# NEW YORK CITY—SECOND AVENUE SUBWAY: MTA'S 72ND STREET STATION AND TUNNELS PROJECT CONSTRUCTION OF A LARGE SPAN STATION CAVERN, RUNNING TUNNELS, CROSS-OVER AND TURN-OUT CAVERNS, SHAFTS AND ENTRANCES

Brian Fulcher ▪ J.F. Shea Construction and SSK Joint Venture

Sean Menge ▪ Kiewit Infrastructure Company and SSK Joint Venture

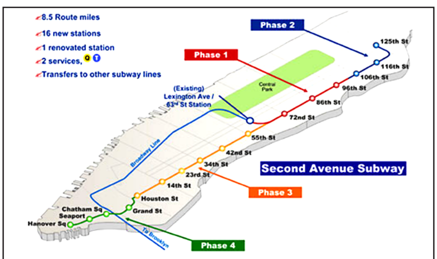
James Grillo ▪ Schiavone Construction and SSK Joint Venture

## ABSTRACT

New York City's extensive transit system had not been expanded for several decades until construction of the MTA's Second Avenue Subway program was re-started in 2007. Under Phase 1, the 72nd Street Station and Tunnels Project represents a significant portion of the extensive program. This paper describes the overall project design and unique construction challenges encountered to date for the fast-track excavation and final concrete lining of the underground works. This includes a large span station cavern, cross-over and turn-out caverns, running tunnels as well as three entrances and two ancillary shafts. All work is being performed in a densely developed urban environment, with a restricted surface work site, significant operational constraints and an aggressive construction schedule.

## SUMMARY

The design and construction of the 72nd Street Station and Tunnels Project represents a substantial undertaking by the MTA as part of its ambitious Second Avenue Subway construction program. It is one of three primary station and tunnel contracts that forms the core of the civil works portion for Phase 1 of the program. The integrated design of the 72nd Street project required approximately eight years to complete, in conjunction with the corresponding designs for adjacent stations and connecting tunnels in the program. Construction of the heavy civil portion of this station will require more than three years of continuous, multi-shift operations—to complete the excavation and final concrete lining of the station, cross-overs and turn-out caverns as well as running tunnels, Ancillaries and Entrances. The fast-paced construction schedule will result in the timely commencement of the follow-on finishing and systems contracts; linked to a planned Revenue Service Date in December 2016 for Phase 1.




Phases of Construction
Courtesy of MTA Capital Construction Company

**Figure 1. MTA's general arrangement route plan for the Second Avenue Subway in Manhattan, New York City**

The 72nd Street project is located between the existing 63rd Street

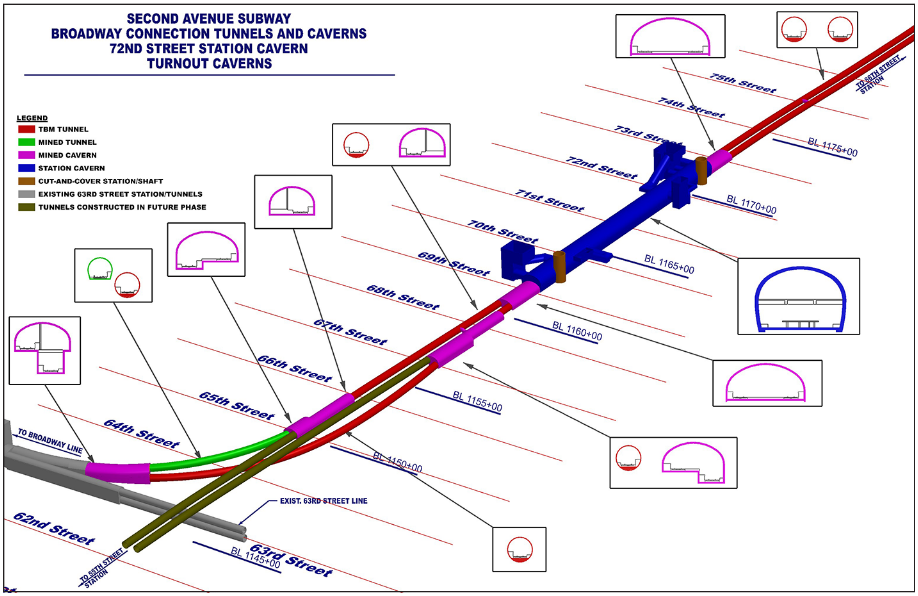



**Figure 2. Overall site plan for the 72nd Street Station and Tunnels Project for the MTA. The project extends from 73rd Street in the north to the tie-in point at the existing 63rd Street Station for a distance of about 3,000 LF.**

Bellmouth section and 73rd Street where it connects to running tunnels constructed under a separate contract. The project includes a 1,300 foot long station cavern with two cross-over caverns. The south tunnels and turn-out caverns cover an additional 2,000 LF south of the station. The site is located in a densely developed portion of the Upper East Side in New York City and as such, provides limited construction areas.

Work restrictions and controls confine day-to-day operations to the extent that extensive planning is constantly needed to meet the 37 month construction schedule with timely deliveries of materials and equipment, along with continuous removal of spoil materials.

At present (early 2013), the excavation work is in its final stage. Meanwhile, approximately 30% of the final lining is already in place in accordance with the construction schedule requiring multiple concurrent activities. An interim milestone date covered approximately 40% of the northern portion of the station. Refer to Figures 1 and 2 for location and layout details.

## KEY DESIGN FEATURES FOR THE PROJECT

The overall design of the station, turn-out caverns and south tunnels along with the Entrance and Ancillaries had to conform the NYCTA requirements but also satisfy recent NFPA and FTA guidelines. The new stations on the Second Avenue Subway would, therefore, be substantially different than most other existing MTA stations in New York City. They would have more voluminous interiors, center platforms, have more entrances, be fully ADA compliant and focus on longer life cycle use with minimum maintenance requirements. Some of the key features of the design of the caverns and tunnels for the project include the following.

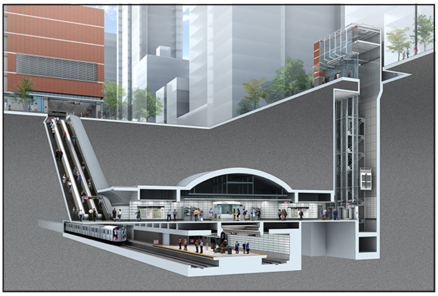


**Figure 3. Section rendering of the 72nd Street station at completion. Finishing work will be done separately.**

**Figure 4. Rendering of the station mezzanine level at completion. Finishing work will be done separately.**

- **Fully drained tunnels and caverns**
  - All tunnels and caverns are designed as fully-drained and waterproof-lined structures, complete with a final concrete lining installed.
  - Ground water pressure is relieved through an extensive system of piping and gravel filters to a passive sump and discharge facility in the station invert.
- **Initial ground support with shotcrete and rock bolts defined in the Contract**
  - The ground support design for the caverns, tunnels and adits included detailed requirements, known as *Initial Support*, to be supplemented as needed with *Additional Support* of the same nature and materials.
  - Ground support included fully-grouted and tensioned rock bolts and dowels as well as multiple layers of steel fiber reinforced shotcrete (SFRS).
  - The design lengths and patterned spacing of rock bolts and dowels varied depending on location in the tunnels and caverns. Shotcrete thickness was also variable depending on the location with the final (exposed) layer placed without steel fibers.
- **Two TBM-bored tunnels running throughout the project length**
  - The station and tunnel design included the pre-excavation by TBM of two “pilot” tunnels. This was primarily done to complete the lengthy running tunnel excavation by mechanical methods (and avoid blasting) starting at 96th Street and ending at 63rd Street. Portions of these TBM bores were enlarged into the station, cross-over and turn-out caverns.
- **Provisions made for follow-on mezzanine and platform construction**
  - The heavy civil contract did not include the construction of the mezzanine or station platform. Just the same, considerable provisions were made for this specialized construction in the exterior walls and invert in the station cavern (Figures 3 and 4).
  - Access for the construction of the station mezzanine and platform would be through both Ancillary structures as part of the follow-on finishing contract.
- **Starter construction shafts provided for early access to the station cavern**
  - The civil works contract did not include the construction of the initial 30 VF of the two temporary construction shafts—one located on 2nd Avenue

near 69th Street and other on 2nd Avenue near 72nd Street. These shafts were later developed and became the primary access to the station cavern and south tunnels to a maximum depth of 95 feet.

  – The temporary construction shafts will be backfilled and the areas restored as part of the heavy civil contract. This is consistent with completion of the underlying station cavern arch final cast-in-place lining.

- **Fan driven ventilation system with a cooling system for the station**
  – Forced ventilation and an "air tempering" system for cooling in the station cavern and entrances
  – Dedicated intake and exhaust systems for normal and emergency operations
- **Twin track station and parallel running tunnels**
  – The station cavern includes two tracks (Uptown and Downtown directions)
  – Two parallel running tunnels contain a single track to connect the 72nd Street Station to the Bellmouth area of the existing 63rd Street Station
- **Station and Cross-Over Cavern center platform and mezzanine**
  – The Station Cavern and Cross-Over caverns are self-supporting in rock
  – A center platform runs the full length of the station
  – The mezzanine (to ticketing level) is supported from the station walls
- **Entrances with escalators/stairs and a separate bank of five elevators**
  – Public access to the station cavern mezzanine level includes two entrances equipped with twin escalators and stairs. Additional escalators and stairs connect the mezzanine to the platform level.
  – Five elevators enclosed in a separate entrance connect the street level to the mezzanine. Additional elevators connect the mezzanine to the platform level.

## SCOPE OF WORK FOR THE HEAVY CIVIL CONTRACT

The scope of the heavy civil contract—for the excavation and final lining of the station and turn-out caverns as well as the running tunnels, ancillaries and entrances—included the following generalized primary scopes covered under the Lump Sum contract. Refer to Figures 5 and 6.

- **Underground excavation, support and lining in rock of the following:**

| | |
|---|---|
| – Station cavern | 980 LF |
| – Cross-Over caverns | 2 × 160 LF |
| – G3 Turn-Out cavern | 1 × 285 LF |
| – G4 Turn-Out cavern | 1 × 385 LF |
| – 63rd Street Stub Cavern | 1 × 165 LF |
| – Horseshoe tunnel | 1 × 410 LF |

- **Surface excavation, support in soil and rock of the following:**

| | |
|---|---|
| – Ancillary 1 shaft | 11,800 BCY |
| – Ancillary 2 shaft | 14,000 BCY |
| – Entrance 1 and 2 inclines | 4,400 BCY |
| – Entrance 3 shaft | 5,600 BCY |

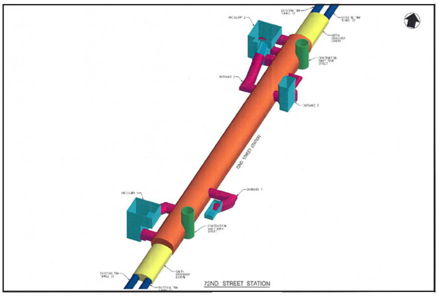



**Figure 5. General arrangement of the station cavern, cross-overs, ancillaries and entrances**

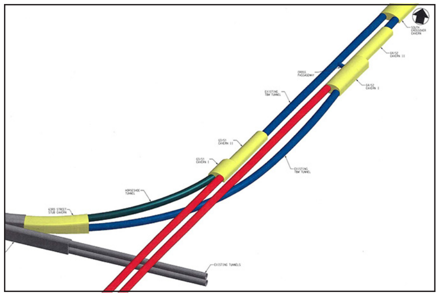


**Figure 6. General arrangement of the south tunnel caverns and tunnels to the existing 63rd Street Station**

The scope of the work also was performed within a 37-month construction schedule with one interim milestone date after 31 months. The work restrictions also included two separate "no blasting" periods that were planned to occur in the midst of the station and tunnel rock excavation programs. This was due to the concurrent (and conflicting) excavation of two underlying TBM bored running tunnels—located between 96th and 63rd Streets.

## CONSTRUCTION SCHEDULE

The overall schedule for the civil construction contract was 37 months long beginning on 01 Oct 10. The schedule included one interim milestone date, *Milestone 1,* after 31 months and a *Substantial Completion* date after 37 months. This schedule was always considered to be very aggressive and considerably challenging in light of other site and contractual conditions.

It should be noted also that the Notice-of-Award (NOA) of the Contact also coincided on the same date with the MTA's Notice-to-Proceed (NTP) with the work and, therefore, the start of the contract time. *Milestone 1* defined the completion of approximately the northernmost 40% of the station along with the North Cross-Over, Ancillary 2 and Entrance 2.

The construction schedule was detailed in CPM using Primavera P6 software, then submitted for approval by the MTA. The CPM schedule was carefully reviewed and updated monthly. The Critical Path and float relative to *Milestone 1* (Month 31) and *Substantial Completion* (Month 37) were computed and analyzed. The MTA used this data to assess progress relative to its master Second Avenue Subway construction program. Overall, the CPM schedule included the primary construction activities and durations as listed below and shown in Figure 7.

- **Rock excavation and support** NOA + 23 months (±)
  - Station, adits, cross-overs
  - South caverns and tunnels
- **Final concrete lining (cast-in-place)** NOA + 23 to 37 months (±)
  - Station, adits, cross-overs
  - South caverns and tunnels
- **No blasting periods (per the contract)** No.1 3 months (fixed duration)
  No.2 4 months (fixed duration)

Owing to SSK's ability to coordinate its construction operations with an adjacent contractor responsible for boring two underlying TBM tunnels, the two "no blast" periods were substantially eliminated. Nonetheless, other blasting restrictions were experienced which impacted the work and extended the planned excavation period.

Rock excavation was completed generally as listed in Figure 8. Meanwhile, several concurrent operations including the initial stages of the final lining were underway in the same period (but not shown in this figure for clarity).

Concrete final lining operations are currently underway and tracking well with the CPM schedule for the planned completion of *Milestone 1* and the *Substantial Completion* date. Refer to Figure 9 that lists the primary final lining operations in the station and south tunnels. In order to complete the post-mining schedule, several concrete lining operations were underway concurrently. This posed many logistical problems that had to be balanced with competing and conflicting goals in the station and south tunnel work areas in the final 15 months of the schedule. Nonetheless, the work

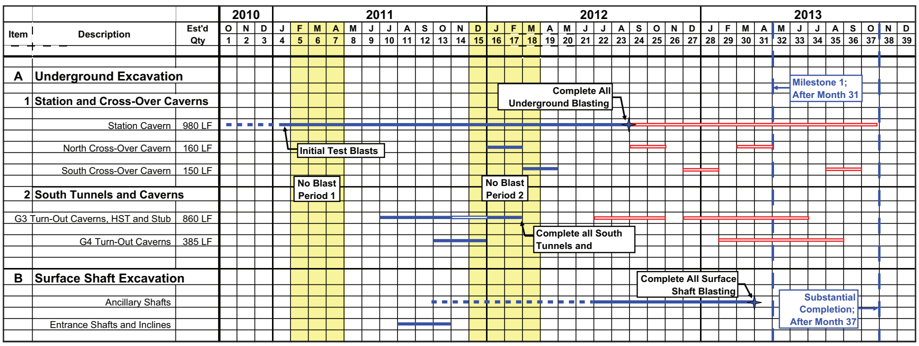



**Figure 7. Overall excavation and final lining schedule for the project—including all caverns, tunnels, adits, surface shafts and entrances. Additional construction activities are detailed in the following figures.**

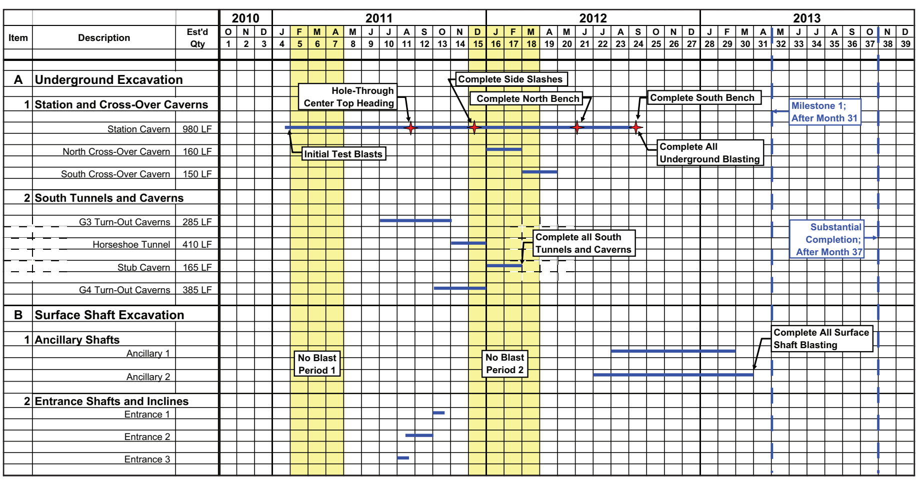



**Figure 8. Overall excavation schedule for the project—including all caverns, tunnels, adits, surface shafts and entrances. The work required multiple heading operations while constantly mucking to two construction shafts.**

proceeded well with planned early completion and hand-over of the south tunnels and caverns to the MTA for follow-on contracts.

## SITE CONDITIONS AND WORK RESTRICTIONS

The project is located in a very densely developed area in New York City with the “linear site” confined only to designated portions of 2nd Avenue. Refer to Figures 10 and 11. No “off-site” areas were included by the MTA in the Contract for staging and storage of materials and equipment. The site is surrounded by numerous high-rise residential buildings with 2nd Avenue acting is the primary thoroughfare to and from the area. In fact, 2nd Avenue is also one of the primary access routes to mid and lower Manhattan from the Bronx (to the north) and Brooklyn (to the east). As such, all construction operations had to be carefully planned to provide for “just-in-time” deliveries (and removals) on a daily basis while complying with numerous other traffic and site use working hours and restrictions. In this manner, there is a very delicate “dynamic balance” between essential construction activities and local neighborhood interests—all while maintaining the day-to-day pace in the construction schedule.

All work for the construction of the station caverns and south tunnels was performed through two temporary shafts located on 2nd Avenue near 69th and 72nd Streets. Significant all-weather temporary enclosures were built at these locations to minimize construction-related environmental issues such as noise, dust, odors, construction activities, security and appearance within the well-established neighborhoods. These structures were also designed to enclose the electrically-powered (silent) overhead

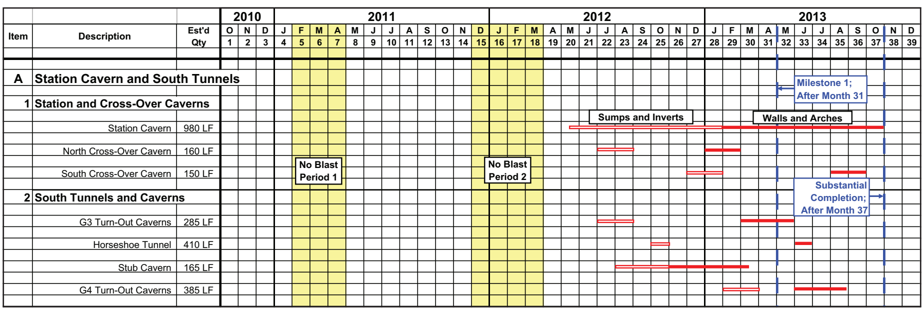



**Figure 9. Overall final lining concrete schedule for the project—including all caverns, tunnels, adits, surface shafts and entrances. The work required many concurrent operations while constantly supplying concrete from drop shafts.**

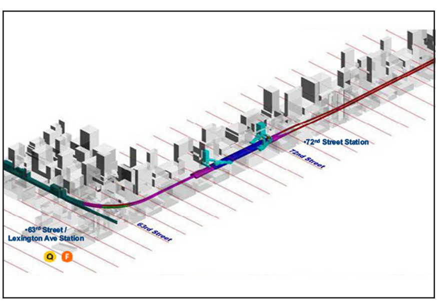



**Figure 10. Rendering of the general project layout along 2nd Avenue—from 73rd to 63rd Streets**

**Figure 11. Aerial view of 2nd Avenue in the area of the project site. Note the dense building development.**

**Figure 12. Construction of one of two Muck Houses erected at the site—for efficient materials handling**

**Figure 13. Operational Muck House at 72nd Street site. Ventilation and electrical systems are also enclosed.**

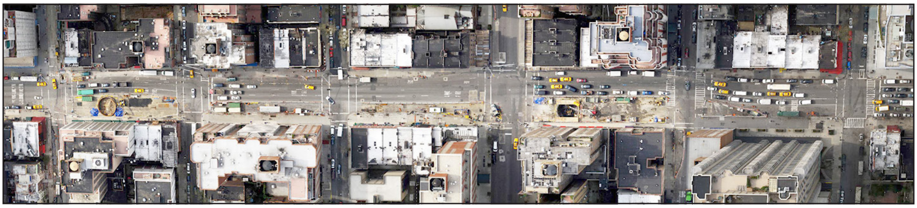


**Figure 14. Aerial view along 2nd Avenue as the shaft sinking work started in late 2010 at 69th and 72nd Streets. Four lanes of traffic had to be maintained except for specific periods of the day—Monday to Friday.**

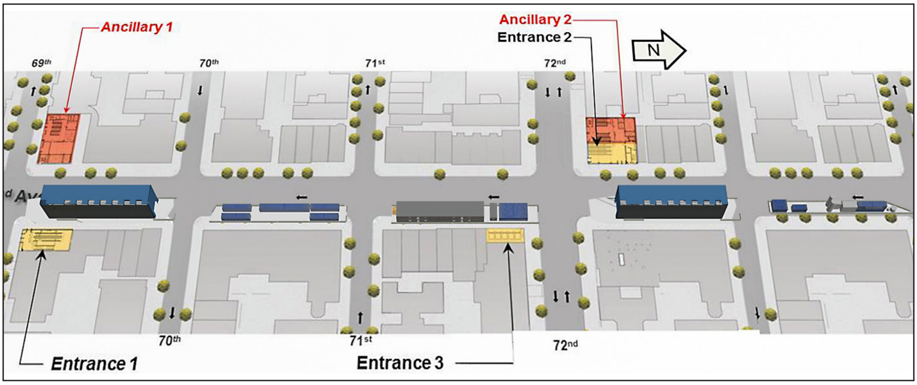



**Figure 15. Rendering of the site with temporary facilities in place. These facilities include Muck Houses equipped with electrically-powered overhead cranes for materials handling, field offices, materials storage and water treatment.**

gantry cranes that were used throughout the excavation and final lining phases. Muck handling and sequent concrete form and rebar handling tasks were efficiently performed by the overhead cranes from within these enclosures (Figures 12 and 13).

Figure 14 provides an aerial view of the site on 2nd Avenue at the start of the project, with the two temporary construction shafts being excavated. Later and as the underground operations progressed, two Muck Houses were constructed over the shafts. Refer to Figures 15–18.

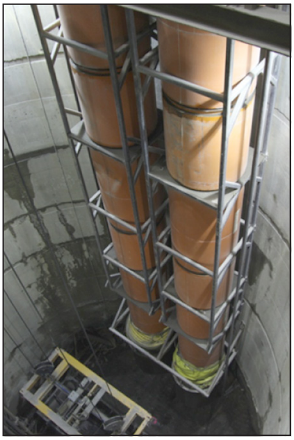


**Figure 16. Interior view inside one of two construction shafts at the site**

**Figure 17. Looking up inside one of two construction shafts at the site**

**Figure 18. Hoisting a muck box in the shaft—for off-site disposal**

The Contract imposed significant daily restrictions on the performance of the surface work activities even though underground operations could potentially proceed on a 24-hour per day basis, 7 days per week. In general, all surface work operations could be performed from 7:00 AM to 10:00 PM daily, Monday to Friday with restricted hours on weekends. Blasting was restricted to the hours of 7:00 AM to 7:00 PM.

Overall, there was reasonable "give and take" in light of the confined site and restrictive working conditions—with neighborhood concerns frequently addressed along with periodic construction-related special operations needing accommodations outside of the normal work space and hours.

## GEOLOGICAL CONDITIONS AND SUBSURFACE BEHAVIOR

The anticipated geological conditions and behavior for the project were described in the Contract Documents that included a GBR (contractual), a GDR and GIR (reference documents only). The site geological profile was enclosed in the GIR. An extensive geological investigation program was undertaken by the MTA for the entire Second Avenue Subway Program with key portions of this substantial task incorporated into the Contract Documents.

The rock, soil and ground water conditions were anticipated and later found to be generally very good for the construction of the caverns, tunnels, adits and inclines. In broad terms, the rock was found to be very amenable for drill and blast excavation methods while being far too hard for roadheader and demolition hammers. Only in a few isolated locations where faults and shears were encountered, was the repetitive drill, blast, bolting and shotcrete cycle interrupted for more intensive excavation and/or ground support measures. The soil layer (including historical fills) was shallow but highly variable in depth. Ground water inflows were expected to be modest, localized and controllable through panning and sumping methods. The following subsections will describe the anticipated and "as encountered" conditions and behavior for rock, soil and ground water to date and as the project approaches the final stages of excavation.

### Rock Conditions and Behavior

Throughout the project site, the rock was generally Manhattan schist with some intrusions of amphibolite, granite and pegmatite. In all but a few locations, the rock conditions

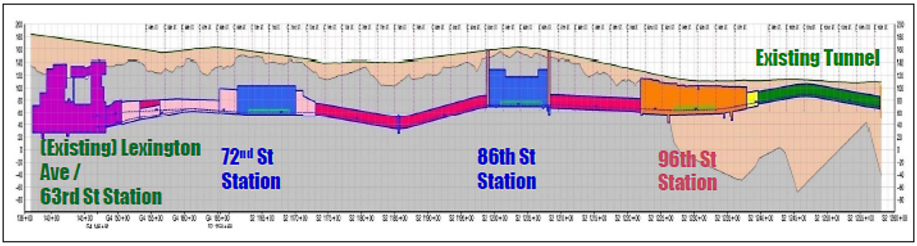



**Figure 19. Simplified geotechnical profile of the Second Avenue Subway showing all three stations and tunnels**

were anticipated to be tight, largely impermeable and respond well to controlled blasting techniques without extensive support or ravelling. Accordingly, the prescriptive ground support design, known as *Initial Support* together with the detailed excavation sequence, took account of the relative consistency and anticipated behavior of the rock for all caverns, tunnels and adits. In only a few locations based on information in the GBR, GDR and GIR documents were the rock conditions anticipated to be difficult and potentially in need of *Additional Support* provisions. The simplified geological profile for the Second Avenue Subway route is shown in Figure 19.

### Soil Conditions and Behavior

Soil (and historical fill) conditions were encountered in all Ancillary and Entrance excavations. The soil cover depth varied considerably from location to location but was generally in the range of 5 to 20 feet. Prior building construction at the sites contributed to the depths encountered. When found, undisturbed soil layers consisted of naturally occurring sands and silts, often in gouge areas overlying weathered bedrock.

Only in the Ancillary excavations was the soil layer deeper (highly variable in depth) and required Support-of-Excavation systems—for retention of soil and surrounding utilities as well as for the overlying temporary decking system. Due to the modest quantity of ground water, Support-of-Excavation systems and designs did not need to be watertight.

### Ground Water Conditions and Inflows

The ground water table was located above the caverns and tunnels throughout the project site and may have been influenced by tidal fluctuations in the nearby East River. Just the same, and with the benefit of tight rock conditions, only small inflows were anticipated. This proved to be the case and especially after the underlying TBM-driven tunnels had been completed under a prior contract. During the excavation and final lining phases in the caverns and tunnels, only small quantities of ground water have been encountered and were easily captured with panning methods. To date, no grouting for ground water control has been required.

## ROCK EXCAVATION AND GROUND SUPPORT

The majority of the work (measured in cost and schedule time) for the project has been devoted to rock excavation by drill and blast methods. Mechanical and chemical excavation methods were only seldom used—with limited success owing to the in-situ rock quality. The following subsections will describe the rock excavation methods, materials and equipment as well as the ground support systems used in the station and turn-out caverns, tunnels and adits.

**Table 1. Summary of the prescribed ground support, generally known as *Initial Support*. These materials and installations were used in all designated areas of the site—without regard to the ground conditions encountered.**

| Item | Description | Overall Length | Principle Dimensions | | | | Estimated Qty | | Principle Ground Support Materials | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | W | H | Arch | Slope | Face | Vol | SFRS | Bolts | Dowels | Spiles | Girders |
| A | **Station Cavern and Access** | | | | | | | | | | | | |
| | Station Cavern | 980 LF | 68'-10" | 48'-10" | variable | 0° | 3,125 SF | 113,400 BCY | ● | ● | ● | | |
| | Construction shafts | 85 VF | 30'-0" | 85 VF | 2 each | vertical | 707 SF | 4,450 BCY | ● | ● | ● | | |
| B | **Cross-Over Caverns** | | | | | | | | | | | | |
| | North Cross-Over | 155 LF | 61'-0" | | variable | 0° | 1,777 SF | 10,200 BCY | ● | ● | ● | ❍ | |
| | South Cross-Over | 165 LF | 61'-0" | | variable | 0° | 1,777 SF | 10,860 BCY | ● | ● | ● | ❍ | |

**Figure 20. Drilling the top heading west side slash in station cavern after completing the center drift**


**Figure 21. Final muck removal in the station cavern after completing the cross-overs and bench excavation**

## Station Cavern Excavation and Ground Support

The project included the excavation of six caverns in addition to tunnels and adits for Ancillary shafts and Entrances. Table 1 summarizes the principle dimensions and quantities of rock excavation, without regard to the initial “pilot” tunnels (TBM-bored) underlying the Station Cavern, Cross-Overs and throughout the south turn-out caverns.

The above-listed work required approximately 20 months to complete but not before the permanent final (concrete) lining had commenced. The work was performed on a three shift-per-day basis in all areas with a fleet of underground equipment specially designed for this work and supported with surface hoisting facilities as described above. Figures 20, 21 and 23 illustrate the work underway, whereas Figure 22 is a diagram of the general work sequence used for the excavation of the station cavern.

All blasting for the caverns and tunnels was performed under the guidance and authority of the New York City Fire Department (FDNY) who also provided licenses for powder handlers and Blasters-in-Charge as well as permits for the supply of explosives to the site. All underground blasting was performed on swing shift, Monday to Friday.

Powder and detonators used were all commonly available from Austin Powder Company and included, for example, Emulex (emulsion) and Red-E Lite-D (trim powder) as well as 200/5,000 milli-second non-electric detonators and 9 to 42 milli-second surface delays. No primacord or ANFO was used anywhere on the project—in accordance with FDNY.

The quantity of powder per detonator varied linearly with the blast hole depths and would range from 3.0 to 9.0 lbs per delay. The Powder Factor for a typical top-heading (center-cut) round varied from 4.5 to 6.0 lbs/BCY (Figures 24–25).

Blast hole patterns and loading for the station cavern varied considerably in accordance with the face area, round length (vibration limited) as well as other factors

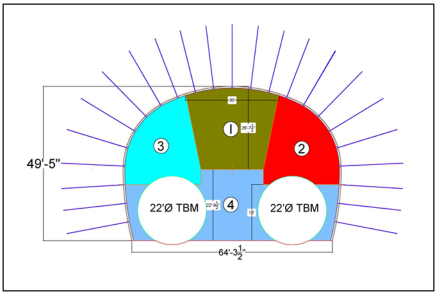



**Figure 22. Station cavern excavation sectional plan showing the top heading and bench excavations**

**Figure 23. Holing-through the center top heading ① before starting the east and west side slashes, ② and ③**

**Figure 24. Final stage in the station cavern—for the removal of the rock surrounding the TBM tunnel**

**Figure 25. Final stage of station cavern excavation before the start of final lining operations**

**Table 2. Summary of the prescribed ground support, known as *Initial Support*. These materials and installations were used in all designated areas of the site—without regard to the actual ground conditions encountered.**

| Item | Description | Est'd Qty | Blast Round Length (Plan ) | | | Prescribed Ground Support Materials and Installation | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Shotcrete | | Rock Bolts | | | | | Rock Dowels | | | |
| | | | Var | 10' | 12' | 5" | 7" | Dia | Len | Tension | Load | Pat'n | Dia | Len | Tension | Pat'n |
| A | Station Cavern and Cross-Overs | | | | | | | | | | | | | | | |
| | Main Station Cavern | 980 LF | | ❍ | ● | | ● | 1.25" | 20' | Yes | 30 kip | 6' x 6' | 1.25" | 20' | No | 6' x 12' |
| | North and South Cross-Overs | 310 LF | | ● | | | ● | 1.25" | 16' | Yes | 20 kip | 6' x 6' | 1.25" | 20' | No | 6' x 12' |

including geological conditions, rock fragmentation and ground support considerations. Similarly, the prescribed *Initial Support* varied in accordance with the overall dimensions of the heading and included tensioned; fully resin-grouted rock bolts above springline on a preset pattern in addition to untensioned fully resin-grouted dowels in the walls below springline, also on a preset pattern. The steel fiber reinforced shotcrete (SFRS) layers varied also with the heading dimensions—from 5 to 7 inches thick. Refer to Table 2.

Limiting ground vibration values in many areas of the project often curtailed the blast round length and, therefore, the total weight of powder per delay. Notwithstanding, the maximum round lengths were shown in the Contract documents and varied from 10 to 24 feet. Field vibration measurements were intended to only measure ground transmitted blast energy, and not dynamic building response. Refer to Table 3 and Figure 26.

**Table 3. Summary of the prescribed (and adjusted) ground born allowable blast vibrations; velocity and frequency data, as measured at the location of various buildings and utility systems along the route tunnel and cavern route**

| Item | Description | Blast Vibration Data | | | | | Affected Work Areas | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Original Values | | | Revised Values | | Caverns | | | Tunnels and Adits | | |
| | | Velocity | Freq. | Distance | Velocity | Freq. | Station | T/Os | Stub | G3 | G4 | Adits |
| 1 | Normal Buildings | 1.92 ips | >40 hz | | 1.92 ips | >40 hz | ● | ● | ● | ● | ● | ● |
| 2 | Fragile Buildings | 0.50 ips | >40 hz | None | 1.20 ips | >40 hz | ● | ● | ● | ● | ● | ● |
| 3 | Sensitive Buildings | 0.50 ips | >40 hz | None | 1.20 ips | >40 hz | ● | | | | | ● |
| 4 | Historic Buildings | 0.50 ips | >40 hz | None | 1.20 ips | >40 hz | ● | ● | ● | ● | ● | ● |
| 5 | Landmark Buildings | **0.50 ips** | >40 hz | | **0.50 ips** | >40 hz | | ● | | ● | | |
| 6 | Underground Utility Systems | 0.50 ips | >40 hz | | 0.50 ips | >40 hz | ● | | ● | | | ● |

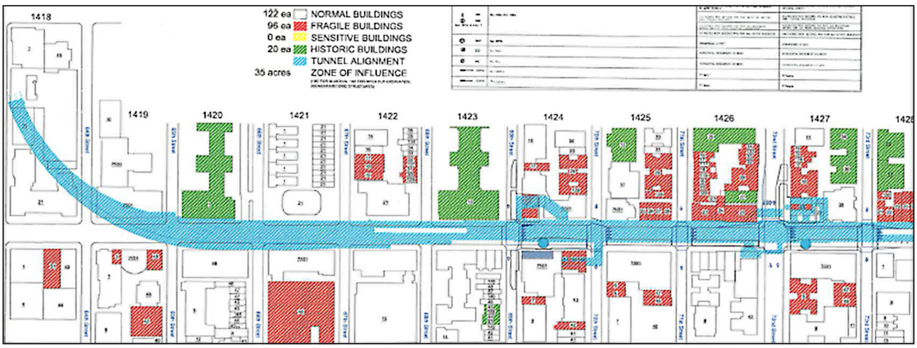



**Figure 26. Plan of the project site showing the type and number of buildings having special character and classifications related to vibrations from underground and surface blasting**

Considerable attention was given to blast vibration measurements and control and especially when excavations were in the vicinity of fragile, sensitive, and historic structures where the threshold value was restricted to 0.50 in/sec. After some discussions, this threshold value was adjusted to the levels, listed in Table 3. The required placement of seismographs, vibration measurements were greatly influenced by the building dynamic response and not solely blast induce ground vibrations.

A more detailed study of ground and building vibration responses is warranted in light of the Contract directed means for placement and measurement of "fixed" and "floating" seismographs. Only in areas where the "fixed" and "floating" seismographs were properly installed—in a manner to avoid measurement of building responses—could the true blast induced ground transmitted energy be correctly measured.

## SOUTH TUNNEL AND ADIT EXCAVATION AND GROUND SUPPORT

The project included the excavation of one running tunnel (Horseshoe Tunnel) as well as ten unique adits to connect the station cavern to the adjacent Ancillaries and Entrances. A small cross-passage was also excavated between the G3 and G4 running tunnels. Table 4 summarizes the principle dimensions and quantities of rock excavation

**Table 4. Principle dimensions and the quantities related to excavation of the south tunnels in addition to adits leading from the station cavern to the ancillaries and entrances**

| Item | Description | Overall Length | Principle Dimensions | | | | Estimated Qty | | Principle Ground Support Materials | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | W | H | Arch | Slope | Face | Vol | SFRS | Bolts | Dowels | Spiles | Girders |
| A | **South Tunnels** | | | | | | | | | | | | |
| | Horseshoe Tunnel | 410 LF | 22'-0" | 22'-0" | variable | variable | 405 SF | 6,150 BCY | ● | ● | ● | | |
| | Cross-Passage | 20 LF | 10'-0" | 10'-0" | variable | variable | 113 SF | 85 BCY | ● | ● | ● | | |
| B | **Station Area Adits** | | | | | | | | | | | | |
| | **Ancillary 1** | | | | | | | | | | | | |
| | Ventilation tunnel | 38 LF | 24'-10" | 20'-4" | variable | 0° | 589 SF | 830 BCY | ● | ● | ● | ● | ❍ |
| | Egress / Service tunnel | 110 LF | 35'-0" | 18'-0" | variable | 0° | 655 SF | 2,670 BCY | ● | ● | ● | ● | ❍ |
| | **Ancillary 2** | | | | | | | | | | | | |
| | Ventilation tunnel | 80 LF | 24'-10" | 20'-4" | variable | 0° | 457 SF | 1,350 BCY | ● | ● | ● | ● | ❍ |
| | Service tunnel | 20 LF | 20'-0" | 18'-0" | variable | 0° | 328 SF | 250 BCY | ● | ● | ● | ● | ❍ |
| | Egress tunnel | 20 LF | 20'-0" | 28'-6" | variable | 0° | 539 SF | 400 BCY | ● | ● | ● | ● | ❍ |
| | **Entrance 1** | | | | | | | | | | | | |
| | Access adit | 75 LF | 24'-10" | 17'-1" | variable | 0° | 377 SF | 1,050 BCY | ● | ● | ● | ● | ❍ |
| | Escalator incline | 70 LF | 24'-10" | 17'-1" | variable | 30° | 536 SF | 1,390 BCY | ● | ● | ● | ● | ❍ |
| | **Entrance 2** | | | | | | | | | | | | |
| | Access adit | 60 LF | 24'-10" | 17'-1" | variable | 0° | 428 SF | 950 BCY | ● | ● | ● | ● | ❍ |
| | Escalator incline | 70 LF | 24'-10" | 17'-1" | variable | 30° | 511 SF | 1,325 BCY | ● | ● | ● | ● | ❍ |
| | **Entrance 3** | | | | | | | | | | | | |
| | Access adit | 17 LF | 29'-0" | 17'-9" | variable | 0° | 450 SF | 1,090 BCY | ● | ● | ● | ● | ❍ |
| | Emergency tunnel | 90 LF | 10'-0" | 11'-0" | variable | 0° | 97 SF | 825 BCY | ● | ● | ● | ● | ❍ |

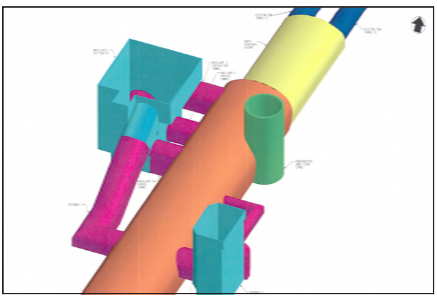


**Figure 27. Rendering of north portion of the station cavern, showing Ancillary 2, Entrances 2 and 3**

**Figure 28. Drilling an adit to Ancillary 2 from the station cavern area—as the top heading proceeds**

for the tunnels and adits. Figures 27 and 28 illustrate the nature and complexity of station adits.

The above-listed work required approximately 10 months to complete but not before the permanent final (concrete) lining had commenced. The work was performed on a three shift per day basis in all areas with a fleet of underground equipment specially designed for this work and supported with surface hoisting facilities as described above. Figures 29 and 30 illustrate the work underway in the turn-out and stub cavern enlargements.

Powder and detonators used were all commonly available from Austin Powder Company and included, for example, Emulex (emulsion) and Red-D Lite-E (trim powder) as well as 200/5,000 milli-second non-electric detonators and 9 to 42 milli-second surface delays.

Blast hole patterns and loading data for the tunnels and adits varied considerably in accordance with the face area, round length (vibration limited) as well as other factors including geological conditions, rock fragmentation and ground support considerations. Similarly, the prescribed *Initial Support* varied in accordance with the overall dimensions of the heading and included tensioned, fully resin-grouted rock bolts above springline on a prescribed pattern in addition to untensioned fully resin-grouted dowels

**Figure 29. Drilling for rock excavation in the G4 turn-out cavern. A previous TBM tunnel is on the left.**

**Figure 30. Completion of the G3 and G4 tunnels at the Stub Cavern—with a final separation of only 6 feet**

**Table 5. Summary of the prescribed ground support, known as Initial Support. These materials and installations were used in all designated areas of the site—without regard to the actual ground conditions encountered.**

| Item | Description | Est'd Qty | Blast Round Length (Plan ) | | | Prescribed Ground Support Materials and Installation | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Shotcrete | | Rock Bolts | | | | | Rock Dowels | | | |
| | | | Var | 10' | 12' | 5" | 7" | Dia | Len | Tension | Load | Pat'n | Dia | Len | Tension | Pat'n |
| A | **South Tunnels and Caverns** | | | | | | | | | | | | | | | |
| | G3 - Cavern I | 85 LF | ❍ | ● | | | ● | 1.25" | 14' | Yes | 20 kip | 6' x 6' | 1.25" | 14' | No | 6' x 12' |
| | G3 - Cavern II | 185 LF | ❍ | ● | | ● | | 1.25" | 12' | Yes | 20 kip | 6' x 6' | 1.25" | 12' | No | 6' x 12' |
| | G4 - Cavern I | 285 LF | ❍ | ● | | | ● | 1.25" | 14' | Yes | 20 kip | 6' x 6' | 1.25" | 14' | No | 6' x 12' |
| | G4 - Cavern II | 85 LF | ❍ | ● | | ● | | 1.25" | 12' | Yes | 20 kip | 6' x 6' | 1.25" | 12' | No | 6' x 12' |
| | Horseshoe Tunnel | 410 LF | ❍ | ● | | ● | | 1.25" | 10' | Yes | 20 kip | 6' x 6' | 1.25" | 10' | No | 6' x 12' |
| | 63rd Street Stub Cavern | 165 LF | ❍ | ● | | ● | | 1.25" | 14' | Yes | 20 kip | 6' x 6' | 1.25" | 14' | No | 6' x 12' |
| B | **Adits and Inclines** | | | | | | | | | | | | | | | |
| | Ancillary Adits | Various | ❍ | ● | | | ● | 1.25" | 10' - 12' | Yes | 20 kip | 5' x 5' | 1.25" | 20' | 10' - 12' | 5' x 10' |
| | Entrance Adits and Inclines | Various | ❍ | ● | | ● | | 1.25" | 12' | Yes | 20 kip | 5' x 5' | 1.25" | 20' | 12' | 5' x 10' |

in the walls below springline, also on a prescribed pattern. The steel fiber reinforced shotcrete (SFRS) layers varied also with the heading dimensions—from 5 to 7 inches. Refer to Table 5.

## FINAL CONCRETE LINING—CAVERNS AND TUNNELS

### Station Cavern and Cross-Overs—Inverts, Walls, and Arch

Final lining operations in the station and cross-over caverns involved considerable planning to allow for multiple concurrent operations for inverts, walls and arches. To this end, the deep sump at the 72nd Street shaft was completed first, followed by inverts in north and south directions, with station walls cast immediately afterwards. Refer to Figures 31 & 32. The station and North Cross-Over arch forming systems were deployed following the completion of a minimum number of station wall pours.

#### *Station Inverts*

The station and cross-over inverts were complicated to the extent that they were considered to be the most complex and burdensome of all concrete pours on the project. This was due to the extensive system of embedded ductile iron and PVC pipes and

**Figure 31. Constructing a station invert slab with rebar and forms. Note the waterproofing in the NXO.**

**Figure 32. Placing concrete in a station invert slab after all forms, rebar and piping were in place**

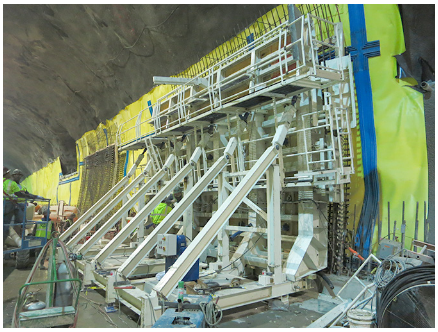


**Figure 33. Station cavern single-wall form in operation—following a checker-board pattern**

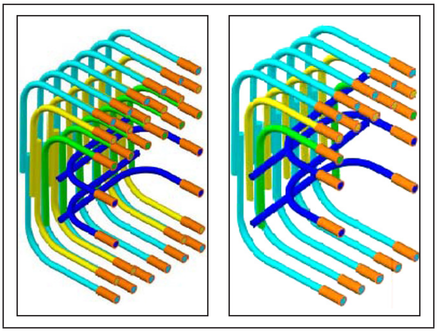


**Figure 34. Renderings of complex prefabricated beam couplers needed for the station lower wall pours**

fittings needed for the pressure relief drain system in addition to the traditional track drain system—both discharging into the large sump pit at the north end of the station cavern. All invert pours were 60 feet long and coincided with the placement of water barrier materials. PVC waterproofing membrane was installed throughout the entire underside of all invert pours. A double layer of reinforcing steel was also placed.

***Station Lower Walls***

The station lower wall pours were limited to 30 feet in length and included 33 pours on each side of the station cavern. There were no discrete wall pours needed for the cross-over caverns owing to the shape of the arch that extended to the invert level. Whereas the station lower wall pours had little embedded piping materials, they did, however, include several special forming arrangements needed to suit the intersecting adits—inverts and walls.

All station lower wall pours were formed and poured using MCT single-wall forms as shown in Figure 33. The forms were rail-mounted and included pour platforms and a slickline distribution system. The station wall pours included a double layer of reinforcing steel as well as a complex prefabricated beam coupler arrangement—needed for the follow-on mezzanine beams and slab pours. Refer to Figure 34.

***Station Arches***

The station and cross-over arch pours were limited to 30 feet in length and included 33 pours overall for the station cavern in addition to 5 more for each Cross-Over cavern. Whereas the station arch pours had no embedded piping materials they did include formed coffer recesses and embedded unistrut channels in public areas. Special forming arrangements were needed to suit the intersection of numerous adits.

All arch pours were formed and poured using MCT arch forms as shown in Figures 35, 36 & 37. As shown, the station arch forms, gantry crane and rebar template were all located on a mobile, rail-mounted platform deck—needed to efficiently access and construct the arch as well as place key portions of reinforcing steel. The forms were rail-mounted on the deck and included pour platforms, a slickline and placer concrete distribution system. The station arch pours required a double layer of reinforcing steel.

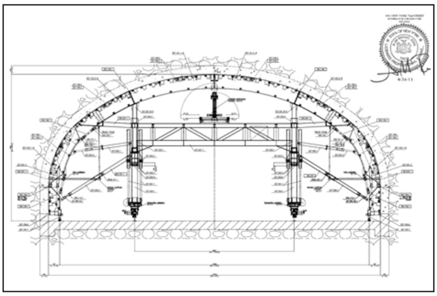


**Figure 35. Cross-Over arch form sectional drawing. This was a custom-built form for the NXO and SXO.**

**Figure 36. Cross-Over arch form in place in the North Cross-Over—ready for the first pour**

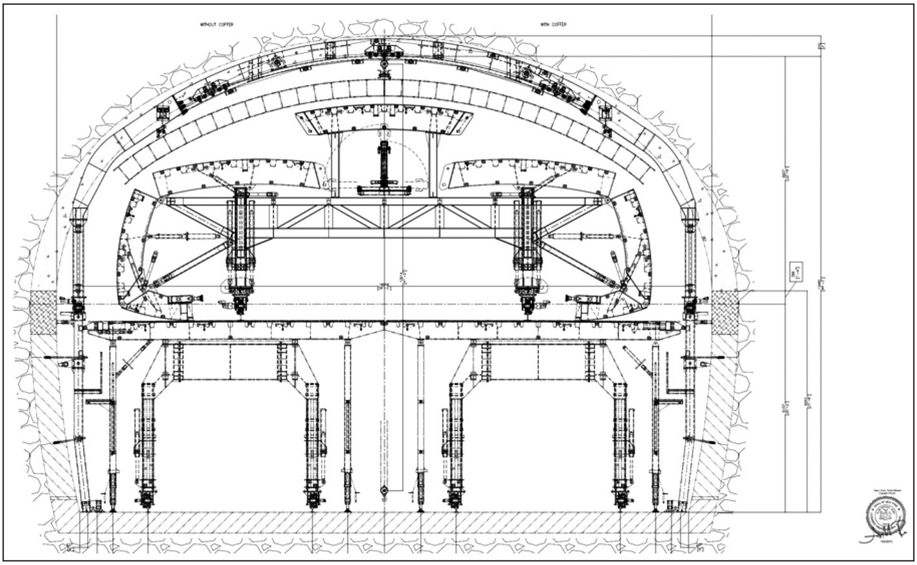


**Figure 37. Detailed view of the elaborate custom-built station arch form and traveller over top of a rail-mounted sectional decking system. The lower station walls are poured first, to be followed by the cavern end walls and arch pours—while connecting the adjacent adits—to entrance and ancillary facilities.**

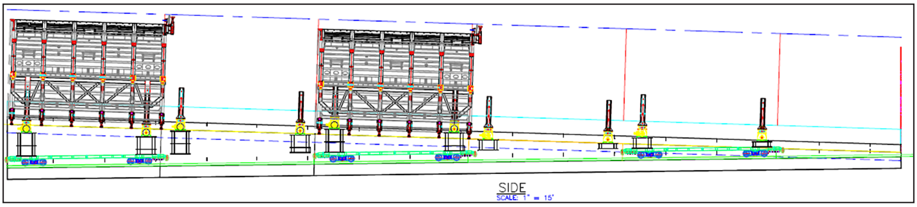



**Figure 38. Planned general arrangement for installing the final lining in the Turn-Out cavern arches—after accounting for complex track alignment and grade changes**

### Turn-Out and Stub Caverns—Invert and Arch

Final lining operations in the turn-out and stub caverns involved considerable planning to allow for multiple concurrent operations for inverts, walls and arches. To this end, the lower level of the 63rd Street Stub Cavern was completed first, followed by inverts in the G3 and G4 running tunnels, then inverts in the G3 and G4 turn-out caverns—all in a northward direction—retreating from the 63rd Street Bellmouth area. Cavern arches followed afterwards. The final concreting stage required lining of the running tunnel arch.

#### *Cavern Inverts*

The turn-out cavern inverts were complicated to the extent that they had an extensive system of embedded ductile iron and PVC pipes and fittings needed for the pressure relief drain system in addition to the traditional track drain system—both ultimately discharging into the large sump pit at the north end of the station cavern. All invert pours were 60 feet long with construction joints coinciding with the location of water barrier materials. PVC waterproofing membrane was installed throughout the entire underside of all invert pours. Whereas steel fiber reinforced concrete (SFRC) was used for the adjacent running tunnel inverts, a double layer of reinforcing steel was placed in the cavern inverts (and arches).

#### *Cavern Arches*

The turn-out and stub cavern arch pours were limited to 30 feet long and included 27 pours overall; 5 each for the stub cavern, 9 each for the G3 cavern, and 13 each for the G4 cavern. Special temporary works were needed for the arch forms in the G3 and G4 caverns due to the slope and bifurcating track alignments.

All arch pours were formed and poured using MCT arch forms as shown in Figure 38. As shown, the arch forms were all mounted on a mobile, rail-mounted form traveller—needed to efficiently form and pour the arch. The forms included pour platforms and a slickline and placer concrete distribution system. The cavern arch pours required a double layer of reinforcing steel placed in advance of arch form assembly.

The 63rd Street Stub Cavern was a difficult undertaking owing to the over/under configuration of the tracks and tie-in to the existing Bellmouth structure. The lower portions this structure was straightforward and required single-wall forms and soffit shoring. Following this, a custom-built arch form was obtained to place the final lining in the arch along the curved track alignment. Refer to Figures 39 and 40.

## RUNNING TUNNELS—INVERTS AND ARCH

The TBM bored and Horseshoe running tunnel final lining was divided between inverts and arch pours. Overall, there was approximately 2,400 LF of tunnel split into four separate sections—all having the same final interior dimensions and reinforcing


Figure 39. Stub Cavern walls at G4 tunnel. A soffit slab will follow to complete this over/under structure.


Figure 40. Stub Cavern with G4 (lower track level) completed. A soffit slab and arch pours will follow.


Figure 41. Invert waterproofing installation in the running tunnel. The blue material is water barrier.


Figure 42. Tunnel invert forms in place for the pour. A follow-on arch pour will complete the tunnel lining.

requirements. Difficulties, however, were experienced whenever the tunnel arch lining intersected a cavern. In these cases, additional special forms were needed to the address the transition geometry from flat walls to curved walls and arches in the tunnel. Figure 41 shows the general arrangement of the waterproofing in these tunnels and Figure 42 illustrates the running tunnel invert form general arrangements.

## WATERPROOFING SYSTEM AND MATERIALS

All tunnels and caverns were designed to not only be fully drained but also to be fully enclosed in a waterproofing system. The specified waterproofing system included the following components—supplied and installed by WISKO America under a fixed price Subcontract Agreement. A performance warranty was also provided.

- Fleece layer in all areas
- Geodrain layer in specified locations
- PVC membrane
- PVC water barrier materials
- Grouting tubes

Figure 43 illustrates the general arrangements and components of the waterproofing system, linked the pressure relief drainage system in the tunnels and caverns, throughout the project. The complexity of the pressure relief drainage system should not be overlooked since it required careful planning and integration into many separate operations; including waterproofing, reinforcing steel and concreting. Figure 44 provides a view of a completed installation in one of the running tunnels.

## ANCILLARIES AND ENTRANCES

The station cavern construction required numerous connections to adjacent Entrances and Ancillary areas. While the Entrances are generally for public needs, the Ancillary areas were needed to enclose essential services to the station—for fire life safety needs as well as for routine station operations and maintenance. The following provides a summary of the excavation and the *Initial Support* requirements for the entrances and ancillaries. There was no final lining requirement needed in these areas under the Contract since this work was assigned to the follow-on finishing contract. Refer to Figures 45 & 46 for renderings of these work areas.

### Excavation and Initial Support Scope and Requirements

The Ancillaries and Entrance excavations were constructed in similar ground conditions and, therefore, required similar ground support provisions. These excavations were approached as shafts with multiple faces—to sequence the progress of the advance in a manner to allow for manageable blast size while concurrently installing ground support.

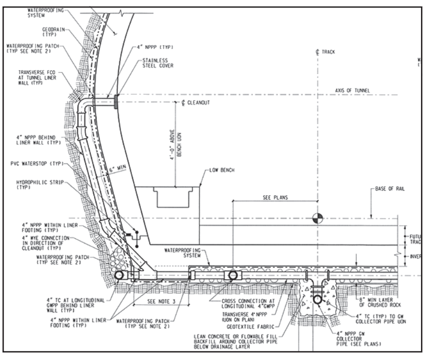



**Figure 43. Sectional view of the waterproofing and drainage system. Similar for all areas of the site.**

**Figure 44. Completed waterproofing materials in the Horseshoe Tunnel, complete with water-barrier**

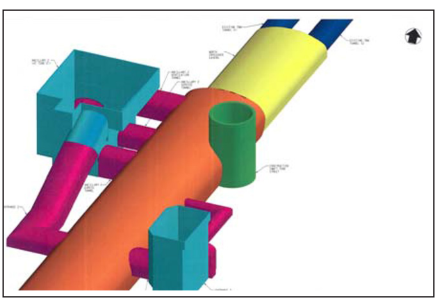


**Figure 45. Rendering of adits for Entrances 2 & 3 and Ancillary 2—all at the north end of the station**

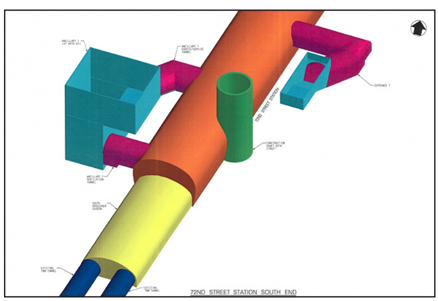



**Figure 46. Rendering of adits for Entrance 1 and Ancillary 1—all at the south end of the station**

- **Ancillary 2**
  - 14,000 BCY rock by drilling and blasting methods
  - Final bottom elevation 80’ below street level
  - Full channel drill near columns and in areas of faulty rock (5" holes)
  - 10' Swellex rock bolts on 6' × 6' pattern
  - 5" minimum SFRS shotcrete liner
  - Escalator adit mined primarily from station cavern
  - Egress, Service, and Ventilation adits excavated from station cavern
- **Entrance 3**
  - 3,229 BCY soil excavation (ENT-3 and ANC-2 combined)
  - 5,600 BCY rock excavation by drilling and blasting methods
  - Final bottom elevation and 86' below street level
  - Extensive planning and coordination in “Top Down” break-in shots
  - Emergency tunnel mined from station cavern
  - 10’ Swellex rock bolts on 6' × 6' pattern
  - 5" minimum SFRS shotcrete liner
- **Ancillary 1**
  - 2,104 BCY soil excavation
  - 11,800 BCY rock excavation by drilling and blasting methods
  - Final bottom elevation 78’’ below street level
  - Full channel drill near columns and in areas of faulty rock (5" holes)
  - 10' Swellex rock bolts on 6' × 6' pattern
  - 5" minimum SFRS shotcrete liner
  - Egress/Service, and Ventilation adit tunnels excavated from the station cavern

### Temporary Decking Systems

Elaborate temporary decking systems were designed, fabricated and installed at the shaft sites at Ancillaries 1 and 2 as well as at Entrance 3. These decks were designed to support unique construction and equipment loads owing to the confined nature of the sites and the specialized material handling needs during construction periods.

### Support-of-Excavation Systems (Soils)

Support-of-Excavation systems were designed and installed at the shaft sites at Ancillaries 1 and 2 as well as at Entrance 3. These system were not designed as water tight structures but were very effective for retaining the soil and fill layers, prior the placement of temporary decks and the advancement of shaft excavation through rock by drilling and blasting methods. The principle components included the following.

- Minimum 5" SFRS shotcrete liner
- No. 10 Dywidag bars, 10' long at 6' × 6' pattern
- Additional rock support (25' Grade 150 No. 11 bars) required in certain areas around deck beam support columns
- Mine straps and welded wire mesh as required

### Schedule and Work Sequences

The construction of the entrances and ancillary shafts was a challenging portion of the project—largely due to their location, size, depth and to some extent, the intricacies of the excavation surrounded by multi-storey buildings. The schedule and coordination efforts required attention to the following tasks, for example.

- Coordination with the station cavern during blasting operations and drift break-ins (9 each)
- ANC 2 was on the Critical Path and, therefore, needed special attention
- All adits mined from station cavern to allow excavation to continue
- Building demolition delays caused impacts to excavation schedules

## CHALLENGES FOR PROJECT COMPLETION

At the time of this writing, approximately 70% of the entire scope of work (and time) has been accomplished. The work is generally on schedule with some Extensions-of-Time for the performance of Extra Work pending MTA approvals. Nonetheless, there are still many challenges to address as the project moves quickly into the final lining stages in all remaining areas of the site. While the station cavern and the northern portion of the work are subject to the *Milestone 1* date, concurrent completion of the south tunnels and caverns is also important. At present there are *seven active areas* receiving the final liner. These specialized operations require five arch and two wall forming systems in addition to separate tunnel invert and arch forms. The work includes the concrete lining of cavern inverts, walls, arches as well as tunnel inverts and arches—all on a well sequenced and closely coordinated basis—while linked to *Milestone 1* and the *Substantial Completion* dates.

### Milestone 1—North of Grid Line 17 in the Station Area for Turn-Over

As described earlier, *Milestone 1* occurs at the end of Month 31 in the CPM schedule. The work includes excavation and final lining from Station Grid Line 17 northward—or approximately 40% of the station length together with the North Cross-Over, Entrance 2, and Ancillary 2. Six out of the nine adits leading from the station cavern are included. Overall, the coordinated work requires waterproofing, reinforcing steel, forming and concrete placing from the 72nd Street construction shaft while the final excavation phases in Ancillary 2 (4 adits) and Entrance 3 (2 adits) are still underway.

### Substantial Completion—Entire Remainder of the Job for Turn-Over

The *Substantial Completion* date occurs at the end of Month 37 in the CPM schedule. Whereas, *Milestone 1* addressed completion and turn-over of the northern ±40% of the station area, *Substantial Completion* defines the completion and turn-over the remaining portion of the project, including the south tunnels and turn-out caverns. Only Punch List tasks will be outstanding after the *Substantial Completion* date. At present, the south turn-out caverns are being concrete lined on a sequential basis using three separate arch forming systems—to be followed later with other arch forms in the running tunnels. In general, the G3 and G4 running tunnels will be lined concurrently in a retreat direction from the 63rd Street Station Bellmouth area. This will provide for an efficient and concurrent use of all forming systems, followed by an early turn-over of these tunnels and caverns to the MTA for the follow-on Systems and Finishes Contract.

## CONCLUSIONS

This project is generally considered to be one of the more difficult challenges in the Second Avenue Subway construction program. This is due to the scope and complexity of the work in conjunction with the fast-paced schedule and milestone dates. Limited access to the underground work areas in addition to street level restrictions have had a continuous influence on planning and day-to-day construction operations. Nonetheless, and after over two years continuous successful construction activities, the project has progressed well and is tracking for completion in the scheduled time. The ground conditions for excavation have generally been favorable and with few exceptions, the prescribed *Initial Support* has been satisfactory. Concreting operations started as planned during the final stages of rock excavation and have grown to include seven separate concurrent operations. Custom-built wall and arch forms are in use for the placement of the final cast-in-place concrete lining in the tunnels and caverns.

## ACKNOWLEDGMENTS

The authors would like to acknowledge the considerable contributions to this paper (and corresponding oral presentation) from the MTACC (Program Manager), NYCTA (Project Owner), Aecom-Arup (Project Designers), Parsons Brinckerhoff (Construction Manager) and Hatch Mott MacDonald (SSK's geotechnical engineer). In particular, very helpful information was provided and included in this paper from Bill Goodrich and Anil Parikh (MTACC), Tom Peyton, Amitabha Mukherjee, and Jaroslav Prokop (PB) as well as Jaidev Sankar and Verya Nasri from Aecom-Arup. Additionally, Julian Prada, Eric Jordan and Philip Lloyd from Hatch Mott MacDonald provided timely assistance and review.

## REFERENCES, SELECTED READINGS, AND ADDITIONAL INFORMATION

There have been many recent papers and publications written on the design and construction of the 72nd Street Station and Tunnels project as part of MTA's Second Avenue Subway. While many pre-date the events of the site work described in this paper, they should be considered as useful pre-construction references.

Desai, D., Nail, M., Rossler, K., Stone, C., New York Subway Caverns and Cross-Overs—a Tale of Trials and Tribulations, 2005, *Proceedings of the Rapid Tunnels and Excavation Conference*, 2005. Littleton: Society of Mining Engineers.

Desai, D., Lagger, H., Stone, C., New York Subway Stations and Cross-Over Caverns—Update on Initial Support Design, 2007, *Proceedings of the Rapid Tunnels and Excavation Conference*, 2007. Littleton: Society of Mining Engineers.

Nasri, V., Fulcher, B., Redmond, R., 2008; Design of the Second Avenue Subway in New York, 2008; *Proceedings of the World Tunnel Congress 2008*, Agra, India, International Tunnelling Association.

Nasri, V., 2008; Design of Large and Shallow Cavern of the New York Second Avenue Subway, 2008; *Proceedings of the North American Tunneling Conference 2008*. Littleton: Society of Mining Engineers.

Nasri, V., Bergeson, W., 2010; Continuum and Discontinuum Modelling for Design of Shallow Caverns in Jointed Manhattan Schist New York, 2010; *Proceedings of the World Tunnel Congress 2010*, Vancouver, BC, Canada, International Tunnelling Association.

Nasri, V., Fulcher, B., Redmond R., and Parikh, A. 2011, Geotechnical Investigation for the Second Avenue Subway in New York. *Proceedings of Planning and Development of Underground Space*, Hong Kong, China, September 23–24, 2011, pp 101–108.

Nasri, V., Fulcher, B., Redmond, R., and Parikh, A. 2012, Design and Construction of 72nd Street Large and Shallow Rock Cavern Station in New York City. *Proceedings of the North American Tunneling Conference 2012*, Indianapolis, Indiana, June 20–23, 2012, pp. 337–343. Littleton: Society of Mining Engineers.

Nasri, V., Fulcher, B., and Redmond, R. 2012, Design and Construction of 72nd Street Station Rock Cavern in New York. *Proceedings of the World Tunnel Congress 2012*, Bangkok, Thailand, 18–23 May, 2012, International Tunneling Association.

Parikh, A., Fosbrook, G., Phillips, D., 2005; Second Avenue Subway—Tunnelling Beneath Manhattan, 2005; *Proceedings of the Rapid Excavation and Tunnelling Conference 2005.* Littleton: Society of Mining Engineers.

Snee, C.P., Ponti, M.A., Shah, A.N., 2004; Investigation of Complex Geologic Conditions for the Second Avenue Subway Tunnel Alignment in New York City, *Proceedings of the North American Tunnelling Conference 2004, Levent Ozdemir (ed.).* Littleton: Society of Mining Engineers.

Snee, C.P., 2008; Engineering Geology and Cavern Design for New York City, *Proceedings of the North American Tunnelling Conference 2008, Levent Ozdemir (ed.)*. Littleton: Society of Mining Engineers.

## SELECTED ADDITIONAL READINGS

Garavito-Bruhn, E., Napoli, A., Towell, N., 2012; Second Avenue Subway Project, New York: Refurbishment of an Existing Underground Station, *Proceedings of the Structures Congress 2012, Carrato and Burns (eds.)* American Society of Civil Engineers.

Parikh, A., Phillips, D., Sykes, M., Second Avenue Subway Project—History and Construction Challenges, Proceedings of the Geotechnical Engineering for Transportation Projects, American Society of Civil Engineers.