The geological setting of New York City and the geotechnical challenges in urban construction

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Abstract: Situated at the mouth of the Hudson River, the City of New York is one of the largest cities and a leading seaport of United States of America. The deep and navigable estuaries of the Hudson River have separated the five boroughs viz., the Bronx, Manhattan, Queens, Brooklyn and the Staten Island.

The three physiographic units i.e. Atlantic Coastal Plain in the south east, New England Upland in the north west and Triassic lowland in the south west have exhibited variety of landscapes. The overburden in the area has been mainly due to the past glacial activities and their retreat has formed the important features viz., Flushing Meadows in Queens and an east west trending Terminal Moraine Ridge covering Brooklyn, Queens and Staten Island. The rocks underlying Manhattan, the Bronx, parts of Queens and Staten Island constitute the New England Upland, consisting of Manhattan and Hartland Formations, separated by Cameron Thrust Fault. These rocks have undergone five deformational phases and have contributed various fault systems and their resultant joints and fractures. The present physiography of the region is a direct reflection of the type and form of underlying rock structures and the agents that erode them.

The complicated geological setting, the extreme variability in their geotechnical parameters and the underground streams has posed considerable challenges in construction. The in-situ stresses within the rocks and the resultant rock movements associated with various deformational phases have been observed during construction. The faults and the resultant seismic zones have been well marked. Liquefaction and soil amplification phenomena in the event of major earthquakes have been recognized and the problems of compressible soils in the foundation design have been witnessed. The human activities and interference on natural physiography contributed more geotechnical challenges in the design and construction activities in the New York City area.

Resume: "Le contexte geologique de la ville de New York et les obstacles geotechniques de la construction urbaine"

Situee a l'embouchure du fleuve Hudson, la ville de New York est l'une des plus grandes villes et ports des Etats-Unis. Les estuaires profonds et navigables de l'Hudson ont cree les cinq arrondissements du Bronx, Manhattan, Queens, Brooklyn et Staten Island.

Les trois unites physiographiques (Plaine de Cote Atlantique du sud-est, Plateau de Nouvelle Angleterre du nord -ouest, et bassin Triassique du sud-ouest) forment des paysages varies. L'apport local est du aux activites glaciaires passees, et leur retrait a forme Flushing Meadows dans le Queens et le sillon Terminal Moraine d'est en ouest qui relie Brooklyn, Queens au Steten Island. La roche sous Manhattan, le Bronx et certaines parties de Queens et de Staten Island forme le Plateau de Nouvelle Angleterre, constitue des formations de Manhattan et de Hartland, separees par la faille de Cameron. Cette roche a subit cinq series de deformations et a contribue a plusieurs systemes de failles ainsi que leurs articulations et fractures. La physiographie actuelle de la region est un reflet direct du type et de la forme des structures rocheuses souterraines et de leurs facteurs d'erosion.

Le contexte geologique complexe, les variations de parametres geotechniques, et les voies d'eau souterraines representent des obstacles considerables pour la construction. Les stress locaux au sein de la roche et les deformations qui en resultent ont ete constates durant la construction. Les failles et leurs zones de seismes ont ete identifiees. Les phenomenes de liquefaction et d'amplification de sol lors de tremblements de terre notables ont ete constates et les problemes representes par les sols compressibles lors de la creation de fondations ont ete observes. Les activites humaines et l'interference sur la physiographie naturelle ajoutent de nouveaux obstacles geotechniques a la creation et construction dans les environs de la ville de New York.

Keywords : Lithotectonic, Deformations, In-Situ stress, Buried stream, Seismicity, Geotechnical parameters.

INTRODUCTION:

The City of New York is one of the largest cities in United States of America, which covers about 950 sq. Km of area. Situated at the mouth of Hudson River, New York City has developed one of the leading seaports on the east coast of the United States. The deep and navigable estuaries of the Hudson River have separated the five boroughs of New York City, i.e. Manhattan from the Bronx, from Queens and Brooklyn, and from Staten Island.

The City has been divided in three physiographic provinces, viz., Atlantic Coastal Plain in the south east, the Triassic Lowland in the south west and the New England Upland in the Northwest (Figure 1). The Atlantic Coastal Plain comprises the glacial deposits and the New England Upland comprises the Manhattan Prong rocks. The topography is well marked by high undulating scenic terrain in Manhattan and the Bronx. These undulations trend NNE-SSW and WNW-ESE, configuring ridges and valleys respectively. These landscapes are the result of complex geological processes that began since Proterozoic times. The present physiography is a direct reflection of the type and form of underlying rock structures.

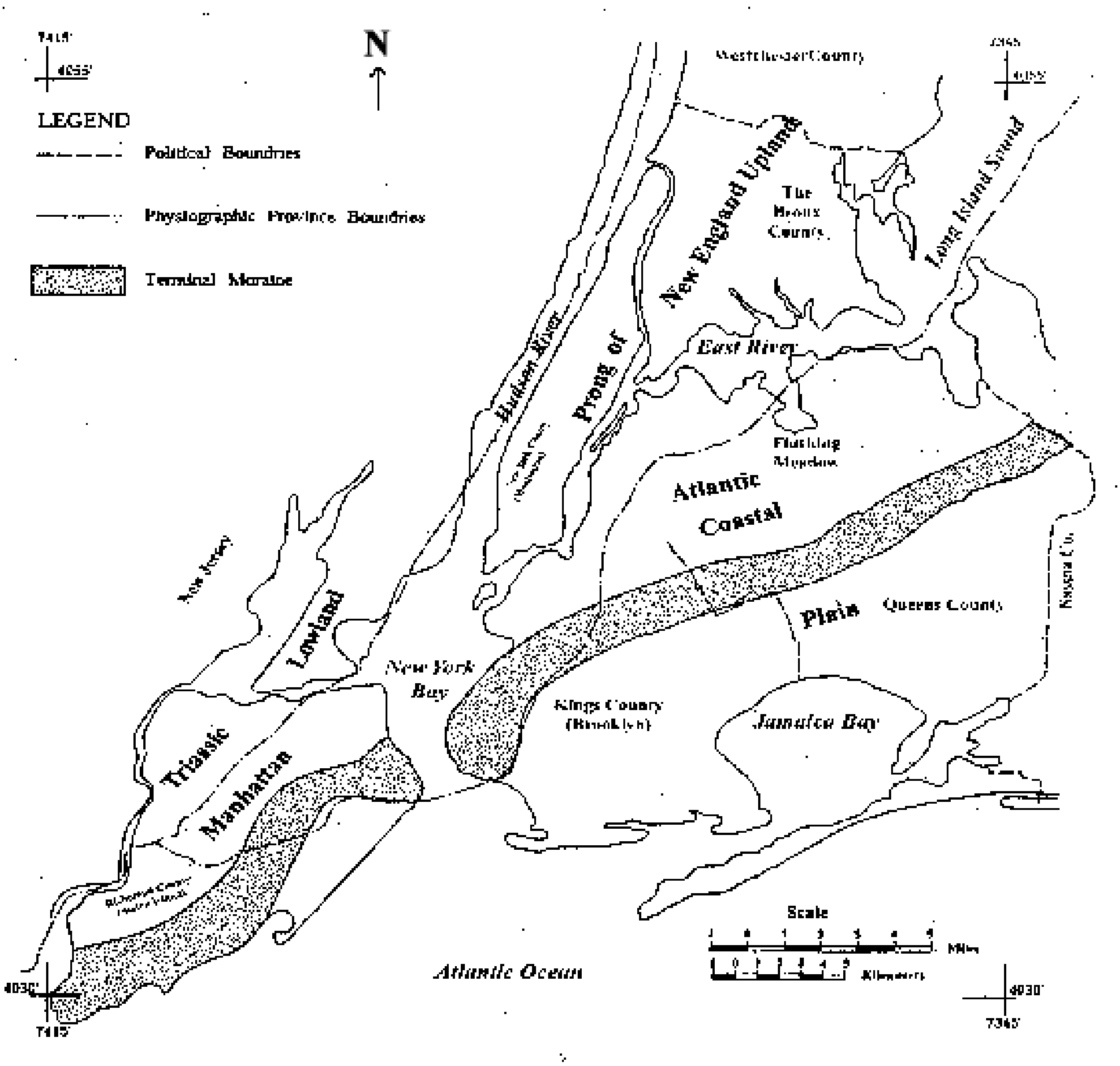

Figure 1. Physiographic provinces of New York City (Modified after Baskerville 1982)

GEOLOGICAL SETTING:

Geological setting of New York City is very complex. Overlying the bed rocks, the soil cover is found to consist glacio-fluvial and glacio-marine lacustrine drift and till. The terminal moraine ridge which traverses in an ENE-WSW direction covering a large area in Brooklyn and Queens, is composed of this glacial till deposit. The soil cover comprises boulders, gravels, sand, silt, clays and compressible soils. The fill which overlies the soil cover, is formed by both human interference and natural phenomena. The vast constructed areas in the city has back filled much of the Manhattan Island, especially around the Lower Manhattan.

The New York City comprises two main lithotectonic units recognised as, (a) Manhattan Formation and (b) Hartland Formation, separated by the Cameron thrust fault (Baskerville, 1982; Shah, Wang and Samtani, 1998). This major regional northeast striking structural feature in the area extends from Connecticut through New York City and further South in Central and Southern New Jersey (Figure 2). Both these tectonic units have been formed in different tectonic and depositional environments.

The Manhattan Formation has been formed by the meta-sedimentary depositional sequence on the continental margin of the Proto North American Continent during Late Proterozoic to Cambro-Ordovician times. The Hartland Formation has been formed by the meta-igneous volcano sedimentary activities in the Island Arc/trench environment within the Iapetus Ocean (Proto Atlantic Ocean).

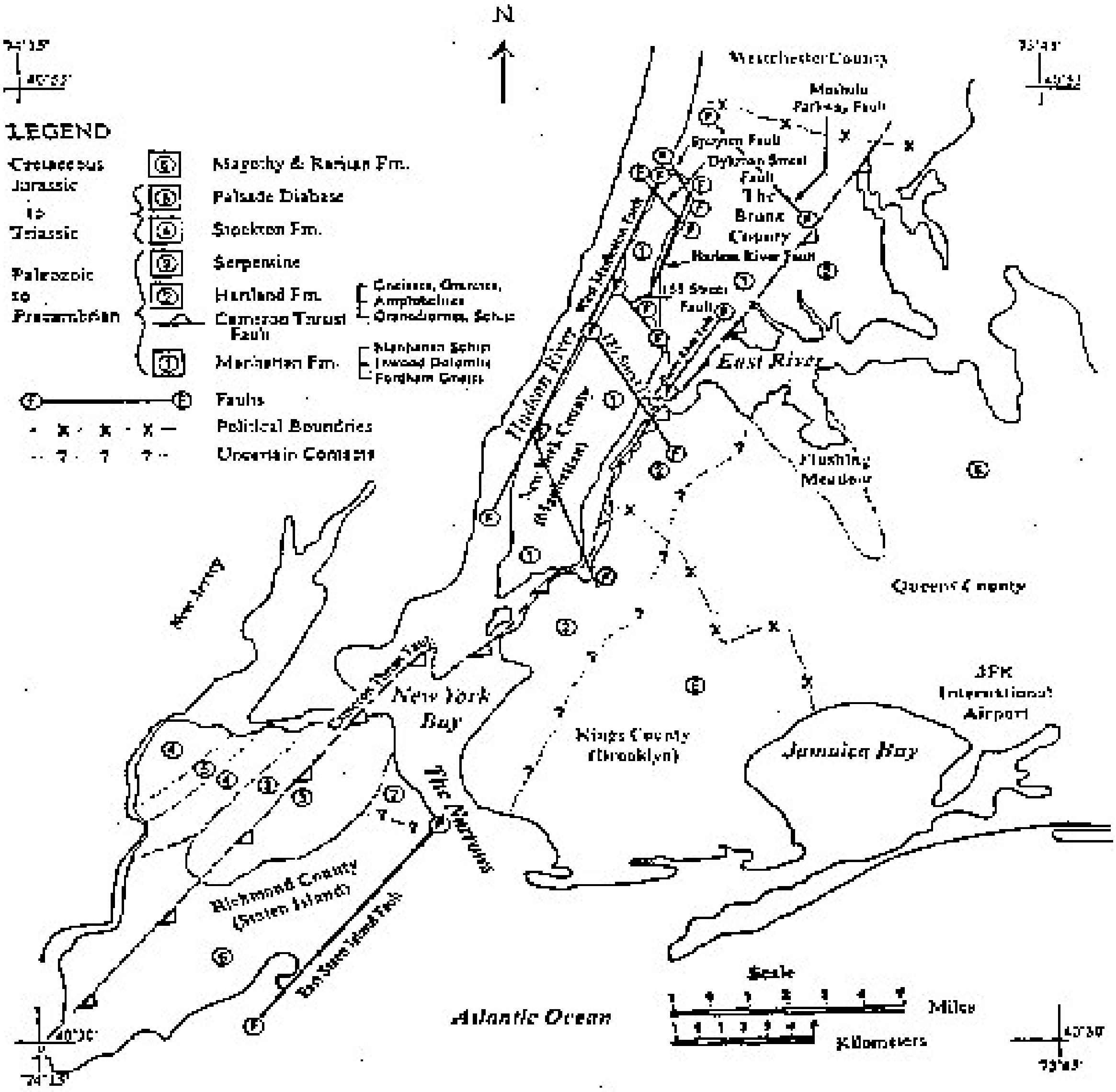

Figure 2. Generalised geological map of New York City (Complied and modified after New York State Museum and Science Service 1971, Baskerville 1982, and Shah et al 1998)

(a) Manhattan Formation

The crystalline metamorphosed rocks west of the Cameron thrust fault are referred to as the Manhattan Formation, which includes:

Manhattan Schists
Inwood dolomite-marble and related calcareous rocks
Fordham Gneiss

Fordham gneiss is the oldest member of the Manhattan Formation whose age is Precambrian and is considered as Basement Gneissic Complex (Hall, 1968; Chesman, 2002). The overlying Inwood dolomite-marble and related calcareous schists are found to occupy the majority of the valleys and low lying areas of Manhattan Island. Based on the fossil evidence (crinoid stems in Inwood marble), a Cambrian to Middle Ordovician age is assigned to these rocks. These rocks consist of pure calcite marble, pure dolomitic marble, coarse dolomite, actinolite-tremolite silicone marble and foliated calc-schists. The Manhattan Schists overlie the Inwood calcareous rocks and form the youngest rocks of Manhattan Formation. This formation varies from quartzo-felspathic schists, quartzose schists, quart garnet mica schist, muscovite schists, biotite schists and hornblende schists.

Numerous pre-syn and post kinematic pegmatitic and ptygmatitic intrusions of varying dimensions were recorded within the Manhattan Formation. At places, these intrusions have locally elevated the metamorphic grade of the schists which almost resemble gneisssic, aplitic, granofelsic to granitic rocks (Fluhr, 1941)

(b) Hartland Formation

The rocks to the east of Cameron thrust fault are termed as Hartland Formation. This formation comprises the meta-igneous-volcano-sedimentary rocks, viz, granites, granitic gneisses, granodiorites, granodiorite gneisses, diorites, dacite and hornblende schists (Fluhr, 1969). Rice and Gregory (1906) first used the name Hartland Formation for the western Connecticut rocks. Fluhr (1969) gave the name Brooklyn Injection Gneiss to these rocks. Seyfert and Leveson (1969) termed these rocks as Hutchinson River Group in the New York City.

(c) Serpentine Rocks

These ultramafic (remnant oceanic rock matter) intrusive rocks are found to occupy approximately 90 sq. Km of the North Central area of Staten Island. Smaller exposures are found at many locations in all the boroughs along fractures and fault planes. These rocks perhaps were intruded during the Late Ordovician to Early Devonian Period (Late Taconic to Early Acadian Orogeny).

DEFORMATIONAL EVENTS:

The Manhattan Formation and Hartland Formation have undergone multiple deformational events. The imprints of these events can be seen from their structural fabric (Figure 3). These rocks have undergone five phases of deformations (Shah et al, 1998):

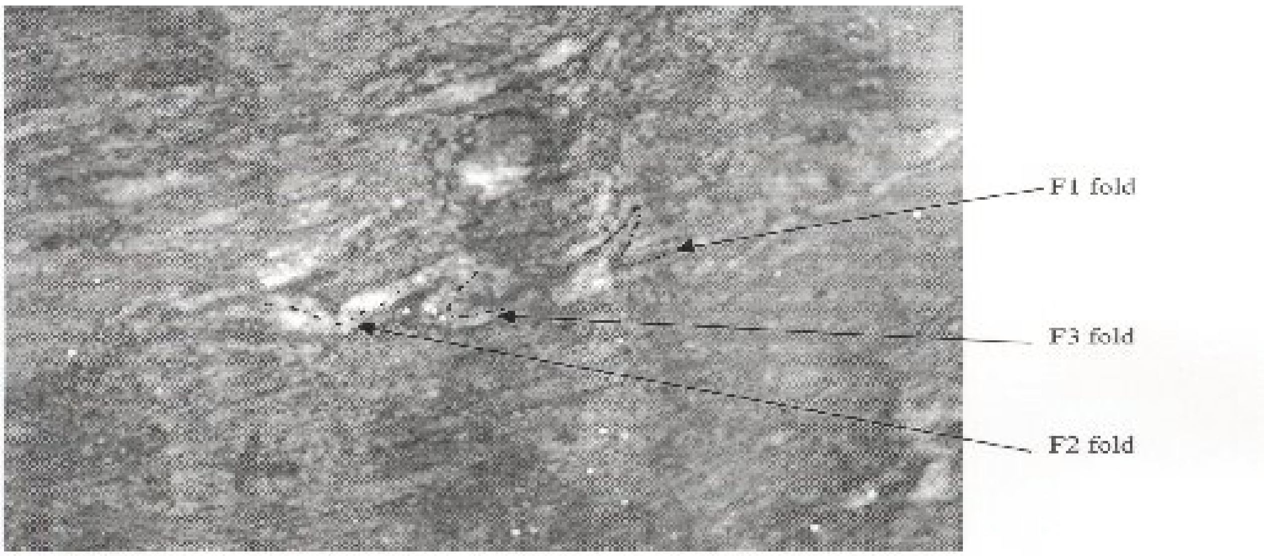

Figure 3. Folds shown by quartz veins in Manhattan Schist. Location: Metro North Tunnel, 49th Street between Park and Madison Avenue

D1: This deformation has resulted in isoclinal recline folds (F1) in the meta-igneous suite rocks of Hartland Formation and produced a strong foliation/cleavage in oceanic trench/crust environment during Late Proterozoic to Early Cambrian period. During the same period meta-sediments of the Manhattan Formation were deposited on a continental marginal environment producing bedding planes (S0).

D2: During this event isoclinal recumbent folds (F1) developed in the Manhattan Formation due to the ESE-WNW stresses generated during the process of closing of the Proto Atlantic (Iapetus) Ocean. These folds trends NE to ENE. A strong cleavage (S1) has developed in Manhattan Formation and also the fractures, joints and the cleavages (S2) having the same orientation developed in the Hartland Formation during the Cambrian to Midddle Ordovician Period.

D3: The major regional antiforms and synforms were developed during this event. Numerous small scale folds developed trending NNW/SSE to ENE/WSW depending on the original bedding/schistosity surfaces. Strong moderate to vertical cleavage/schistosity has developed in both the rock formations during Middle Ordovician to Late Ordovician Period. The main regional metamorphism (Upper almandine –amphibolite facies with staurolite, kyanite, Silimanite zones) developed during this deformational event.

D4: During the Late Taconic to Early Acadian Orogeny (Late Ordovician to Early Devonian Period), the continent carrying the meta-sedimentary deposits (Manhattan Formation) collided with the Island Arc (trench arc) meta igneous - volcano sedimentary Hartland Formation during the closing of the Proto Atlantic Ocean along the "suture" (Baskerville and Mose 1989; Gates 2000). The Hartland Formation rocks overthrusted the Manhattan Formation rocks along the Cameron thrust fault (Figure 4). The serpentine rocks were squeezed up mainly along the fractures and faults at the end of this event and are found scattered in the entire region.

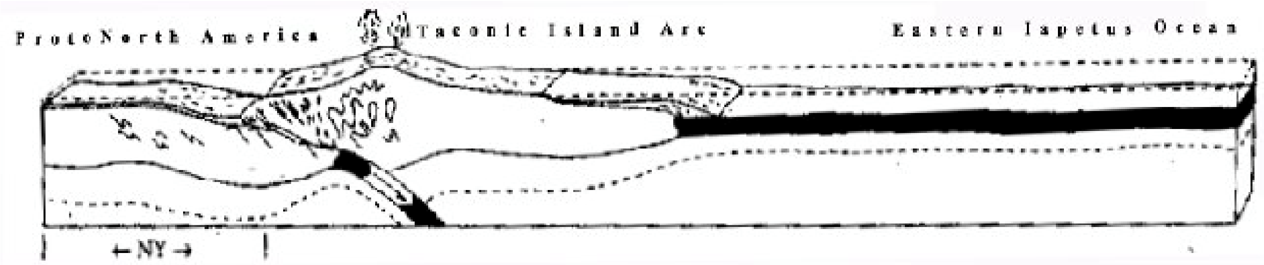

Figure 4. Taconic Orogeny-Collision of Island Arc and Proto North America (Gates 2000)

D5: In this final phase of deformation, moderate to steeply plunging WNW-ESE trending folds (F3) were developed with consistent moderate to steep cleavages (S3). During this deformation widespread fractures, faults and joins were developed. The major fault system developed during this event is the 125th Street (Manhattanville) fault. A number of parallel faults connected to this event form a major structural element in New York City area.

GROUND WATER CONDITIONS:

The major source of groundwater in New York City is the adjacent East River and Hudson River. Other sources of ground water recharge include precipitation, leaking drains and water lines. Recharge in the bedrock mass is unlikely to be from precipitation filtration due to the relatively impermeable nature of the city streets, building foundations, underground constructions like subway tunnels and other obstructions. There are also evidences that the natural groundwater flow follows the old buried streambeds (Townsend, 1609; Figure 5). Groundwater flow in the rock mass is controlled by the interconnection of the open joints and fractures in the rocks. The ground water level in the soils tends to follow the bedrock elevation, suggesting that they are probably perched on the top of the bedrock, wherever rocks have formed the ridges and valleys. The complex nature of ground water flow through soil and the rocks make the dewatering plan more challenging during the construction which is often encountered in the projects like subway tunnels, water tunnels and in the complex deep foundations where water tables are shallow. Construction of the New South Ferry Terminal is an active case study in the complexity of groundwater flow and its impact on construction activities. The close proximity of the site to the Hudson River further complicates the dewatering process.

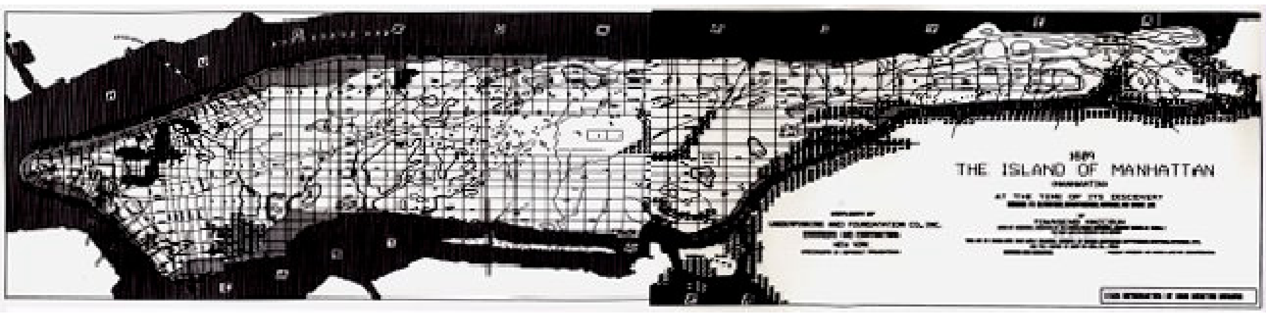

Figure 5. Buried streams, shore line and marshes in Manhattan Island (Townsend, 1609)

GEOTECHNICAL CHALLENGES:

The complex structural geology of bed rocks, consisting of two major rock formations, along with igneous intrusions impose major geotechnical challenges. The major fault systems related to viz., Cameron thrust fault and 125th Street (Manhattanville) fault, pose great challenges in the design and construction activities for the bridges, highways, tunnels, and rehabilitation of new and existing structures in the New York City Metropolitan area. Each physiographic province constitutes the topography, which directly reflects; (a) the lithology of the underlying surface, (b) structural setting, (c) geologic processes such as erosion and deposition by glacio-marine-fluvial and lacustrine activities and the crustal activities operating through the intervals of geologic times. Number of old as well as ongoing projects are discussed in this paper along with the nature and type of geotechnical challenges.

The major geotechnical challenges:

(1) Lithology

The bedrock geology of New York City is represented by schistose, gneissose, intruded igneous rocks (pegmatites, granite, etc.) and calcareous group of rocks. Schistose rocks vary considerably with their different mineral facies and compositions. The hard quarz-mica schists form the ridges and softer varieties along with underlying calcareous rock forms the valleys in major portion of the Manhattan Island. Gneissic rocks along with the igneous intrusion such as granites, pegmatites etc. have formed the high grounds. The bedrock elevation is controlled by their structural geology, i.e. complex folding and faulting. The determination of the exact nature of lithology (mineral composition, textures and hardness) and their structural fabric requires close scrutiny prior to the foundation design and in the selection of the Tunnel Boring Machines and blasting techniques for the projects. Various problems have been encountered due to lithology in the present major projects viz., East Side Access Project, Water Tunnel Projects, Second Avenue Subway Project, No. 7 Subway Extension Project, New South Ferry Terminal Station Project and in the foundation design of 100th street Bus Depot.

(2) The major fault zones

The faults, shears, fractures and joints are controlled by two major faults; i.e. Cameron thrust fault and 125th Street Manhattanville fault.

(a) Cameron thrust fault forms a major lithotectonic boundary between Manhattan and Hartland Formations in the area (Figure 2), which was developed during the D4 deformational event as discussed earlier. This structure is broadly correlated with the zone of seismicity that includes most of the larger earthquakes. The imprint of this event is observed in number of test borings. The shearing, brecciation, fracturing, pulverization, and chloritization are observed in Manhattan and Hartland Formations. The smaller ductile faults of the same generation are located as: (1) Bronx River fault, (2) Harlem River fault, (3) West Manhattan fault, (4) East Staten Island fault.

(b) The second major fault system is related to the 125th Street Manhattanville fault having the orientation WNW-NW/ESE-SE direction. These faults were developed during the last (D5) deformational event and are found in both Manhattan and Hartland formations. The known faults related to this event are located as: (i) 125th Street Manhattanville fault, (ii) Dyckman Street fault, (iii) Mosholu Parkway fault, (iv) Spuyten Duviyal fault, and (v) 155th Street fault. These strike-slip faults are short and brittle compared to the Cameron thrust fault system. The fault zones are marked by fractures, shears, brecciated with gauge matter and slickensides.

These fault zones and related shears and fractures have posed considerable challenge in the design and construction of buildings and major facilities, bridges, highways and the tunnels. These weak zones either have to be treated or taken care in the design to withstand natural ground movement phenomena.

(3) Seismicity

There are number of evidences of seismicity around the faults related to these fault systems. The recent earthquakes are recorded along the faults genetically related to 125th street fault system. Seeber (1987) has correlated the seismicity and stress concentration with preexisting faults and the inferred seismogenic faults striking at large angles to them. Seeber and Armbuster (1989) have shown the seismicity between 1800 and 1985 in the greater New York City area (Figure 6) where seismicity tends to be clustered along the preexisting faults.The recent earthquakes recorded are: Ardsley (Weschester County; M = 4) in October 1985 (Seeber and Dawers, 1989), and in Manhattan (M=2.4) nearby 125th Street fault on the 102 nd. Street and Park Avenue, and at 55th Street and Eighth Avenue (M=2.2) in 2001 (Merguerian, 2004). Building Code of The New York City (2000) recognises a seismic zone factor of Z = 0.15 for seismic design of buildings in New York City.

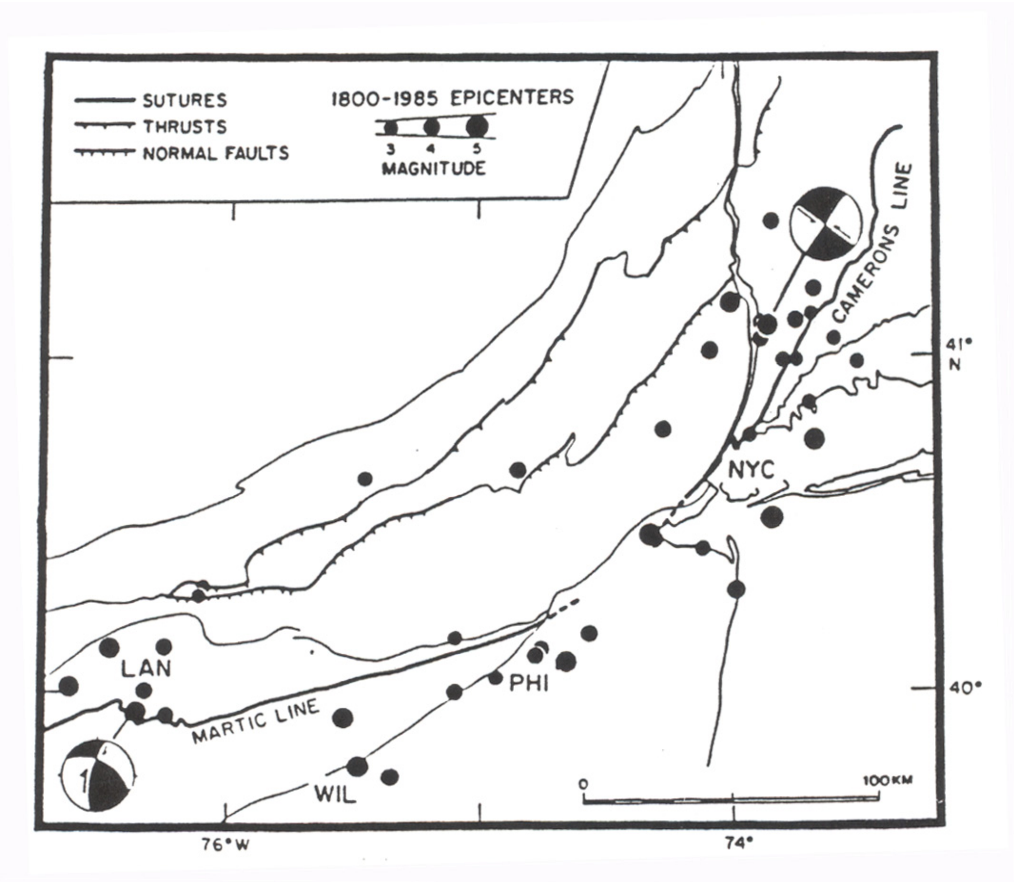

Figure 6. Epicenters of significant earthquakes (felt –area magnitudes Mfa >3) in the Greater New York area during last two centuries (Seeber and Armbruster 1989)

(4) In-Situ Stress

High in situ stresses have been observed during construction of subsurface structures in New York City in the past several decades in many locations during construction of water tunnels and subway tunnels. They have been reported as 'Rock Burst', 'Popping Rock', 'Damaging Stress Conditions' or 'High Natural Stresses'. Since the late 19th century when tunnelling was first undertaken in the New York area, engineers and geologists have been aware of the substantial in-situ stress that occur in the New York region. The first documented reference to stressed rock in this area dates from 1895 when Kemp reported "popping rock" in the construction of the Ravenswood gas tunnel between Manhattan and Queens.

Since then, other construction projects have also encountered difficulties resulting from these high residual stresses. In 1976, the New York City Transit Authority encountered similar highly stressed rock in Long Island City during construction of the 63rd Street subway line. During tunnel construction there were reports of "popping rock". Another example of residual stresses impacting underground construction occurred during the construction of the 21st Street Subway Station. Transit Authority engineers observed movement in several housing structures adjacent to the site. Rock dowels and pipe braces were installed to guard against further movement. Wire strain gages showed significant strain buildup on the struts.

In another attempt to quantify stress conditions, overcoring tests were performed for the Transit Authority by Ciancia, Millet and Dorreler (1979). The results of these tests supported the presence of substantial horizontal in-situ stress. They reported the post excavation stress measurement results ranging from 1,650 to 3,950 psi for the maximum horizontal stress acting in ENE direction in the vicinity of the subway construction in Long Island City, Queens.

More recently, in - situ stress measurements have been carried out to support design of subway tunnel structures. Results indicated high horizontal stresses. Shah, Chang and Kim (2004) described the relationship between the deformational history and the state of in-situ stresses. They have suggested that the stresses result not only from the overlying strata but also from the locked in stresses due to the deformational stresses of tectonic origin. Excavation through these rocks disrupts the stress field and a new set of stresses is induced within them. Orientations of maximum horizontal stresses exhibited a great variability, depending upon the influence of major tectonic feature nearby. More efforts are being made to attain a quantitative understanding of the state of in situ stresses.

In a number of ongoing major projects viz., water tunnels, subway tunnels and most of the underground constructions, the in-situ stresses are measured, evaluated and considered in the design and construction process.

(5) Liquefaction

During an earthquake the build up of excess pore water pressure in the soil can cause soils to lose its strength and bearing capacity almost completely resulting in ground failure. Structures founded on or surrounded by liquefiable soils may suffer damage from settlement, tilting or lateral spreading. Use of soil zonation maps can identify many potential problem areas. Costantino & Miller (1987) have prepared such map for New York City area (Figure 7). From this map three major potential areas for liquefaction in the event of earthquakes are specified i.e. (I) along Hudson and East River banks, (ii) at the southern and west end of Brooklyn and, (iii) at the southern end of Queens near JFK International Airport. The land of these areas were either reclaimed by dumping of fill along the riverbanks or filled by using hydraulic method. These soils are very loose and highly unstable during major earthquakes.

(6) Soil Amplification

The effect of ground motion amplification during seismic event is another potential geotechnical challenge in the New York City area, especially at the Flushing Meadows in Queens where a major buried stream valley of the Hudson River has traversed from north to south (Soren 1978). The consistent subsidence observed from the stratigraphic sequence of the deposits contributes to this morphotectonic feature. Numerous test borings have revealed that a 3-m to 4.5 m of compact sandy stratum underlies at an interval of approximately 20-m to 25 m of loose silt/clay/sand strata. The subsurface up to first 18-m below the ground comprise mainly the soft young Holocene deposits, viz., silt, clay, organics (peat), and fine sand. These shallow soft deposits tend to modify the bedrock ground motion characteristics, amplify them and bring them up to the ground surface to excite the structures.

Soil Amplification was a major design consideration in the design and construction of the Arthur Ash Tennis Stadium, MTA's Corona Yard Maintenance Shop and new constructions in Laguardia Airport, which are located in Flushing Meadow.

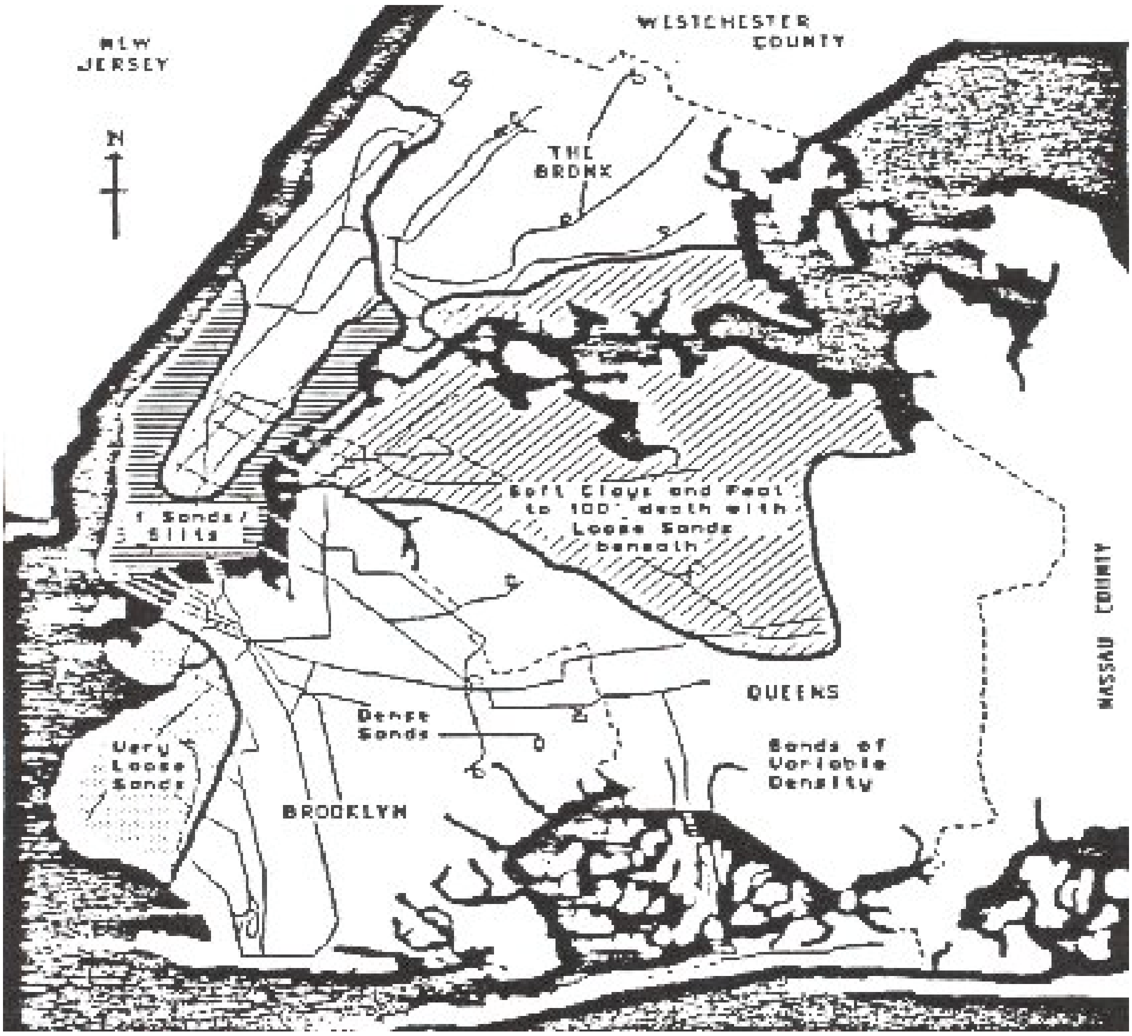

Figure 7. Soil zonation in the New York City area (Costantino and Miller, 1987)

(7) Compressible Soils

The soft young Holocene deposits such as peat and clay present another challenge for foundation design and construction. Due to their poor physical characteristics (high plasticity, compressibility and tendency to consolidate when dewatered) these deposits present problems in building development, foundation design and tunneling.

Significant settlements in constructed structures can result from the presence of an underlying compressible clay or peat layer. Depending on their thickness and depth, such layers must be removed, reinforced or penetrated by deep foundation piles to avoid their effects.

(8) Slope Stability

Surface erosion, tunnel gullying and landslides occur along steep fractures, joints and foliations aided by rain and melted waters from snow and ice. Erosion of the incompetent rocks i.e. Inwood calcareous rocks in contact with Manhattan schistose and Fordham gneissic rocks have contributed to slope development at many locations in Uptown Manhattan and the Bronx. This is also accelerated in some areas where the natural slopes were reshaped for urban development. Slopes fail along the heavily jointed rocks such as rock falls, soil slumps and earth flows have become a maintenance problem of many highways.

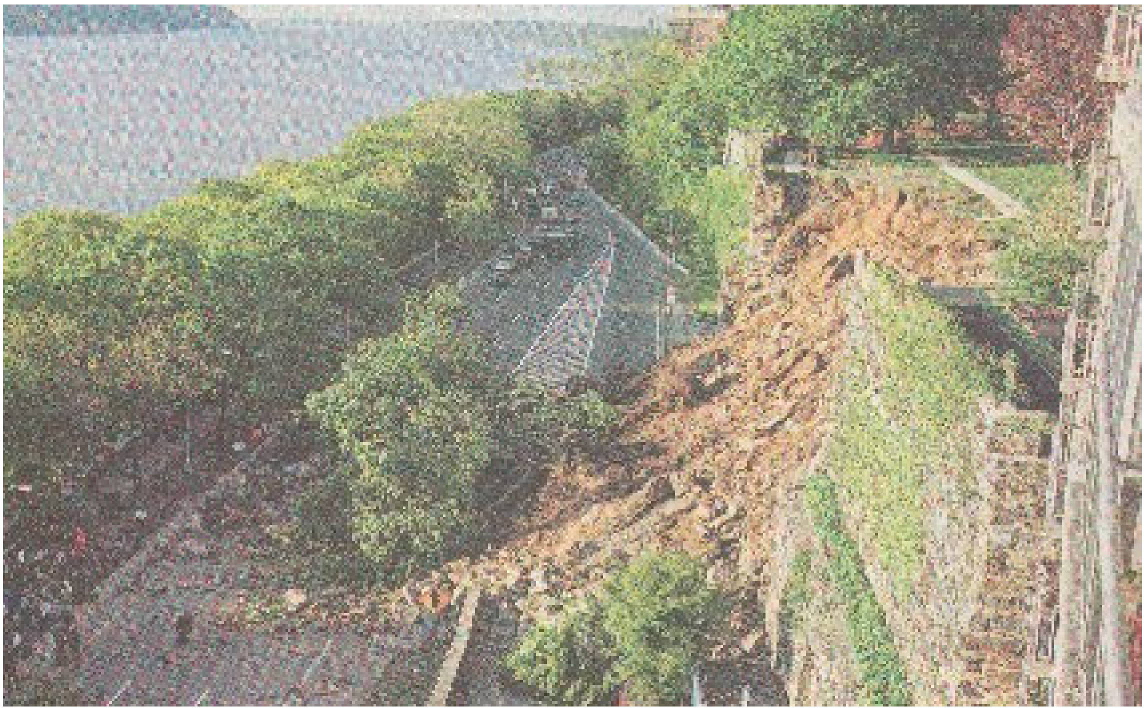

Figure 8. Photograph showing the collapse of 25 meters stone retaining wall on May 12, 2005. Soil slump and earth flow blocked the Henry Hudson Parkway of Upper Manhattan

CONCLUSIONS:

The geology of New York City is extremely complex due to its long and complicated depositional and deformational history from the Pre-Cambrian to the Middle Devonian Period, which has resulted in highly deformed and metamorphosed rock. This complicated geological setting has imposed extreme variability in the geotechnical parameters. The underground streams and complex ground water system within the rock mass have further posed considerable challenges in the design and construction activities. The in-situ stresses within the rocks and the resultant rock movements have been observed during the construction. The faults and the resultant seismic activities have been well marked. Liquefaction and soil amplification phenomena in the event of major earthquakes have been recognised and the problems of compressible soils in the foundation design have been encountered.

The human activities and interference on natural physiography as a part of urban development have contributed more geotechnical challenges in the design and construction activities in the New York City area. Construction activities are impacted by large concentration of sky scrapers, the critical surface, underground structures, numerous land mark buildings in the heart of the City, high population density, commercial activities, and high traffic flow in the New York City area. All these factors restrict the constructibility and construction activities in the New York City. Changes in design and construction due to unanticipated geological conditions can have serious consequences in this urban environment. Therefore, extensive subsurface exploration, testing, geotechnical data interpretation and sound baseline reports are required for successful implementation of projects in urban area.

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