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ABSTRACT

A thorough understanding of the local geologic and tectonic environment, the seismological history as well as very detailed site specific geotechnical and geophysical data are essential to the proper prediction of local site effects and seismic design in New York City (NYC). The site response in the NYC metropolitan area is affected by the widely varying geologic conditions encountered in the five boroughs. Along the spine of Manhattan Island rock extends well above sea level at the northern reaches, and falls to depths in excess of 250 m at the barrier islands at the southern extremities of NYC. Large areas in the City have been filled to cover soft sediments and marshes to accommodate the need for building space, such as the present area of Chinatown that is built on fills that have replaced a large lake known as Collect Pond; the World Fairs site in Long Island Sound Embayment in Flushing, Queens, and the ground on which JFK Airport is constructed by placing hydraulic sand fill in the south shore of Brooklyn. The highly variable geologic conditions, along with the lack of strong ground motion recordings create uncertainty in predicting site response. This paper will present an overall review of the geological and seismological characteristics of the NYC metropolitan area and will examine how current, applicable codes deal with predicting soil amplification and evaluating liquefaction hazard. Issues of concern not covered in codes, such as the effect of high impedance contrast between hard bedrock and soft soil and the response of soft-high-plasticity organic clays and silts will be examined using typical NYC soil profiles and state-of-practice design motions and hazard levels.

INTRODUCTION

New York City (NYC) lies on very old geologic formations. Its bedrock in some areas is more than a billion years old, which makes it older than the Rocky Mountains or the walls of Grand Canyon. Because of its age, both bedrock and surficial geology within the region are amazingly complex, tracing the history of earth and bearing the imprints of continental collisions, long-dead mountains, and forgotten seas (Mittelbach & Crewdson, 1998). NYC geology continues to be revised and argued as more subsurface data become available.

In terms of seismic design, the important consideration of NYC geology is that subsurface conditions within the City boundaries span the entire range of conditions that affect seismic amplification factors, as they vary from sound bedrock at ground surface to total overburden depths exceeding 300 meters and including deep, soft clay and silt strata. A lack of quantitative recordings of strong earthquake motions in the area introduces additional uncertainty in predicting site effects. Current seismic design criteria are primarily based on strong motion data from the Western United States (WUS), where soils are generally stiffer and rocks substantially softer.

Currently, design site factors for the metropolitan area given in the 1995 New York City (NYC) Building Code and the 1998 Seismic Criteria Guidelines of NYC Department of Transportation (DOT) are intended to evaluate soil overburden amplification effects on the seismic motions measured on bedrock. In 2001, the Structural Engineers Association of New York (SEAoNY) undertook an internal review of the seismic aspects of the Building Code. At this time, the City of New York is considering adaptation of the seismic part of the 2003 International Building Code (IBC), with modifications for local effects.

This paper will present a review of the geological and seismological characteristics of NYC. A brief historical visit on the evaluation of site factors in the City regulations will be made. The effects of local seismicity, seismic hazard, and unique geological conditions on soil response will be examined. The treatment of soil in different applicable codes will be compared and selected results from research on soil amplification for several profiles for hazard levels of 2,500 and 500-year return periods will be given. It will be shown that actual site effects may be significant in the area, and underpredicted by generic site factors in codes, largely due to: (i) the presence of soft high-plasticity organic clays and silts, with low shear wave velocities of the order of 100 m/s and small values of effective damping; (ii) the presence of hard bedrock at shallow depths, with measured shear wave velocities exceeding 2 km/s; and (iii) the strong high-frequency content of the expected rock motions, which can trigger resonance in shallow soil profiles. Surprisingly, although the seismic hazard in the area is moderate, large surface motions can be generated due to strong site amplification effects that far exceed those derived from Western experience.

NEW YORK CITY AREA GEOLOGY

The New York City area covers approximately 950 sq. km and is divided into the five boroughs of Manhattan, Bronx, Queens, Brooklyn, and Staten Island (Fig. 1).

There are two main rivers in the area. The western boundary, Hudson River, is connected to the Harlem River at 220th Street by Spuyten Duyvil Creek. The East River runs from Long Island Sound, where it connects with Harlem River and then meets Hudson River at the south (Fig. 1). The shores of NYC area are deeply indented by bays and estuaries, such as Newtown Creek, Flushing River and Harlem River. Detailed information can be found in Parsons (1976), Baskerville (1982), Merguerian and Sanders (1989). A summary is given herein, mainly based on information collected over the past 90 years by Mueser Rutledge Consulting Engineers (MRCE) and presented in greater detail in Tamaro et al (2000).

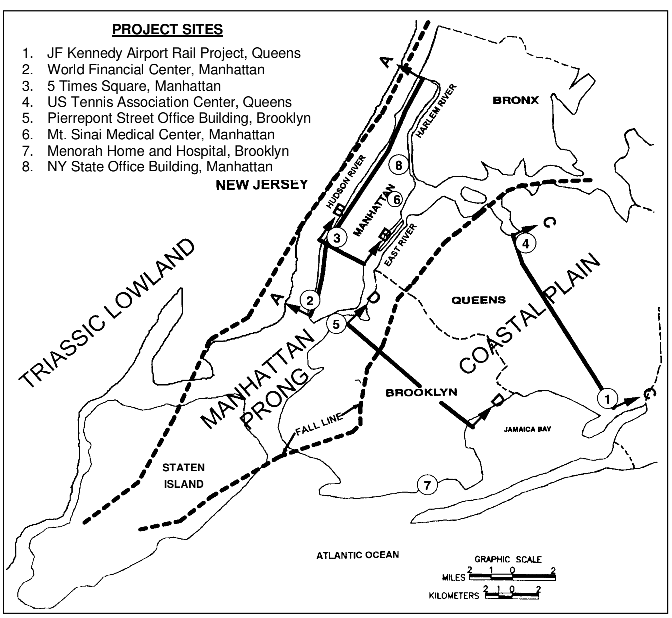


Fig. 1. New York City physiographic provinces and geotechnical case studies of interest.

Figure 1 shows the three major physiographic provinces where NYC lies on: the New England Upland to the northwest, the Triassic Lowland to the southwest and the Coastal Plain to the southeast. Several rock types and numerous soil deposits represent geologic history spanning over a billion years. The Bronx, Manhattan and parts of Brooklyn, Queens, and Staten Island lie in a region of the New England Uplands locally known as the Manhattan Prong, a northeast trending deeply-eroded sequence of metamorphic rocks. Eastern Queens and Brooklyn are in the low-lying Coastal Plain province (Baskerville, 1982). The boundary between the Manhattan Prong and the Coastal Plain is called the Fall Line, separating the highlands and the lowlands (Fig. 1).

Bedrock Geology

The bedrock of NYC is a deeply eroded sequence of metamorphic rocks (Fig. 2), a result of complex geological processes including mountain building, erosions, and volcanic activity (Merguerian & Sanders, 1989).

Much of the rock depth varies radically and was altered by glacial activity and is interspersed with filled-in swamps, creeks, ravines, ponds, and valleys and have long since disappeared from view. Bedrock is visible in several locations as it outcrops in the Bronx, in upper and central Manhattan (Fig. 3), and on Staten Island. The rock surface in Brooklyn and Queens slopes southeast and reaches depths up to 300 m at Jamaica Bay. Important rock formations and corresponding geological periods are briefly described below. More details can be found In Tamaro et al (2000) and Isachsen et al (2000).

The oldest and one of the hardest NYC rocks is the Fordham Gneiss. It consists of dark gray to black/white gneiss with

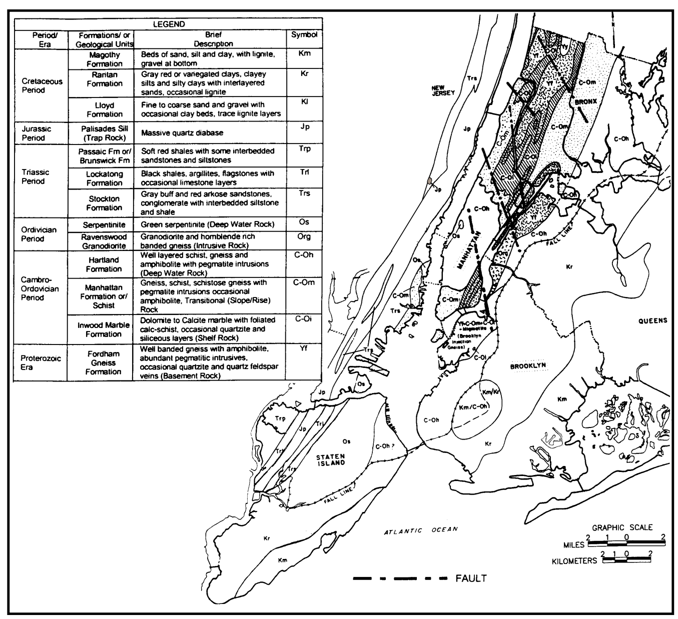


Fig. 2. New York City and eastern New Jersey geological map (modified after Tamaro, Kaufman, & Azmi, 2000).

pegmatite and granite and forms the basement cover sequence of rocks. The Fordham Gneiss is found in upper and lower Manhattan, Roosevelt Island, Wards Island, northwestern Queens and western Bronx (Fig. 2).

Fig. 3. Manhattan bedrock subsurface (developed by Mueser Rutledge Consulting Engineers, 2000).

Most of the known rock types of the area were formed during the Cambro-Ordovician period, 500 million years ago; a time full of continental collisions and geologic activities. New York City is on the edge of the North American Plate that collided with the Ancestral African Plate during that period. Upon collision, the eastern margin of the North American Plate slid beneath the African Plate, resulting in the formation of an offshore arc of volcanic islands. In the middle of this period, the volcanic island arc moved towards the east coast of the proto-North America, and scraped up sedimentary rocks from the bottom of the ocean (Fig. 4). Continuing movement caused these deposits to be stacked in layers, later changing to metamorphic rocks. The easterly continental shelf deposits of limestone changed to Inwood Marble, shale transformed to part of Manhattan Schist and the deep-water ocean deposits of Terrigenous silts became Harland Formation and part of Manhattan Schist.

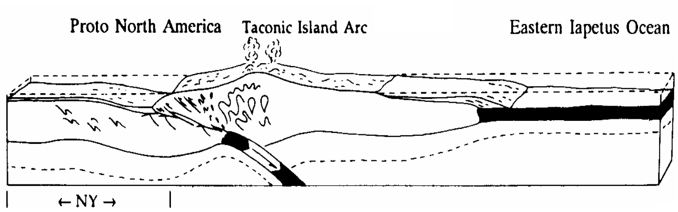


Fig. 4. Collision of Island Arc and Proto North America (Isachsen et al, 2000). Notice location of NY and volcanic arc pushing sedimentary rocks.

The movement eventually resulted in folding and buckling of the continental margin and the creation of the ancestral Taconic Mountains.

Some of the rock formations created at the time are:

- *Inwood Marble*: Located in upper Manhattan, western Bronx and along the East River alignment, extending south likely between Governors Island and Brooklyn. It is a metamorphosed shallow shelf deposit of lime-mud, with occasional quartzite and siliceous layers.
- *Manhattan Schist*: This formation outcrops in northern and southern Manhattan, Wards Island, and west Bronx. It includes layered schist and gneiss.
- *Hartland Formation*: A deep-water oceanic deposit underlying most of central Manhattan, and eastern Bronx. It is interbedded with marble and consists of units of schist, white/pinkish granite with minor greenish amphibolite and granitic intrusions.
- *Ravenswood Granodiorite*: Found on the sides of lower East River, it contains granite and diorite.
- *Serpentine*: Mostly found in Staten Island, and rarely in Manhattan and Hoboken. With a distinctive, soapy green look it comes from oceanic crust caught between North American Plate and ancient volcanic Island Arc.

In 1986, an excavation for a new water supply system revealed, at a depth of about 200 m below the bed of East River and buried under a mountain of solid stone, a 30- to 50-meter-wide band of fractured rock. Geologists believe that this line, called Cameron’s Line, is the mend point between the ancient continents of Africa and North America. This old fault extends from western Massachusetts and Connecticut into NYC at the bed of Bronx River, under the Roosevelt Island in the East River, and passing by western Queens. Cameron’s Line is the mark of the focal point where most of New England was pasted on the North American Continent and created the foundations for Manhattan, eastern Bronx, and Staten Island (Mittelbach & Crewdson, 1998). The mapping of this fault keeps changing as more data become available.

About 350 million years ago another mountain was built, the Acadian Orogeny. As a result, earlier metamorphic rocks were again buried to great depths and remolded by intense pressure and heat. The underlying Fordham gneiss and Hartland Formation were again severely deformed and recrystalized, squeezed like an accordion into sweeping patterns of tight folds. The erosion that followed removed the Acadian mountains and exposed their roots, creating a banded surface of roughly parallel rock strata, which run north south, (Merguerian & Sanders, 1989).

<u>Soil Geology</u>

Soil deposits in NYC are derived largely from the Cretaceous and the Pleistocene periods.

During the Cretaceous period, 80 million years ago, the sea level rose after the continents separated and covered most of NYC with sand and clay deposits. After the Pleistocene glaciation, a complex stratigraphy remained after most of the existing soil in the area was destroyed. Cretaceous deposits of the time found in eastern Queens, Brooklyn, and Staten Island are the Lloyd Formation, overlain by the Raritan Formation and Magothy Formation at the top.

During the more recent Pleistocene (or Glacial Deposits) period, about 1.5 to 0.1 million years ago, the landscape was modified due to glaciation and the work of glacial meltwaters. Continental ice flowed slowly from the north, picking up on the way loose rock material. During the melting of ice, clay, sand, gravel and boulders were transported from north. This mixture, known as the terminal moraine, forms the spine of Long Island and extends west across Staten Island. The glacier deposited the dense glacial till over the bedrock in much of the NYC area. As the glacier melted, the south shore of Long Island, including the southern part of Brooklyn and Queens was formed as a broad sand/gravel outwash plain extending south from the moraine and overlying a thick series of dense cretaceous clays and sands reaching bedrock at depths exceeding 300 meters.

Glacial lakes formed north because the terminal moraine blocked drainage to the sea. Deep deposits of varved silt, clay and silty fine sand were deposited in them. When the glacial meltwater finally breached the terminal moraine, the varved clays were overlain at many locations by a stratum of sand and gravel. The deep varved silt deposits underlying Harlem and lower Manhattan are known locally as “bulls liver” because of their instability when excavations extending below ground water are attempted in the formation.

Typical glacial deposits found in NYC are:

- *Jameco Gravel*: Found in Brooklyn and Queens, it consists mostly of dark coarse sands and gravels, and some cobbles, boulders and layers of silt and clay. The formation is very permeable and is a chief aquifer for many public water supplies (Suter et al, 1949).
- *Gardiners Clay*: Located below Jameco Gravel consisting mainly of dark gray silty clay grading to clayey and silty sands near its upper surface. Its gray color is the result of carbonized woody material.
- *Recent Holocene Deposits*: Most recent deposits are soft clays and silts deposited by erosion and rising sea levels due to the glacial retreat in the Hudson and East River valleys and in other depressions, waterways and embayments.

To obtain greater building space, surficial soils were placed by man. They include heterogeneous deposits of fill, artificial layers of sand, silt, gravel, boulders, miscellaneous materials, construction debris and occasional hydraulic sand fills. Examples are fills of the City’s western shoreline up to 1500 meters into the Hudson River, fills over Long Island Sound Embayment in Flushing, Queens on which two World Fairs were constructed, and hydraulic sand fill placed to create the land on which JFK Airport is built.

Figure 5 shows the large lake known as Collect Pond that once existed in lower Manhattan under the present area of Chinatown, just north of the present City Hall. The natural spring-fed Collect Pond was the main source of fresh water for NYC until the Croton Aqueduct system was opened (NY Public Library, 2002). It has now been obscured by fills. All these areas are interesting from earthquake stand point since the underlying deep, soft subsoils may create large seismic amplifications.

Fig. 5. Map of Collect Pond (City of New York, 1783).

SEISMOLOGICAL BACKGROUND

Faults

About 200 million years ago, during the Triassic-Jurassic period, the Atlantic Ocean was formed as a result of the rift between the North American and African continents. About the same time, renewed movement occurred along an old fault west of the Hudson River, known as the Ramapo Fault. The Newark Basin was born from tectonic activity when an area southeast of the fault dropped possibly 8 to 9 km. Deposits of this era are found below glacial deposits in northeast Staten Island, below the Lockatong and Brunswick Formations. The thick diabase of Palisades Sill was created from solidified lava, and can now be seen in the majestic cliffs of the Palisades (Tamaro et al, 2000).

There is no evidence of major faulting younger than 65 million years. The more dramatic faults are expressed as surface features; others are visible in rock exposures or were mapped during tunnel excavations (Fig. 6). Some faults are open and act as channels for water flow and others contain gouge or secondary mineralization and are healed.

Although the closest plate boundary is thousands of miles away, the city has an unusually high number of earthquakes. Most of the tremors are quite small and cannot be felt (AMNH, 1998). To this date, no particular faults are considered responsible for observed earthquakes. The evidence of increasing seismic activity in NYC and the shock felt during the Quebec earthquake in 1988 resulted in the first seismic provisions in the Building Code, in effect since 1995.

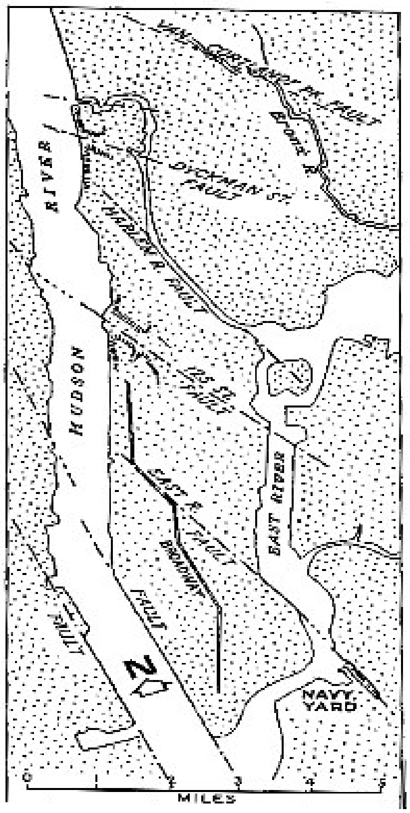


Fig. 6. Major faults of New York City (after Lobeck, 1939).

<u>Historic Seismicity</u>

A compilation of the historic seismicity since 1534 is depicted in Fig. 7. Recordings of seismic events in the metropolitan area are available for the past 50 years. Prior to that, magnitudes are derived using earthquake intensity data. The most severe events occurred at Rockaway beach in 1737 and 1884, with estimated local magnitudes of 4.6 and 5.1, respectively, and in Morris County, New Jersey (NJ) in 1783 with magnitude 4.8.

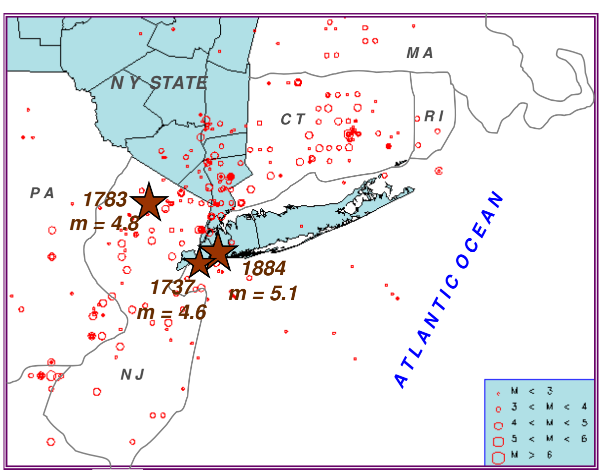


Fig. 7. Spatial distribution of historic seismicity and major events around NYC from 1534 to today (after Nikolaou, 1998).

These earthquakes were felt in large areas in northeast. The 1737 event created chimneys to fall and was felt in Boston, Philadelphia, and parts of Delaware. During the 1884 earthquake, the New York Tribune reported that chimneys fell and cracks in houses were observed in southern NY, eastern Pennsylvania, northern NJ and Connecticut. Some beach houses reportedly tilted and subsided, most likely evidence of liquefaction of the surficial beach sands (Tuttle & Seeber, 1989). Figure 8 shows a seismograph print of the earthquake as recorded from the Dominion Observatory in Ottawa, Canada.

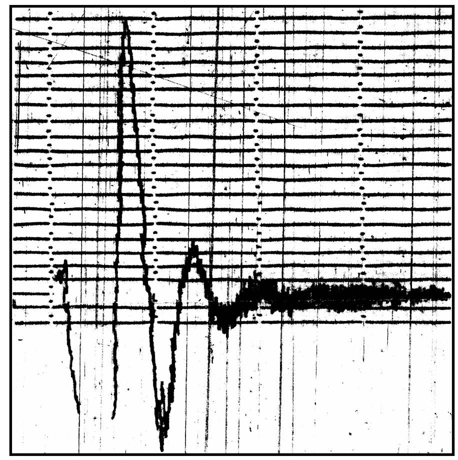


Fig. 8. 20-sec seismogram of the 1884 earthquake (Dominion Observatory, Can.). From NY Tribune - scale not available.

NYC SEISMIC CODES

In 1995, the Building Code of the City of New York was amended to consider earthquake loads. The provisions of Section 2312 of the 1990 version of the Uniform Building Code (UBC) were incorporated, with modifications, into the Code by the amendment. The NYC Seismic Code was developed following the philosophy of one-parameter codes. In 1998, the NYC Department of Transportation (NYCDOT) released Seismic Criteria Guidelines for bridges and other highway structures based on a study by Weidlinger Associates. The Guidelines are based on the most recent, two-parameter codes developed after 1994 (Whitman 1992; NEHRP-94).

The fundamental differences between one- and two-parameter models of codes are shown in Fig. 9. A comprehensive review on the evolution of site factors in seismic codes can be found in Dobry et al (2000). The one-parameter model follows the ATC-3 scheme created in 1978, based on studies by Seed and coworkers (1976a, b) using few available records. The one-parameter NYC Code is based on a seismic event that was intended to have a return period (T_r) of approximately 500 years and a Peak Ground Acceleration PGA=0.15g at the surface of shallow stiff soil or weathered rock profiles overlying hard bedrock. The reason for selecting a PGA on stiff soil or weathered rock was that the Code Committee elected to retain the value of an older "Seismic Zone Factor" assigned to NYC in the UBC. That Zone Factor was based on

Western US (WUS) bedrock that is less competent than NYC bedrock and more equivalent to NYC glacial tills and weathered rock.

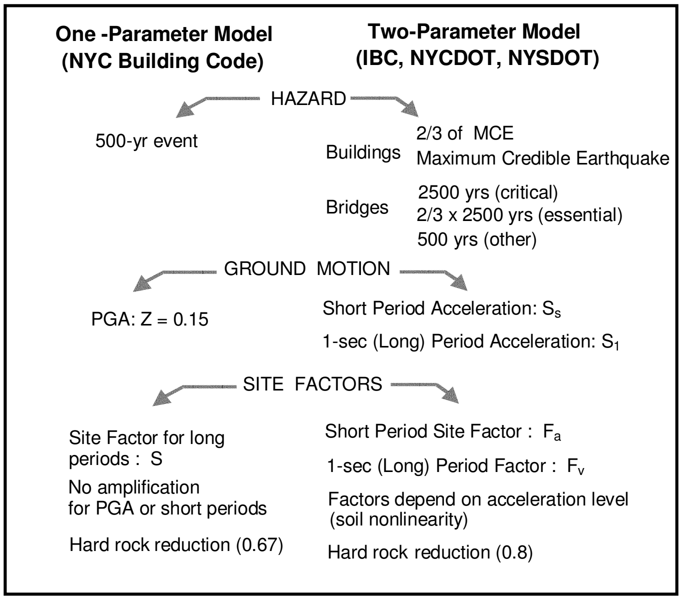


Fig. 9. One and two-parameter code fundamentals.

New York City Code profiles are classified in five types, designated S0 to S4, based on soil type and stiffness as well as on depth to rock. According to the one-parameter model, only one index, the site coefficient S, is used to determine soil amplification in long-period spectral accelerations (SA). No amplification is recommended for PGA or short-period SA. The site coefficients are equal to S = 0.67, 1.0, 1.2, 1.5, and 2.5 for the five soil classes. A de-amplification factor of 0.67 was introduced for soil type S0 (hard rock), to reflect the fact that NYC bedrocks are much stiffer than those in WUS.

The NYCDOT Guidelines follow the same two-parameter model for soil classification and site response as does the International Building Code (IBC) that was recently adopted by NY State. Specifically:

- The soil is classified using weighted average of geotechnical data (standard penetration test resistance, undrained shear strength, or shear wave velocity) within the first 30 m below ground surface. Five soil types "A" through "E" are established to incorporate very stiff (Class A) and very soft sites (Class E). Class "F" is introduced for special soils (very soft or liquefiable) that require site-specific evaluation.
- The ground motion and site factors are determined by two parameters, one at period of 0.2 sec and another at period of 1 sec. The factors also depend on the acceleration level, to account for non-linear soil behavior. Figure 10 shows the site coefficients for short (F_a) and long (F_v) periods as a function of the corresponding short period rock spectral acceleration S_S, and long period S_1, and soil conditions, as given in the latest IBC/NEHRP recommendations. The same factors are used in the DOT Guidelines, with some modifications for NYC.
- Two design hazard levels are included: a "functional evaluation event" with return period of 500 years and a "safety event" of 2,500 years to be applied in different importance categories of structures.

The approximate correspondence between new and old site categories are summarized in Table 1 and a comparison of the site factors is given in Table 2.

At present, the City of New York is performing an internal review of the seismic aspects of the Code and comparing it with the model IBC-2003. A paper that appears in this conference (Alperstein et al, 2004) presents the findings and views of an *ad-hoc* committee of geotechnical engineers that reviewed the liquefaction section of the Code and suggested changes to the Structural Engineers Association of New York (SEAoNY), to be considered for inclusion in the recommendations to the NYC Department of Buildings (DOB). The City's review is still underway and is expected to be completed in 2004. In the following paragraphs site-specific results from recent seismic amplification studies for typical NYC sites will be presented and compared with the recommendations of applicable codes.

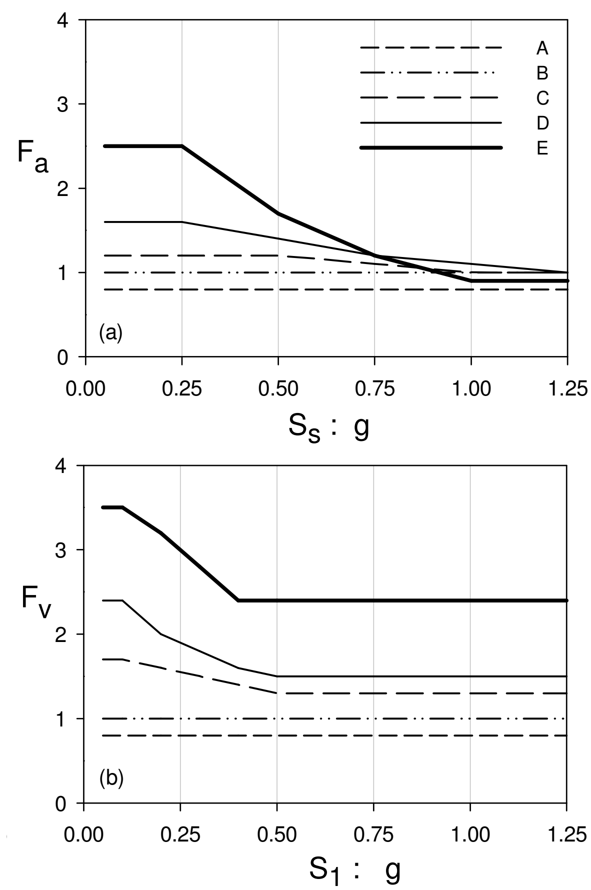


Fig. 10. Site factor coefficients for soil profiles "A" to "E" at: (a) short and (b) long periods based on two-parameter codes (NEHRP-97/2000 and IBC-2000/03).

Table 1. Site classification in seismic codes after 1994 and approximate correspondence with old provisions (modified from Dobry et al 2000).

Site Class			Average Properties within top 30 meters		
			Shear Wave Velocity	Standard Penetration Test Resistance	Undrained Shear Strength
NYCDOT NEHRP-97	**Old Code Equivalent**	**Description**	$\overline{V_s}$ m/s	$\overline{N}$ blows/300 mm	$\overline{S_u}$ kPa
A	S_0 (NYC)	Hard Rock	> 1500	---	---
B	S_1	Rock	760 – 1500	---	---
C	S_1 , S_2	Soft to Firm Rock / Very Dense Soil	360 – 760	> 50	> 100
D	S_1 , S_2	Stiff Soil	180 – 360	15 – 50	50 – 100
E	S_3 , S_4	Soft Soil	< 180	< 15	< 50
F	S_3 , S_4	Site-specific Evaluation Required	---	---	---

Table 2. Site factors with respect to Site Class B (NYCDOT) or S1 (NYC Code), for different hazard levels and structural periods.

T_r (years)	Site Class	Surface Acceleration / Rock "B" Acceleration			
		NYCDOT (1998)			NYCSC (1995)
		PGA	T = 0.2 s	T = 1 s	Long-Period
500	**C**	1.1	1.2	1.8	1.0 or 1.2
	D	1.5	1.6	2.5	1.2 or 1.5
	E	2.5	2.5	3.5	1.5 or 2.5
2500	**C**	1.1	1.7	1.7	N/A
	D	1.2	1.9	2.3	
	E	1.2	1.9	3.4	

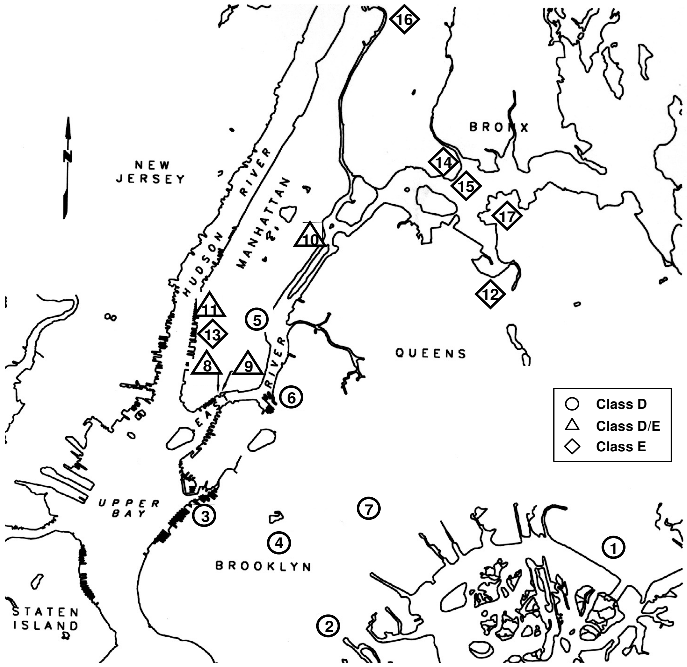
SITE-SPECIFIC STUDIES

Soil amplification studies

Selected results from a comprehensive soil amplification study of typical NYC profiles (Nikolaou et al, 2001) representative of S2 (medium compact soils) and S3 (soft, loose soils) profiles, as per NYC Code, and categories D (stiff soils) and E (soft soils), as per NYCDOT, are presented. The sites are spread geographically in Manhattan, Queens, and Brooklyn with overburden thickness ranging from 10 to 250 m. Soil properties are determined by borings made for foundation design and by geologic references. Shear wave velocity profiles were derived using correlations with Standard Penetration Tests (SPT) and from in-situ geophysical testing data. The shear wave velocity in the bedrock is assumed to range between 2 to 2.5 km/s for all profiles. The fundamental natural period of the profiles ranges between 0.2 (relatively stiff) to 1.4 sec (very soft). The site locations and a summary of soil properties and code classification are given in Fig. 11.

Geotechnical case studies

Of particular interest from geotechnical and foundation engineering stand point, are two sites in Queens: the John F. Kennedy (JFK) Airport Light Rail Project (Site 1) and the US Tennis Association (USTA) National Tennis Center (Site 12). A short description of each project is given below.



Profile No.	Depth to Rock (m)	Aver. $V_{s\,30\,m}$ (m/s)	Period T (s)	NYC Class	NYCDOT Class
1	250	250	1.37	S_2/S_3	D
2	200	228	1.30	S_3	D
3	60	303	0.57	S_2	D
4	90	275	0.81	S_2	D
5	15	224	0.23	S_2	D
6	40	230	0.62	S_2	D
7	120	305	1.07	S_2	D
8	55	250	0.59	S_2	D/E
9	30	255	0.42	S_2	D/E
10	52	202	0.67	S_3	D/E
11	10	210	0.18	S_3	D/E
12	120	206	1.12	S_3/S_4	E
13	44	165	0.78	S_4	E
14	23	192	0.43	S_3	E
15	23	171	0.38	S_3/S_4	E
16	20	153	0.59	S_3	E
17	55	136	0.81	S_4	E

Fig. 11. Sites analyzed, soil properties and site classification (after Nikolaou et al, 2001).

Site 1. JFK Airport Light Rail Project, Queens: The 8-mile rail system connects JFK International Airport to the Long Island Railroad (LIRR) Jamaica Station, the NYC Transit Authority (TA) Howard Beach Station, the car rental areas and the long term parking lots. The project includes an elevated guideway, one below grade tunnel and two grade level embankments.

A geologic profile at the site is presented in Fig. 12. The site is underlain by about 3 to 6 m of fill composed of sand, gravel, some silt and clay, and traces of concrete, wood, and cinders. Within the limits of the Airport, beneath the fill there is a discontinuous stratum of soft silty clay and peat up to 2 m thick. The fill and organic layer are underlain by a deep stratum of glacial sand composed of fine to coarse sand with traces of gravel, silt, and clay. Most structures are founded in this layer. Rock is at depths in excess of 250 m and groundwater is found at an average depth of 3 m below grade. Extensive amplification and liquefaction studies were performed using in-situ geophysical measurements. The site response generally matched the average response of Class D profiles (Nikolaou et al, 2001). Details of the liquefaction studies can be found in Elsaid (2001).

Approximately 6000 piles were used, founded in the glacial outwash sands. The piles are either 1,350 kN Monotube® or 1,350 or 1,800 kN Tapertube™ piles. Several of the piles have been tested to ultimate vertical loads up to 4,100 kN and horizontal loads of 450 kN with lateral deflections of 75 mm or less. A Monotube® pile is 450 mm in diameter with a 3-gage wall thickness and a 7.6 m long taper with 200 mm tip dia. The Tapertube™ piles have 450 mm dia. with 10 mm wall thickness and similar taper as the Monotube®. Lengths vary from 12-20 m; pipe piles of comparable capacity would have to be 24 to 34 m long. Minor structures were supported on timber piles or spread foundations.

Site 12, USTA National Tennis Center, Queens: The existing field tennis courts were replaced by a 23,000-seat stadium. The natural soil formation is a result of deposition in three distinct geologic periods in a basin that was probably formed by water currents during Tertiary time or the eroding action of melt-water from a receding ice face. Other locations in New York City with similar soil conditions are the Flushing Meadow World's Fair and LaGuardia Airport areas.

The project is built over man made fills consisting of cinders, ash, and fine to coarse sand with silt. Fill is generally medium to compact and has a thickness ranging between 5 and 10 m. Four organic layers lie beneath the fill. The first organic layer is a 1.0 to 1.5 m thick meadow mat, followed by a 9 to 18 m of thick gray soft organic silty clay with traces of shells, vegetation and fine sand. The third organic layer is a brown fibrous peat with decomposed vegetation and has a thickness of 1.5 to 3 m, followed by 3 to 6 m of loose gray organic silty fine to coarse sand with gravel, shells, and peat. These organic layers extend about 23 m below grade. Beneath the organic layers are two layers of glacial lake deposits. The upper layer is typically 3 m thick consisting of medium compact to compact gray fine to coarse sand with trace to some silt, and trace gravel. The bottom layer is medium to stiff gray varved silt, clay, silty clay, or clayey silt, with occasional fine sand and mica seams. The bottom layer extends to depth of greater than 65 m below grade. Groundwater is a depth of 3 m below grade. A geologic profile at the site is given in Fig. 13.

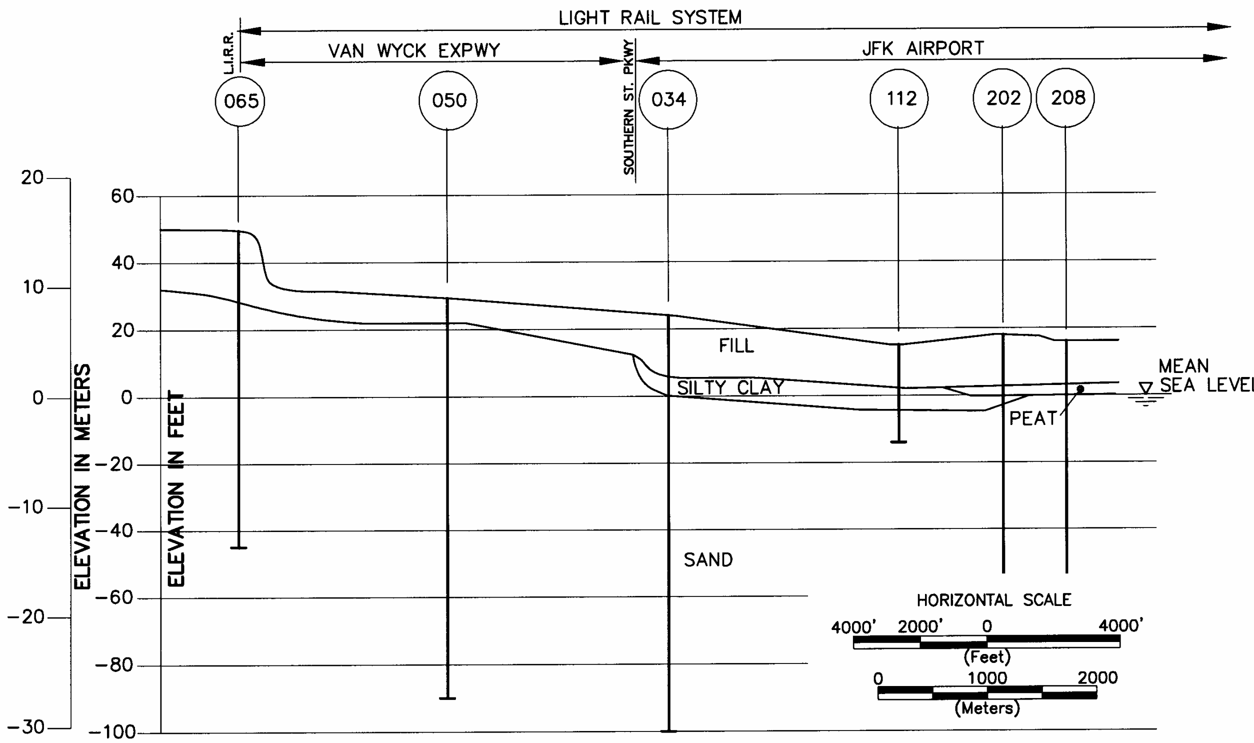


Fig. 12. Geologic section at JFK Airport Light Rail project in Queens.

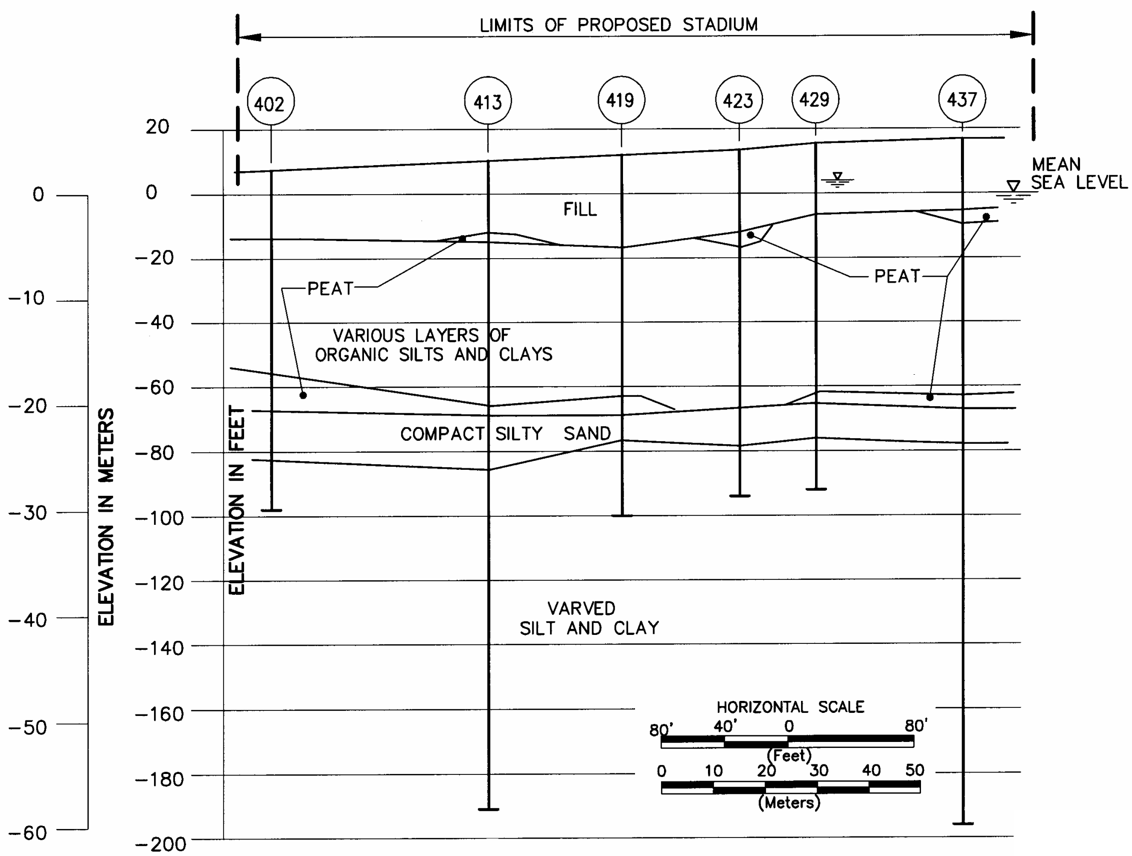


Fig. 13. Geologic section at US Tennis Association National Tennis Center in Queens.

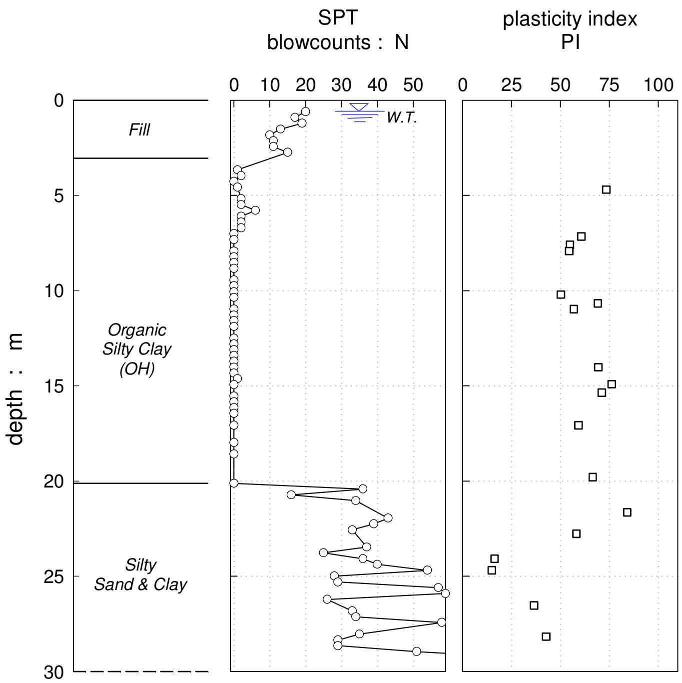


Fig. 14. Geotechnical properties for typical Fig. 13 section.

The new stadium is supported on approximately 1300 piles. Because of the difficulty of the varying subsurface conditions, several foundation alternatives were considered, including a mat foundation and a load compensating (i.e., "floating") foundation. Several types of piles were also considered, including pipe piles and Tapered Pile Tip (TPT) piles. The pile selected for final design and construction was a composite pipe/Monotube pile, consisting of a 7.5-m long Monotube tip tapering 200 to 400 mm spliced to a 12 m long – 400 mm dia. by 3-gage Monotube straight section. The remainder of the pile consists of 400 mm dia. by 10 mm thick wall pipe attached to the 20-m long Monotube section by a special, shop fabricated, splicer. The piles are designed for an allowable structural load of 800 kN and a soil downdrag load of 350 kN. The piles were successfully tested to a proof load of 1,950 kN.

Production pile lengths ranged from 30 m, with piles bearing in the upper glacial lake outwash sand, to 58 m, for piles bearing in the lower glacial lake varved silt. Lightly loaded support structures, such as concession structures, were supported on footings in the fill.

The site has particular interest from the seismic perspective as it contains thick organic silty clay layers of high plasticity. A simplified profile with geotechnical soil properties is shown in Fig. 14. Results from an extensive study that illustrates the importance of these soil index properties is presented herein.

<u>Design motions</u>

The rock input motions used in the parametric studies were artificial time histories developed by Risk Engineering, Inc. for the NYCDOT study for hard (Class "A") rock. The expected motions resulted from a probabilistic seismic hazard study incorporating the history of previous events and the intensity attenuation versus distance from epicenter patterns of Eastern North America (ENA). Predicted rock PGA's range from 6% of gravity for an event with 10% probability of being exceeded in 50 years (return period of 500 years) to 24% of gravity for an event with 2% chance of being exceeded in 50 years (return period of 2500 years). Three motions were applied for each hazard level. Shown in Fig. 15, the DOT design spectra have evident high-frequency content with peaks around 0.1 sec. The figure also shows the present NYC Code spectrum, which is close to the NYCDOT 2500-year spectrum.

The design levels of the spectra of Fig. 15 correspond to low shaking hazard compared to areas in WUS. However, the corresponding risk is much higher due to the density and value of existing pre-seismic code structures which lack of earthquake-resistant design. To illustrate the high risk, Fig. 16 presents contours of structural ductility demand (μ) for simple elastoplastic structures with an elastic natural period 0.1 sec

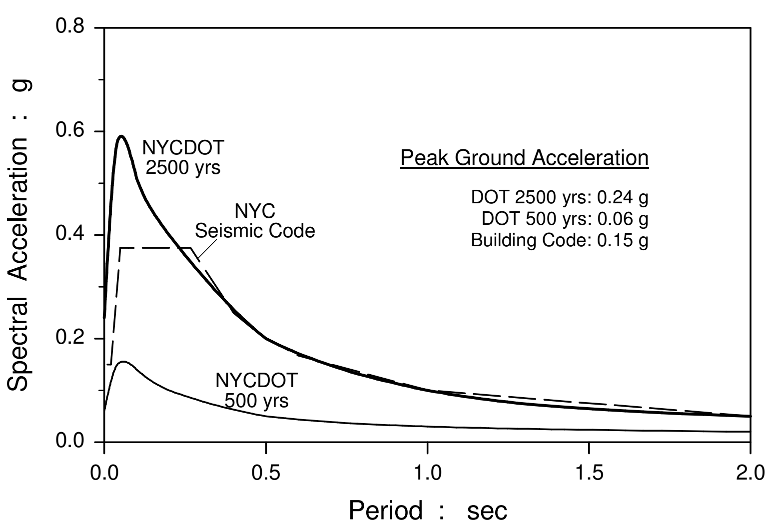


Fig. 15. Design rock spectra in NYC Codes.

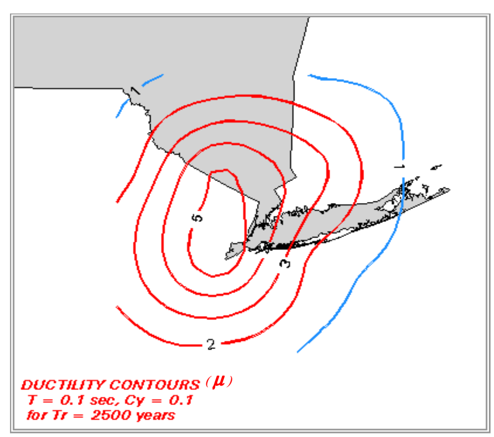


Fig. 16. 2,500-year ductility contours for T = 0.1 sec.

and yielding structural strength exceeded at an acceleration of 0.1 g, for a 2500-year event and assuming foundations on rock. Such structures, represented by low-rise masonry buildings that make up much of the housing in NYC, could sustain severe damage as significant structural yielding will occur at $\mu \geq 3$. The role of soil could amplify seismic intensity and increase damage levels.

Analyses results

A summary of one-dimensional wave propagation analyses using SHAKE (Schnabel et al 1972) for soft, Class E, sites is presented in Fig. 17 for surface Spectral Accelerations (SA) and surface-to-rock amplification Ratios of Response Spectra (RRS). It should be noted that the RRS results have been normalized to a ratio with respect to an "S1" profile or class "B" rock (both of which have a Site Factor = 1.0), in order to be directly comparable to the Site Factors in Codes.

Results for the 500-year return period are shown in Figs 17a and 17c, against corresponding values in current codes. Average calculated amplification values are on the order of 3 to 5, which is in fair agreement with the DOT values for periods up to 1 sec, although DOT appears conservative beyond 1 sec (only mean+σ calculated RRS values are higher than the DOT factors for a period range of 0.4 to 1.2 sec). In contrast, the site factors of the NYC Seismic Code are smaller and unconservative at practically all periods. The mean response spectra of DOT appear to be conservative at all periods. Despite the small amplifications in NYC Code, the spectral ordinates of the Code are always higher than DOT and those computed. This is a result of conservative bedrock spectrum and high PGA of 0.15 g adopted in the NYC Code.

For the 2500-year return period, SA and RRS results are plotted in Figs 17b and 17d. Note that NYC Code does not define a spectrum for this return period. The amplification values are smaller than those for 500 years, as expected due to higher levels of strain and damping in the soil. Average values do not exceed 3, while de-amplification (RRS < 1) develops at periods smaller than 0.15 sec. Computed PGA values are at around 0.35 g and the spectra agree well with the DOT curves. Similar trends have been observed in the same study for Class D stiffer soils, not shown in this paper.

Of special interest for structural design, composite spectra are given in Fig. 18 that presents seismic demands for Spectral Acceleration (SA, in the vertical axis) and Spectral Displacement (SD, in the horizontal axis) on the same plot. Radial lines emanating from the origin correspond to different structural periods. Maximum displacement demands for long-period structures of about 100 to 150 mm were calculated for the 2500-year event. These plots can be combined with "pushover" curves to analyze the yielding of a structural system, identifying the point of intersection between pushover and spectral curves, where failure may be initiated.

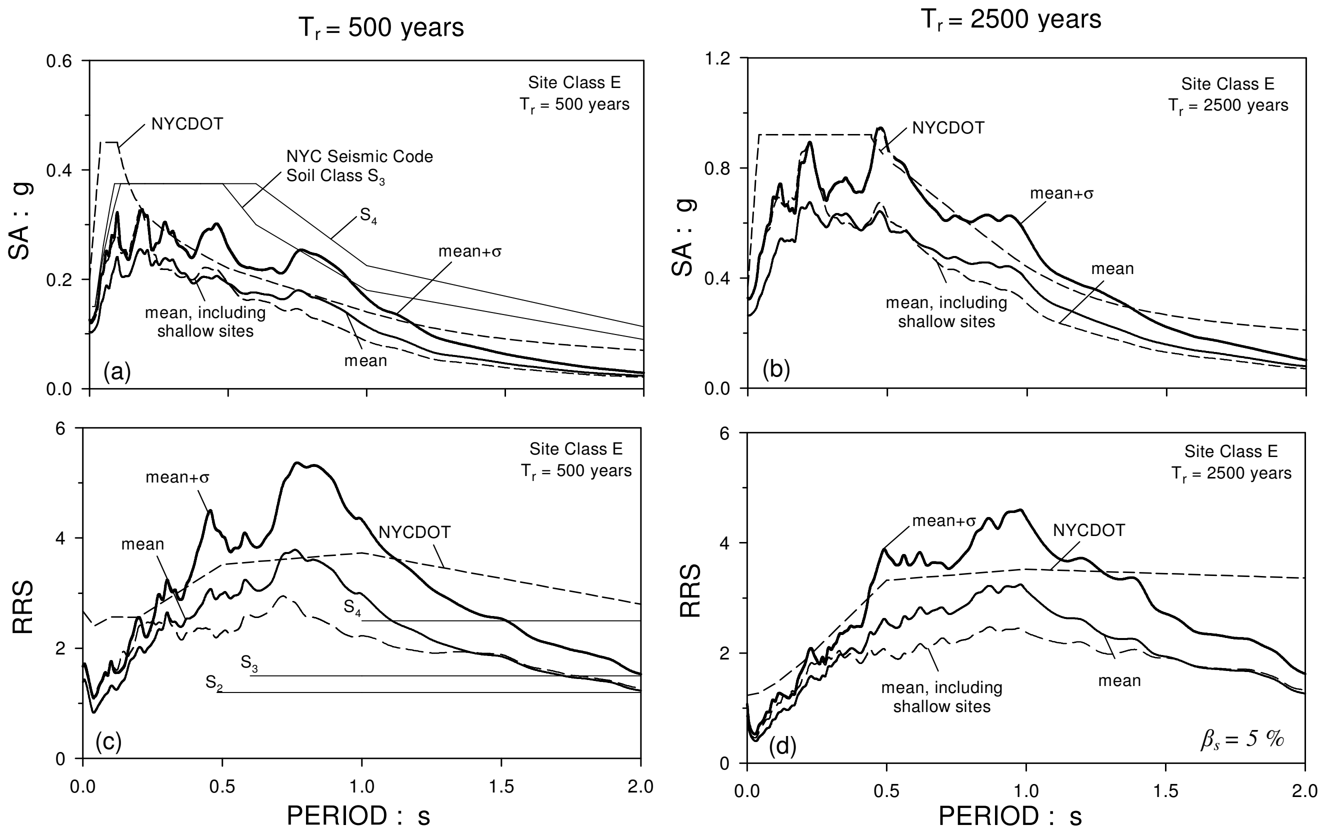


Fig. 17. Surface acceleration response spectra for (a) T_r = 500 and (b) T_r = 2500 yrs for Class E sites. Corresponding response spectral ratios are shown in (c), (d).

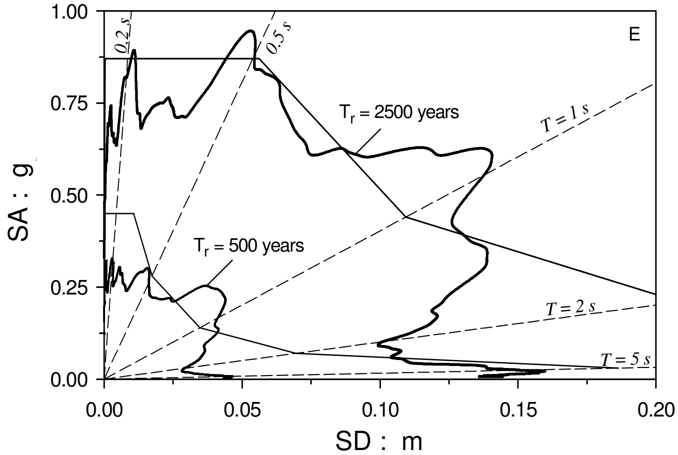


Fig. 18. Mean+σ composite spectra (Class E).

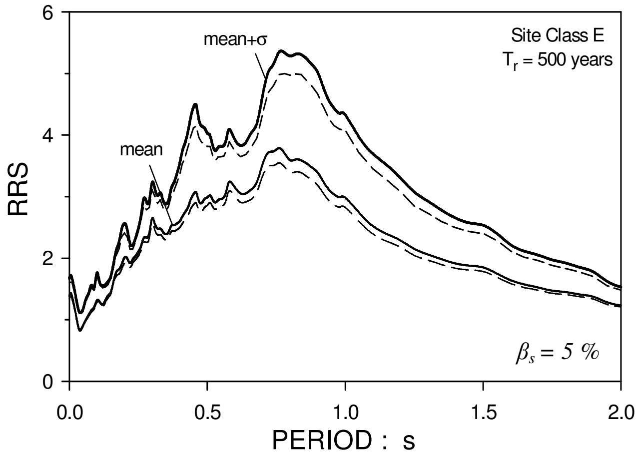


Fig. 19. RRS for rock velocity $V_r = 2$ (dashed line) and 2.5 km/s (solid).

The effect of the impedance contrast between rock and soil is depicted in Fig. 19 for a return period of 500 years. It is seen that an increase in rock shear wave velocity from 2 to 2.5 km/s leads to an increase in RRS of about 5-15%. This increase, not considered in either of the current codes, demonstrates the need for accurate in-situ measurements of rock velocities for seismic design in the area.

Special considerations

The characteristics of the USTA National Tennis Center site were presented earlier (Fig. 13). A parametric study was performed for the simplified 55-m thick profile of Fig. 14 to examine differences that may result from ignoring soil index properties. Of particular interest are: the very small SPT blow-count resistance, the low strength (S_u < 20 kPa) and the high plasticity index of the organic layer. The low-strain period of the profile is about 0.9 seconds.

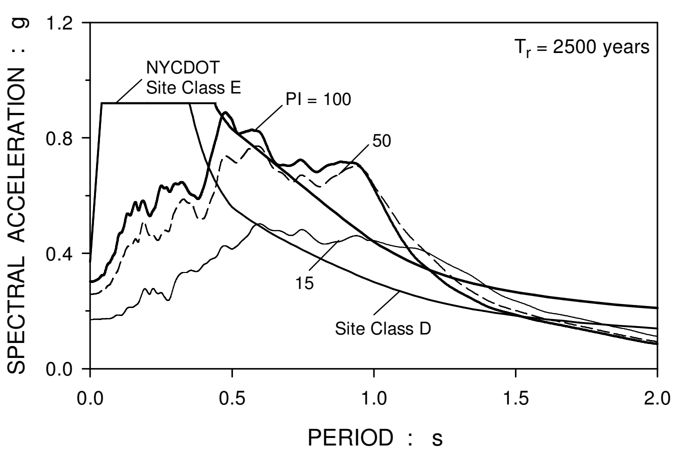


Fig. 20. Surface spectra for the profile of Fig. 14. Notice sensitivity of site response in selection of plasticity index.

Average computed spectra at the soil surface are given in Fig. 20 for the 2500-year event. The importance of plasticity index was examined by using the Vucetic-Dobry curves of PI = 15, 50, and 100 for the organic layer. Significant errors in the unsafe side are generated if the high plasticity index of the profile is not taken into account. This stems from the small values of effective damping that tend to develop with increasing values of plasticity index, as demonstrated by Vucetic & Dobry (1991). Large errors would be generated in this case if the general engineering practice of using PI = 15 for clay or the generic design spectrum of "Class-D" soil was used. A comprehensive review on the importance of obtaining accurate geotechnical data for seismic analyses of bridges can by found in Yegian (2003).

Additional design issues of concern that are not addressed in existing codes, such as the response of shallow sites with thickness less than 30 meters, and the soil amplification of vertical ground motions are discussed in detail in Nikolaou et al (2001).

Liquefaction criteria

The current NYC Seismic Code contains a liquefaction screening diagram that defines two boundaries, obtaining three category areas for liquefaction screening (Fig. 21):

- *Category A:* N less than the lower boundary, soil shall be considered liquefiable.
- *Category B:* N between the upper and lower boundaries, liquefaction possible, and soil shall be considered liquefiable for soils underlying "Essential" and "Hazardous" facilities.
- *Category C:* N above the upper boundary, liquefaction unlikely.

Site-specific liquefaction studies performed by various practitioners in the NYC metropolitan area indicate that, for certain sites, this screening diagram may be too conservative.

In 2001, an *ad-hoc* committee of geotechnical engineers was formed to review the liquefaction section of the Seismic Code, and proposed a revision of the screening diagram shown in Fig. 22. The analyses performed and assumptions made to generate this diagram along with a proposed revision in the Code's language are presented in detail in the paper by Alperstein et al that appears in this conference. The proposed diagram of Fig. 22 has the intent to provide input for the Code revision process and not to substitute the present diagram of Fig. 21. The City's review is still underway and the revisions to be approved by the NYC Department of Buildings (DOB) are expected to be complete in 2004.

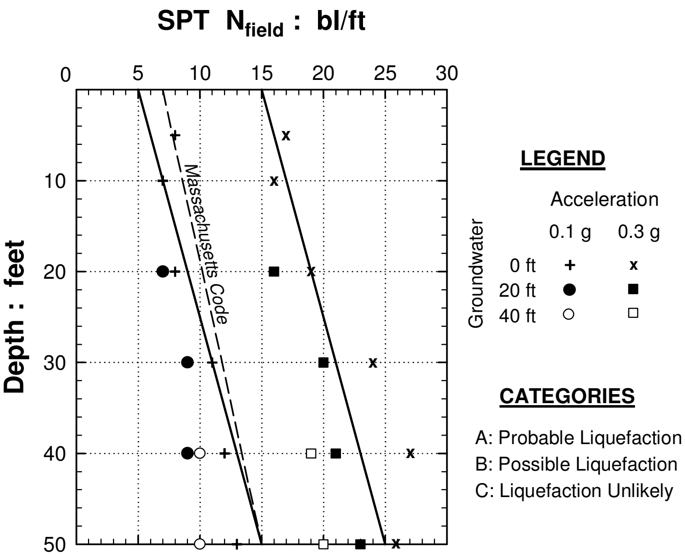


Fig. 21. Liquefaction screening diagram in NYC Code.

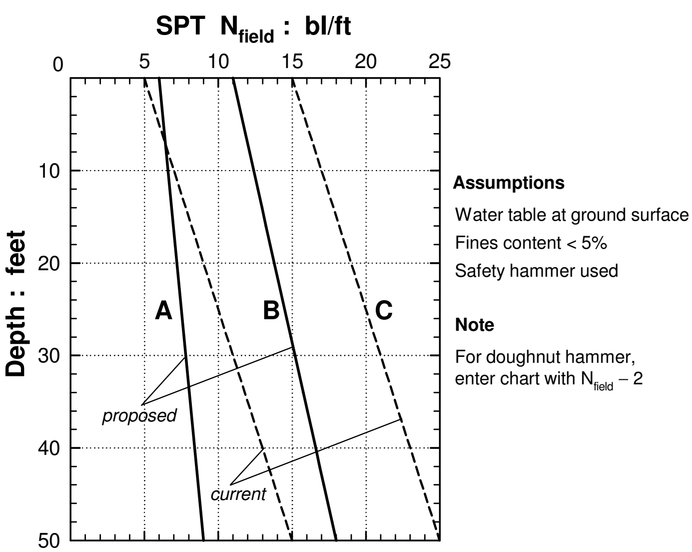


Fig. 22. Proposed modification in liquefaction screening diagram of Fig. 21 (Alperstein et al, 2004).

CONCLUSIONS

The unique geological and seismological characteristics of NYC that affect seismic soil response were presented. The evolution of seismic codes applied in NYC and their treatment of soil behavior was examined and compared with one-dimensional site-specific analysis results for typical soft profiles for 500- and 2500-year return periods. Proposed updates for liquefaction assessment in NYC were presented.

It was shown that the NYC Seismic Code provides conservative design spectra for the 500-year event. However, this seems to be the combined result of the 1995 assumption of a conservative bedrock spectrum, which is much higher than the more rational uniform hazard spectrum of the NYCDOT specifications and the lower site factors of the NYC Code. Class D DOT design spectra could underpredict soil response at periods below 0.5 sec and overpredict it at long periods, mostly at the 500-year hazard level. An update of the design earthquake in the NYC Seismic Code would be sensible.

The rock stiffness and its contrast with the overlying soil can affect significantly surface motions. An increase of the contrast by 25% increased the site factors by about 5 to 15%. Accurate, in-situ field measurements of rock wave velocities are necessary in the area, especially in shallow and soft sites. Proper consideration should be given to accurate laboratory tests, as their results could alter significantly the prediction of soil response. Site factors for shallow sites and for vertical ground motions, and effects of soil nonlinearity need to be studied further.

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