Geology and Tunneling in New York City

Considerations for Planning, Design and Construction

By Dr. Christopher Snee

There is no shortage of geological information about New York City, which is a testament to its diversity and complexity. Although the geological complexity requires skill to decipher, the rocks lend themselves to simplification for the purposes of engineering. A key factor in this simplification is relating geological characteristics to the scale of the project. For example, as the cross-sectional area of an excavation increases there is a transition from dominance by intact properties to dominance by flaws and discontinuities.

In the case of the caverns that are required for several stations in New York City, the role of large-scale features such as faults, shear zones, weathering, alteration and in-situ stress control ground behavior. When we understand which characteristics apply to an engineering problem, the possible solutions become clearer and it isn't quite so important to achieve geological precision. This short note presents an overview of the geological characteristics of Manhattan that should be accounted for in planning, design and construction of tunnels.

Engineering Geology of Manhattan

The evolution of our understanding of Manhattan geology is covered comprehensively by the encyclopedic works of Professor Charles Merguerian (1996). This is only part of a substantial body of work that is a credible and evolving alternative to the Baskerville map, such as Bennington and Merguerian (2007). The quasi-official map of the city by Baskerville (1994) is the most common reference for engineering projects.

New York City is made up principally of ancient metamorphic Precambrian to Cambro-Ordovician rocks that are divided into two major units separated by at least one regional northeast-southwest trending thrust fault that runs through Manhattan. The Manhattan Formation is found west of this major thrust fault and the rocks to the east are known as the Hartland Formation. There are alternatives to this division, and further reading will introduce the Manhattan Schist, the Inwood Marble and the Fordham Gneiss. It is important to recognize that the geological names for the rocks have no engineering meaning, for example the Inwood Marble contains schist and quartz and the schist rocks contain marble, pegmatite and serpentinite. Furthermore, recent investigations (Snee, 2004 & 2006; Merguerian and Moss, 2007) have revealed that a polar change in rock type can occur on a city block scale, for example the rock can change dramatically from weak mica rich schist to very strong crystalline granite with a distinct vertical contact.

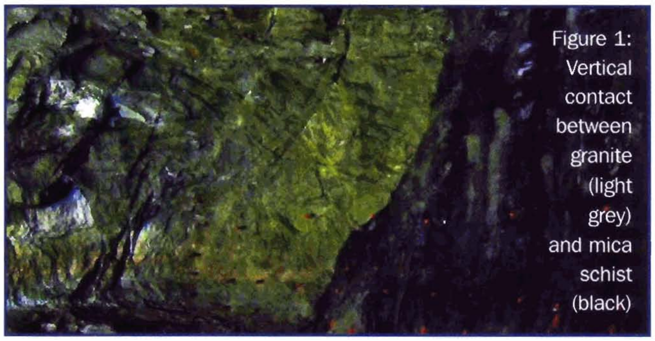
Figure 1: Vertical contact between granite (light grey) and mica schist (black)

Even though the lithology and structural geology vary quite dramatically, the following rock mass characteristics are fairly universal and possibly the most relevant from a construction perspective:

Unpredictable top of rock profile
- Local deep weathering
- Deep glacial erosion

Faults and shears
- Mineral alteration
- Joints
  - Variable joint surface characteristics
  - Open vertical joints
  - Wavy joints
  - Rotation of joint systems
  - Joint clusters
- High horizontal stresses

Rock Profile - The bedrock surface is undulating, incised and unpredictable, reflecting the geological and geomorphological past.

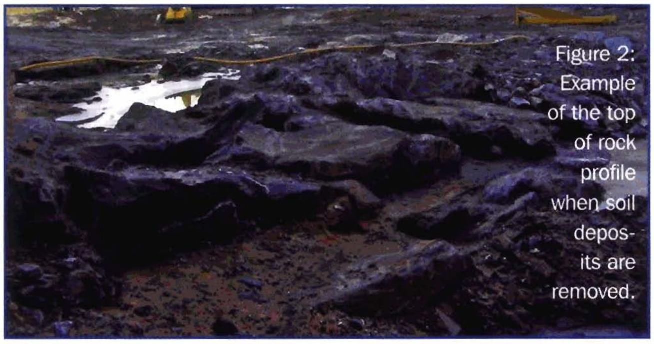
Figure 2: Example of the top of rock profile when soil deposits are removed.

Some of the deeper depressions in the top of rock are valleys created by erosion from water and ice that exploited weak rock due to faulting, shearing and hydrothermal alteration. These often became stream channels or inlets that have since been infilled by natural and anthropomorphic deposits.

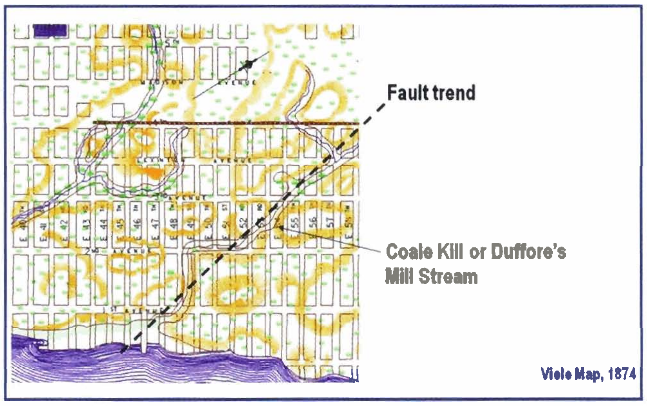

Figure 3: Extract of the Vieile Map showing the location of buried stream channels and valleys.

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Where the rock is near to the present ground surface the glaciers have removed most of the weathered material, leaving behind a thin but impersistent mantle of decomposed to weathered rock overlain by basal till followed by a sequence of glacial till, outwash and reworked till deposits and lake deposits of silt and fine sand. There are substantial thicknesses of decomposed rock where the rock is at a substantial depth below the current ground surface such as Chinatown where it is about 300 ft thick.

Faults and shears – The geology of New York City is dominated by two large-scale thrust faults named Cameron's and St. Nicholas thrusts, which have created or influenced subsidiary faults, shear zones and joint systems (Merguerian and Moss, 2007). There are numerous but lesser thrusts and faults passing through Manhattan and these are normally associated with local increases in fracturing, decomposition, release or imposition of in situ stress and abrupt changes in rock type. The most prominent regional fault in New York City is the northwest-southeast trending 125th Street or Manhattanville Fault that is accompanied by en-echelon faults with parallel west-northwest to east-southeast strike and a very deep eroded valley from the north Harlem into the Bronx that was filled by an extensive swamp.

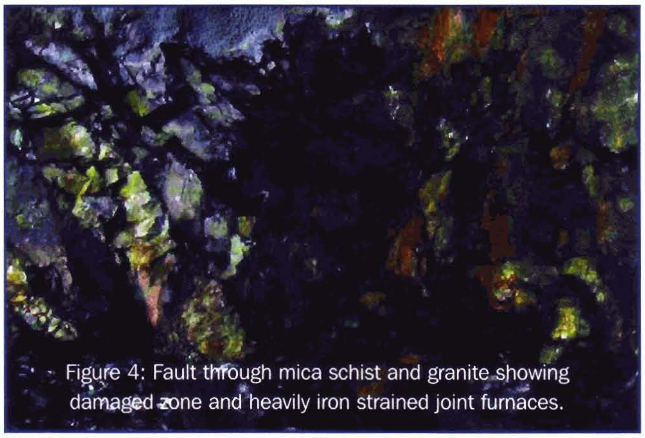


Figure 4: Fault through mica schist and granite showing damaged zone and heavily iron strained joint furnaces.

There are less well documented faults throughout the City and examples occur at Broadway and 14th Street, 12th Avenue and 35th Street, 2nd Avenue and 86th Street and 69th. These are characterized by disturbance and distortion of the foliation, fault gouge, fault breccia, mylonite and damaged zones that range between a few inches to tens of feet thick.

Figure 5: Baskerville Map for north Manhattan showing the 125th Street Manhattanville Fault

Rock Types — *The following table presents the dominant rock types found in Manhattan.*

Table 1. Fundamental Lithology for Some Manhattan Rock Types

Rock name	General location	Mineralogy	Characteristics
Quartz mica SCHIST	Pervasive	Quartz, biotite and muscovite mica, feldspar and garnet	Strong, medium to coarse grained with distinct mineral alignment, particularly of the mica. Variable degree of segregation of metallic and alumino-silicate minerals
Mica SCHIST	West side of Midtown	Biotite, muscovite, chlorite and quartz	Moderately strong, dark grey to black medium to coarse grained, dominated by black mica with intercalated quartz lenses
Amphibole SCHIST		Hornblende, quartz, biotite and muscovite mica, feldspar and trace garnet	Strong, very dark green, coarse grained, poorly foliated with very thin garnetiferous bands. Dense, strong rock and relatively isotropic
GRANOFELS	Pervasive transitional within the schist	Quartz, biotite and muscovite mica, feldspar and garnet	Strong, medium to coarse grained, eguigranular with absent or poorly developed foliation
PEGMATITE	Pervasive	Quartz, muscovite mica, alkaline and feldspar	Strong, pink or slightly greenish light grey, very coarse grained with individual crystals of alkaline feldspar greater than 1 inch
SERPENTINITE	West side of Midtown	Serpentine, sillimanite, muscovite	Weak, light to dark green fine to medium grained with very small proportion of asbestiform minerals
GRANITE	West Side	Quartz, feldspar and mica	Strong to very strong, cream to pink coarse grained, strong brittle rock intruded in to the schist
MARBLE	North, west Midtown and Lower East Side	Calcium and magnesium carbonate, quartz and mica in banded marble	Strong, white, banded grey and brown coarse grained saccheroidal dolomite intercalated with schist near junction with schistose rocks

The majority of the rocks are classified as schist, which implies alignment and layering of the minerals and consequently a tendency to break in a preferred orientation. However, the degree of schistosity and segregation varies widely, from pure black mica schist, to gneissic texture to a complete absence of fabric in granofels.

The minerals are chemically altered to quite a significant degree yet this is not obvious by visual inspection of core samples. The alteration, which can be seen under a microscope, ranges from coating of crystal surfaces to complete conversion to another mineral. The most common alterations are:

Orthoclase — sericite, calcite, clay
Plagioclase — calcite, sericite
Hornblende — magnetite
Biotite — chlorite, pyrite, epidote
Calcite — dolomite

The biotite tends to be more altered than the muscovite. The plagioclase appears to be more chemically stable than orthoclase, which is usually altered to sericite by as much as 90 percent.

Joints - There are three fundamental joint families or sets in New York City, Set 1, Set 2 and Set 3, with subsets (Snee 2004). Set 1 joints are parallel to the foliation, Set 2 are sub-vertical to vertical cross-foliation joints, and Set 3 is a conjugate to foliation joints typically sub-horizontal to moderately dipping with perpendicular dip and parallel strike to the foliation. In addition there are sub-ordinate sets or random fractures produced by faulting and folding creating blocky conditions where as many as five joint sets can be found.

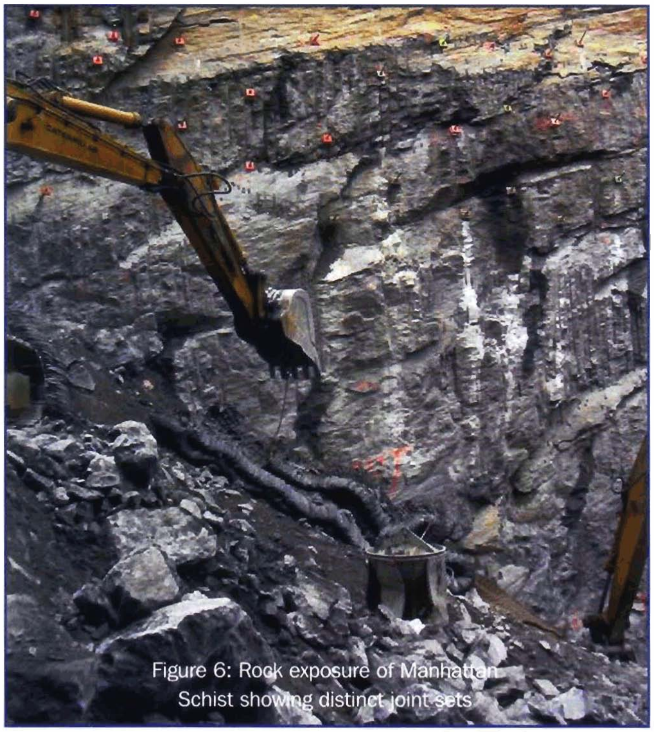
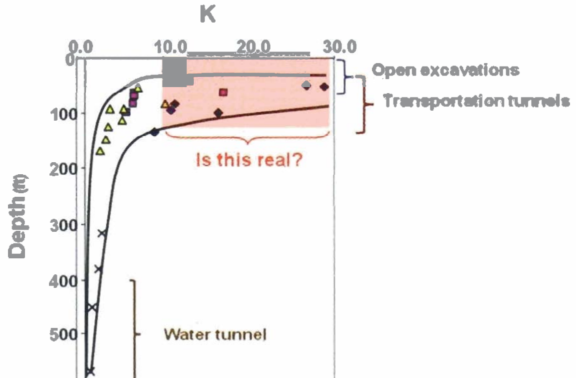


Figure 6: Rock exposure of Manhattan Schist showing distinct joint sets

Although Manhattan is almost completely urbanized, there are many useful exposures of rock that show the complex shapes of discontinuities such as beneath Grand Central Terminal and alongside the Amtrak loop track on the west side of the island around 35th Street. Recent studies of these exposures have revealed that the joints are wavy and the waviness increases the intrinsic stability of the rock mass significantly (Snee, 2006). Furthermore, frictional strength of the joints is controlled by the roughness of the profile, interlocking and coating (typically iron oxide, sericite, kaolinite and chlorite) of the joint surface.

Stress - New York City is a relatively dormant region even though it still experiences an occasional seismic "bump." However, the geological past of New York is a dramatic story of at least five mountain building phases and most recently glacial loading and unloading. The legacy is a state of stress that is extremely difficult to measure, which is unfortunate because the magnitude and orientation of in situ stress has a significant bearing on the stability of a rock mass because the stress causes the fractures and faults to lock together which encourages arching in the crown of a tunnel. Recent investigations have found that the horizontal stress at shallow depth in Manhattan is significantly higher than the vertical overburden stress and the orientation of the principal stress tensors is fairly consistent, which not only explains why excavations in rock have traditionally required little to no support but offers opportunities for economic design of support for future underground excavations (Snee 2006).



K values are maximum horizontal stress calculated from hydrofracture test data and a lithostatic vertical stress gradient

Figure 7: Calculated values of the horizontal to vertical stress ratio using the hydrofracture method in Manhattan.

In terms of the ratio between the horizontal to vertical stress, or K-value, the general cluster of data is between 2 and 5. Although K-values greater than 5 have been measured indirectly, they are counter intuitive to geological argument because they would manifest as obvious ground movements such as floor heave, slabbing from walls and explosive fracture of massive rock at shallow depth (there are anecdotal records of slabbing in deep tunnels in the New York area but not in the shallow depths corresponding to the location of the tests where high K values were measured).

Conclusions

The geology of Manhattan is complex but this complexity can be rationalized and understood for design of tunnels and caverns by characterizing and classifying the essential geological features and relating them to the geological history. It is important to reflect the reality of the geology because a substantial proportion of the strength and stability of the rock mass can be derived from features such as the waviness of the joints, the condition of joint surfaces, and the relatively high horizontal stress.

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Dr. Christopher Snee is a Chartered Scientist and Certified Professional Geologist with 25 years experience in engineering geology, geotechnical engineering, tunneling, mining, education and research. For more information visit sneegeeoconsult.com.