An Underpinning Scheme for the Red Line Subway at South Station, Boston

A construction method based mainly on jacking steel pipes offers a way to minimize harmful ground movements, worker risk & interference with normal daily operations.

BURTON P. KASSAP

The proposed alignment of the northbound Central Artery (Interstate 93) passes under the Massachusetts Bay Transit Authority (MBTA) Red Line South Station subway at the intersection of Atlantic Avenue and Summer Street in downtown Boston. To accomplish the task of placing the highway beneath the subway, a method of construction for underpinning the Red Line at South Station was adopted that utilizes jackpipe tunneling techniques, in conjunction with alternate pit underpinning and square set mining methods. The primary concerns of this undertaking are to properly safeguard the running rails of the MBTA during all phases of construction, to avoid any penetration into the subway that might prevent continuous train operations, to avoid interfering with the riding public and to provide a construction-free environment at the intersecting street surfaces. Emphasis is placed on minimizing the exposure of the unsupported areas of excavation during the underpinning operation and on minimizing the amount of deflection of the structural members used to support the Red Line at South Station during and after load transfer.

Both the method of constructing a deep tunnel for the proposed northbound Central Artery lanes and the construction procedure to underpin the MBTA Red Line subway and station at South Station involve the use of jacked pipes, which are modified to form a permanent arched-roof structure beneath the Red Line subway, permitting excavation of the tunnel below. The method was proposed in the preliminary design for the deep tunnel, and will be further refined and modified during final design. The underpinning will be needed to support the excavation and construction of the deep cut-and-cover tunnel for the north-

bound Central Artery lanes.

Each part of the proposed underpinning method relies on (and uses) positive structural elements, provides for remedial action if unforeseen soil movements occur, controls the amount of structural deflection, satisfies the concerns mentioned above and minimizes the risk of structural damage and bodily injury during and after construction.

Background

The Central Artery/Third Harbor Tunnel Project consists of approximately seven miles of new and reconstructed roadways, which includes the construction of a widened underground portion of Interstate 93 (northbound), that extends from Kneeland Street in a northerly direction to Causeway Street (see Figure 1). This route, which is along Atlantic Avenue, is in the heart of downtown Boston. The overall project is being designed to improve both the capacity and safety of the existing highway facilities, and will provide an additional harbor crossing for access to Logan Airport.

The current accident rate on the Central Artery is nearly twice the nationwide average for the Interstate System. The major elements of the proposed reconstruction will substantially reduce that rate by an estimated 35 percent. The Central Artery/Tunnel Project will have beneficial transportation impacts in every part of central Boston and the surrounding area.

Traffic volumes are forecasted to average 221,100 vehicles per day by the year 2010 along the Central Artery between Kneeland and Causeway Streets. This volume will require widening the Central Artery from six to eight lanes, with additional operational lanes for weaving movements, acceleration and deceleration.

The portion of the proposed northbound Central Artery that falls within the South Station area consists of a four-lane reinforced concrete structure. Its subgrade distance below street level is approximately 90 feet where it will pass under the existing MBTA Red Line subway station at South Station (see Figure 2).

The location of the subway station is directly beneath the busy intersection of Summer Street and Atlantic Avenue. This intersection is the site of a complex of important buildings, including the 32-story Federal Reserve Bank of Boston building and garage located on the northeast corner, the five-story South Station railroad building and depot servicing Amtrak and the MBTA commuter rail system on the southeast corner, and the 46-story One Financial Center building on the southwest corner of the site. The Dewey Square Tunnel vent shaft structure and a bus terminal occupy the northwest corner of the site. The intersection handles heavy vehicular and pedestrian traffic. Maintaining this traffic in an uninterrupted manner, as well as commercial services to this area, were important objectives for the preliminary design.

The construction of the northbound Central Artery under the existing South Station will require a method of underpinning that will safeguard the station structure and running rails from any settlement or excessive deformation. Also, it is imperative that both passenger service and train operations not be interrupted. Towards those goals, a series of preliminary design studies were conducted that resulted in the development of a method that employs jackpipe tunneling techniques in conjunction with alternate pit underpinning and soft ground mining methods.

Underpinning Design Factors & Procedure

The technical term, *underpinning,* is used to denote the placing of new foundations or supports under existing structures. The design of a successful underpinning scheme depends on the following factors:[1,2]

- An assessment of the condition of the structure to be underpinned in order to determine its ability to sustain the loads and stresses that may be imposed by the underpinning operation.
- An examination of the geologic profile that falls within the influence lines of the structure that is to be underpinned.
- An assessment of the structure's environmental aspects as they pertain to its continual and functional usage during construction.
- An assessment that determines whether

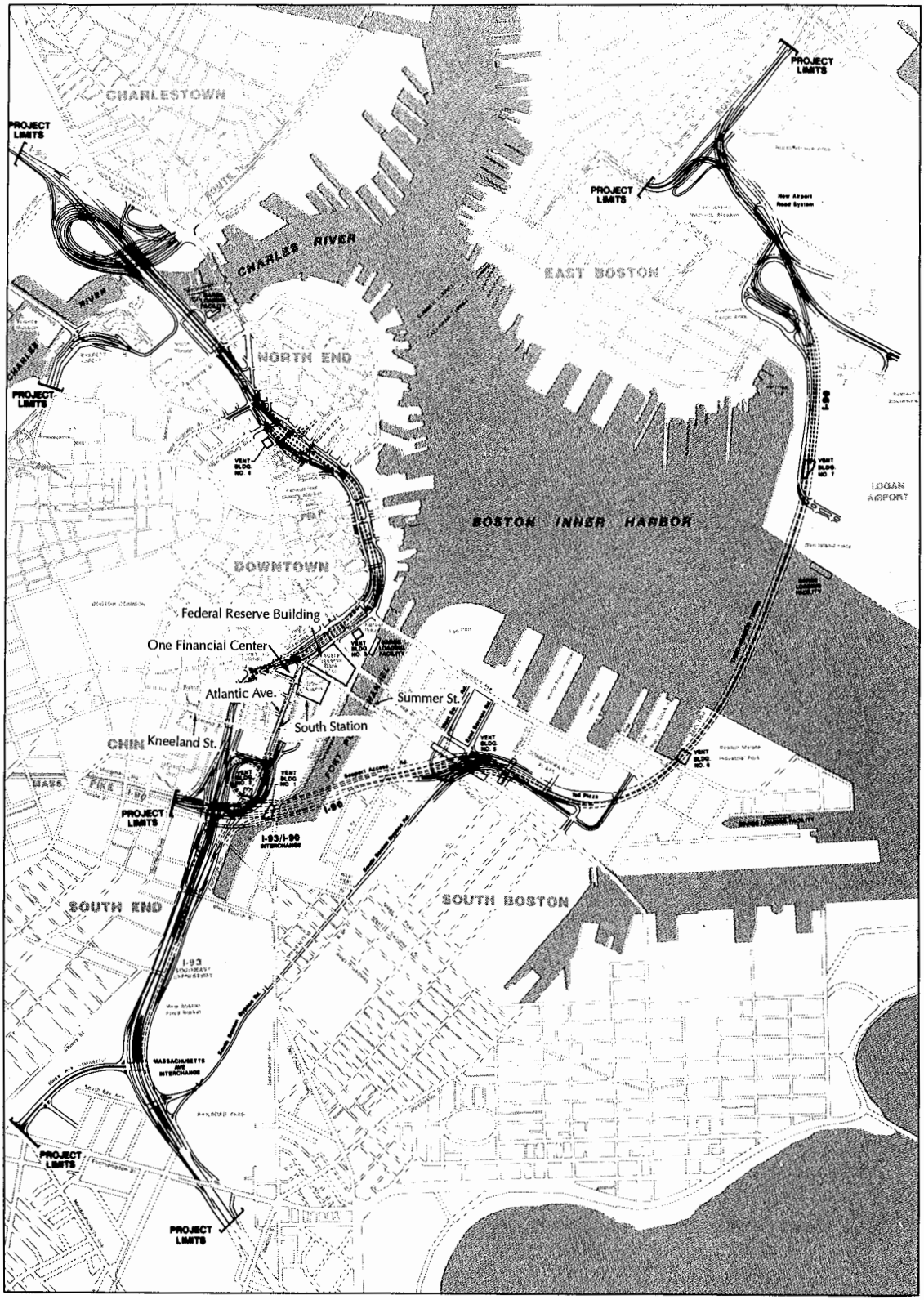


FIGURE 1. Central Artery depression/Third Harbor Tunnel project plan.

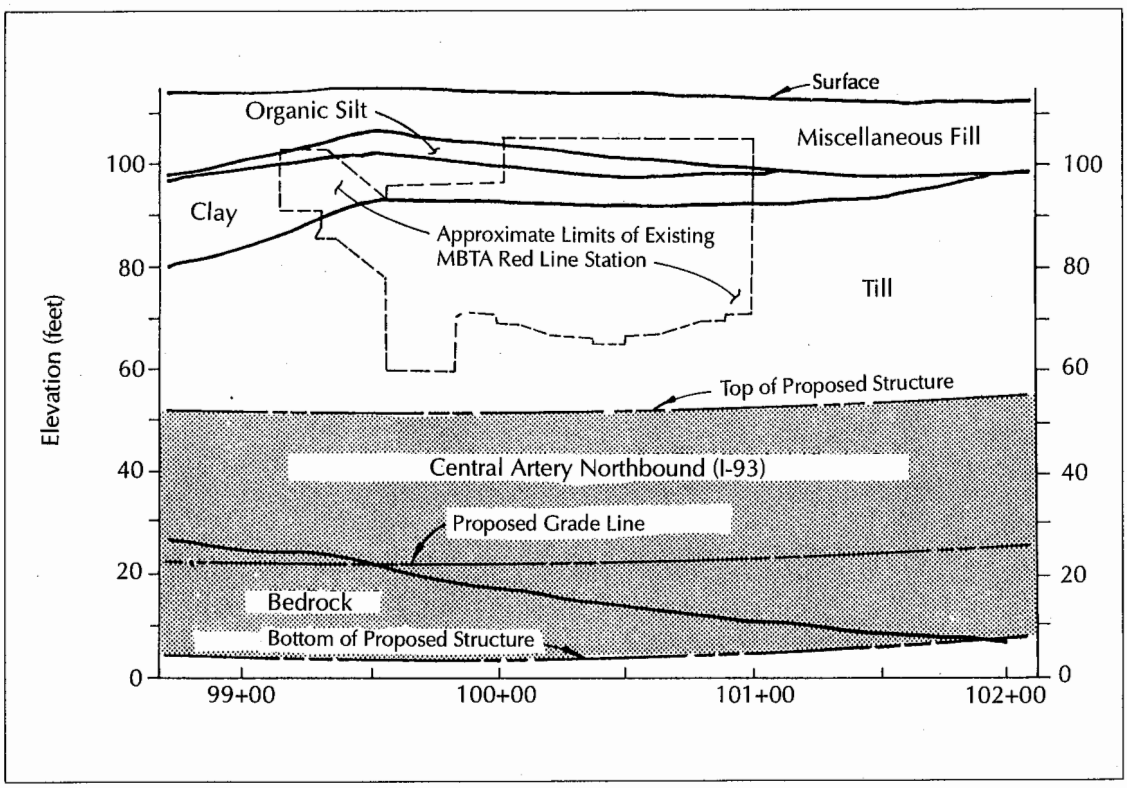


FIGURE 2. Profile of the proposed northbound Central Artery at South Station.

the people involved in the use of the facility during and after underpinning, as well as those involved in the underpinning construction operation itself, will be placed at risk.

The existing South Station Red Line transit system was constructed in 1914 and 1915 under the auspices of the Boston Transit Commission. Cut-and-cover construction was the method used to build this two-level (*i.e.*, platform/track and mezzanine) structure. The depth of the structure subgrade is about 55 feet below the street surface and it is founded on hard grey silt and clay (see Figure 3).

During the original construction, interlocking steel sheetpiling was utilized for the lateral earth support. Based on a review of the original structural contract drawings and preliminary design site field inspections, it appears that this subway station is in good condition. All beams and columns are rolled structural I-beams, many of which are reinforced with riveted plate members. Concrete slabs between the beams are reinforced with various size steel square bars that are spirally deformed. The concrete appears quite sound considering its age. Signs of leakage, cracks and deterioration are visible, but are minimal and have been repaired and replaced by recent modernization contracts.

It should be noted that an examination of the existing structure will be critical to final design decisions of underpinning and the particular methods to be used. The preliminary appraisal revealed a structure that is working well within its original design criteria and is capable of taking certain measured stresses and strains that might be imposed by the underpinning operation.

The preliminary geologic profile shows approximately 20 feet of fill measured from the street surface. This fill is underlain for the next 35 feet by grey silts and clays (blow counts of 20 to 40 blows/foot). Below the station subgrade, the soil begins to develop higher blow counts and reveals varying layers of silty till and fine to coarse sands that predominate in the till material. These layers occur in an area that

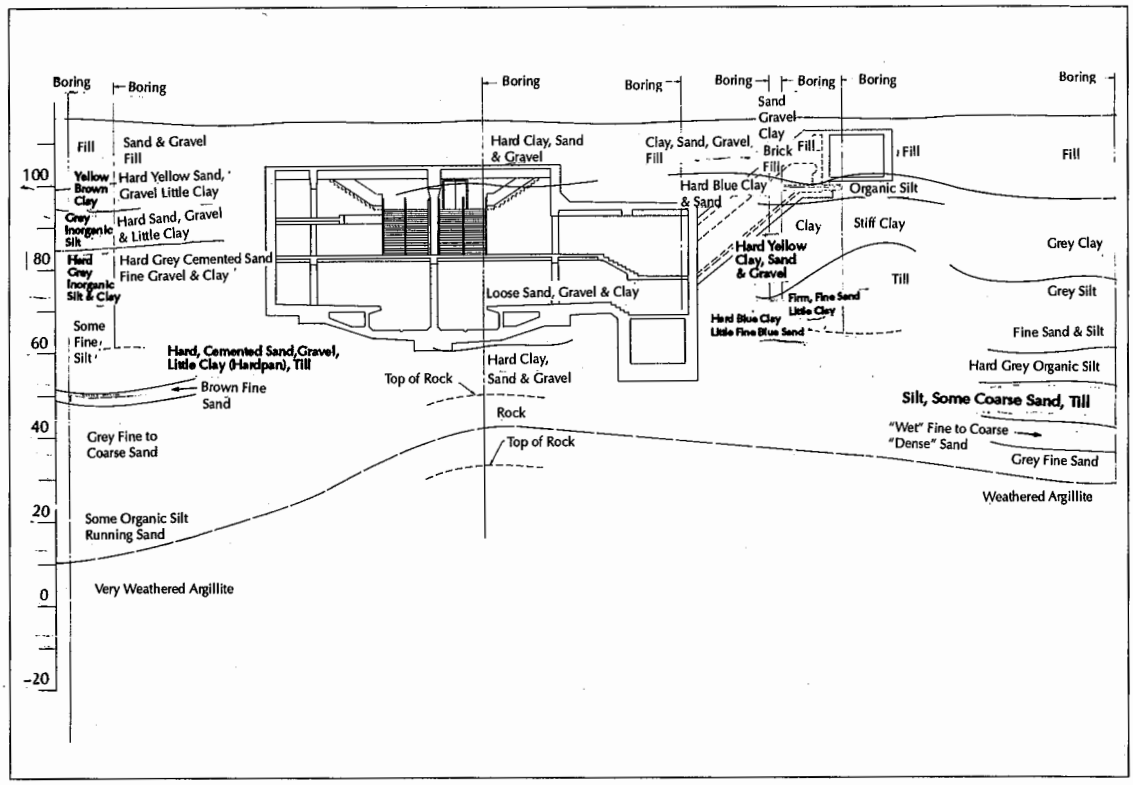


FIGURE 3. Subsurface profile at South Station.

ranges in thickness from 35 to 55 feet below the station subgrade to the top of rock. Interspersed in the soil profile are intermittent layers or pockets of relatively clean sand and gravel that are known to exist in the Boston area. These layers are highly permeable, and can be conduits for large short-term flows of water and soil into excavations.

The top of bedrock, as shown by borings, is between 90 and 110 feet below the street surface. The bedrock underlying South Station is primarily a fine-grained argillaceous rock of low metamorphic grade known as Argillite. The Argillite commonly appears in varying degrees of alteration. The upper surface is generally weathered and partially decomposed. The extent of the decomposed layer is quite varied, but ultimately overlies sound or unaltered rock. The sound rock is usually hard, and typically dark grey.

Determining the water table level in the till is an important factor in evaluating the underpinning alternatives. A previous investigation revealed that the groundwater level is not consistent over the entire site and tends to slope downward to the north.[3] Tests have indicated a highly variable water level in the till, ranging from 17 to 30 feet below the ground surface within a horizontal distance of 50 feet. It was reported that there are some minor leaks into the subway station that drain to a sump and pump facility, which could be the cause for a localized water level depression in the till. Further borings will need to be made adjacent to this structure in the immediate future to better define the hydraulic gradient and the characteristics of the subsurface soil material for the final design.

It is estimated that the Red Line South Station is used by more than 17,000 commuters daily. Recent construction modifications have provided for underground passageways from the Red Line South Station to the adjoining MBTA commuter railroad terminal, also known as South Station. Pedestrian access and flow, both beneath and on the street surface, is critical and must be maintained. Any disruption of this service by construction operations

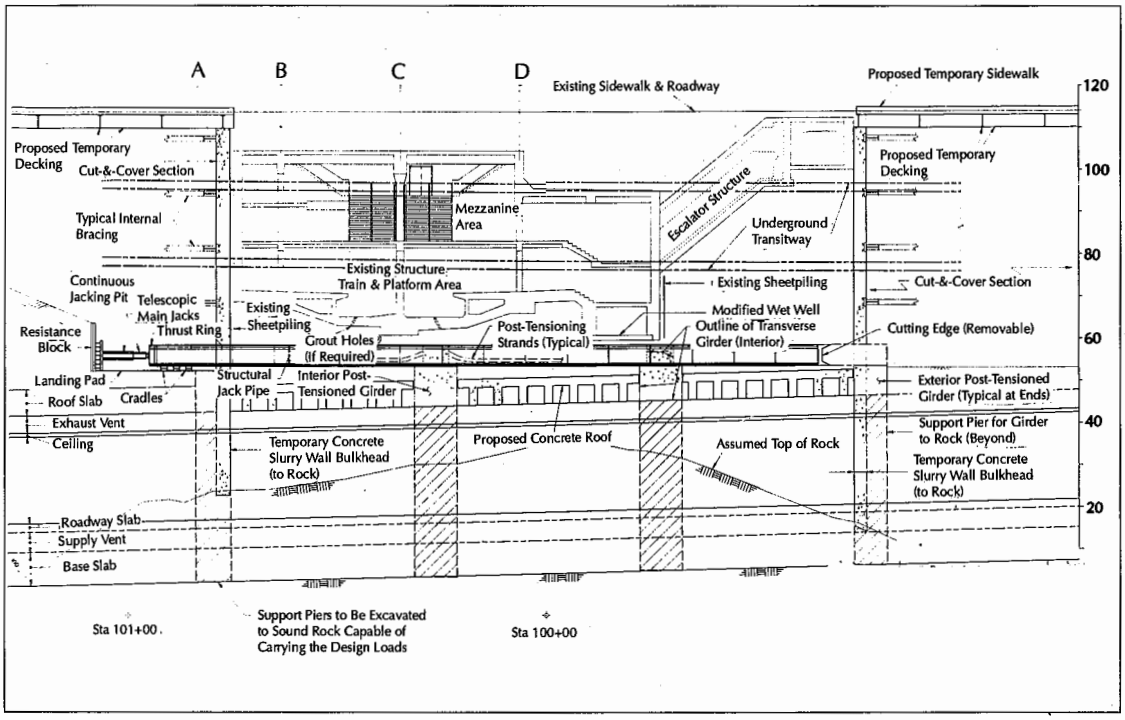


FIGURE 4. Profile of the jackpipe operation and support pier underpinning.

during the operating hours cannot be tolerated. Any penetration into the running tunnels and station must be avoided. The maintenance of the continual and functional usage of the MBTA facilities is a prime consideration and determining factor for the choice of underpinning method.

Underpinning Analysis

A review of the existing structure shows that there are separate distinct zones or areas to be considered (see Figure 4). The lower level of the two-level subway station contains the running rails that carry the trains and the train platforms. The upper mezzanine level services the toll collection and passenger distribution facilities. The zone between Columns B and D is considered critical with respect to underpinning methods. It is desirable to have as rigid a support as possible that will achieve minimal movements due either to deflection of the supporting members or any disturbance of the supporting soils that could cause settlement during underpinning. The underpinning members should be capable of spanning approximately 75 feet in the east-west direction and 55 feet in the north-south direction.

Viewing the structure in the lateral direction (see Figures 3 and 4), note the mezzanine overhangs, underground passageways, stairways and escalators. These areas were viewed as being less critical than those previously discussed. The station structure should be capable of tolerating strain and added stress without affecting train operations or public safety. It is recognized that the working mechanical escalators may require some special support treatment to keep potential movement within operating tolerances during underpinning.

In order to keep the surface street intersection clear of construction activity, the length of underpinning must be extended along the Central Artery alignment from column line A to the southern most wall of the underground passage that connects One Financial Center with the railroad station. Cut-and-cover construction utilizing temporary roadway decking would be carried up to line A coming from the north and the outside wall of the underground passage, coming from the south. Temporary bulkheads would be constructed across Atlantic Avenue using reinforced concrete slurry

walls at the limits of the extended underpinning. Access to the underpinning operation can be accommodated from below the decking and through the temporary bulkheads. The temporary slurry wall bulkheads will act as soil containment structures to prevent the soil moving laterally from under the station when the underpinning operation and excavation commences.

As determined by the preliminary design, the method of underpinning chosen to provide support of the subway and station, in part, will utilize jacked steel pipes reinforced with post-tensioning strands filled with concrete and stressed to predetermined values. These jacked pipes, which are installed tangent to each other, will act as beams to provide continuous support directly below the station trackbed and platforms. They will be installed from jacking pits constructed under the decking and in the cut outside of the temporary bulkhead wall on the north side. These pipes will all be jacked from the north side using an alternate/opposite sequence and will exit through the temporary concrete slurry wall on the south side, facilitating reuse of the cutting edge.

During the jacking operation, two parallel tunnels or adits will be mined approximately 75 feet apart on the east and west boundaries of the proposed alignment. These tunnels will be constructed by the square set method and will provide access for the construction of two transverse girders and four interior girder piers (that will support the transverse girders). Access will also be provided for the concrete side walls, all of which will be constructed using the horizontal pit board method. The walls will be constructed in an alternate sequence.

When all of the pipes have been jacked to their final position, the two transverse girder tunnels will be mined under the jackpipes using the pipes as the roof support of the transverse girder tunnels.

Since the jackpipes are tangent to each other, the lower portions of the pipes may be removed to the springline, leaving a series of "barrel arch" pipe segments to support the roof of the transverse girder tunnels. Their removal will also afford easy access into the jackpipes for cleaning, setting the end bulkheads, wiring strand, placing concrete and post-tensioning the jackpipe beams. The maximum span length of the five-foot diameter jackpipes acting as beams will be 55 feet. They will act as simply supported beams resting on the transverse girder beams. This array of jackpipe beams will be directly beneath the station.

The transverse tunnels will be reinforced and filled with concrete. The girders will then be supported by the reinforced concrete underpinning piers that were previously excavated through the parallel access tunnels using the horizontal pit board method down to the top of rock. Any weathered or decomposed rock will be removed within the confines of these piers until competent sound rock is reached to develop the load bearing capacities required. The maximum span length of the transverse girders carrying the jackpipe beams is 75 feet.

Since the underpinning system will be designed to carry all of the station and overburden loads, it was unnecessary for the preliminary design of the northbound Central Artery tunnel box to carry those loads. The underpinning structure will be permanent and load transfer to the Artery structure is not required.

Jackpipe Tunneling Technology

Pipe jacking is a method of tunnel construction wherein a precast concrete pipe or steel pipe liner section is pushed into the soil face by means of hydraulic jacks located in a jacking pit or gallery.[4] An excavating shield or reinforced steel cutting edge makes contact with the soil at the face, behind which the pipe segments are placed and jacked from the jacking pit. Excavation at the face may be performed by hand or by mechanical means.

Pipe jacking was introduced in this country in the late 1890s on the Northern Pacific Railroad. It was employed as a means of installing culverts without disturbing or interfering with the railroad operations. Major jacked installations were also performed in the New York and Detroit areas in the late 1950s. Jackpipe tunneling has recently become quite commonplace in England and other European countries. It has been used principally for sewer tunnels of various diameters in urban areas. Multiple jackpipes have also been used to form a roof of a larger tunnel such as the

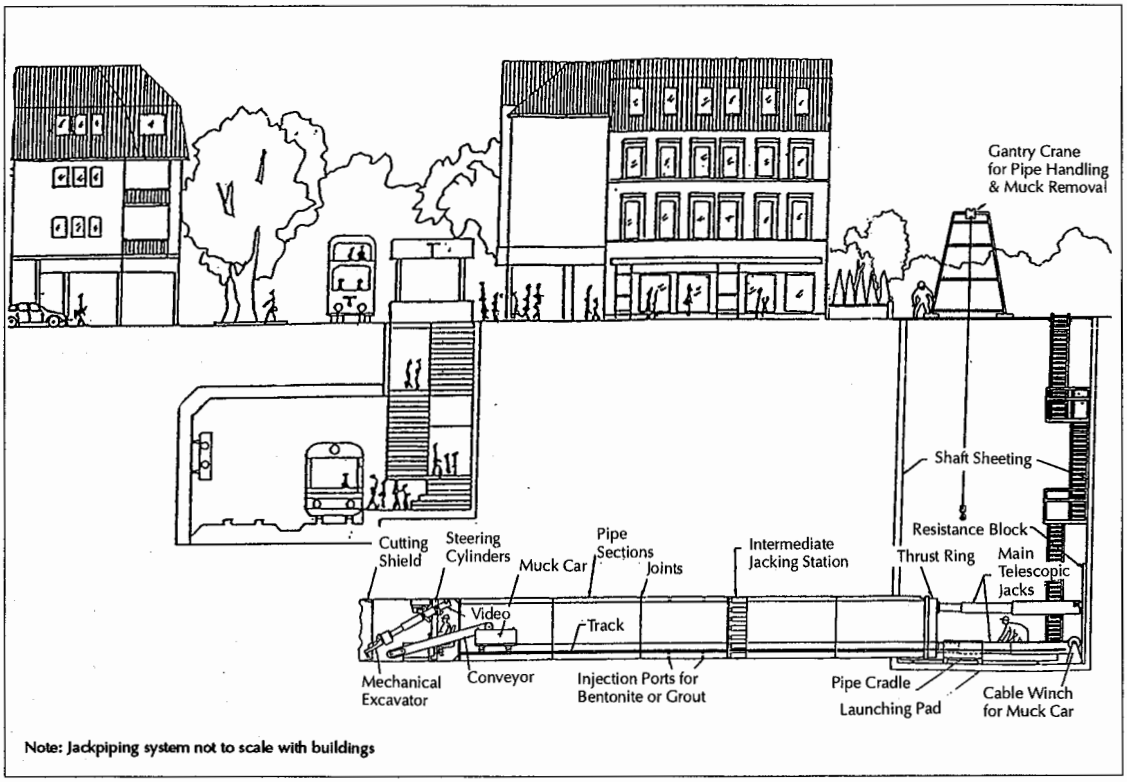


FIGURE 5. Typical elements of jackpipe tunneling.

project described here.

The typical elements of a pipe jacking operation are shown in Figure 5. A jacking pit or shaft must be constructed to a size that depends on the diameter and length of the pipe to be jacked, the throw or extension of the jack rods and sufficient space for thrust block material that receives the total reaction from the jacking operation. The cutting edge and the first section of pipe are started into the soil from a launching pad that includes a guide rail setup or a cradle. The cutting edge and pipe passes through vertical support sheeting that must be removed. The pipe is advanced to the maximum extension of the thrusting jacks, which are hydraulically operated. The jacks are retracted, another section of pipe is lowered into place and the sequence is repeated. Bentonite slurry may be injected between the soil and the pipe to provide lubrication at the soil/pipe interface.

The spoil or tunnel muck may be removed by hand, a mechanical excavating arm fitted within a tunnel shield or by a sophisticated tunnel boring machine. Depending on the size and length of the jacked tunnel, the excavated spoil may be transported by wheel barrow, muck cars, or track and locomotives. Some installations convert the spoil near the face into a slurry by the addition and mixing of water. It is then pumped and discharged to a settlement pond at the surface wherever space allows. De-sanders and cyclones may be employed for the removal of the solids and the slurry is then recirculated back to the face. Where concrete pipe is used, extra reinforcing is required at the bell and spigot to account for possible stress concentration. The major jacking load is applied in axial compression.

A pipe jacking ring is used to distribute the stress evenly and plywood cushioning material is used between pipe joints. O-rings or welded joints may be employed to provide water tightness.

When steel pipe is used in jacking, its thickness may vary depending on the usage. The steel pipe may be used as a carrier for a permanent pipe and acts, in effect, as an external

sleeve. The void between the sleeve and the permanent pipe may be filled with sand or cement grout. The final usage of the steel pipes jacked into position in the underpinning design for this project serves as a form for concrete and post-tensioned support beams.

Hydraulic jacks used in jackpipe tunneling may vary in capacity from 50 to 500 tons each. As few as two jacks may be used, although it is common to use as many as six to jack one pipe. The jacks must be placed in a position around the pipe to allow for spoil removal. Operating pressures on this hydraulic system range from 1,000 to 8,000 pounds per square inch (psi). Depending on the hydraulic jack thrust available, care must be taken to assure that the maximum pipe compressive stress not be exceeded. It is not unusual to use telescopic jacks that extend from eight to eleven feet per total "shove."

A resistance block must be constructed at the pit or shaft wall to react against the jacking loads. The type of soil available for passive reaction and the space available will dictate the nature of the materials used for the reaction. Resistance blocks made from steel sheeting, soldier piles, concrete, steel plates or cribbing are generally used.

A fabricated steel cutting edge is required on the front of the pipe string. The primary function of the edge is to protect the pipe from damage and deformation. If the soils are poor, an upper steel hood may be added to extend support to the crown. This hood gives the miner some protection while mucking at the face. The use of chemical grouting in advance of the jackpipe tunnel heading may be used to minimize the amount of soil inflow, which could undermine, in this case, the bearing support for the Red Line structure. This technique is used as a remediation measure. For large diameter pipes, mechanical excavators, steering jacks, conveyors, pressurized chambers, *etc.*, are all state-of-the-art components of modern pipe jacking procedures.

The dynamics of jackpipe tunneling in soft ground involves only a few basic fundamentals.[5] Overcoming ground friction and the inertia of the pipe are the two major factors. Injecting bentonite slurry around the exterior of the pipe may be used to reduce friction during jacking. The slurry is injected through holes fabricated or cast into the pipe with appropriate fittings to prevent backflow. The same holes may be used for cement grout injection to fill any voids and displace the bentonite after the pipe is in its final position and it requires no further horizontal movement.

The lengths of jacked pipe used in this underpinning scheme are relatively short (*i.e.*, 160 feet). However, when lengths begin to exceed 250 feet and the total thrust required becomes excessive for jacking and exceeds the compressive strength of the pipe, then intermediate jacking stations may be required. The preliminary design scheme for the Red Line structure did not exceed this limit, thereby not requiring intermediate jacking stations. Intermediate jacking stations, if used, require an external steel sleeve fitted between two pipe sections and contain a complete ring of smaller internal jacks. The jacking force produced by this internal ring reacts against the friction developed by the pipe train behind it. The distance left after retracting the jacks is then closed by using the main jacks located in the jacking pit, shaft or gallery. This action has sometimes been likened to the motion of a caterpillar. Upon completion, the intermediate jacks are removed, leaving the steel shell in place. A concrete filler section is then formed and concreted in place. Utilizing this method (*i.e.*, several intermediate jacking stations), pipes have been jack-tunneled in excess of 1,500 feet for major sewer lines (see "The Performance of a Remotely Controlled Fiber Glass Pipe Jacking System," by Dipak Shah *et al.* on pages 7 to 28, for a discussion on installing 6,900 feet of sewer pipe using pipe jacking). Theoretically, there is no limit to the length that pipe can be jacked.

Soils will produce varying frictional resistance ranging from 100 to 500 pounds per square foot (psf).[6] Clays are good soil for jacking, providing they are not of the squeezing or expanding type. The higher the percentage of silt and sand that occurs in the clay, the greater the frictional resistance. Some soils will have good stand-up time both at the vertical face as well as at the crown or arch, thus permitting for "some" pre-excavation at the face in order to develop a measured and controlled overcutting. Combined with bentonite lubrication, the

high frictional resistance in the soils can be reduced without causing ground settlement and/or collapse at the face.

Soil Behavior

Excavated soils within an underground confined space will exhibit specific characteristics that permit redistribution of stresses developed by the creation of a void.[7] The soil has the ability to structurally support itself prior to introducing any temporary or permanent tunnel supports. The soil develops an arch or dome that supports and transfers the overburden onto the ground located on both sides of the tunnel or void. This phenomenon of stress redistribution and the formation of ground arches is time related. It is a function of the type of soil, its cohesive properties, its water content, the loads that the arch is carrying and the span length produced by the arch. Until such time when structural support members may be introduced to reinforce the opening, the arch is in a state of unstable equilibrium.

The redistribution of stresses and the factor of stand-up time are two of the primary soil characteristics that allow most of the tunneling and underpinning operations in soft ground to achieve a large degree of success. Successful underpinning depends on understanding this ground behavior. It also depends on quality workmanship, careful planning and thorough subsurface investigations. Since underpinning performance is so closely related to limiting ground movement, it is important that some clarifications be made regarding categorizing ground movement.

Ground movement (other than that ground which is classified as firm and does not create any perceptible movement) may be categorized as raveling, running, flowing, squeezing or swelling. A raveling soil will gradually break up into chunks, flakes or angular fragments. As time elapses, more fragments dislodge, leaving a cavity that increases in size. It is the most common form of ground behavior in an excavated condition.

If the soil has no or little cohesive properties, it will run and flow. If the soil has some cohesion, but does not have a friable texture or jointing, and if the stresses are high, removing the soil will produce a response of squeezing into the created void instead of breaking into fragments. Squeezing ground will slowly advance into the void without any signs of fracturing.

In stiff jointed clays, excavation opens the joints in the clay surrounding the excavated opening and causes the relaxation of the stresses in the soil. Water may gradually permeate the joints and create a tendency for the soil to swell.

The soil profiles studied for the preliminary design indicated that the jackpipe support beams will pass through a stratum of hard grey inorganic silt and clay. There are, however, some layers of sand, gravel and silts of varying consistency and strengths below the zone of proposed jackpipe support.

Construction Procedures & Issues

As a result of the inherent uncertainties involved in underground construction, and considering the criticality of the subway trains and platform that are to be supported, it was decided that steel jackpipes, transformed into reinforced concrete post-tensioned structural members, would be the best solution for the support system to be used directly under the trains and platforms in the critical underpinning area. Application of this method minimizes the area of unsupported excavation during the construction procedure.

The construction sequence for installing the underpinning system is described below and is shown in Figures 6, 7 and 8:

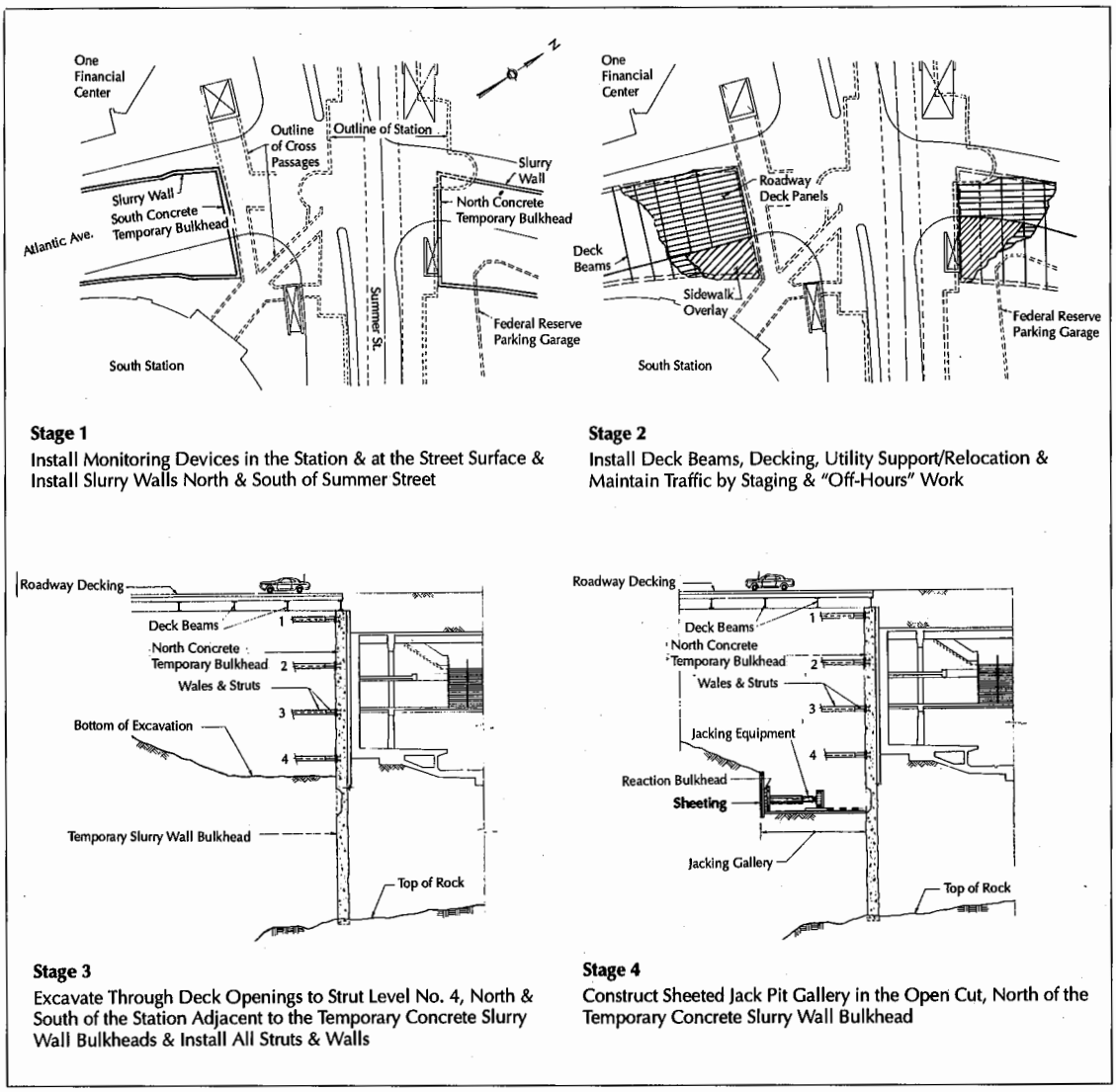
Stage 1. Install monitoring devices in the station and at street surfaces, and install slurry walls north and south of Summer Street.

Stage 2. Install deck beams, decking, utility support/ relocation, and maintain traffic by staging and by "off-hours" work.

Stage 3. Excavate through deck openings to strut level No. 4 north and south of the station adjacent to the temporary concrete slurry wall bulkheads and install all struts and wales.

Stage 4. Construct sheeted jack pit gallery in the open cut, north of the temporary concrete slurry wall bulkhead.

Stage 5. Mine tunnels (square sets) for



Stage 1
Install Monitoring Devices in the Station & at the Street Surface & Install Slurry Walls North & South of Summer Street

Stage 2
Install Deck Beams, Decking, Utility Support/Relocation & Maintain Traffic by Staging & "Off-Hours" Work

Stage 3
Excavate Through Deck Openings to Strut Level No. 4, North & South of the Station Adjacent to the Temporary Concrete Slurry Wall Bulkheads & Install All Struts & Walls

Stage 4
Construct Sheeted Jack Pit Gallery in the Open Cut, North of the Temporary Concrete Slurry Wall Bulkhead

FIGURE 6. Stages of construction — monitoring, decking, constructing the slurry wall bulkhead and bracing.

access to the side wall construction, the girder pier pits and the transverse girder tunnels.

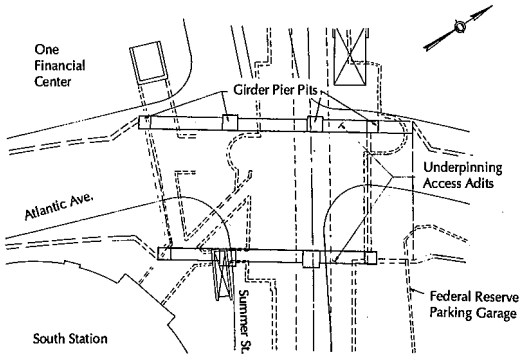
Stage 6a. Penetrate concrete slurry wall bulkheads from the north side and begin the pipe jacking sequence, exiting at the south concrete bulkhead.

Stage 6b. Construct girder beam piers to sound rock and construct the alternate pit walls concurrently with the pipe jacking operation described in Stage 6a.

Stage 7. Mine and construct the cross girder tunnels using the previously jacked pipes to act as the roof of the girder tunnel. Remove the lower section of the pipe to the springline, thus providing a "barrel arch" roof. Clean jacked pipe, complete exterior grouting, set end plates, wire strand, place concrete, cure and post-tension the jackpipe beams (see Figure 9).

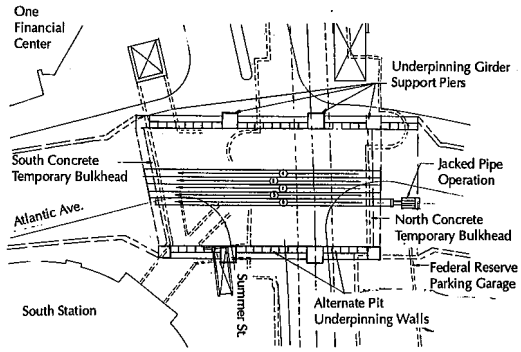
Stage 8. Complete the construction of the girder piers, interior cross girders and pit walls. Form the exterior carrier girders, place the steel strand, place and cure the concrete, and post-tension the jackpipe beams.

Stage 9. Form and place concrete for side-



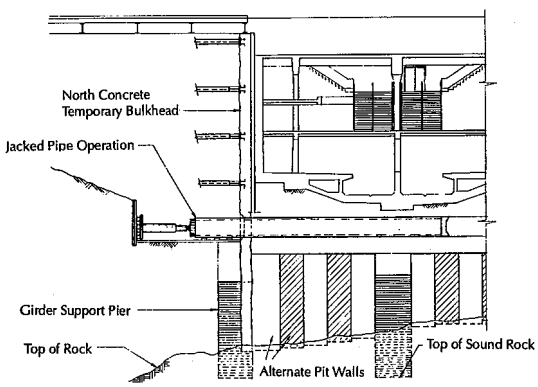
Stage 5

Mine Tunnels (Square Sets) for Access to the Sidewall Construction, Girder Pier Pits & the Transverse Girder Tunnels



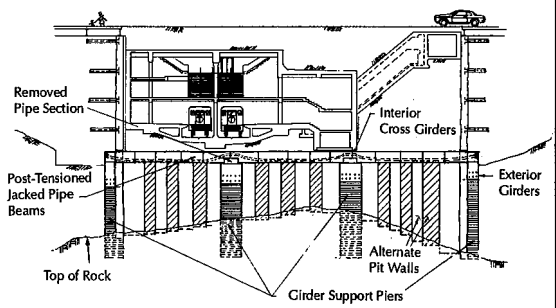
Stage 6a

Penetrate Concrete Slurry Wall Bulkhead From the North Side & Begin Pipe Jacking Sequence, Exiting at the South Concrete Bulkhead



Stage 6b

Construct Girder Beam Piers to Sound Rock & Construct the Alternate Pit Walls Concurrently With the Pipe Jacking Operation



Stage 7

Mine & Construct the Cross Girder Tunnels Using the Previously Jacked Pipes to Act as the Roof of the Tunnel, Remove the Lower Section of the Pipe to the Springline (Providing a "Barrel Arch" Roof), Clean Jacked Pipes, Complete Grouting, Set End Plates, Wire Strand, Place Concrete, Cure and Post-Tension Jackpipe Beams

FIGURE 7. Stages of construction — mining access adits, jacking pipe, and pier and girder construction.

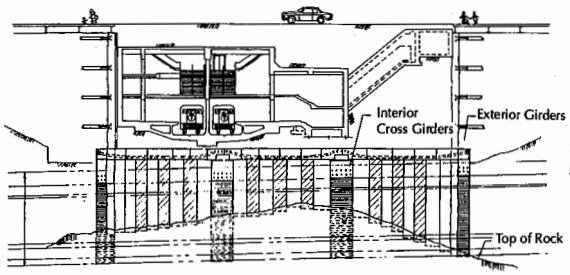
wall extensions and cure. Excavate the soil beneath the jacked pipe beams to the top of rock and break through the balance of the concrete slurry wall bulkhead and remove the wall.

Stage 10. Begin rock removal to subgrade using non-explosive methods. Install rock bolts as required.

Stage 11. Backfill/restore utilities, remove decking and deckbeams, and repave adjoining streets.

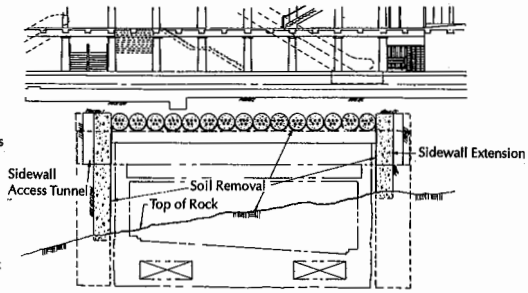
The preliminary design focused on selecting a construction method that reduces the construction risk. For this application, the overall goal of minimizing the unsupported area of exposure is achieved, considering the following:

- A five-foot diameter steel pipe was chosen as the size to be jacked. The area at the face of this pipe is approximately 19 square feet. This method limits and iso-



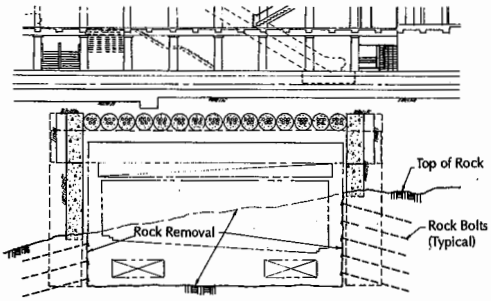
Stage 8

Complete Construction of Girder Piers, Interior Cross Griders & Pit Walls; Form Exterior Carrier Girders, Place Steel Strand, Place Concrete & Cure, & Post-Tension Jackpipe Beams



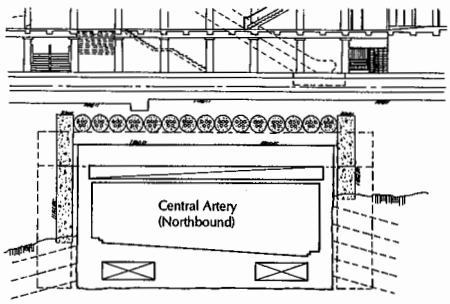
Stage 9

Form & Place Concrete for Sidewall Extensions & Cure; Excavate Soil Beneath Jacked Pipe Beams to the Top of Rock & Break Through the Balance of the Concrete Slurry Wall Bulkhead & Remove



Stage 10

Begin Rock Removal to Subgrade Using Non-Explosive Methods; Install Required Rock Bolts



Stage 11

Construct Central Artery Northbound

FIGURE 8. Stages of construction — post-tensioning, sidewall construction, excavation and begin construction of the new structure.

lates movement at the face to the 19 square feet of exposed area. Should poor soils be encountered at this face, breasting boards or bulkheading can be installed quickly to restrain soil movement. In addition, chemical or cement grouting may be injected by probes through the face to achieve soil stabilization.

- Excavation with hand tools affords the miner direct visual and physical contact at the face with the specific soils encountered.
- Depending on the stand-up time of the soil, the miner can visually inspect the soil immediately ahead of the cutting edge to determine if any voids in the crown of the jackpipe tunnel or the subgrade of the subway slab are present and are in need of filling as the work progresses.
- If obstructions are encountered, the miner has the ability to remove them at the face within the confined area of this size pipe.
- As determined by preliminary design, the diameter of the pipe is efficient for mining and mucking operations.
- The steel pipe provides adequate protection for the miners. A steel hood may be

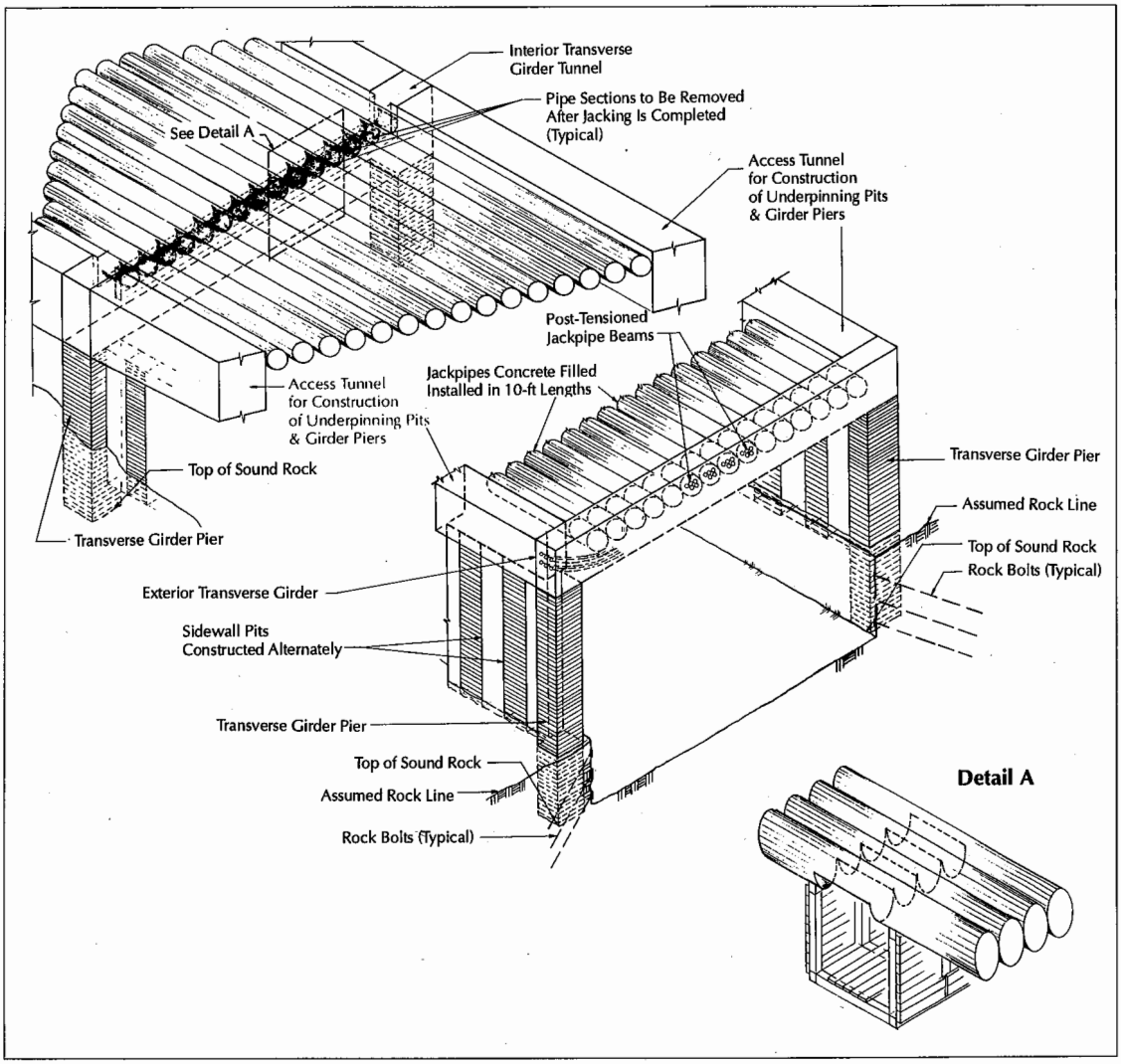


FIGURE 9. Isometric showing jackpipes, access tunnel, girder beams and sidewalls.

used at the face for further protection if soils will not stand at the crown.

- Pipes may be jacked into the soil for initial penetration. Jacking pressures can be set to predesigned values so that overstressing the pipe will not occur, or if an obstruction is encountered, damage to the cutting edge will also not occur.
- Injecting bentonite slurry may be undertaken to reduce skin friction around the pipe.
- The pipe is a rigid, stable and positive structural member. It provides the function of a steel liner plate.
- Grout or soil stabilizers may be injected into the space between the top of the jackpipe and the subgrade of the Red Line tunnels and station (from within the pipe) to further stabilize the soil mass, if needed.
- The ability to limit ultimate deflection may be achieved through post-tensioning the final structural members.

The pipes will be jacked through the temporary concrete slurry wall bulkheads located across Atlantic Avenue just north of the subway station wall and just south of the underground passenger pedestrian tunnels (see Figure 4). The bulkhead walls retain in place those soils

that are adjacent to and under the subway station complex. The jacking pits will be located adjacent to the north bulkhead. Jacking will begin at the middle or centerline of the northbound Central Artery and progress alternately on both sides of the centerline. The pipes are to be jacked so that they are as close as possible to each other. Final cement grouting should not be installed until the tangent pipes are in place on both sides of the pipe.

The pipe ends will terminate at the south temporary slurry wall bulkhead. The temporary concrete bulkhead will be broken through after the cutting edge reaches that boundary. The cutting edge will be retrieved, removed and reused. After the transverse girder tunnels have been constructed and the underside sections of the pipe removed (see Figure 9), the pipe should be cleaned. The ends of the pipes will be bulkheaded and fitted with steel plates for stressing. Provisions for pumping concrete shall be made through the bulkhead and a slick line should be installed to ensure complete filling of the pipe. The strand will be stressed from the cut (open) sides of the excavation and from the transverse girder tunnel.

The transverse girder tunnels (interior and exterior) will contain the ends of the bulkheaded and concrete filled post-tensioned jackpipes. The girder tunnels themselves will be reinforced and filled with concrete. They will act as carrier girders to support the jackpipes. The side tunnels will facilitate the construction of the transverse girder tunnels and will also provide access for the girder support underpinning piers (at the ends of the transverse girders) and the lateral support sidewalls.

The side access tunnels will be constructed by square set and timber lagging methods and become an integral part of the underpinning system. Note that not all underpinning is necessarily performed using "state-of-the-art" methods.[8] "Recent" tunneling history begins around the year 1800 as the industrial revolution and the growth of cities created new demands for transportation, water supply and drainage. The primary means of ground support, at that time, was timbering. Excavation was carried out by pick and shovel. Muck was hauled by manpower or animals. Structural linings were made of hand laid stone masonry. Magnificent tunnels were constructed using these simple tools, many of them of large size and constructed through difficult ground that would impose severe challenges even for today's technology.

In "square sets" and "wood lagging" (see Figure 10), a set consists of a ground sill, two vertical posts and a cap, similar to framing an opening in a building wall. The sets are installed as the mining progresses in two- to five-foot intervals on center. The spacing will depend on the "heaviness" of the ground as it relates to "stand-up" time. The timber sets are precut to size and are often dapped, scabbed or notched. Each timber is placed in its proper position, plumbed, squared, wedged and secured. Lagging boards are placed outside the sets, bearing tightly against the earth to prevent any movement, thus forming a continuous sheeting envelope that may, in some cases, include the floor.

If the working face shows any signs of raveling or running, the face can be similarly lagged with "breast boards." These boards are placed in front of, and are wedged to, the most advanced set and can be further supported by strong backs or kickers to the previously installed set. The boards may be removed one at a time, excavated, advanced and rebraced before the next board is removed. The tunnel face is excavated from the top down. It is carefully advanced board by board, set by set, always limiting the area of exposure. In good ground, this method of tunneling can proceed quite rapidly. In poor ground, it can be very slow.

In running ground, a method of forepoling is utilized (see Figure 10). It is a slow and tedious operation, but it is a safe one if done with care. Poling boards (or spiles), which have been sharpened to a cutting edge, are driven into the face of the heading at the crown with pneumatic hammers, sledges or jacks. When the heading is advanced half the length of the poling boards, a new false set is put in place, which supports and takes the strain from the poling boards. The poling boards are then driven to their full penetration as the section is enlarged. Other timbers are substituted until the complete section is excavated. The upward pitch of the poling board must be enough so

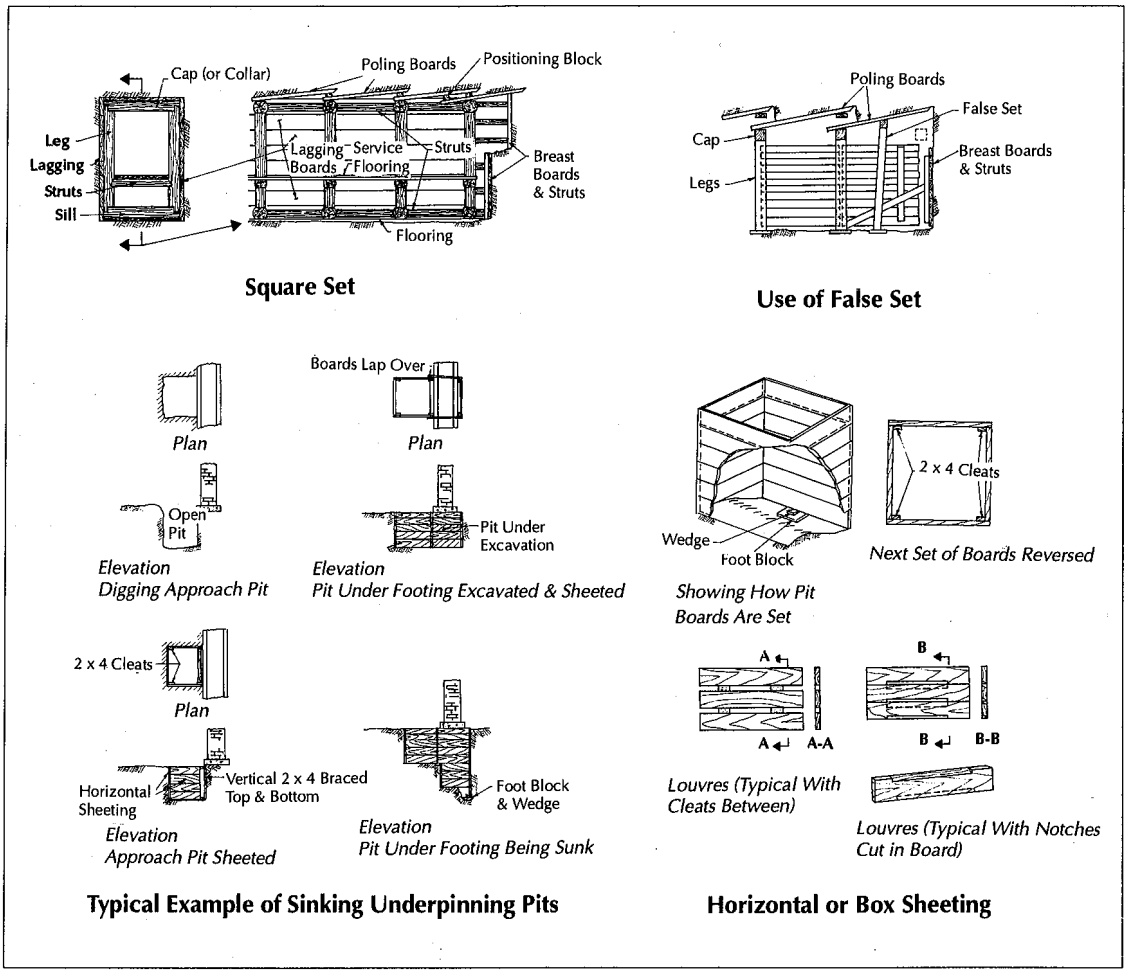


FIGURE 10. Square set tunneling, forepoling and box sheeting methods.

that the next cap may be set (about two inches per foot).

If the exposed area of the tunnel is large, the excavation might advance in two segments. This method is known as the "heading and bench" method. A top heading is constructed (driven) and supported in a manner that is similar to the one described for square sets.[9] The bench cut lags some distance behind the heading, depending on the ground characteristics. The operation then requires extending the side posts, resetting the sills and transferring the loads without disturbing the roof support. Utilizing "positive" structural member supports and minimizing the potential for ground loss typifies this method of construction. This method also relies on the self-supporting characteristics of the soil. These characteristics are used to determine the working loads on the timber bracing. It is the timber bracing that is the prime support of the soil, until the permanent support structures are in place.

The transverse girder tunnels can be constructed in a similar manner, except that the steel jackpipes already provide the roof support members. The only other components that are needed are just the side posts and ground sills.

The adaptability of timber bracing in the tunnel mining operation has definite advantages. It should be noted, however, that this may also be accomplished by the use of a steel horseshoe rib set with steel liner plate lagging. This steel set would be installed with the ribs four feet on center. The access tunnels may be constructed using these steel horseshoe rib sets

installed in a heading and bench excavation process.

The girder support underpinning piers can be constructed by the method known as the box sheeting method, using horizontal pit boards.[10,11]

The piers are rectangular in shape and will be constructed to a suitable depth and must bear on reasonably sound rock. The piers can be sunk to almost any depth in clays and sand using horizontal timber sheeting generally no thicker than four inches. Excavation is by hand tools and the soil is removed using a bucket and tripod wheel. Sometimes a motorized winch is used for lifting. Depending on the soil characteristics and stand-up time, the horizontal pit boards can be placed one at a time in sets, one below the other and with the earth carefully repacked behind each board (see Figure 10). The bottom-most pit board is kept in place by a foot block and wedge. This process is repeated until the top of competent rock, or the bearing capacity of the pier load, is reached. The pier may be keyed or doweled into the rock. Reinforcing steel is then placed into the pit and concrete placed or pumped into the shaft. The construction of the pier would precede the construction of the transverse girders so that drypacking or load transfer devices are unnecessary.

The sidewalls of the excavation for the northbound Central Artery will be constructed by the same method and will be excavated in an alternate sequence.[12] This approach allows multiple pits to be constructed concurrently. Stages 6b and 7 in Figure 7 depict the extent of pitwork to be performed as part of this underpinning scheme. The wall pits may be keyed or doweled together for continuity and load transfer. The walls extend into the access tunnels that, in turn, receive steel reinforcing and concrete, and become the extensions of the sidewalls.

The area of underpinning carrying the stairway entrance, over-hangs, escalator structures, underpasses, sump pits, and previously abandoned rooms will be supported and underpinned by the same method of jackpipe beams and transverse girders. The structures are less critical than the running rails and platform areas with respect to public safety.

Temporary underpinning may be required for special conditions such as stairway overhangs. The use of minipiles, bracket piling, needlebeams and underpinning pits all present reasonable options for such temporary supports, if required.

Remediation Measures

The underpinning of the Red Line subway at South Station will require an extensive network of underground adits, shafts, galleries and pits. The dimensions of the underground openings must be in conformance with sound underpinning practice, recognizing that the *in-situ* soil has the capability of acting as part of the internal supporting structure. Deflections, arching actions, soil slippages and movements, water carrying fines, water under pressure (perched or otherwise) and yielding supports all must be considered and kept to a minimum in order to lessen the impact and effect of construction disturbance. The known or encountered soil strength characteristics must not be exceeded or overstated.

If unpredictable movements are encountered, then the exposed unsupported areas (*i.e.*, face, crown or sides) must be minimized and localized. If soil movement occurs and has been temporarily restrained, the underpinning contractor must have stand-by equipment readily available to provide more permanent stabilizing techniques, such as chemical or cement grouting.[13] The grout may be injected into the poor soil areas, and once stabilization is effected, the underpinning operation may resume.

It may be necessary to extend and improve on a dewatering system, providing that the dewatering is not for a prolonged period. Dewatering may cause consolidation or otherwise induce soil movements, increase loads or expose wood piling to decay action if continued for long durations.

After all of the support members have been installed, reinforced and post-tensioned, excavation through openings in the temporary concrete slurry wall bulkheads to remove the soil beneath the station may commence from either the north, south or both ends concurrently. Depending on the specific structural design, further post-tensioning may take place on the main support and carrier girders. As the exca-

vation proceeds to remove soil from beneath these girders, load is induced and deflection takes place. By adjusting and increasing the magnitude of post-tensioning, this deflection may be controlled and reduced considerably. Earth excavation will continue to the top of exposed rock.

Rock Removal

Rock removal under the Red Line at South Station will be limited to non-explosive methods. Hydraulic splitting (plug and feathering), expansive chemicals, and pneumatic or hydraulic breaking will be allowed.

Depending on the rock quality encountered, rock bolts may be utilized (either cement grouted or fully encapsulated resin types). The rock will be removed in lifts, and the rock bolts should be drilled into the vertical face of the exposed rock to maintain stability and support for the piers and lateral walls (see Figure 8, Stages 10 and 11).

It should be noted that, in the preliminary design construction scheme, the structural underpinning members support all of the induced loads above and around the proposed northbound Central Artery structure.

Instrumentation & Monitoring

Instrumentation and monitoring of the existing structure is a necessary and important factor in determining the success of the underpinning construction methods. Settlement and movement devices must be monitored daily in the station and at ground surface during construction. It is suggested that monitoring devices be installed 12 months prior to actual construction so that a baseline may be established for movements and vibrations in the Red Line subway structure.

One of the benefits of this type of underpinning system is that penetration into the existing station is not required. The operation of the railroad is not interfered with. Figure 4 does, in fact, show provisions for drilled holes in the track invert. These holes are provided in case of an emergency (a void is discovered) that might require grouting below the track invert (assuming that the void was not accessible or detected from the grout holes provided in the steel jackpipe).

Summary

The essential criteria for developing a constructible underpinning method that would allow construction of the proposed northbound Central Artery under the existing Red Line South Station are as follows:

1. Safeguarding the MBTA running rails and train operations, and protecting the station from damage.
2. Avoiding penetration into the subway that might prevent continuous service.
3. Avoiding interfering with the riding public.
4. Providing an environment that is construction-free at the intersecting street surfaces.

A method using three construction/underpinning techniques, which emphasized minimal ground exposure and remediation, was developed during the preliminary design. The parallel jackpipe method is a proven technology, which has been used recently in providing roof support in the Antwerp Metro System.[14] It has also been used for crown reinforcement in the construction of the Hamacho subway station for the Tokyo Metro.[15]

Pipe jacking provides for main support elements directly under the MBTA station, and will consist of positive structural members installed below the decking from the north side of the intersection. The jackpipes will be large enough for a miner to work inside, and small enough to limit exposure at the face. This method has the ability, through controlled overcutting at the face, to relieve excessive soil pressure at the heading caused by the jacking operation.

Square set mined tunnels and horizontal board underpinning pits are also small enough to limit exposure at the face and large enough for miners to work. Movement of the soil is controlled and limited by the specific method of construction.

The utilization of temporary concrete slurry wall bulkheads on both sides of the underpinning contribute greatly towards preventing soil displacement beneath the station.

The proposed underpinning scheme in-

volves various proven techniques that all have the following characteristics:

- Each method relies on, and uses, positive structural elements.
- Each method can control the amount of deflection.
- Each method can provide for remedial action locally, should the occasion arise.
- Each method complies with the project criteria for construction safety and non-interference with normal operations.

A number of alternative methods and schemes were reviewed, such as: the New Austrian Tunnel Method (NATM), horizontal jet grouting, ground freezing, large diameter tunnel shields, both Earth Pressure Balance (EPB) and slurry face. While each of these methods, or a combination of them, offer possible solutions for underpinning the Red Line at South Station, they were not chosen for the preliminary design. The element of risk, safety and the possibility of encountering the unexpected were weighed in each case. The ground disturbance produced by these methods was judged to be excessive for being so close to the station structure. Also, adequate remedial action could not be assured in emergency conditions involving possible localized failures. The potential damage to the station and the public were all too apparent.

NOTE — *With completion of preliminary design, the Red Line underpinning at South Station will undergo final design preparation as part of Central Artery Design Contract, D011A. It was not the intention of this article to specify the final construction procedure that should be selected for the site, but to share some of the thinking and study that went into the preliminary design proposal. The final designer will have additional information to refine, and rightfully change, some of the preliminary design recommendations. These data will include additional borings below the track inverts, permitting evaluation of the hydraulic gradient at various depths and the quality of the underlying rock.*

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BURTON P. KASSAP *is presently the Construction Manager for Bechtel/Parsons Brinckerhoff on the Central Artery/Third Harbor Tunnel project. Before coming to this project in 1987, he worked for thirty years for various heavy construction contractors. His experience includes supervising tunnel, foundation, underpinning and mass transit construction projects throughout the United States. He holds a B.S. in Civil Engineering from C.C.N.Y., School of Technology, and is a Professional Engineer in Massachusetts and several other states.*

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