Innovative Design for Tunnel & Excavation Support for the CA/T I-90/I-93 Interchange

The innovative use of soil-cement stabilization to form berms and deep permanent buttresses and foundations for tunnels provides a way to tackle the difficult ground conditions at this site.

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Two major innovations in US construction practice are part of the solution to a complex and difficult portion of multi-billion dollar Central Artery/Tunnel (CA/T) Project. Deep soil mixing and tunnel jacking, both extensions of technologies used overseas, are being used for construction in very weak soil conditions in the highly congested Fort Point Channel area.

The rebuilding of a major urban interchange between two interstate highways is an especially challenging design and construction undertaking. For the CA/T Project in Boston, the task of extending the Massachusetts Turnpike (I-90) and relocating I-93 northbound (NB) becomes quite formidable when existing conditions include an active railroad yard, a navigable body of water, old buried wharves and foundations, and deep soft ground (more than 35 meters [115 feet] of soft Boston blue clay and channel bottom mud). To extend I-90, three multi-lane tunnels must pass beneath five to nine tracks of Boston's South Station railroad terminal. Two other tunnels that will merge with I-90 skirt along the edge of the Fort Point Channel and must support columns of a new overhead viaduct.

It is difficult to imagine a site presenting a more onerous combination of challenges, first for the designer and then for the contractor. The final design focused on applying two techniques (deep soil mixing and tunnel jacking) in significant innovations for North American construction. The extent of these applications is shown on Figure 1. Although both methods have proven successful in overseas uses, these innovations are being used to magnitudes...
FIGURE 1. Site plan showing tunnels with soil-cement stabilization and tunnels to be jacked.

never before attempted, and in manners quite unlike prior uses. Construction now underway is applying these innovations to effectively overcome site challenges present at the I-90/I-93NB interchange.

Overview of Design Innovations
The first major innovation is the stabilization of the soft thick clay deposit beneath and adjacent to the Fort Point Channel by the processes of deep mixing and jet grouting to create more than 600,000 cubic meters (800,000 cubic yards) of soil-cement. In some areas of Fort Point Channel, a soil-cement berm was designed to buttress the tunnel against lateral loads, but where tunnels are deep, mixing was designed to penetrate more than 35 meters (115 feet) to create large foundation blocks and shear walls for deep foundation support. The construction operations necessary for installing the deep soil-cement in the crowded channel conditions required a preliminary stage of overwater shallow soil stabilization. The soil-cement buttress also was designed to provide temporary excavation support during construction of the tunnels.

The second major innovation developed by the section design engineers is the full-size tunnel jacking under busy railroad tracks of Boston's South Station Transportation Center. Three separate tunnels — one with two lanes and two with three lanes each, at depths of 11 to 18 meters (35 to 60 feet) below ground (or track) level — were designed to advance under active railroad tracks as full-sized, finished tunnel structures. The tunnel structures are first built in deep excavations adjacent to the tracks. These jacking or thrust pit excavations, which are themselves major construction undertakings, use deep concrete slurry walls that incorporate special design features. Using shield tunneling methods, each tunnel is then ad-
vanced by incremental jacking through the
ground under the tracks. The special ground
stabilization provided in the design to stabilize
ground before tunnel advance has been re­
placed by ground freezing.

Tunnel Conditions Requiring
Innovative Approaches

The construction is extending I-90 eastward
about 3.5 kilometers (2 miles) to Logan Interna­
tional Airport from its present terminus at I-93,
and provides major connecting tunnels to link
with a new I-93NB. At the east end of the rebuilt
and expanded I-90/I-93NB interchange, the
tunnels will link with the adjoining design sec­
ion's immersed tube tunnels (ITTs) that will
form the Fort Point Channel crossing. The lo­
cations of major cut-and-cover and jacked tun­
nels being constructed in the area are shown on
Figure 1. The tunnel outlines have been added
to photographs of the preconstruction Fort
Point Channel site in Figures 2 and 3 to illus­
trate both the constituents of the interchange
and complex design considerations.

The location of the tunnels along the edge of
Fort Point Channel impose large unbalanced
lateral earth and water loads as a final design
condition. Excavation basal heave and global
stability factors of safety were determined to be
unacceptably low. Also, the Ramp L tunnel
south of the Wye Connector Railroad Bridge is
a long continuous structure that must support
column loads of the new I-93NB viaduct.
Therefore, uniform foundation support and
stiff lateral restraint was essential.

During the final design, the delineation of a
large area of very soft Boston blue clay in the
channel made it impractical to use the original
preliminary concept design of a series of filled
circular cellular cofferdams founded on exist­
ing soils. The particularly deep soft clay condi­
tions between the Wye Connector Railroad
Bridge and Dorchester Avenue Bridge (see lo­
cations in Figure 1) made it very expensive to
attempt the use of conventional deep braced
excavation support techniques. Furthermore,
the required excavation depths yielded unac­
ceptable low factors of safety against basal
heave and global instability.

As an alternative solution, the designer pro­
posed extending the earlier CA/T Project use
of deep soil mixing to a large area of the Fort
Point Channel interchange. The use of deep
mixing to provide soil stabilization and create
soil-cement buttresses as permanent support
for the tunnels was an innovative extension of
construction methods in Japan. One applica­
tion used in Japan places precast concrete re­
vetment structures on cement stabilized soft
soils in marine areas and creates reclaimed
land by filling (see Figure 4).

The second innovation of installing jacked
tunnels beneath the railroad tracks was pro­
posed by the designer early during project final
design. This method avoids the incremental re­
locating of the railroad tracks and piecemeal
tunnel construction in deep excavations adja­
cent to active tracks that was the basis for the
original conceptual design. The ability to jack
full cross-section tunnels beneath the tracks (as an extension of previ­
ously proven construction technology from

FIGURE 2. Site photo showing the tunnel lo­
cation in preconstruction Fort Point Channel.
Europe) is an important construction expedient that was favored by the railroad authorities. The tracks handle over 450 passenger train movements daily for both commuter rail and the Amtrak northeast corridor passenger service to New York and Washington, DC. Although tunnels of similar magnitude have been jacked in Germany, England and Japan, the subsurface mixed face conditions of soft clay and organic soils, and the high groundwater table make this effort particularly challenging, and an important innovation for construction in the United States.\(^9\)\(^{-11}\)

**Site & Subsurface Conditions**

The existing conditions in the Fort Point Channel are complicated and crowded as seen from Figure 1 and the photographs in Figures 2 and 3. Site area for the work activities is extremely limited, and this limitation on available space is made more challenging because, at the peak of construction activity, four different contractors must work simultaneously in contiguous and sometimes overlapping sites.

Typical stratigraphy for on-land areas of jacked tunnels is shown in two different tunnel profiles (see Figure 5). Beneath the channel, there is similar stratigraphy, but the surficial fill is not present. Greatly complicating the subsurface are the numerous buried structures, both foundations and old wharfs, which were erected on the site in the 1800s. Rock-filled timber cribs, granite block walls on wood piles, corduroy log roads and wharf platforms, and later relieving platforms were all used for wharfs. The design also expected that zones of dumped ballast stones and, perhaps, the remains of boats or ships would be encountered. The depressed trackway structure (circa 1900, with massive granite block and concrete walls and invert) lies in the line of the two jacked tunnels (see approximate location and configuration in Figure 5). The Fort Point Channel also was cluttered with four bridges, the remains of an earlier bridge and an extensive fender pile system. All of these structures had to be accounted for in the contractors’ construction plans for the deep mixing and jacked tunneling.
The soil profile throughout the I-90/I-93NB interchange project site is typical of the filled land areas of Boston, except the filling around marginal areas was much more random and variable than in the major land-side filled areas of Boston’s Back Bay. The organic soil stratum is primarily the former tidal flat mud. On land, where this stratum was filled over, consolidation has resulted in some increase in shear strength, but within the channel it has very little strength. The primary soil stratum is the Boston blue clay, which is over 30 meters (95 feet) thick in some areas. Its shear strength decreases with depth to a point, and then increases, as shown in Figure 6. The profiles also indicate that the shear strength of the clay in the channel is substantially lower than on-land areas. These low shear strengths pose significant basal instability problems for deep excavations. Basal instability potential is being overcome by the application of deep soil mixing to create soil-cement to replace the soft clay. In some isolated areas, the organic soils and the clay are separated by a layer of fine sand and/or silty sand that is up to 1.5 meters (5 feet) thick. The borings indicate this sand occurs in the path of the Ramp D and I-90 westbound jacked tunnels.

A supplemental subsurface exploration program undertaken during final design included a substantial number of overwater test borings to retrieve samples of clay for consolidation testing and for unconsolidated-undrained tri-axial (UU) and direct-simple-shear (DSS) strength tests. In addition, special piezocone in-situ testing was performed beneath the railroad tracks because long train service outages for conventional test borings were not possible. An extensive series of consolidation tests were
performed to apply the SHANSEP approach to assess profiles of existing clay stratum shear strength. Special small strain testing of triaxial samples was performed to determine the appropriate parameters for soil-structure interaction modeling of the excavation support walls of the large deep thrust pits, and ground stability at the face of the jacked tunnels. The small strain testing was conducted at the Massachusetts Institute of Technology (MIT) and included measurement of specimen lateral strains. To establish soil model parameters, each triaxial test was modeled using the program FLAC (Fast Lagrangian Analysis of Continua) imposing the stress conditions recorded in the laboratory tests, and program parameters were varied until predicted specimen behavior agreed with test results. Further validation of the soil model was obtained by back analysis of phased subway excavation next to Boston’s Don Bosco High School where soil stratigraphy is somewhat similar to the area of the jacked tunnels.

Deep Mixing Method

The process called the Deep Mixing Method was used to stabilize the soft soils and create the soil-cement foundation structures that resist both vertical and lateral loads. On this project, triple-shaft mixing equipment has been used with rotary cutting tools on the bottoms that penetrate the ground while injecting either water or cement grout through ports at the bottom of the auger heads. The cutting tools steadily advance into the soil at rates as slow as 25 to 50 millimeters (1 to 2 inches) per revolution, and beater paddles further up the shafts act to disperse and mix the soil and grout, creating a mixture of soil-cement. The three shafts are in one line, with the inner shaft counter-rotating relative to the outer shafts. In granular fill and the organic soils, the deep mixing is fairly easy due to the granular and very soft nature of these soils, respectively. In the clays, the cohesive character requires more effort to churn the clay and grout into a thick paste, which sometimes includes pieces and clumps of clay. (A further discussion of the deep mixing process is in the ASCE Soil Improvement and Geosynthetics Committee Report.)

Ramp L Berm

Within the project limits (see Figure 1), the Ramp L tunnel, which will connect I-93NB with eastbound I-90, descends in grade from a shallow boat structure requiring only a 4.5-meter (15-foot) deep excavation, to a 17-meter (55-foot) deep tunnel where it passes beneath the Wye Connector Railroad Bridge. The tunnel alone in the existing ground conditions would experience significant lateral movement and long-term creep due to the unbalanced lateral loading that would occur with the tidal Fort Point Channel on one side and the ground at a 9-meter (30-foot) higher elevation on the other. Since the Ramp L tunnel also supports several columns from the continuous concrete segmental viaduct system that is parallel to the tunnel along the channel west side, horizontal movement of the tunnel must be prevented. The existing organic soils stratum on the channel side of the tunnel could not provide the necessary lateral shear restraint, and excavation.
and replacement of organic soils beneath the channel with granular fill to form a berm on the top of the clay stratum was not practical.

A soil-cement berm penetrating into the clay was designed to laterally restrain the Ramp L tunnel (see its cross-section in Figure 7). Ramp L was designed to accommodate 13 millimeters (0.5 inch) of horizontal displacement. The berm width was sized so that about half of the clay shear resistance is mobilized. The rock-socketed drilled shaft foundations that support the vertical loads of the Ramp L tunnel and viaduct also provide some resistance to the unbalanced lateral load.

In the deeper, northern section of Ramp L in the vicinity of the Wye Connector Railroad Bridge, a 6-meter (20-foot) thick base of soil-cement was designed to be installed below the tunnel before excavation to resist basal heave and global instability. However, the contractor elected to install deep concrete slurry walls for excavation support and lateral cross walls to provide internal horizontal restraint and resistance to basal heave. Construction of the soil-cement berm for the southerly portion of Ramp L is complete, as is the southernmost portion of the Ramp L tunnel. The principal installation difficulty for deep mixing was with obstructions, including existing woodpiles, timber platforms and wharf decks, and granite blocks for pile caps and building stones (and concrete in some later cases). Obstruction removal was performed on an as-needed basis following the general pre-mixing clearing.

Deep Buttresses for Ramps D & L

At the east side of the project, deep buttresses of soil-cement bearing on glacial till were designed for permanent foundations of the five contiguous tunnels. The principal design issue required deep buttresses to resist unbalanced lateral load. The final geometries of the tunnels themselves in this area narrow the Fort Point Channel to less than half its former width (see Figure 1), thus preventing use of an external berm to resist unbalanced lateral load. Furthermore, the ITT adjacent to cast-in-place Ramp D cannot hold back large unbalanced lateral loads. Different and more complex design issues developed in the application of soil-cement structures as deep buttresses and foundations.

The design layout of deep soil-cement buttress structures is shown in Figure 8. For much of Ramp L east of the Wye Connector shear walls were designed to form triple rows of overlapped, interconnected elements of soil-cement. A typical pattern of auger elements is shown in Figure 9 where the 38 percent coverage makes up the majority of the shear wall width.

For buttress structures to meet the design intent, the soil-cement shear walls require continuity. Therefore, the specification for the installation of the soil-cement by deep mixing required design adherence to close tolerances for alignment, verticality and overlap.

The design and proportioning of soil-cement widths to act as shear panels was determined by structural analysis of internal stresses in the soil-cement. In these analyses, earth pressures and hydrostatic pressures were applied to sides of the buttresses, and base shear resistances developed along the bottom of the buttress in bearing on glacial deposit soils. Particularly high internal stresses developed in portions of the soil-cement buttress along Ramp D due to 15 meters (50 feet) of unbalanced loading. The permanent unbalanced loading was designed to be carried by the adjacent T-shaped slurry wall and Ramp D tunnel down into the underlying buttress. The soil-cement buttresses were designed to develop base sliding resistance on the glacial till (see the cross-section in Figure 10), acting in conjunction with the rock socketed slurry T-wall.
Installing Soil Cement in the Crowded Fort Point Channel

Overwater installation of soil-cement is not an unusual construction procedure in Japan. There, huge barges supporting complete grout batching plants and drilling towers for auger mixing are typical. Unfortunately, the Fort Point Channel is generally too confined and water depth is insufficient at low tide to permit the use of such highly specialized water-borne equipment. The two primary bridges in the deep buttress area (Dorchester Branch Railroad and Dorchester Avenue) had to remain open to rail and vehicle traffic until temporary replacements were constructed. These restrictions created the need for a staged approach to overwater installation of soil-cement. Heavy auger equipment was required to reach the 35-meter (130-foot) depths to base the soil-cement on glacial till. The "working platform" for the huge crawler cranes that serve as the base for the deep mixing equipment was formed between the bridges by first mixing soft organic soils and channel bottom "mud" with cement.
grout to create a stabilized layer of weak soil-cement on top of the clay stratum. This “shallow mixing” was within areas constrained by the existing bridges, and confined by perimeters of steel sheet piling.

Once the shallow soil-cement was installed, the “working platform” was created with granular fill placed on the shallow soil-cement. The heavy deep mixing crane-rig then operated on this working platform. With deep mixing completed in the two initial areas, the temporary railroad bridge and the relocated Dorchester Avenue roadway/bridge were constructed. With the Dorchester Avenue traffic relocated to the temporary crossing west of the current bridge, the old bridge was removed and deep mixing performed by an overwater operation to complete the soil-cement buttress in the easternmost area (see Figure 8).

The old Dorchester Branch Railroad Bridge was a historic bascule bridge on which the new Old Colony commuter rail train service began operations in September 1997 on three active tracks (originally there were six). Since commuter service must be maintained, a temporary bridge with three tracks has been built to the west of the bascule bridge, which has now been removed. In this area, the final portions of the deep soil mixing can then be performed to link the two initial areas. At the same time, on-land deep mixing progressed for the Ramp D buttress and areas east along I-90 westbound. To achieve efficiency in constructing soil-cement buttress structures, conscientious pre-removal of obstructions was essential.

**Soil-Cement Use as Temporary Excavation Support**

Along the 150 meters (500 feet) of Ramp L from the Wye Connector bridge to the Dorchester Avenue bridge, a temporary channel-side cofferdam was designed as two parallel rows of sheet piles installed in a zone of 100 percent coverage of soil-cement, as shown in plan and cross-section in Figure 11. A row of sheet piles was also designed to be installed at the other side of the soil-cement adjacent to the existing seawall (along the railroad yard). Although a free-standing excavation support system at the old seawall was desired, the space available was not sufficient to form a cofferdam to independently hold back earth and hydrostatic pressures. A system of struts between the seawall (railroad-side) sheet piling and the channel-side cofferdam was designed to resist the earth and hydrostatic loads from the seawall during excavation for tunnel construction.

The 9- to 12-meter (30- to 40-foot) wide “channel-side cofferdam” also provides a staging platform for construction of the Ramp L and HOV-EB tunnels. After tunnel construction, the cofferdam will be removed, but the soil-cement below will remain. As indicated in Figure 1, the final channel width will be significantly narrowed; however, hydraulic capacity will be adequate for upstream drainage. The completed north side of the channel will be bounded by the seawall on the outside of the HOV-EB tunnel, which will be faced with granite blocks to simulate the appearance of the existing historic seawall.

Further to the east, the soil-cement placed by overwater operations was designed to support three filled circular cellular cofferdams. These cofferdams form freestanding excavation supports at the southern side of the area where the interface cast-in-place tunnel is to be built. The connection between the jacked tunnels and the ITTs was designed to be built in an open excavation, with major perimeter support provided by the future tunnels and the three cellular cofferdams. For

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**FIGURE 10. A cross-section of the Ramp D full-coverage soil-cement buttress.**
In the last stage of construction, freestanding support systems were designed to be erected on top of the jacked tunnels and the ITTs, with the Ramp D tunnel forming the fourth side. A cross-section through the cellular cofferdam is shown in Figure 12. The foundation design for the circular cells was 100 percent coverage soil-cement carried down to about 6 meters (20 feet) below the bottom of excavation, below which are shear walls of 38 percent coverage.
The Tunnel Jacking Scheme

The three tunnels that are being installed by the jacked tunnel method beneath the mainline railroad tracks leading to Boston’s South Station are of the overall sizes listed in Table 1. The locations of the jacked tunnels in final position are shown in Figure 1. The design sizes of the jacked tunnels were set both by the roadway alignments and tunnel installation tolerances (which determine the final tunnel envelope), and by proximity limits set by the railroad authority for thrust pit and reception pit headwall positions adjacent to the tracks. The tunnel
TABLE 1.
Jacked Tunnel Sizes

<table>
<thead>
<tr>
<th>Tunnel</th>
<th>Length</th>
<th>Width</th>
<th>Height</th>
<th>Depth of Cover</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ramp D</td>
<td>48 m (158 ft)</td>
<td>24 m (79 ft)</td>
<td>11.5 m (38 ft)</td>
<td>7 m (24 ft)</td>
</tr>
<tr>
<td>I-90 Westbound</td>
<td>76 m (249 ft)</td>
<td>25 m (82 ft)</td>
<td>11.5 m (38 ft)</td>
<td>5.5-8 m (18-26 ft)</td>
</tr>
<tr>
<td>I-90 Eastbound</td>
<td>107 m (350 ft)</td>
<td>24 m (79 ft)</td>
<td>10 m (32 ft)</td>
<td>1-7 m (3-24 ft)</td>
</tr>
</tbody>
</table>

alignments must accommodate highway geometries, installation requirements of the jacking technique, and railroad operational constraints. The profiles along alignments of the Ramp D and I-90 westbound tunnels are shown in Figure 5 with relative depths and soil stratigraphy indicated.

The thrust pits, in which each tunnel is cast and then advanced into the ground, are west of the tracks, as shown in Figure 13. In the tunnel-jacking scheme, each tunnel is divided along its length into a number of units that provide manageable jacking loads and practical jack arrangements. Hydraulic jacks are utilized both between each unit at intermediate jacking stations (IJSs), and behind the rear unit. The unit lengths designed were typically 15 to 20 meters (50 to 65 feet), but have been lengthened somewhat by the contractor. The lead unit is as long as possible to aid alignment — for the first tunnel jacked, this length is now about 27 meters (90 feet), yet it must be short enough so direction can be controlled by steerable jacks. The trailing units must be long enough to transfer jacking reaction at base slab level without lifting off the thrust base at its front end. The location of IJSs and jack details prepared for the design of the shorter Ramp D tunnel are shown on Figure 14.

The arrangement of thrust pits and the sequencing for tunnel jacking were designed to fit within limited available site areas between the railroad tracks and the adjacent existing interchange roadways. Unusual measures developed in the design to fit the jacked box units for I-90 eastbound into the jacking pit are illustrated in Figure 15. The very limited I-90 eastbound thrust pit length together with the design requirement to have all units cast prior to the commencement of the jacking operation necessitated design planning whereby the three rear units could be cast off-line within the I-90 westbound thrust pit. These units were then to be slid into line behind the front three sections during the I-90 eastbound jacking operation, in the sequence shown on Figure 15. However, a somewhat different sequence is being applied by the contractor wherein the second set of tunnel units will be constructed after the first set has been advanced into the ground.

**Thrust Pits**

To form the aforementioned thrust pits, special single-strutted excavations up to 70 feet deep have been constructed adjacent to the railroad tracks. The earth support system for the thrust pits consists of rigid soldier pile tremie concrete (SPTC) walls and reinforced concrete slurry walls (T-shaped in plan and post-tensioned for additional stiffness). A base mat of jet grout was provided in the design to be installed from ground surface to form a bracing element in excess of 6 meters below invert level to provide restraint to inward wall movement during excavation. This restraint and the cantilever effect of the walls penetrating below the base mat reduced the potential for ground surface settlement, which is a particularly important issue adjacent to the tracks.

In the design, the excavation sequences required intermediate supports using large pipe struts. Then, after installation of the 1- to 1.5-meter (3- to 4-foot) thick reinforced concrete thrust base slab that acts as a bottom permanent strut, the lower pipe struts would be removed to create approximately 11-meter (35-foot) high working spaces for the construction and installation of the jacked tunnels.
The jacked tunnel units are cast on the thrust base slab. Jacking loads are applied onto an "upstand" wall at the rear of the thrust base, and resistance to prevent backward movement of the thrust base is from skin friction along the soil interface both below the thrust base/jet grout and behind the side earth support walls. The structural analysis of the complete thrust base system was modeled using three-dimensional...
finite element analysis. Lateral movements of the pits were assessed by finite difference analysis using the program FLAC. The calculated thrust pit displacements under working jack loads of approximately 180,000 kN (20,000 tons) are expected to be on the order of 25 millimeters (1 inch).

The thrust pit headwalls are the entry points for the tunnel from the pit and into the ground. Headwall removal must be expedient at the start of jacking since the shield penetrates the headwall and the ground beyond. A cross-section of the shield designed for these tunnels is shown in Figure 16. It includes breasting grillages that can be closed in case of prolonged work stoppage or unstable ground.

The headwall was designed to be modified SPTC elements, comprised of vertical steel wide flange sections in a cement-bentonite matrix (rather than concrete). Headwall entry is usually a critical phase in the jacking operation, because lateral loads supported by the wall must be transferred temporarily to the tunnel shield until the support can be provided by embedment of the shield in the ground. The design provided for a gradual entry with headwalls skewed at 15 degrees to allow for progressive shield advance and wall removal in sections across the face. A skewed headwall does, however, produce an imbalance in ground pressures on the sides of the lead tunnel unit, which, in turn, can cause the tunnel to shift off line during the jacking cycle. This shift is then controlled by guides at the front of the thrust base and by the application of corrective adjustment to the rear jack forces.

**Jacking Forces & Hydraulic Jacks**

The design for the hydraulic jacks used to push tunnel units through the ground called for 4,500 kN (500 ton) capacity. Typically, 40 jacks were to be installed at each IJS. Following initial headwall breaching, the rear jacks pushing against the upstand wall are used to drive the full tunnel forward into the ground until the lead unit is fully embedded. Then, the jacks pushing against the first IJS are used to drive just the lead unit forward. Each trailing unit in turn is then pushed forward by its IJS jacks. Thus, the whole tunnel is moved forward and through the ground in a "caterpillar" action. This use of IJSs at regular intervals reduces the force required at any one time to push the tunnel segments ahead. This arrangement also assists in the directional control of the tunnels during installation and can reduce the amount of ground disturbance.

Multiple jacks are used to provide a factor of safety on calculated working loads on the order of 2, thereby allowing for variations in jacking resistance. This jack "over-capacity" makes additional force available should it become necessary to exert directional control. The use of multiple jacks also allows for the equipment to be operated at lower hydraulic pressure than their rated capacity in order to reduce wear and maintenance.

**Reducing Friction Between the Tunnel & Ground**

There are several benefits in reducing friction between the moving tunnel and the stationary ground. The first benefit is to lessen the pushing force required from the hydraulic jack system. The friction reduction acts to produce a more uniform friction around the tunnel perimeter, which aids in installation alignment, and prevents excessive ground settlement and...
The design included several measures to minimize drag on the tunnel units as they advance beneath the railroad:

- An anti-drag sheet system between the tunnel roof and the overlying soil, with grease pumped through the roof to the underside of the drag sheets.
- Specified close tolerances and smooth finishes on the external concrete faces of the tunnel units.
- Overcut plates down the sides of the leading edge of the shield.
- Lubrication around the tunnel sides with bentonite slurry.

The anti-drag sheets provide a separating membrane between the tunnel and the overlying soil whereby the sheets remain static relative to the soil above to reduce the tendency for the advancing tunnel to drag soil forward, which can result in track movements. The anti-drag sheets have to withstand large tensile forces; they are anchored at the headwall of the thrust pit and, thus, prevent the overlying soil block from being carried forward with the advancing tunnel units. The anti-drag sheet system designed was approximately as shown in Figure 16, with the sheet being comprised of multiple laminated layers of steel sheets 0.8 millimeters (1/32 inch) thick to maintain flexibility for feeding out through roof slots behind the shield. The system was designed to cover about 70 percent of the roof surface. The grease injection ports were designed to be through the roof of the tunnel (not shown on Figure 16). However, the contractor is using a patented anti-drag wire rope system for both the roof and invert slab. The effectiveness of friction reduction accomplished by an anti-drag system is to some degree related to the depth and nature of the overlying soils.

Control of Tunnel Alignment
With Guide Paths

Jacked tunnels can be installed within close tolerances. However, once a tunnel starts to go off-line during the jacking cycle it can be difficult to correct the alignment. Therefore, primary emphasis must be given to ensure that the tunnel starts off in proper alignment. Then, through-out the tunnel advancement, efforts must be taken to accurately maintain the alignment, with corrective steps taken immediately if any deviation becomes apparent.

Highway-sized jacked tunnel units cannot be pushed or pulled back on-line as can small-diameter jacked pipes. When there is concern for the ability to maintain vertical alignment, then “guide paths” can be installed prior to tunnel jacking to aid in resisting the tendency of a tunnel to dive into soft ground. The design of these tunnels included two guide paths per tunnel to provide more positive guidance than that afforded by using only the steerage jacks at the lead IJS. Guide paths were included in the design to mitigate the risk of exceeding the allowed vertical alignment tolerances. The function of the guide paths is to limit the effect of nosing by providing a load resistance ahead of the tunnel face. Essentially, the guide paths act as a pair of skis ahead of the jacked tunnel. They are not intended or designed to support total vertical tunnel loads.

The guide path arrangement, shown in Figure 17, was for reinforced concrete guide paths to be cast into the bottom half of 2.8-meter (9-foot) diameter tunnels driven by conventional means. On top of the guide path, special slide tracks of aluminum/bronze running plates on steel billets were called for, over which the slide base of the jacked tunnels ride.

For long jacking distances, special construction methods must be employed to aid in maintaining vertical alignment. These methods include:

- Careful construction tolerance control to ensure that the tunnels are of regular cross-section without surface distortions or irregularities;
- Control of friction around the tunnel to minimize sudden changes in drag forces;
- Locating IJS jacks in the corners of units to maximize the corrective moment that can be applied;
- Side guides on the jacking base for horizontal alignment for unit entry;
- Continual careful mining techniques; and,
- Application of ground treatment to reduce the chances of local instability that would affect control of shield advancement.
Calculations during design indicate that for the assumed site ground conditions, there could be a tendency for the lead unit to nose down under the peak loads on the shields if guide paths were not provided. The mechanisms in soft ground are such that the propensity for nosing down increases progressively the further the tunnel is advanced. Other related factors also considered in tunnel alignment control for jacked tunnels in soft ground include:

- Remolding of medium sensitive clays in the zone of high contact stress beneath the shield floor.
- The tendency for the clay beneath the shield floor to become softer due to relaxation into the open face.
- The passage of the trailing units over soft ground, which could cause the units to scour themselves deeper into the ground, causing misalignment and more severe settlements at ground level.

To analyze the forces on the guide paths and underlying soil for structural design purposes as the tunnel is jacked over the guide paths, the paths were idealized as beams on elastic foundations. In these analyses, predictions were made of the deformations of the guide tunnels to assess their effectiveness in maintaining the required vertical alignment control. The results indicate that the limited contribution of the guide paths would be sufficient to boost the tunnels and prevent "nosing" into the soft clay. An assessment was also made of the contact pressures between the underside of the jacked units and the slide track at the top of the guide path.

**Control of the Tunnel Face**

Tunnel jacking is, in general, a soft ground tunneling technique that has an essential requirement of controlling ground movements in order to keep resulting surface settlements within tolerable limits. Therefore, the design must incorporate the means to minimize loss of ground into the tunnel face. The tunnel design provided a shield, which can support the ground at the face while providing the means for efficiently excavating the soil at the face. The shield design also included breasting grilles, which can be closed to provide additional face support if the ground stability conditions warrant. Further, ground treatment measures were included for application prior to and during jacking to aid in maintaining face stability, thereby controlling settlements and providing for the safety of the overlying railroad and the workers at the excavation face.

The shield geometry and the level of ground treatment are interrelated — more ground treatment tends to allow for a more open shield face. The balance between these two factors depends on ground conditions, size and geometry of the tunnel face and the means of excavation and integral face support. The tunnel shields designed for this CA/T Project section provided a number of face compartments to...
enhance stability and to provide convenient access to all sections of the face (see Figures 16 and 17). Two horizontal shelves were provided in the design to divide the face into three levels of cells, each with about 3-meter (10-foot) clear height. This height is convenient working headroom, which permits mechanical excavation, and yet is sufficiently low for worker access to the face to remove obstructions. A wide blunt edge was designed for both the shelves and the vertical walls (spaced about 3.3 meters [11 feet] apart) to provide further face support. A conventional steel cutting edge was required at the perimeter of the shield.

The stability of ground in the shield excavation depends on the inherent strength of the soil, its resistance to erosion by water, the degree of control provided by the shield, and the techniques used by the construction workers at the face. In the granular fill materials where strength is provided by friction, the greatest threat to stability is possible erosion resulting from groundwater gradients and flowing water at the face. In the clay, stability concerns center primarily on low undrained shear strength. Due to the relatively thin cover that is largely granular fill, it was essential to pre-drain groundwater from the fill stratum prior to advancing the tunnels. In the lower, soft cohesive strata, horizontal reinforcement was included in the design to enhance face stability.

Design analyses were made of tunnel face stability for two different soil stratification conditions (shown in Figure 5) using FLAC. The first model, for the Ramp D alignment, specifically addressed the strength of the Boston blue clay and its effect on face stability. The second model was for the shallower I-90 eastbound and westbound tunnels that have granular fill in the upper cell, organic soils in the middle shield level and clay at the lower level. The results showed the need for draining groundwater from the permeable layers, and for resisting face pressures in the clay. A soil nailing system was developed in design to add resisting force to the ground at the tunnel shield face.

**Ground Treatment to Enhance Face Stability**

Considerable ground treatment measures were required in the design to enhance stability at the face, comprising a combination of dewatering, grouting and soil nailing. Also, retractable face support grillages were to be provided in each cell of the shield, ready for contingency use and to support the face during any prolonged jacking stoppages. It was not, however, intended that grillages be used during normal jacking operations.

Dewatering of the area near the tunnel is essential prior to breaking through the headwall, and was designed to be carried out from the ground surface. To reduce dewatering-induced ground settlements, a perimeter grout curtain cut-off down to the clay was set out to surround the plan area of the jacking operation. During the tunneling operations, local dewatering could be achieved as needed using lances from the shield.

Face stability analysis indicated that stability is significantly enhanced where the fill is grouted in front of the shield. The grouting also helps support the ground when removal of obstructions is necessary. Therefore, the design required fill and sand strata immediately behind the headwall to be grouted using sodium silicate to at least 6 meters (20 feet) horizontally from the headwall prior to shield entry. The design also required grouting the fill and sand strata within the tunnel cross-section directly from the tunnel face to maintain a minimum 6-meter (20-foot) zone of grouted ground ahead of the advancing shield (with the grouting operation extending ahead of the face by about 12 meters [40 feet] at repeating intervals). Figure 18 shows the pattern of ground treatment designed for I-90 westbound tunnel. To enhance the stability of softer zones in the clay, soil nailing was designed to be installed, as indicated.

**Ground Movements, Track Settlement & Instrumentation Monitoring**

Ground movements are expected during all stages of wall installation, pit excavation and grouting. However, during design, the greatest potential for ground movements was considered to be associated with the tunnel jacking operations. Assessments of face loss and shield overcut were used to produce cumulative settlement contours as jacking proceeds, and to evaluate surface gradients and rates of move-
FIGURE 18. The design requirement for ground pre-stabilization at I-90 westbound.

ment. Lateral ground movement toward the open excavation face at the shield was not expected to be more than 15 centimeters (6 inches). Other factors considered (jacking tolerances, ground lost at major obstructions and in their removal, shield overcut, soil scouring at IJSs and the effects of dewatering) caused predicted cumulative surface settlement to be on the order of 25 centimeters (10 inches). For the rate of settlement that was forecast, it was determined in design that routine railroad maintenance and regular surfacing and reballasting of the tracks could keep net movements within the threshold limit of 25 to 50 millimeters (1 to 2 inches).

The design included extensive geotechnical instrumentation to monitor vertical displacement at the ground surface and vertical and horizontal movements within the ground. The monitoring system will provide early warning of any unexpected ground movements that may cause difficulty to railroad operations. It will also provide data for the track maintenance program as well as permit comparison of actual movements to predictions for back analysis and adjustments to tunneling methods.

The scope of the complex instrumentation layout designed for the path of the I-90 westbound tunnel is shown in Figure 19. Optical surveying will be used to monitor track movement.

Contactor-Proposed Design Changes

The specialist nature of construction activities and the variety of ways in which tunnels can be installed often give rise to benefits in allowing the contractor to develop temporary works to suit its experience, methods of working and equipment. The case on the CA/T Project in Boston allows the contractor to implement several modifications to the original design, including:

- An anti-drag steel rope system (contractor’s patented method) instead of the laminated steel sheet method called for in the baseline design for this project section.
- Ground freezing to support the ground ahead of the jacked tunnel instead of extensive grouting and soil nailing.
- Elimination of the guide paths in expectation that the frozen ground will relieve pressures that would otherwise drive the tunnel downward.

Ground freezing is expected to provide a more homogenous ground improvement than the array of grouting and soil nailing originally designed. It does, however, require a great degree of access over the tracks in order to install the brine freeze tubes, which was not an option for the designers. The freezing process (installation and soil solidification) requires substantial installation, operating equipment and maintenance; however, the contractor has accepted these requirements so that jacking can
proceed with fewer disruptions once the freeze zone is established than would be required for incremental application of grouting. Freezing the ground ahead of the tunnels also has allowed modification of the shield details because soil movement into the face can be significantly restrained.

Summary
The use of soil-cement stabilization to form berms and deep permanent buttresses and foundations for tunnels is an important innovation in the design of measures to "tame" the difficult ground conditions in the complex I-90/I-93NB interchange at Fort Point Channel that is currently under construction. The southern 250-meter (950-foot) long portion of Ramp L tunnel's buttressed against 11 meters (35 feet) of unbalanced lateral earth loads by a 12-meter (40-foot) thick by 37-meter (120-foot) wide berm of soil-cement that stabilized miscellaneous granular fill and a very soft stratum of organic silt. In narrower channel areas where the berm is not possible, the soil-cement was designed to extend to depths of 30 to 38 meters (100 to 125 feet) to bear on glacial till deposits, thus forming rigid buttress shear walls that resist the unbalanced soil and water lateral loads. In all, approximately 600,000 cubic meters (800,000 cubic yards) of soil-cement are being formed to stabilize soft organic soils and marine clays to provide excavation base stabilization and resist unbalanced lateral loads.

The tunnel jacking technique was designed for the crossing beneath the busy railroad at Boston's South Station Transportation Center. It was proposed as a solution to avoid extensive relocating of the tracks for incremental cut-and-cover tunnel construction. The three tunnels at depths of 11 to 18 meters (35 to 60 feet) with lengths from 48 to 107 meters (158 to 350 feet) are first built in large braced excavations adjacent to the tracks, and then jacked under the tracks using shield tunneling methods by incremental jacking and excavation.

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