JACKING LARGE TUNNELS BENEATH ACTIVE RAIL TRACKS

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ABSTRACT

Tunnel jacking represents a technique that has been developed in recent years to install large tunnels beneath active rail tracks, while continuing to allow uninterrupted use of the tracks. The technique developed from pipe jacking, when available circular sections were either too small, or inefficient, for the final use of the tunnel. Early tunnel jacking projects involved the construction of relatively small section pedestrian tunnels, with 100 sq.ft. face or less, through to the current day when tunnels with a face area in excess of 3,000 sq.ft. are being installed. The paper will focus on the recent completion (Spring 2001) of the successful jacking of three tunnels forming part of Boston’s $14.5 billion Central Artery/Tunnel Project. The tunnel sections represent the largest, most complex tunnels ever to be installed using jacking methods. At 80ft wide by 40 ft high, the typical tunnel cross-section is ten times larger than previously attempted within the United States.

The tunnel sections, which are up to 370 ft in length, pass just a few feet beneath 8 operational rail-tracks, carrying over 400 Amtrak and MBTA trains per day into and out of Boston’s South Station.

The tunnel project is an award-winning example of what can be accomplished with innovative engineering and strong collaboration with construction forces. The project will be described from initial design concept and planning, through the development of contract documents, and on to the construction – where the designers, contractor, client and railroad operators worked cooperatively towards the realization of the end goal.
INTRODUCTION

The Central Artery

The existing I-93 Central Artery, which passes through Downtown Boston, was originally constructed in the 1950’s. When opened, this elevated ‘Green Monster’ could comfortably accommodate 75,000 vehicles per day. The same structure now carries in excess of 190,000 vehicles per day resulting in severe congestion and delay.

The concept of replacing the now dilapidated, elevated eyesore, has come to fruition. A new, widened I-93 is under construction beneath the city of Boston. The project also provides an underground connection between the Massachusetts Turnpike, I-90, and Logan Airport, further reducing Artery traffic.

At $14.5 billion, Boston’s Central Artery/Tunnel project represents the largest publicly funded construction project in the United States.

Contract D09A4

Two of Boston’s major highways, I-90 and I-93, meet at the South Bay Interchange, located less than 1km from Boston South Railway Station. The interchange – which needs to accommodate through traffic in all four directions, together with numerous additional local on/off ramps – consists of multiple levels of tunnel, open depressed (boat) sections, surface road and viaduct structure.

Figure 1. Plan of Tunnel Site
At the lowest level there was a requirement to construct highway size tunnels beneath the eight tracks serving Boston South Station. These tracks support 400 train movements per day and carry over 40,000 commuters to and from the city. The rail tracks could not be (practically) relocated to allow the construction of cut and cover tunnels, which ordinarily would have been the preferred construction method.

Therefore the tunnels had to be constructed while the train operations, just a few feet above, continued unaffected by the tunneling. Hatch Mott MacDonald proposed the use of tunnel jacking. The proposal was accepted by the Program Manager, a joint venture of Bechtel/Parsons Brinckerhoff.

Figure 1 shows the location of the existing rail tracks and the adjacent jacking (thrust) pits, and indicates the completed tunnel sections in their final position.

**The Tunnel Jacking Process**

The major features of the tunnel jacking operation are shown in Figure 2 below.

![Figure 2. Schematic of Tunnel Jacking Operation](image)

The tunnel box sections are completely constructed within purpose built jacking pits, excavated immediately adjacent to the rail tracks. Once complete, the tunnel boxes are advanced through an
opening formed in the headwall, by means of hydraulic jacks, located at the rear of the jacking pit. This is a crucial part of the tunnel jacking operation and a carefully sequenced method of progressive removal of sections of the headwall and transfer of ground support to the tunnel is often required. Excavation of the tunnel face proceeds from within a purpose-built shield. The shield is designed to allow the contractor to excavate the open face of the tunnel as jacking proceeds. Details of the shield depend on the ground conditions, size of the tunnel, and the means of excavating and removal of the soil from the tunnel face.

Excavation followed by jacking continues until the tunnel is pushed into its final position.

Due to the size and complexity of this project, and due to the extremely poor ground conditions, which will be described in detail later, a number of additional, unique design features were implemented. These include:

- The used of intermediate jacking stations. Due to the size of the tunnel boxes and the friction forces capable of being generated by the surrounding soils, jacking forces required to move a single tunnel box would be unachievable. Intermediate jacking stations (IJS) were introduced at the tunnel midpoints to reduce the motive force required to propel the tunnel boxes.

- A ground freezing scheme was implemented to improve the anticipated ground conditions and stabilize the face of the tunnel excavation.

- A patented system of greased, steel anti-drag cables was used to reduce friction forces at the tunnel roof and base slabs.

TUNNEL CONSTRUCTION

Jacking Pits

Slurry Walls

Prior to any fabrication of the tunnel boxes the construction of the jacking pits must be complete. The jacking pits were sized to accommodate the tunnel sections and the equipment required to install the tunnels.
The walls of the jacking pits were constructed using slurry wall methods, typically comprising 4 ft thick concrete walls reinforced with a combination of structural steel shapes and conventional reinforcement cages. The overall depth of the slurry walls varied to a maximum of approximately 100 feet. CA/T Project design criteria placed strict limitations on spacing of internal bracing members for excavation support. The criteria would have required bracing at 12 – 15 ft centers horizontally and vertically to support the slurry walls. As such a bracing configuration would interfere with both the tunnel construction and the jacking process the design team suggested the installation of a brace at the top of the slurry wall, with a clear excavation to the base of the jacking pit. The team obtained waivers from project standards to permit clear vertical slurry wall spans of up to 55 feet.

In some cases due to either the geometry of the pits or the height of the jacked tunnel sections, portions of slurry wall had to be designed as cantilevered T panels, constructed using 3 ft wide slurry wall panels with approximately 15 ft ‘flange’ and approximately 12 ft ‘web’. Many of these panels were reinforced using either post-tensioning techniques or using structural steel sections due to limitations on fabrication space and available crane lifting capacity.

The slurry walls had to withstand external soil and groundwater pressures, and surface surcharge loads from rail and road traffic, while keeping ground movements adjacent to the pits to within acceptable levels. The walls also had to be robust enough to withstand the very large forces imposed during the jacking of the tunnels.

Jet Grout

The revised bracing scheme proposed for support of the jacking pit walls resulted in instability at the base of the slurry wall, regardless of the wall embedment depth below the bottom of excavation. Predicted wall movements could be effectively controlled by installing a compression strut beneath the base of the excavation for the jacking pits. Jet grouting was chosen as the preferred method of improving the in-situ soils. The footprint of the jacking pits was covered by a series of 6 ft diameter, overlapping, jet grout columns between 20-25 ft deep.
After completion of the jet grouting operation, and installation of the top layer of bracing, excavation to invert level was completed.

The floors to the jacking pits comprised heavily reinforced concrete slabs. The slabs acted as further stiff support to the slurry walls, and transferred forces from the tunnel jacking operation. The slabs were typically 3 ft thick, but thickened locally to 5 ft at the rear of the jacking pits, where the effects of the jacking forces were greatest. The top surface of the floor slab was constructed to exacting tolerances, as this surface provided the form against which the tunnel base was constructed.

Wall deformations did occur during construction. Figure 3 shows actual deformations for typical braced wall panels and cantilevered wall panels. It can be seen that the recorded deformations are well within the acceptable limits.

![Figure 3. Slurry Wall Deformations](image)
Ground Freezing

Approximately 200 years ago the bulk of the current tunnel site would have been underwater. The area has been progressively filled in over the years. The material remaining reflects the varied history of the area including waterfront, industrial, and rail facilities.

The geology of the site comprised a 20 – 25 ft layer of fill material, which was known to contain an abundance of obstructions including cobbles, boulders, timber piles, granite blocks, and fragments of concrete and brick foundations, as well as an abandoned, depressed rail track. Groundwater levels at the site are typically 6 to 10 ft below existing grade.

The fills overly deposits of organic materials in the range of 10 to 15 ft thick. Below the organic deposits are local lenses of relatively dense alluvial material, generally less than 5 ft thick, which in turn overly a thick layer of marine, or Boston Blue clay, consisting of clay and silt. This material is stronger and less compressible at the top, over a thickness of approximately 15 ft. The lower section of the marine clay is considerably softer, and is very sensitive when disturbed.

Therefore a significant concern for the jacked tunnels was stabilization of the weak soils through which the tunnels were to be advanced. Controlling the loss of ground into the face during installation of the tunnel is critical, both to limit ground movements and to aid directional control. In soft ground conditions, ground loss can be controlled by either providing sufficient support from the shield, or by improving the ground so that it does not tend to come in towards the face, or by a combination of these.

A ground freezing program was developed to improve the in-situ stability of the existing soils. An array of approximately 1,800 freeze pipes, spaced at 5-6 ft centers was developed, to encapsulate the soil mass through which the tunnels would be jacked. The 4-½-inch diameter steel freeze pipes were vibrated into the soils and interconnected to a compact refrigeration plant located on site. Brine at a temperature of -20° Celcius was pumped through main feed lines to the freeze pipes. The chilled fluid froze the groundwater in the soils over a period of 5-6 months, effectively
turning the ground into a giant ice cube. Figure 4 shows ice visible at the heads of the installed freeze pipes.

Figure 4. Ground Freezing In Progress

Water expands by approximately 9% when it freezes. When ground freezes it also has the potential to expand. The amount of expansion is dependent upon how much water is in the ground and how much of that water can permeate away from the area being frozen as it passes through the phase change between liquid and solid. This is a function of ground permeability, the speed of the freezing process, the geometry of the ground being frozen and the sequencing of the freezing operation.

After an assessment of the ground characteristics and laboratory testing of the soils, it was determined that expansion would occur in two orthogonal horizontal directions from the center of each frozen mass, and vertically upward from the base of the frozen mass. The majority of the expansion was caused by freezing of the organic and clay strata. The fill had sufficient permeability to allow the water to dissipate as it froze.

Maximum vertical heave was estimated at approximately 7 inches for Ramp D and I.90 Westbound tunnels, which were the deepest, slightly less heave was predicted for I.90 Eastbound tunnel, which was the shallowest and which required less freezing in the clay strata.
Figure 5. Plot of Ground Heave versus Time

Figure 5 shows a plot of the anticipated maximum ground heave against time, together with the actual heave experienced. It can be seen that the actual ground heave, though seemingly large, occurred over a period of many months. Daily surveys and monitoring of track positions and elevations were undertaken to ensure track movements were within specified MBTA/Amtrak tolerances. Working crews were always on hand to re-ballast areas as necessary.

**Tunnel Box Construction**

On completion of the tunnel jacking pits, construction of the tunnel boxes themselves could begin. The first step in the construction process involved the fabrication of a steel baseplate, covering the footprint of the tunnel. This plate principally served as a bond-breaker between the concrete surfaces of the jacking pit floor and the tunnel base slab, allowing the tunnel section to be pushed across the pit floor. Thereafter, a regular pattern of sequential base, wall and roof concrete pours was followed. The structural concrete members were typically in the region of 5-6 feet in thickness and very heavily reinforced.
**Tunnel Jacking**

*Excavation*

The tunnel jacking process comprised sequential excavation of frozen ground at the face of the tunnel, followed by jacking of the tunnel box by hydraulic jacks located at the rear of the tunnel section.

After completion of the opening in the headwall, the excavation of frozen soil commenced. The frozen soil exposed within the box face consisted of layers of historic fill, organic materials and soft clay. The freezing process transformed these soil types into an almost uniform mass with an estimated strength of 5-10 kPa. The freestanding vertical face, 38 ft in height, was capable of supporting its own weight, even after several days of inactivity.

Excavation of the frozen soils was undertaken using Webster 2000CS roadheaders, specially imported from Europe. Typically, production rates of 15 yd$^3$/hr were achieved. The soil removed at the face was gathered using a Gradall 2200 and a CAT Loader 906, and transported out of the tunnel box. The soil was lifted from the pit, using a 4 yd$^3$ bucket and a Manitowoc 4100 crawler crane on the surface adjacent to the rear wall of the thrust pit.

Well ahead of the excavation, the brine was removed from the freeze pipes near the face. The pipes were exposed, cut with magnesium lances, and removed from the tunnel.

Obstructions encountered during the excavation of the included timber piles, and masonry foundations. The freezing had fixed these obstructions well into the surrounding soil and they could be removed relatively easily using the available equipment.

*Jacking*

The motive force to propel the tunnels was produced by hydraulic jacks. The jacks were located at the rear of the tunnel and at intermediate jacking stations between individual segments of tunnel. All jacks were positioned at the elevation of the tunnel base slab. Each jack was capable of generating a working load of 500 tons, and an ultimate load of 1,000 tons. As approximately
30 jacks were grouped at each jacking station, the total jacking force available at any one time was 30,000 tons.

A reaction block was cast on the thrust pit floor slab to transfer the jacking loads into the surrounding ground. From this block the loads are transferred through the slab and the pit walls into the surrounding soil, with the distribution in relation to the resisting stiffness of structure and soil.

After the maximum stroke of the rear jacks is reached, packers were inserted between the jacks and the thrust block, allowing future jacking to continue against the packers. The packers comprised of 3 ft-diameter steel pipes, with a wall thickness of ¾ inch, and with nominal lengths of 3 ft and 12 ft. The shorter spacers were used after each jacking cycle, until the larger sections could be installed. A 4-inch thick steel plate was used to transfer the load from jacks to packers. Figure 6 shows the hydraulic jacks being retracted to the left of the photograph, having recently completed a cycle. Additional steel packers will be placed in the gap left by the jacks, and the process repeated.

To reduce the amount of friction between the tunnel box and the surrounding soil, an anti-drag systems (ADS) was introduced.
The ADS comprised ¾ inch diameter greased steel cables, which formed a bond breaker between the tunnel roof and base slabs and the surrounding soil, preventing the wedge of soil above the tunnel moving with the tunnel as jacking progressed. The cables ran from reels mounted within the tunnel boxes, exited through holes in the tunnel shield, and passed between the tunnel concrete surfaces and the soil, to anchorages within the jacking pits. The base ADS cables were anchored in dovetail shaped slots in the jacking pit floor, using a high strength epoxy resin. The roof ADS cables were anchored to plates attached to the jacking pit headwall bracing beams, using crimped-on copper sleeves.

Due to the size of the boxes and the potentially enormous jacking forces required to move the tunnel sections, intermediate jacking stations (IJS) were utilized. The IJS’s were designed to mitigate conditions where the required rear jacking load is too large to be transferred to the surrounding soil or exceeds the capacity of the jacks.

Advance rates for the tunnel sections were dependent upon the times taken for excavation and soil removal. The actual time used for the jacking was less than 30 minutes for each 3 ft cycle. The follow-on installation of the spacer system did not interfere with the soil removal and therefore did not affect the cycle. The jacking operation was executed in 2 shifts of 10 hours each, 6 days per week. After an initial learning curve and some start-up problems with equipment, typical advance rates of 3 ft per day were achieved.
CONCLUSION

Many claim that Boston’s Central Artery/Tunnel project is the most ambitious and complex urban highway construction project ever undertaken. The project features many engineering innovations, of which contract C09A4 is one.

On a scale never previously attempted, this tunnel jacking operation beneath 8 active MBTA/Amtrak rail tracks was a complete success. In the four years of construction, there were no disruptions to train service. The project was completed on schedule, and close to the original bid price of $397 million. The success of this project was clearly a testament to the cooperation of all parties involved.