Controls on Megaconstruction - Geotechnical Advances in NYC Capital Projects

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Introduction

New York City bridges and tunnels are some of the most heavily used modes of transportation and means of utility distribution in the world. Over 50 connections (Figure 1) have been made between Manhattan Island and surrounding regions, all of them the result of various means and methods of heavy construction. These construction efforts have stood out in engineering history for decades. Projects such as the Brooklyn, Williamsburg, George Washington, and Verrazano-Narrows bridges were the world's longest suspension bridges when opened in 1883, 1903, 1931, and 1964 respectively. Even today, the George Washington Bridge is one of the busiest in the world. Ground-down digging techniques in soft ground together with drill and blast techniques in hard ground have matured with the use of specialized equipment and/or the use of tunnel boring machines (TBMs). Recent capital construction projects in New York City either recently completed or under construction employed TBMs (Figure 2) with the NYC DEP Brooklyn, Queens, and Manhattan Water Tunnels and the Croton Water Treatment Plant, the Con Edison Utility and Cable Tunnels, the MTA #7 Line IRT Extension, Second Avenue Subway, and East Side Access Manhattan and Queens Tunnel projects.

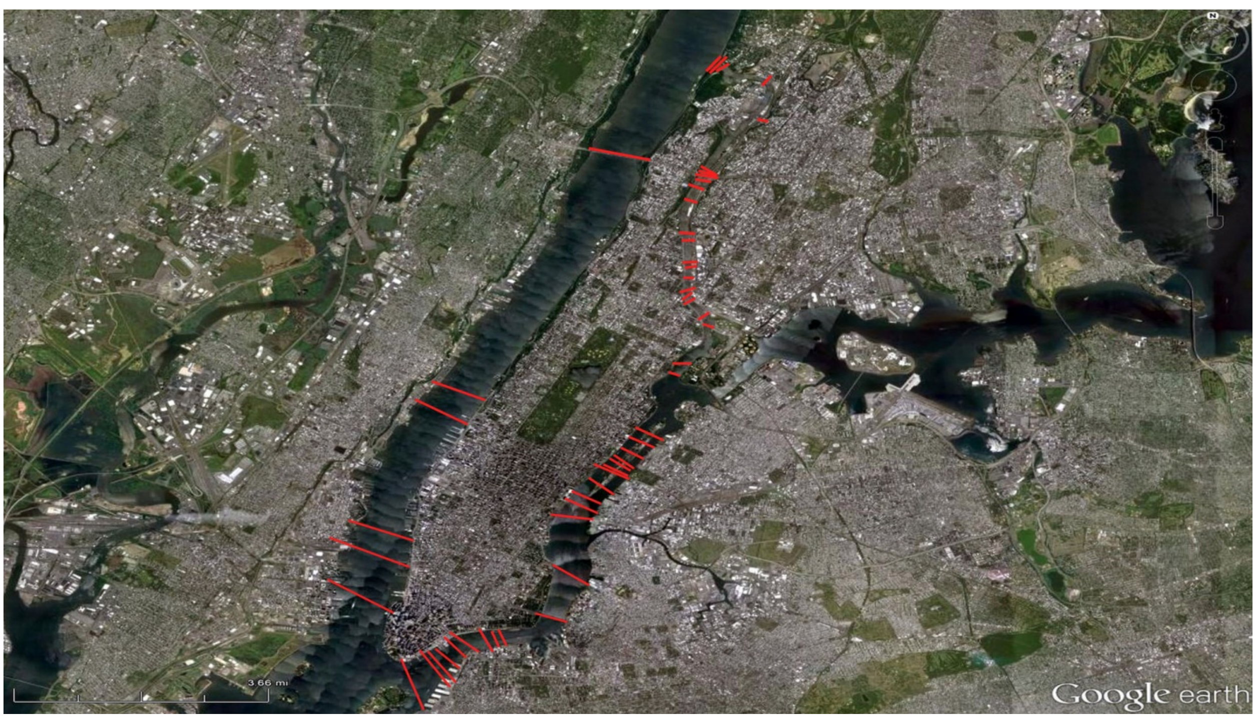

Figure 1 – Google map view of New York City showing the 51 bridge and tunnel alignments that connect Manhattan Island with surrounding regions. (Diagram plotted by Vanessa Fernandes.)

Rock does not equal rock when it comes to cost-efficient rock excavation in New York City. The bedrock is varied, complexly deformed, highly metamorphosed and covered by a thin veneer of Pleistocene glacial drift and, in places, sediment strata of Cretaceous age. Proactive geological investigations in the pre-bid and as-built periods can mitigate losses encountered during both soft- and hard-rock excavation. The details of NYC geology and the types of geotechnical investigations necessary for predicting tunneling destiny are covered in detail in Merguerian (1999, 2005a, b; 2008a, b) and Merguerian and Ozdemir (2003). Both Type I and Type II changed rock condition claims and the associated litigation can be avoided with early professional geological study, identification of risk factors and risk sharing between owners and contractors. Drawing from three decades of standard geological mapping and rock analysis experience in NYC and from geological data gathered from all of the major capital projects and a multitude of shallower building excavations, this paper will discuss advances in excavation means and methods utilized for the variable ground conditions of New York City. These are described below under the headings Soft- and Hard-Ground Methods and be discussed as case histories during our presentation.

Figure 2 – View N within excavation for the Jacob Javits Convention Center station cavern of the MTA's #7 Line Extension. To the right note that the hard-rock TBM and trailing gear has begun tunneling. (Web image.)

Soft-Ground Methods

1) Caisson Construction – A caisson is a box-like structure used in construction work underwater or in a shallow subsurface foundation work to ultimately maintain load. Caissons are usually rectangular or circular in plan and may be tens of meters in diameter. They are usually constructed in five basic ways:

a) Box Caisson – These are open at the top and closed at the bottom and usually constructed on land, then launched, floated to position and then sunk onto a previously prepared foundation, leaving its upper edge above water level. It serves as a suitable shell for a pier, seawall, breakwater, jetty, or similar work, remaining permanently in place on the sea bottom.

b) Open Caissons – These are box caissons open at both the bottom and the top and fitted with a cutting bottom edge which facilitates sinking through soft material while excavation is carried out inside through a honeycomb of large pipes, or dredging wells. As the excavation proceeds and the caisson sinks, additional sections are added to the shaft above. This process is continued until the caisson has sunk to the required depth. A floor, usually of concrete, is then laid to provide a bottom seal. The dredging wells can later be filled with concrete to complete the structure.

c) Pneumatic Caissons – During construction of the Brooklyn Bridge in the late 1800s, a technique similar to open caissons provided an airtight bulkhead above the cutting edge. The space between the bulkhead and cutting edge, called the working chamber, is pressurized to the extent necessary to control the inflow of soil and water; thus excavation can be performed by workmen operating in the working chamber at the bottom of the caisson (Figure 3). Proper depressurization may be needed by workers at the end of a shift to prevent health issues related to the “bends”.

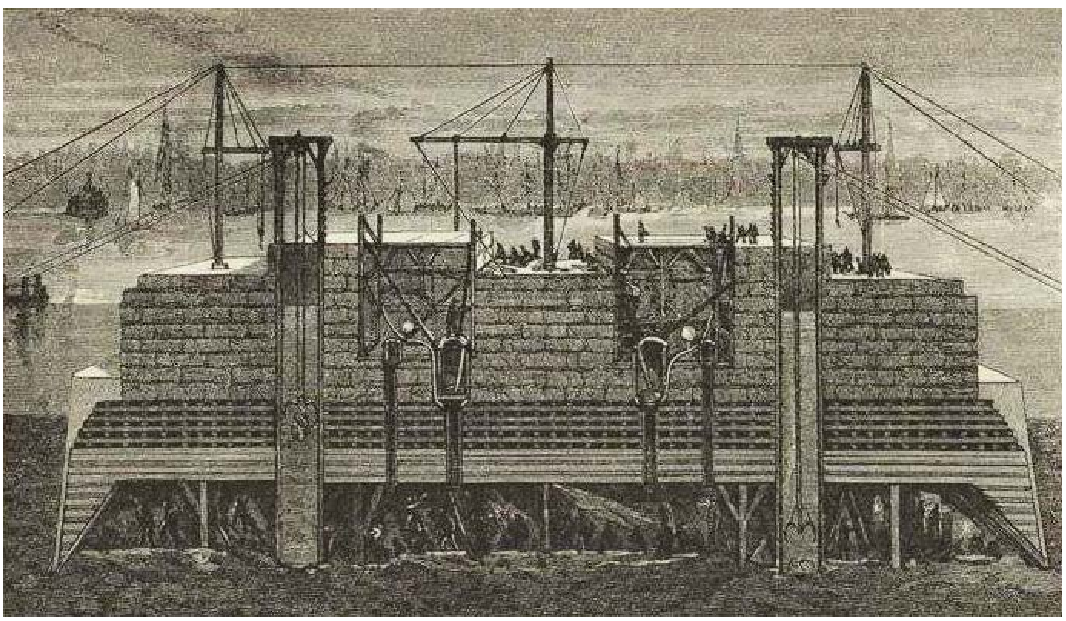

Figure 3 – View of pneumatic caisson used in construction of the Brooklyn Bridge towers (1870-1883). (From www.history1800s.about.com.)

d) Secant Piles – A technique typically used for shaft construction in places with high water tables with a thick soil profile (Con Edison Cable Tunnel). Here, interlocking concrete piles are bored through the soil to form an interlocking ring that is rooted in bedrock (Figure 4). Usually, every other pile has an I-beam inside that is socketed into sound rock. Concrete is fed into the open pile borings to produce a water-tight ring (caisson) of concrete secant piles that shuts off water inflows and enables safe excavation of the interior soil and eventual access to the bedrock for shaft deepening. In the case of the Con Edison shaft, over 100' of rock were removed to intercept an existed D&B tunnel connecting Manhattan and the Bronx. In some areas, freeze-wall techniques are employed to curtail high water inflows (see section below).

Figure 4 – View of bedrock surface exposed below secant piles about 50' below the ground surface at the Bronx shaft of Con Edison's Harlem River Cable Tunnel. (C. Merguerian digital image taken 03 Aug 2009.

e) Cast-in-Place/Poured in Place – A fifth type of cut-and-cover construction especially useful in tunneling is called cast-in-place. In this method, a trench is excavated with forms being built directly inside the trench. Concrete is then poured or cast into the concrete forms. After the concrete cures the forms are removed. The trench is then backfilled and the work site reinstated. A shoring system supports the sides of the excavation to prevent the shifting of soil. A subcategory of the cast-in-place methodology is called **Sunken Tube** where immersed tubes form an underwater tunnel composed of segments (Figure 5). The segments are constructed elsewhere and floated to the tunnel site after trenching to be sunk into place, linked together, and pumped free of water before backfilling. In 1909 this technique was used effectively during construction of the Hudson River Railroad Tunnels (now PATH) connecting lower Manhattan with New Jersey.

Figure 5 – Sunken tube technology dates back to the 1909 construction of the Hudson River Railroad Tunnels (now PATH) connecting lower Manhattan with New Jersey. (Archival image.)

2) Cofferdam Construction – This is a temporary enclosure built within, or in pairs across, a body of water and constructed to allow the enclosed area to be pumped out, creating a dry work environment for the major work to proceed. Enclosed coffers are commonly used for construction and repair of oil platforms, bridge piers and other support structures built within or over water. Cofferdams are usually welded steel structures with components consisting of sheet piles, wales, and cross braces. Such structures are typically dismantled for re-use after the ultimate work is completed.

3) Slurry Wall – A technique used to build reinforced concrete walls in areas of soft earth close to open water or with a high ground water table (World Trade Center). This technique is typically used to build water-blocking (diaphragm) walls surrounding tunnels and open cuts, and to lay foundations. Usually a trench is excavated to enclose a form for each wall. Reinforcement, consisting of rebar cages lowered into the trenches, precedes trench filling with bentonite-rich cement slurry. Because it is kept full of high-density slurry at all times, the slurry prevents the trench from collapsing by providing outward hydrostatic pressure. This also balances the inward hydraulic forces and thus prevents water flow into the trench. Concrete later displaces the slurry to encase the steel rebar and leave a reinforced concrete wall.

4) Freeze-Wall – When groundwater inflows are excessive and draw-down pumping or injection of grout is not feasible (ground subsidence issues) or effective (wide aperture fractures and interconnected fracture systems), frozen ground techniques must be employed (Figure 6). Although expensive, the use of patterned drilled holes and continuous pumping of cryogenic fluids allows for in-situ ground freezing to a desired depth which shuts off water inflow and allows for the continuation of halted construction. This technique was used with success at the Bronx Shaft of the Con Edison Cable Tunnel and Shaft 22 of the Brooklyn Water Tunnel where high water inflows dewatered the ground and caused localized subsidence.

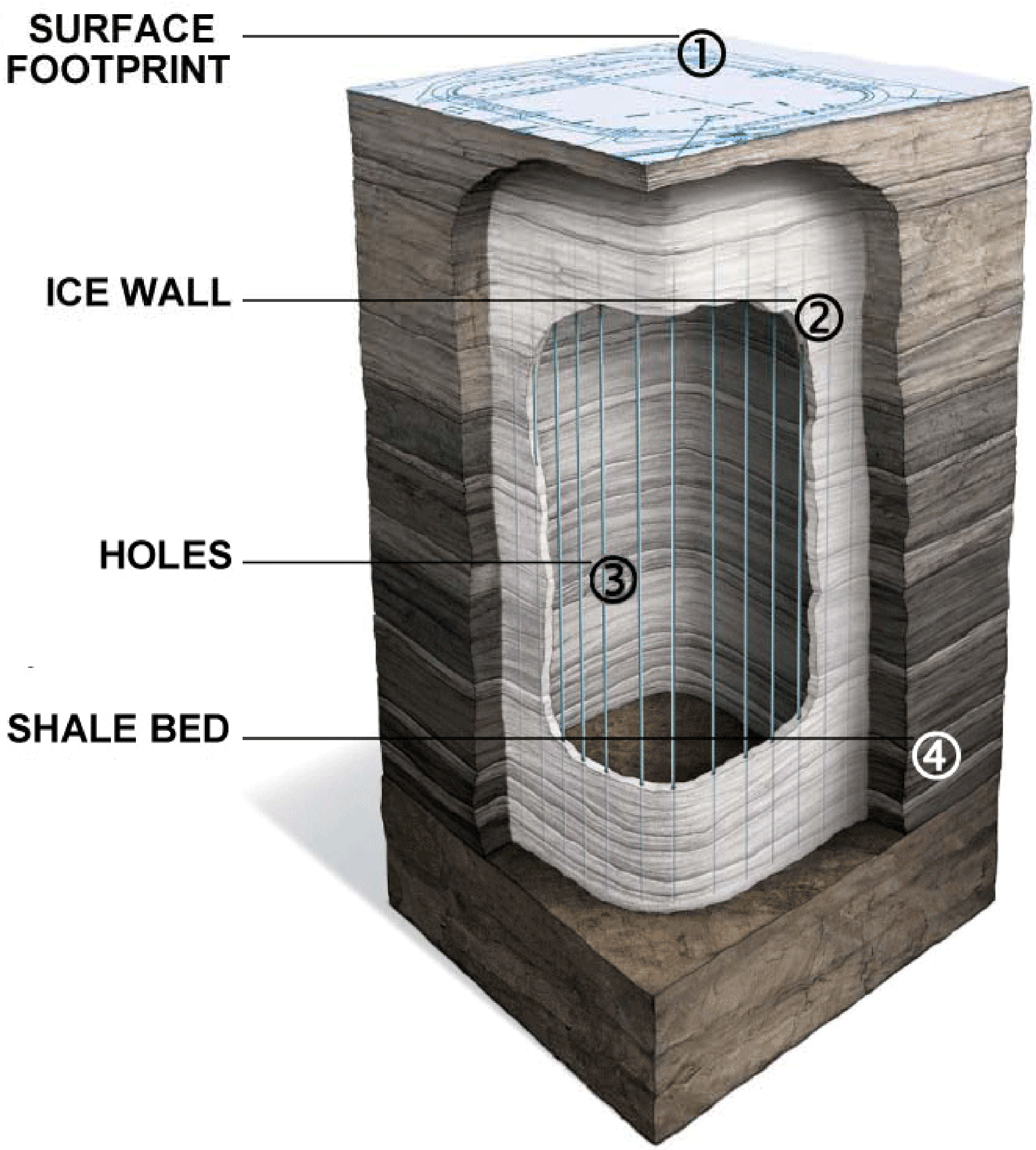

Figure 6 – View of typical freezewall technique for injecting cryogenic fluids through a closed loop system managed from the surface. The chilled liquid freezes intergranular water in surrounded water-saturated sediment to produce an ice wall frozen ground curtain that impedes water inflows. (From www.ceri-mines.org/documents/29thsymposium/presentations09/PRES_03-3_Deeg-Wolfgang.pdf.)

Once a freeze-pipe hole is drilled but before ground freezing is initiated, **down-hole geophysical instruments** can image ground conditions and also gain important information regarding faults and fractures (fracture density, apertures, extent), permeability, orientation of bedding or foliation, and other measurements pertinent to understanding subsurface geological conditions.

Hard-Ground Methods

5) Drill and Blast – Before the advent of tunnel boring machines in the 1950s, drill and blast techniques (D&B) were the only economical way of excavating long tunnels through hard rock, where simple ground-down digging was not possible. Classic tunnel blasting and advance requires drilling 8' to 10' patterned holes in a working rock face before detonation and mucking. The decision whether to construct a tunnel using TBM or D&B or a bit of both depends upon a number of factors such as 1) tunnel diameter and length, 2) managing the risks of variation in ground quality, 3) contract specified construction window, 4) contract-specified final alignment and tunnel shape, 5) job-site footprint and ability to construct TBM launch box, and 6) neighborhood impact. The East Side Access – Grand Central Terminal, #7 Line Extension – Jacob Javits Center Station, Second Avenue Subway – 72nd, 86th, and 96th Street Station complexes all have employed both TBM and traditional D&B technologies.

Accurate rock wall blasting employs the use of **line drilling** techniques. Line drilling accomplishes rock excavation by drilling a series of closely spaced holes, about 4-8 inches apart at the perimeter of a planned rock cut so as to break the rock with a series of wedges, hydraulic splitters or a controlled blast to create a vertical wall. Used effectively in many NYC construction jobs (Figure 7), the technique minimizes ground shaking and is especially useful where historic or older buildings are situated near active construction alignments.

Similar support techniques used in TBM tunneling (described below) are used in D&B construction efforts. The pitfalls of D&B tunneling include issues of worker and site safety, post-blasting scaling and support, overbreak, and tight scheduling. In addition, ground acceleration must be monitored and public impact for safety and noise be addressed. Advance rates are typically slow with a typical 24-hour shift (drilling, blasting, scaling, mucking cycle) capable of about 8'-10'/day of hard rock excavation if all goes right. D&B techniques along with mechanical methods (see below) are used exclusively in areas where TBM's are simply not feasible or controlled excavation is needed (Con Edison Cable Tunnel; South Ferry Subway Station Complex).

6) Tunnel Boring Machines – First used in 1952, a tunnel boring machine (TBM; also known as a "mole") is a complex automated machine used to excavate tunnels by employing a rotating cutterhead armed with rotating carbide cutters. They excavate rock by taking advantage of crack propagation in hard rock and by simply scooping sediment and soil on soft ground (Figure 8). Thus, they can cut a circular cross section through a variety of strata. Directed initially by GPS and then by standard surveying techniques, they can bore very accurately through anything from hard rock to unconsolidated sediment and need to be planned and constructed for crystalline rocks (Queens, Brooklyn, and Manhattan Water Tunnels; Con Edison Utility Tunnel; Croton Water Treatment Plant; East Side Access – Manhattan Tunnels; Second Avenue Subway),

Figure 7 – Northward view of ancillary cavern of Second Avenue Subway 86th Street Station complex showing line drilling in progress in excavation floor and line-drilled walls. This sensitive excavation (adjacent buildings) went down nearly 100' more by April 2013 by stepping downward in lift increments. (C. Merguerian digital image taken 06 November 2012.)

soft ground and mixed face conditions (East Side Access Queens Tunnels). Hence, detailed pre-bid geotechnical investigations and as-built mapping are essential tools toward a successful TBM project (Merguerian 1999, 2005a, b). Tunnel diameters can range from about a meter (micro-TBMs) to 19.25 m to date. Tunnels of less than a meter or so in diameter are constructed using trenchless construction methods or horizontal directional drilling rather than TBMs. TBM's are also used in mining and some TBM's use a cast place method of completing tunnels by erecting concrete segments as they pass (#7 Line IRT Tunnels; East Side Access – Queens Tunnels).

Tunnel boring machines are used as an alternative to drill and blast (D&B) methods in rock and conventional ground-down "hand mining" in soil. TBMs have the advantages of limiting the disturbance to the surrounding ground and producing a smooth tunnel wall. This significantly reduces the cost of final lining of the tunnel. Indeed, major losses can be incurred by contractors during the concrete phase of tunnel finishing as a result of filling in irregular tunnel walls caused by overbreak, bad ground, and supported areas.

The major disadvantage to TBM usage is the upfront cost. TBMs are expensive to construct (>$10M) and can be difficult to test, transport, and erect on-site. However, as modern tunnels become longer and multi-tubed, the cost of tunnel boring machines versus drill and blast is actually less. Experienced TBM crews can achieve penetration rates of 8'-10'/hour in hard-rock terrains vs. 8'-10'/day in D&B jobs. Workers enjoy much safer working conditions and contractors can hire leaner support staffs. As such, tunneling with TBMs where warranted is much more efficient than D&B and results in a shorter and thus less-expensive capital project bids and final cost. A few different types of TBMs are currently in use for construction and mining:

- Open beam machines – for crystalline or hard rock
- Shielded machines – for soft ground tunneling
- Earth pressure balance – for wet, soft ground, and,
- Mixed face machines- mixture of hard and soft rock

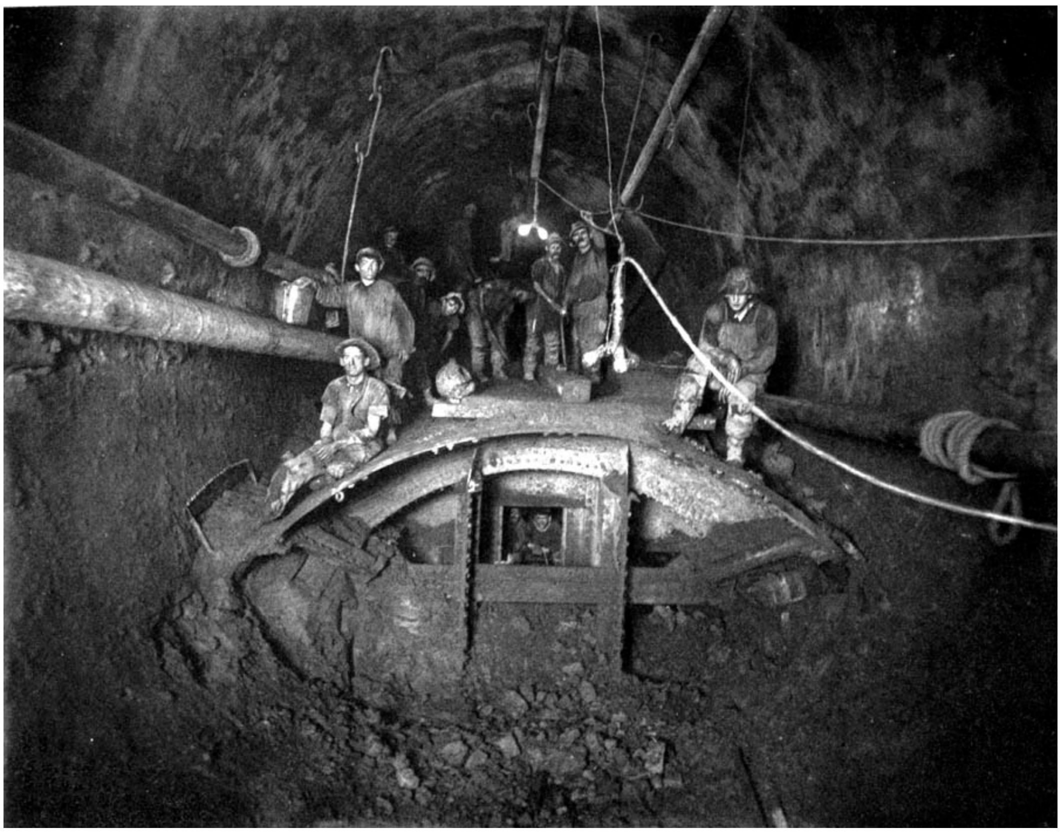

Figure 8 – Mechanical mole (TBM) of 1909 vintage, used to excavate the Hudson River Railroad Tunnels (now PATH) connecting lower Manhattan with New Jersey. (Archival image.)

Tunnel length is a key issue that needs to be addressed because large TBMs for a rock tunnel have a high capital cost, but because they are usually quicker than a drill and blast tunnel the price per meter of tunnel is actually lower. This means that shorter tunnels and smaller excavations tend to be less economical to construct with a TBM and are therefore usually constructed by drill and blast (South Ferry Subway Station Complex; Con Edison Cable Tunnel). Ground conditions can also have a significant effect on the choice between TBM and D&B with different methods suited to different hazards and potential risk factors.

7) Raise-Bore – Basically a rotating TBM head on a cable pulled upward for small diameter shafts and interconnecting valve chambers. Used effectively in the City Water Tunnel #3 valve chamber beneath Roosevelt Island, raise bore technology relies on a directional drill hole to introduce a pull cable downward. The cable is connected to a small version of a TBM cutterhead which is pulled upward to higher elevations as the cutterhead excavates a shaft upwards.

8) Mechanical Means and Methods – Many types of heavy construction equipment are used in large-scale capital projects including cranes, loaders, muck cars, trains, and trucks. Roadheaders and hoe rams are essential to the rock removal process yet their efficiency depends upon many factors of the rock mass that control excavation (rock type, density, mineralogy, petrography, fault and fracture systems, metamorphic grade, structure, and fabric orientation) to name a few. Used in mining for many years, the use of roadheaders and hoe rams in capital projects have become commonplace today (East Side Access; South Ferry; Building Excavations).

9) Support and Finishing Methods – Depending upon the excavation method, various types of support and concrete coatings are necessary to maintain tunnel and excavation stability both during and after the excavation phase. These include the use of:

- Ring Steel
- Steel Channels
- Steel Straps
- Wire Mesh
- Timber Cribbing
- Patterned and Individual Rock Bolts
- Shotcrete

Summary

A number of geological properties of coalescing importance dictate the destiny of hard rock excavation in the city of New York. Critical to both surface and subsurface geotechnical design engineering, a thorough investigation of such properties can provide important clues concerning performance and productivity during the bid and as-built stages of major construction efforts and help to avoid the expense and inefficiency of changed condition claims. Investigations over the past century have shown that the geology of NYC is complex with over a billion years of geological history emblazoned in the rock mass. NYC’s former position at the core zone of convergent mountain building during Proterozoic and Paleozoic times has created a unique set of geological formations and variable rock mass properties that, when ignored (i.e. – “Rock” is “Rock” mentality), have proven to be an impediment to efficient mining and excavation and has resulted in claim hardships for owners and contractors.

In addition to normal core data analysis and standard geotechnical testing for establishing rock mass properties, prudent contractors and design engineers must factor in intrinsic geological properties. Often overlooked, targeted petrographic microscopic analysis of mineralogy, texture, lithology, structure, and metamorphic fabrics are critical rock mass properties to establish. Megascopic study of stratigraphy, rock mass density, fabric orientation, ductile and brittle fault analysis and joint analysis are also paramount. Such allied studies hold the clues toward fully understanding the excavation behavior of the rock mass and will establish the proper means and methods for safe and efficient rock removal (roadheader, hydraulic ram, drill and blast, mini-mole, TBM, or a medley of methods).

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