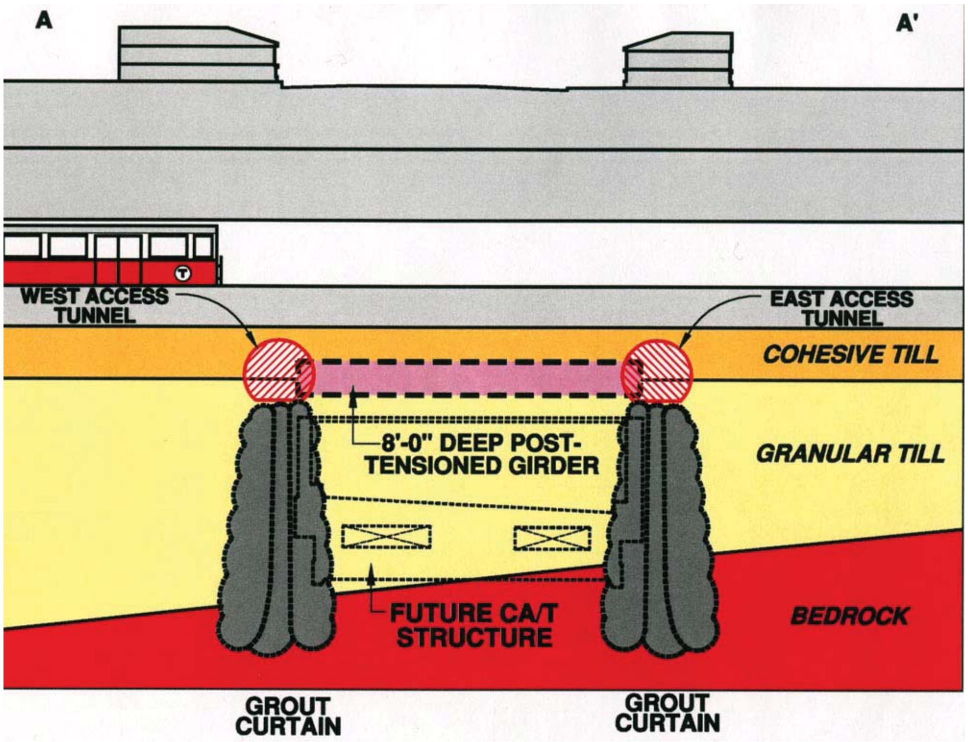


Figure 8 Building the I-93 Tunnel Beneath the I-93 Viaduct.