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ABSTRACT

The East Side Access (ESA) Project to connect the Long Island Railroad to New York's Grand Central Terminal in Manhattan will be one of the largest tunneling projects ever undertaken in New York. The Manhattan segment of the project includes a series of tunnels and caverns that will be excavated in rock to connect the existing 63rd Street tunnels to twin three-level station caverns beneath Grand Central Terminal, accommodating eight tracks and four platforms.

A comprehensive geotechnical investigation program has been conducted and the data has been analyzed to develop a geological model along the tunnel route and rock mass mechanical properties have predicted to evaluate TBM performance and tunnel stability along the alignment. Along with the geological uncertainties associated with TBM tunneling, there are operational complexities that must be incorporated in TBM tunneling in Manhattan. Given the dearth of available real estate in Manhattan and with a view toward minimizing community impact, the TBM components must be lowered to the tunnel level from a shaft in Queens, transported through the existing 63rd Street tunnels to Manhattan, where a chamber will be built to assemble the TBMs. Furthermore, after the TBMs have excavated the first two tunnels, they must be reversed through these tunnels, re-assembled at two chambers constructed for this purpose, and re-launched to bore two other tunnels.

This paper presents the geotechnical and physical challenges the project faces and the progressive engineering approach used to address these problems.

INTRODUCTION

The Long Island Rail Road (LIRR) presently provides passenger service from Long Island through Amtrak's tunnel under the East River to the west side of Manhattan into Penn Station. The East Side Access (ESA) project will enable LIRR to provide direct service to the east side of Manhattan. The service will connect LIRR Main Lines through the unused lower level of the existing two-level four-tube tunnel under the East River (upper level tubes are used by the New York City Transit – NYCT) into a new terminal station to be constructed beneath the existing two level underground Grand Central Terminal (GCT) servicing Metro North commuter rail road (MNR). The ESA alignment is shown on Fig. 1. A portion of the existing Madison Yard at the lower level of GCT will be reconstructed to serve as a concourse for the new LIRR station.

The Manhattan segment of ESA project consists of three major underground construction elements:

- Manhattan tunnels including 55th Street ventilation shaft.
- GCT caverns, tunnels and shafts connecting the new three level LIRR terminal to the Madison Concourse and 44th Street ventilation structure.
- Tail Track tunnels and caverns and 38th Street ventilation structure.

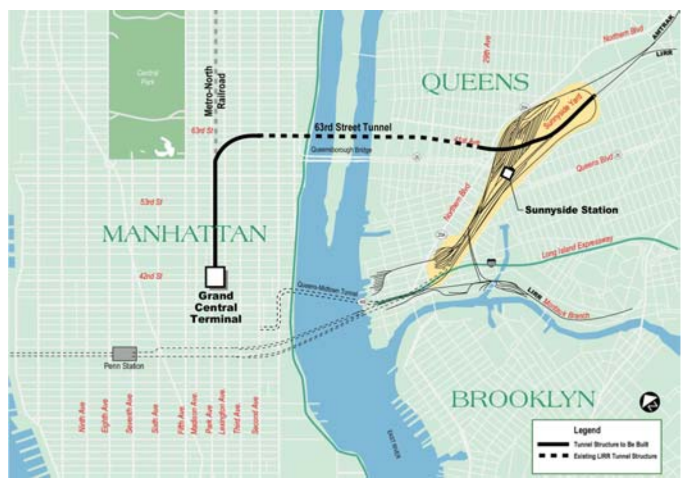

Fig. 1. Location Plan of the East Side Access Project.

Manhattan Tunnels

As shown on Fig. 2 and Fig. 3, and documented by Sarkar et al. (2002), Munfah (2001), and Della Posta and Zlatanic (2001), the first construction contract includes excavation of four single track tunnels (approximately 21.5 ft diameter totaling 24.200 linear feet) using two Tunnel Boring Machines (TBMs).

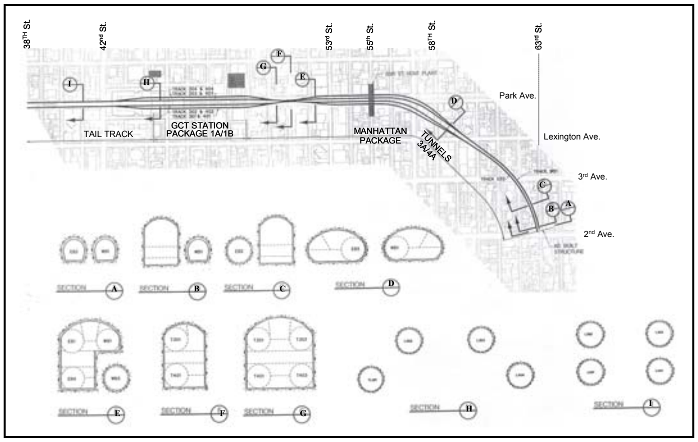

Fig. 2. Typical Sections Along ManhattanTunnels.

This contract also includes a TBM assembly chamber at 63rd Street, a three-level Wye cavern structure at 59th Street, a crossover cavern at 51st Street and nine raise bores (five vertical and four inclined at 30° to the horizontal) at various proposed shaft locations. The station caverns, ventilation structures and final shaft configurations will be enlarged to their final configurations in future construction contracts. TBM mobilization, demobilization, mucking and all other services required for the tunnel construction will be conducted through an access shaft constructed in Queens under a separate construction contract.

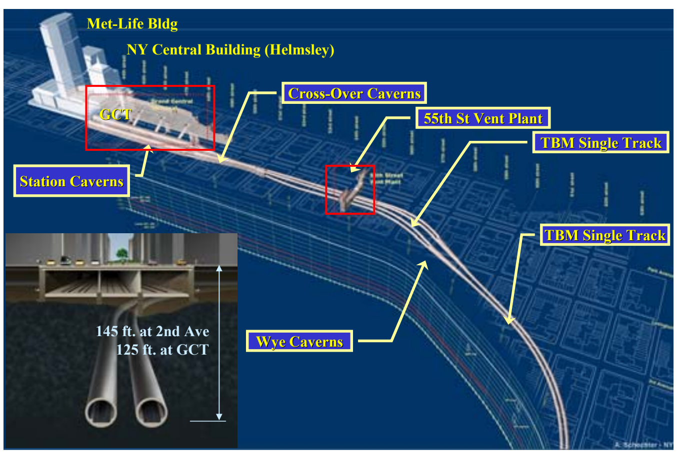

Fig. 3. ManhattanTunnels.

The tunnel construction will start at the existing lower level tubes of 63rd Street tunnels at Second Avenue by constructing approach tunnels using drill and blast methods. An assembly chamber will then be excavated once the approach tunnels have adequate horizontal and vertical separation from the operating NYCT tunnels. The assembly chamber and two starter tunnels will be excavated by drill and blast for launching the two TBMs. The TBMs will be driven to the end of tail tracks at East 38th Street. They will be partially disassembled and relaunched from the 59th Street three level Wye structure (constructed by drill and blast) and again driven to East 38th Street. After all four TBM drives are completed the machines should be partially disassembled and hauled back to the assembly chamber where they can be further disassembled as needed to allow the parts to pass through the existing smaller diameter 63rd Street tunnel into the Queens shaft for removal.

The Station Cavern

GCT station caverns consisting of two parallel caverns approximately 60 ft wide by 78 ft high and 1200 ft long, will be constructed by drill and blast method by enlarging from the four TBM bores. Figure 4 shows a cross section of GCT caverns. Each cavern houses two upper level and two lower level tracks and a mezzanine in between. At the mezzanine level the caverns are intersected by cross passages to provide connections between them and to the escalator shafts, elevators, stairs, and utilities that connect with the Madison concourse. The primary ingress and egress are provided by three banks of four escalators to connecting to the Madison concourse.

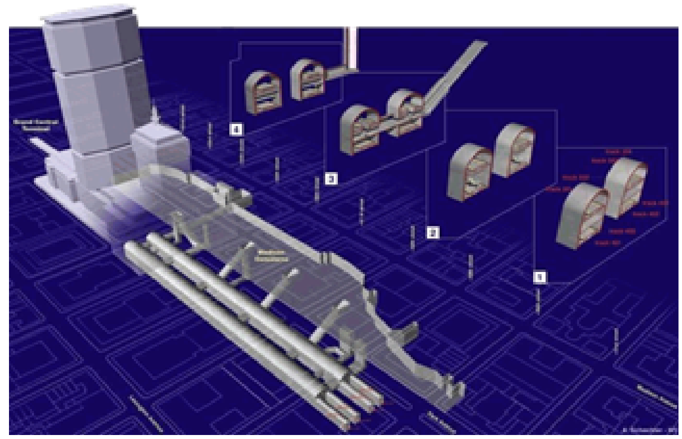

Fig. 4. Grand Central Terminal Caverns.

The two caverns are horizontally about 98 ft apart with 40 ft nominal rock pillar between them. In general there is about 33 ft of rock cover between the crown of the caverns and the bottom of viaduct and building column foundations located below the existing lower level of GCT. A cross section through the GCT at 46th Street looking North is shown on Fig. 5.

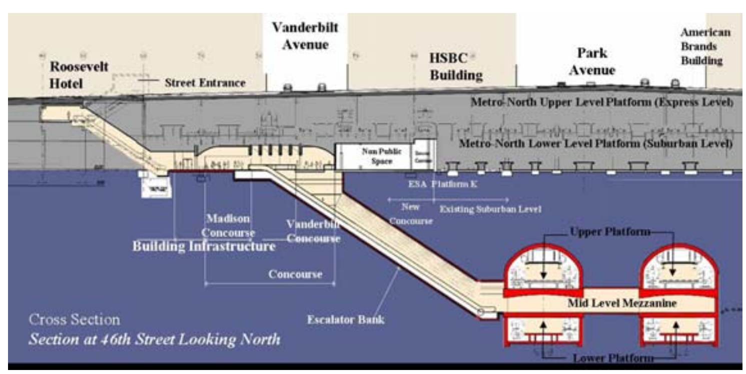

Fig. 5. Typical Cross Section through Grand Central Terminal Caverns.

CHALLENGES POSED BY GEOLOGIC CONDITIONS

The metamorphic rock underlying Manhattan, consisting of foliated schist and gneiss, is known to be highly variable, ranging from very hard competent rock to very soft and partially disintegrated material (fault breccia and sheer zones). Significant tunneling stability problems on past projects have been reported by many authors. The geologic conditions have been presented by the authors in a companion paper (Sarkar et al., 2004) and details can be found in Snee et al. (2003). The tunneling challenges posed by the geologic conditions are presented below. The engineering behavior of the rocks will be a function of the interaction of geological characteristics, environmental conditions and a particular construction activity.

Discontinuities

The discontinuities of the rock mass are the metamorphic fabric (foliation and foliation joints) and joints caused by tectonic activity or granitization. At the project site the foliation, foliation joints and other joints exhibit a wide range of spacings that is typical of this rock which has undergone major tectonic episodes such as folding, faulting and intrusions. Joint clustering is another consequence of the intense tectonic disturbance that this rock has undergone.

The most prominent joint set is one that is parallel to the plane o weakness formed by foliation and is termed as Set 1. Set 1 dips typically west to southwest from East 38th Street to East 52nd Street. However, the dip direction is typically south from East 52nd Street to East 57th Street. North and east of East 57th Street there is intense folding and faulting that produces a highly variable dip direction until approximately East 62nd Street where the dip direction is to the east. Set 1 foliation joints are typically planar to undulating and rough. The TBM drive will be along and across foliation joints.

The Set 2 cross fabric joints are steeply dipping southeast to southwest display welding, healing, infill, open aperture, and coating. They are typically undulating, rough to very rough with occasional infill of sand and clay and surface staining by iron oxide, particularly close to shear zones and in areas of more intense pegmatic formation. They are more closely spaced near the top of rock and close to previous excavations where they occur in clusters with a much closer spacing.

The Set 3 joints are conjugate to the foliation joints, dipping to the east beneath Park Avenue and varying in association with the folding and faulting east of Park Avenue.

The Set 4 joints occur in clusters with a wide variation of dip direction typically to the northwest. The dip angle clusters into shallow or steep groups and alteration and decomposition appear to be characteristic.

Faults and Shears

The tectonic history of the rocks has left the rock underlying Manhattan fractured and dislocated. The faults are singular or narrow features with relative displacement of individual planes or group of planes. The shears range from inch scale features to major regional features. The inch scale features are classified as micro-shears and they are subtle and only noticeable by distinct zones of weak friable and extremely fractured rock. Often the joints have a polished or slickensided surface identified as a shear. Micro-shears occur throughout the tunnel alignment with typical thickness of less than 6 inches. Shear planes were identified during site investigation / rock wall mapping (Sarkar et al., 2003).

Major shear zones are characterized by fractured rock greater than 10-foot scale with zone of influence on 100-foot scale; with more intense destructive effect showing distinct breccia bounded by Mylonite. The boundary of the breccia and the undamaged rock is distinctive but the zone of influence includes clusters of open infilled and mineralized joints. Major shear zones have been identified by site investigation along the alignment in the East 57th Street to East 58th Street area and in the vicinity of East 54th Street.

Pegmatite

These granite layers of igneous origin occurring with the metamorphic rock are found generally parallel to foliation. However, some intrusions are observed as dikes cutting across foliation such as at the exposed face of the existing 63rd Street tunnel end wall. Pegmatite occurs in as very thin veins on inch scale to thick layers of massive rock generally in layers parallel to foliation. The thin pegmatite often occurs in clusters of similar thickness that can be continuous over several feet of core. A major pegmatite approximately 15 feet thick dipping west was found during site investigations beneath Park Avenue from East 56th Street to East 52nd Street along the tunnel alignment.

The pegmatite is a relatively strong and competent rock and generally shows a distinctive contact with the host rock, although in places the contact can be mixed.

Mineralogy

The site investigation has recovered core samples of schist, schistose gneiss, granofels, amphibolite and pegmatite. All of these rock types with the exception of amphibolite, contain significant proportions of hard minerals that are abrasive to TBM cutterheads. The essential minerals are muscovite, biotite, quartz and feldspar. The principal accessory mineral is garnet. The pegmatite has the combination of feldspar, quartz, biotite and muscovite but in places it contains nearly pure quartz veins.

Groundwater

The sources of groundwater recharge in Manhattan are surface infiltration, leaking sewers, drains and water lines, and adjacent East River and Hudson River in the north and the New York Bay in the south.

The permeability of intact rock is very low, however, network of joints and fractures control the groundwater conditions of the rock mass. The permeability of the discontinuities can be influenced by several factors including the intimacy of adjacent surfaces, alteration processes that have removed or deposited on fracture surfaces, and joint wall materials that have been fragmented or crushed by faulting and shearing. Also larger scale features, such as mylonite, act as a regional hydraulic barrier whereas major shear zones act as regional storage and conduits of groundwater.

Rock Mass Behavior

Rock mass behavior during tunnel construction will be governed by characteristics of the rock mass including joint intensity, their orientation with respect to the tunnel and spacing relative to the size of excavation, and water inflow conditions. The degree of difficulty that will be faced during construction will be dependent upon the method and type of construction, e.g. TBM or drill and blast, and ground support and muck handling systems employed.

The combination of the joint sets described above will divide the rock mass into prismatic blocks depending upon the orientation of the excavation relative to the joint sets and their spacing relative to the size of the excavation. Blocks formed by joint surfaces are prone to fallout by gravity particularly when the joint surfaces are open, slickensided, or contain mineral coatings or gouge material. The probability of fallout will be high when the joints are persistent and closely to moderately spaced, especially in the fault and shear zones. These blocks tend to fallout of the crown and sidewalls unless promptly supported during excavation.

Three types of block fallouts can occur, namely, wedged shaped fallout, slab fallout and face fallout. Wedged shaped fallout is generally characterized by blocks bounded by three or more intersecting joints. In general, these may occur due to presence of steeply dipping joints intersecting the tunnel combined with shallow dipping foliation joints. Slab fallouts can occur at the intersection between the schistose gneiss and other rock types, such as pegmatite and amphibolite, or at intersections with shear zones. It can also occur due to the presence of a combination of closely spaced shallow foliation joints or shear zones and one or more moderately to widely spaced steeply dipping joints.

Fallouts from the face during TBM excavation can occur due to the presence of closely to moderately spaced persistent joints or joint clusters adversely oriented relative to the tunnel face, especially where joints are open or contain gouge material, micro-shear zones or major shear zones. Face fallouts can be wedge or slab fallouts and can cause cutter and cutterhead damage and muck handling problems. Blocky face conditions can contribute to overbreak in the crown and sidewalls of the tunnel.

Major progressive failures may occur by gradual loosening and fallout of small blocks when initial support is not installed immediately after the tunnel is excavated.

PAST TUNNELING EXPERIENCE IN MANHATTAN

A thorough search of existing literature and discussions with personnel involved with past tunneling projects in Manhattan and surrounding boroughs provided a good list of tunneling problems and issues with TBM and drill and blast method of tunneling in Manhattan (Ziegler and Loshinsky, 1981; Loshinsky, 1983; McCusker and Dietl, 1974; Almeraris, et. al., 1985; Guertin and Plotkin, 1979; Werbin, 1916; Lavis, 1914; Interborough Rapid Transit Company, 1904, and others). A long history of tunneling exists in New York City both for transit and water conveyance. However, almost all of the transit tunnels have been constructed using cut-and-cover and drill and blast tunneling methods and the TBM water conveyance tunnels were much deeper than the proposed ESA tunnels. The 63rd Street subway tunnel is the only comparable large diameter TBM tunnel in the last 25 years. The 63rd Street subway line is directly relevant to the ESA tunnels because they are in the close proximity and the TBM and drill and blast methods of construction.

The issues and problems that were identified during previous construction and relevant to the ESA project are listed below:

- Highly variable rock conditions from extremely competent rock to extremely poor rock: This variability had significant impact on the TBM advance rates, initial rock support types and installation methods that included virtually no need for initial support to closely spaced steel sets. Abrasivity of rock and cutterhead maintenance as well as soft shear zones have contributed to progress of the tunnels.
- Rock fall and face instability during TBM and drill and blast tunneling: These included rock overbreak to large scale wedge failure. The TBM face instability was dependent on the direction of rock foliation and the tunnel drive. ESA tunnels will be driven along and across the foliation joints.
- Gripper pressure: In the extremely soft rock and shear zones gripper pressure cannot be achieved and the pressure caused deformation of rock pillars between tunnels. Vertical grippers in addition to horizontal grippers were used to overcome the problem.
- Fault and shear zones: Occasional problems of ground support, ground movement and settlement of adjacent buildings were recorded where shear zones were encountered during construction.
- Water Infiltration: Water infiltration of excessive quantities was encountered in fault and shear zones. Also uneven pressure in the cutterhead resulted from excessive water in the tunnel face.
- Deterioration of rock mass and initial support with time: The permanent liners of the ESA tunnels will be installed several years after the tunnel construction and may encounter this problem if it is not adequately addressed.
- Stray current influence on blasting with electrical detonation: Untimely and out of sequence detonation resulted in some severe incidents.

CHALLENGES POSED BY SITE CHARACTERISTICS

Physical site characteristics pose challenges that include the fully built environment in densely developed Manhattan island and the most expensive real estate in the U.S. The site includes historic residential districts, hi-rise condominiums and commercial buildings, fully developed infrastructure with numerous continuously operated transit and railroad tunnels, buildings with deep basements adjacent to the alignment, hi-rise building column foundations in conflict with the construction or resting above the crown of cavern excavations with GCT complex, and the historic GCT station with expansive open space under the historic dome and multiple retail outlets. These constraints are described below.

TBM Access and Muck Removal

There is virtually no space to construct a TBM access shaft at around East 63rd Street and 2nd Avenue and the real estate acquisition cost is prohibitive. In addition, a shaft construction at that location will generate substantial disruption and public opposition. The TBM access and mucking will be done through an access shaft in Queens. Since the existing 63rd Street tunnel is smaller than the size of the TBM, the TBM cannot be assembled at Queens and walked through the tunnel. A TBM assembly chamber will be constructed as discussed above. The size of the chamber will be the contractor's responsibility.

Railroad Tunnels and GCT

The alignment passes directly beneath the MNR tunnel under Park Avenue from approximately East 57th Street to GCT. GCT and the MNR tunnels were constructed from 1908 to 1913 by open cut using drilling and blasting rock down to about 60 feet below the surface. The cut was decked over to accommodate Park Avenue, Vanderbilt Avenue and various cross streets. At East 57th Street, the four track MNR tunnel branches out to a ten track configuration with four tracks continuing to the lower or suburban level and six tracks continuing to the upper or express level. At approximately East 52nd Street, the track configuration, using ladder tracks and the associated switches, lead into the various yard configurations. The upper level tracks are supported on an independent steel framed structure with foundation footings founded on rock below the lower level. The various building columns, including the 59-story Met Life building and the 34-story story New York Central (Formerly Helmsley) building, passing through the upper and lower levels of the terminal are founded on separate foundations. There are numerous tunnels and passageways to adjacent buildings as well as numerous utility lines and utility connections throughout the facility.

Beneath the lower level tracks, there are cross passages at East 48th Street, East 45th Street and East 43rd Street. At East 45th Street, four shafts that once housed hydraulic elevators have been abandoned. The plungers of these elevators and the casing may not have been removed along with the elevators. These are very deep and likely to intersect the proposed TBM drives.

ESA construction must have only minimal impact on the facilities and minimal settlement on viaduct and building foundations.

Transit Tunnels

The alignment is adjacent to or beneath six different NYCT subway lines. These facilities and the MNR facilities will remain fully operational during ESA construction.

The ESA tunnels will extend the two existing unused LIRR tunnels that presently terminate at the West Side of Second Avenue beneath East 63rd Street. At this point the existing lower NYCT tunnel and the proposed ESA tunnel are approximately 6.5 feet apart vertically. The vertical separation between other NYCT tunnels is larger, about 15 feet at the 53rd Street subway line and about 20 feet at the Flushing subway line and more for other subways.

ESA construction must have minimal impact on the subway operation. Vibration due to blasting and deformation of tunnels due to ESA excavation must also have little impact on these tunnels.

Buildings

Land use along the alignment is mixed, including hi-rise office buildings, residential properties, health care facilities, house of worship, and hotels. North of East 42nd Street, between Fifth and Third Avenues and north to East 60th Street is the heart of the East Midtown Office district. East of Third Avenue, the land use is generally residential. The area along East 42nd Street, south of and including GCT, is densely developed with large office buildings and some residential buildings. Several hi-rise buildings are located directly about the GCT. The area along Park Avenue, from GCT to East 59th Street is marked by tall office buildings containing corporate headquarters for companies such as Chase/JP Morgan, Westvaco and Bankers Trust. Side streets to the east and west of Park Avenue contain office of relatively smaller scale. Also located along this corridor are several historic landmark structures.

Eastwards around Second Avenue are several of the city's prestigious residential neighborhoods, including historic Treadwell farms. Residential development includes brownstones and townhouses, walk-up apartments and hi-rise apartments. The southern portion of East Midtown between East 34th Street and East 40th Street, and centered on Park Avenue is a residential area known as Murray Hill. Construction impact must be kept to a minimum.

Roadway Structures

Two roadway structures that will be affected by ESA construction are Park Avenue viaduct and the Park Avenue tunnel. The Park Avenue viaduct is a deck structure supported by steel columns founded at the lower level GCT. A portion of the viaduct, between East 42nd Street and East 40th Street consists of a three span steel arch bridge. The Park Avenue Tunnel is a two-lane roadway beneath Park Avenue between East 40th Street and East 30th Street carrying two-way traffic in the northbound and southbound directions.

ENGINEERING APPROACH TO MEET THE CHALLENGES

In order to overcome the above described challenges, the project team, including, the owner, the program manager and the tunnel designer, took a deliberate and proactive approach to meet the challenges through public participation, geotechnical and site investigations, design development and preparation of bid packages. Presented below is the approach taken by the team.

Engineering Peer Review

Recognizing the complexity and the challenges, the project team instituted a peer review process that started at the conceptual stage and continued through the final design and preparation of bid documents. Initial peer review consisted of over a dozen of outside tunnel consultants and construction specialists from Europe and North America, as well as PB in-house experts at the conceptual stage. This review resulted in the recommendation of lowering the tunnel/station cavern profile below the lower level GCT-then called deep tunnel option. This recommendation was implemented to avoid direct underpinning of numerous building columns that were required for the recommended shallow MIS option.

Peer review of experts in smaller groups was conducted during preliminary engineering design, final design, and preparation of bid packages. The peer review resulted in optimization of initial tunnels supports, construction staging and sequence, rock and water loads on the final liner, waterproofing design of TBM tunnels and caverns, contracting strategy, TBM machine specifications and instrumentation and monitoring design.

Alignment Selection

Once the deep tunnel option was chosen, the alignment was kept within the 140 feet curb-to-curb right-of-way of Park Avenue. This eliminated the need of direct underpinning of numerous building columns as well as minimizing impact of these columns. The only columns that require underpinning are the ones that are directly affected by the escalator and elevator shafts within GCT. The alignment was also refined with the site investigation findings thus avoiding construction of major project elements within known poor ground conditions, e.g., the three level cavern was relocated away from the East 58th Street shear zone.

Choice of the TBM Excavation method

As mentioned earlier, the first construction contract on the ESA project consists of the four TBM drives. The station caverns, crossover structures, and shafts will be excavated from these four TBM runs. Given the complexity of the structures to be excavated, it was deemed prudent to construct the first excavations using a TBM, which will result in minimal disturbance to the surrounding rock and consequently will have minor impact on surrounding structures. Also, these excavations will provide direct access to the prevailing ground conditions in such critical areas as the station caverns. The construction sequencing and initial support of the enlargements can then be modified to suit rock mass conditions actually encountered. Excavation of these four TBM driven tunnels is therefore tantamount to having four large diameter pilot bores through the most critical areas of the project. Finally, certain areas along the alignment could not be explored through core borings due to overlying buildings, and TBMs in these areas will provide valuable data for future enlargements.

Geotechnical Investigation and Rock Characterization

A very comprehensive geotechnical and site investigation program was undertaken to meet the project challenges identified in this paper. The program included research of existing geologic and geotechnical data; past tunnel construction experience in New York City; vertical and inclined borings of various sizes with in-situ testing for rock properties, orientation of discontinuities, permeability of rock mass, and various core samples for general and specific rock testing; rock mapping of existing rock walls within GCT and laboratory testing for rock properties that included general properties, anisotropic strength properties and TBM performance properties.

The results addressed many of the challenges including:

- General geologic conditions and rock mass characteristics along the alignment. The alignment was subdivided into eight geologic zones including zones identified as fault and shear zones. The zones were based upon the complex association of rock mass properties, stress conditions, and groundwater regimes; such classification allowed the selection and assessment of construction methods, estimation of progress rates, the design of classes of initial rock support, and the estimation of loading conditions for the design of final liner. Superimposed over this was the requirement of minimizing or eliminating any effect on adjacent and overlying structures. This type of classification of rock mass, construction methods and support classes ultimately lead to what is believed to be realistic construction cost estimates.

- Engineering properties of rock was determined from in-situ and laboratory testing (intact and jointed rock mass, strength along and across joints, rock modulus, and friction along joints) that was used in continuous and discrete numerical model/analyses of excavations. These engineering properties used for deformation analysis and for assessing the effects of construction on structures above and adjacent to excavations.

- Engineering properties specific to construction methods such as TBM drillability and roadheader performance provided better handle of their use and productivity rate estimation.

Design Criteria and Initial Ground Support

Design criteria such as rock load and water load were developed based on the results of rock characteristics and ground water conditions developed from the investigation. In addition to the numerical analyses, rock wedges were analyzed using the software UNWEDGE (Rockscience, 1998) in determining the rock load on the permanent liners. Initial ground support was designed to minimize ground deformation and impact on existing tunnels and buildings. Also considered was the number of years life of initial support prior to installation of the final liner in an aggressively corrosive environment.

Numerical Analyses

In order to confirm the stability of excavation and ground deformation around the excavation numerical analyses were performed simulating the sequence of construction using continuum and discrete elements. The discrete elements emulated the discrete joint geometry, spacing and joint characteristics. The stresses were generally well within the yield stresses of the competent rock but the analyses produced the ground deformation due to excavation, initial support and final liner. Interaction analyses provided proper initial support design and confirmed the allowable deformation of the sensitive structural elements. In the cavern area with complex geometry, 3-D and pseudo 3-D analyses were performed for both continuum and discrete element methods using 3-D FLAC and 3-DEC programs (Itasca, 2000)

Instrumentation and Monitoring

A comprehensive and integrated instrumentation and monitoring program has been developed to monitor trend, and to provide control of and notification of impacts in a timely manner. The contractor will be responsible for procurement, installation and maintenance of the instruments and data loggers. The Resident Engineer will take readings, interprets and evaluates the data. The instruments will be installed early well before the construction activities so that readings can be taken to establish baseline conditions prior to construction.

The instrumentation data will be used to confirm design assumptions of ground behavior and closely monitor threshold levels of settlement and vibration. Instruments installed must be robust and able to provide measurements accurately and reliably for many years until the end of ESA construction.

Deformation of ground will be monitored by real time measurements using Multiple Position Borehole Extensometers (MPBX) and In-place Inclinometers (IP). Settlement at ground surface will be measured by surface settlement points in conjunction with manual optical survey.

Ground water levels will be monitored by observation wells and open stand pipe piezometers.

Deformation of existing tunnels will be measured by Liquid Level Settlement Sensors (LLSS) and Automated Motorized Total Stations (AMTS). Both are real time measurement instruments. LLSS measures settlement at sensor locations. AMTS measure movement along X, Y and Z axes at the optical prism target locations.

AMTS and LLSS will also be used in GCT complex to monitor all building and viaduct structure columns within the zone of construction influence. At certain selected columns and beams within GCT complex, tiltmeters will be used for tilt or slope of these structural members. Periodic optical survey will be performed for quality control. Typical locations for Liquid Level Settlement Sensor (LLSS) and Survey Prism targets for Automated Motorized Total Station (AMTS) inside GCT for Column Movement Monitoring are shown on Fig 6.

A number of portable seismographs will be used to monitor peak particle velocity during drilling, blasting and TBM excavation. At locations where a structure is in the close proximity to the blasting and where high frequency vibration is anticipated, accelerometers and dynamic strain gauges will also be used.

Inside the ESA tunnels conveyance measurements will also be measured by tape extensometers.

GIR/GBR and Bid Documents Provide Needed Data to the Contractor

In order to meet the construction challenges imposed by the above described geotechnical, site and environmental conditions, all relevant data and design bases must be clearly passed on to the contractor through contract bid documents. These were done via various reports such as Geotechnical Data Report- GDR, Geotechnical Baseline Report -GBR, Geotechnical Interpretive Report –GIR, Building Condition Survey Report and Ambient Noise and Vibration Reports, drawings and specifications. Some of the major challenges are discussed below.

Rock Mass Behavior

Rock mass characteristics that are expected to be encountered during excavation of the tunnels and raise bores are presented in detail in geologic zones defined by specific tunnel reaches with approximate stationing. Anticipated range of Q and RMR values for each zone has also been presented in the Geotechnical Interpretation Report (GIR). Also presented are engineering properties of rock and the most probable range anticipated.

Minimum performance requirements for the TBM were specified depending upon the expected ground conditions with the stipulation that the TBM must be capable of excavating through the entire range of rock conditions predicted by the geotechnical investigation

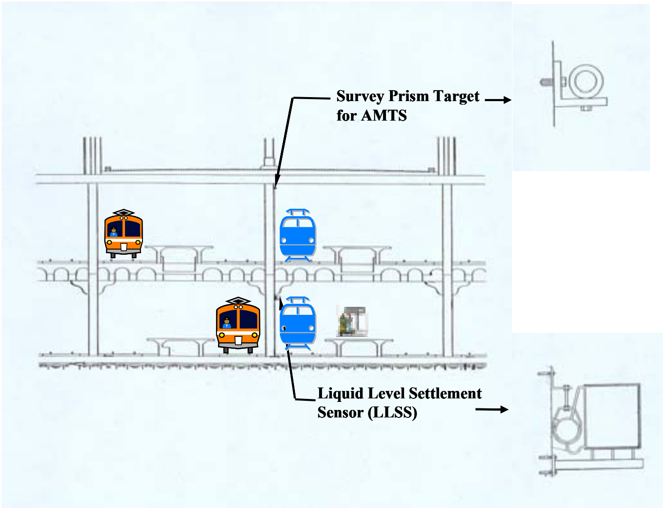

Fig. 6. Typical Locations for Liquid Level Settlement Sensors (LLSS) and Survey Prism Targets for Automated Motorized Total Station (AMTS) inside GCT for Column Movement Monitoring.

Groundwater Control

Groundwater conditions, anticipated permeability as well as estimates of groundwater inflow and control have been presented in the GIR for each geologic zone. The groundwater inflow estimates include sustained flow, local instantaneous flush flow and face inflow incidental to TBM. The TBM will require probing ahead for groundwater conditions and grouting ahead of the face will be required if excessive groundwater inflow is encountered.

Initial Rock Support

Initial support selection is primarily based on geotechnical conditions, size and configuration of the underground openings, proximity to existing structures and tunnels and method of excavation. An important consideration in the design of the initial support system is the fact that the tunnels excavated under the first construction contract will be required to remain stable with only initial support for several years until the final concrete lining is installed in a future construction contract. Discussion of initial support installation with respect to expected rock mass behavior at each geologic zone has been presented in the GIR. The contract drawings show approximate limits of various support classes. Support class types and their locations will vary during construction based on observed geologic conditions in the excavated tunnel. Provisions have been made for installation of additional support as necessary over and above those shown on contract drawings. Initial support generally consists of #8 and #9 steel dowels and bolts and 4 inch to 10 inch shotcrete with one or two layers of welded wire fabric. Lattice girders or steel sets are required in certain areas. In addition, unsupported lengths are restricted by maximum allowable round length for drill and blast and maximum TBM stroke, prior to installation of initial supports. These measures will keep the ground deformation to a minimum thus creating minimum impact on the adjacent tunnels and structures.

Gripper Pressure and Pillar Maintenance

For TBMs with side grippers consideration must be given to the gripper bearing pad surface area to minimize local overstressing of rock. Gripper problems are anticipated along shear zones. Special consideration is required for the pillar stability between adjacent TBM runs especially at the Wye structures. Where pillar width is less than 12 feet, special pillar reinforcement is required.

Ground-Borne Vibration

Ground-borne vibration from blasting for the excavation of the enlargements and TBM operations is an important issue in terms of impact on surrounding structures. A study was undertaken to determine the likely levels of vibration in order to provide contractors with guidelines for the explosive charge and delay configuration during blasting, as well as to establish estimates of expected blast vibration for interested parties. Ground-borne vibration due to blasting, drilling, and TBM/Roadheader operations were also addressed.

A method was established to measure the attenuation, or decay with distance from the source, of such vibration from an origin at the base of the lower level of the MNR tracks, through columns in Grand Central Terminal (GCT) and building columns to the structures themselves. The train passage at the lower level of GCT was used as the main source of vibrations in the absence of a design-phase test blast program. The Contractor will perform test blasts before production blasting starts for each construction contract. This test blast program will confirm the applicability of the vibration regression equations resulting from the vibration study recognizing that significant extrapolation was required in the adopted approach. Furthermore, the test blast program will aid in determining necessary adjustments to the blasting procedure.

Although modeling and limited round length and scale distance indicate vibration values within the tolerable structural damage values for transit tunnels, within close proximity of the blast source, such blasts will cause significant concern and limit such activity within small windows in between train passages. The project looked at alternative methods of mechanical excavations.

A series of rock samples were tested to assess the use of a road header for rock excavation. It appears marginally feasible and as such can not be specified for the project. However, a road header demonstration project is included in the first construction contract to assess feasibility of excavation. The demonstration will take place in the approach tunnels beginning at the existing 63rd Street tunnel at Second Avenue. Upon successful demonstration, the contractor may use roadheader to excavate the enlargements.

CONCLUSION

The paper has presented the various geotechnical and physical challenges that needed to be overcome on the ESA project. A well thought out progressive engineering approach to the various problems has been implemented. Along with conventional geotechnical investigations, the decision to have initial TBM bores not only provides early access to the site, but also allows a more comprehensive rock mass characterization at the exact location of the large caverns and shafts, so that they may eventually be constructed with minimal impact on surrounding structures, buildings, and quality of life.

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