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SEISMIC AMPLIFICATION
OF TYPICAL NEW YORK CITY SOIL PROFILES

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ABSTRACT

Amplification studies for New York City (NYC) soil sites are summarized herein. Ten (10) typical soil profiles from Brooklyn, Queens, and Manhattan, are analyzed using one-dimensional SHAKE methods. Dynamic soil properties are derived using state-of-practice correlations with standard penetration resistance and compared to available in-situ geophysical measurements. Three different rock motions are utilized, each modified from real records to match 500- and 2500-year probabilistic spectra. Results are presented in terms of dimensionless ratios of response spectra (RRS) and surface response spectra. The effect of the impedance contrast between soil and rock on soil amplification is examined. It is shown that although seismic hazard in the area is only moderate, significant soil effects can be generated and lead to large soil amplifications. By comparing the derived spectra with the design spectra defined by the 1998 NYC Department of Transportation guidelines, it is shown that the latter may be unconservative at short periods. Comparison of the results with the design spectra of the 1995 NYC Seismic Code shows that the Code provides conservative design parameters, but unconservative amplification values.

KEYWORDS

Amplification, Site Coefficient, New York City, Manhattan, Provisions, Hazard, Eastern United States

INTRODUCTION

New York City (NYC) is an area where soil amplification effects may be significant. This is due to the following factors:

- the presence of soft soil deposits such as high-plasticity and organic clays with shear wave velocities on the order of 100 m/s
- the presence of hard bedrock with measured shear wave velocities of the order of 2-3 km/s

In addition, the lack of quantitative recordings adds to the uncertainty regarding possible soil amplification effects. Current seismic design criteria are based almost exclusively on data from the Western United States (WUS), where soils are generally stiffer and rocks substantially softer (shear wave velocities ≈ 0.8-1.2 km/s). Hence, the currently used site factors, which are based on western experience, may be unconservative for NYC soils. Unfortunately, few related studies are available today (Jacob 1990, Dobry 1998).

In this study, results from ten (10) soil amplification studies in NYC metropolitan area are presented. The analyses were performed for two different hazard levels and different assumptions regarding the stiffness characteristics of the underlying bedrock. The objectives of the paper are: (1) to briefly discuss the seismicity and geology of the area; (2) to derive soil amplification factors and corresponding surface response spectra; (3) to compare the findings against existing code design spectra and site factors.

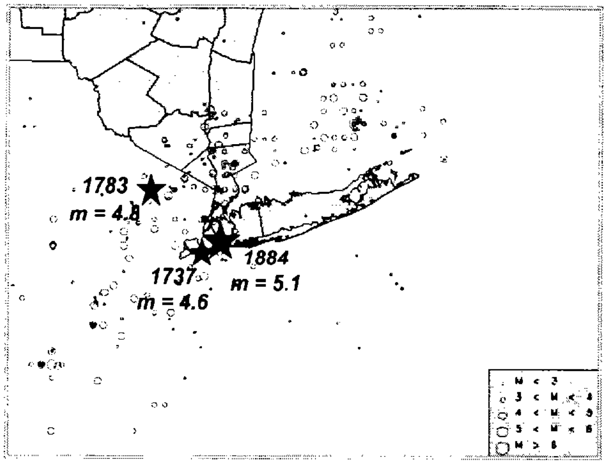

Fig 1. New York City historic seismicity: 1534-today.

New York City Seismicity Information

The historic seismicity of NYC metropolitan area dating from 1534 is shown in Fig 1. Several events have occurred with the most severe cases being those at Rockaway beach in 1737 and 1884 (estimated magnitudes 4.6 and 5.1, respectively), and at Morris County of New Jersey in 1783 (estimated magnitude 4.8). These magnitudes were derived indirectly based on available intensity data. Information for the seismic history of the area is limited to the past 300 years, while recordings are available only for the last 50 years.

Recent seismic hazard studies (Risk Engineering 1998; Nikolaou 1998) based on the available information have shown that a 2500-year event (2% probability of exceedance in 50 years) can produce a peak acceleration on rock of 0.24g. A 500-year event (10% probability of exceedance in 50 years) can generate approximately 0.06 g.

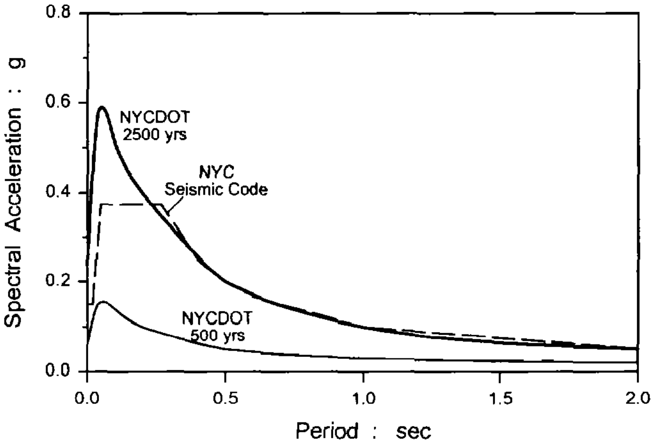

Fig 2. N YC bedrock acceleration response spectra according to the NYC Code and the NYCDOT guidelines (ξ =5%).

Figure 2 shows acceleration response spectra for New York City bedrock with shear wave velocity greater than 2000 m/s given in the NYCDOT (1998) specifications. The design spectrum of the 1995 NYC Seismic Code is plotted for comparison. Both NYCDOT probabilistic spectra attain their maxima at very short periods (about 0.1 s). The ordinates of the NYC Seismic Code spectrum lie between the NYCDOT spectra for periods less than 0.25 seconds; at longer periods they are almost identical to those of the 2500-year NYCDOT spectrum. Evidently, the anticipated intensity of seismic shaking in the NYC is low compared to more seismic prone areas in the Western United States. However, most engineered structures in the area have not been designed to withstand earthquakes. The density and monetary high value of the existing structures combined with their seismically unprepared state make NYC an area of high seismic risk, despite the moderate seismicity.

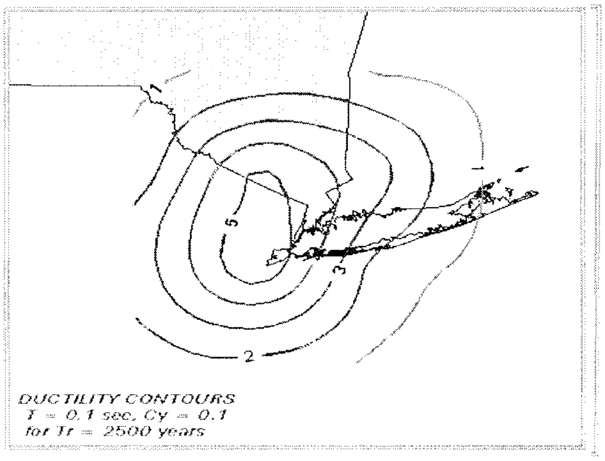

Fig 3. Seismic risk for structures of 0.1 sec for a 2,500-year event in New York City (after Nikolaou, 1998).

As an example, Figure 3 presents contours of ductility demand for simple elastoplastic structures with elastic natural period 0.1 sec and yielding strength 0.1g, for a 2500-year event. Such structures, represented by low-rise masonry buildings that make up much of the housing in NYC could sustain severe damage ($\mu \geq 3$) in such an earthquake. The role of soil in amplifying seismic intensity and increasing damage levels is the focus of the present study.

SEISMIC CODES AND SOIL EFFECTS IN NYC

The most widely used seismic codes in the metropolitan area are the 1995 NYC Seismic Code and the 1998 NYCDOT Seismic Criteria Guidelines.

The first was developed for building design and is based on a seismic event that was intended to have a return period of approximately 500 years and a seismic coefficient of 0.15. Profiles are classified in 5 types (S_0 to S_4), based on soil type and stiffness as well as the depth to rock. The soil amplification from the S_1-type profile to the surface is expressed through the site coefficient S that is 1.0, 1.2, 1.5, and 2.5 for soil classes S_1, S_2, S_3, and S_4, respectively, following the one-parameter amplification scheme of ATC-3. The Code also includes class S_0 for very hard bedrock, assigned a site coefficient of 0.67.

In 1998, the NYC Department of Transportation (NYCDOT) released Seismic Criteria Guidelines for bridges and other highway structures that include two hazard levels: a functional evaluation event with return period of 500 years and a safety evaluation event of 2,500 years. The performance criteria established in that study apply to three major importance categories: the critical, essential and "other" structures, each analyzed at different ground motion levels. The soil amplification effects are accounted for by classifying the site profile from A for hard rock to E for very soft sites with thick organic layers. Figure 2 shows the probabilistic response spectra specified in the NYCDOT guidelines, for hard rock class "A" that is assigned a site coefficient of 0.8 for both hazard levels. The classification procedure for soil profiles is based on a weighted average of either the standard penetration test (SPT) resistance and the undrained shear strength or the shear wave velocity for the top 30 m of the profile. The soil amplification is determined in a manner similar to the NEHRP-97 provisions with some modifications for NYC (Dobry, 1998). Different amplification is recommended for the low excitation level of the 500-year event and for the higher excitation of the 2,500-year event.

SOIL AMPLIFICATION STUDIES

Ten sites within the New York City area representative of S_2 and S_3 soil profiles defined by the 1995 NYC Seismic Code and soil category D of the 1998 NYCDOT were selected for the parameter study. Shown in the map of Fig. 4, the sites are spread geographically in Manhattan, Queens, and Brooklyn. Nine of the profiles are relatively deep, with total soil thickness ranging from 30 to 250 meters, while two are shallow, having thickness of 10 to 15 meters.

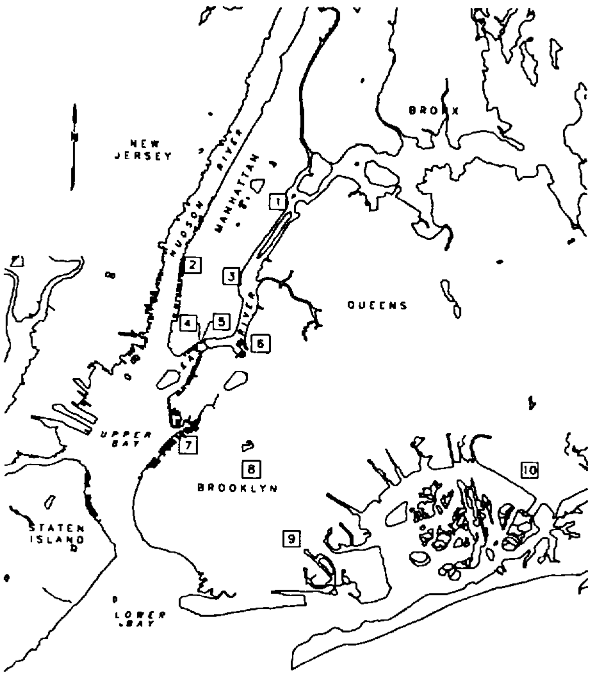

Fig 4. New York City map and the sites analyzed.

Soil profiles

The soil profiles selected are presented in Fig 5. Soil properties are defined by borings made for foundation design at the site and geologic references for the area. Soil type is indicated by USCS group symbols. Soil strata designated as CL and OH are recent river bottom and tidal marsh sediments, soft to medium in consistency. Strata designated as SP, SM and ML are generally glacial outwash soils, although the shallowest of these strata may be recent outwash from adjacent uplands. Unless otherwise indicated, the SP, SM and ML strata are generally medium compact to compact in density. The glacial till layers overlying bedrock are generally dense granular soils. Bedrock is sound schist and gneiss, occasionally overlain by a relatively thin layer of decomposed rock.

Shear wave velocity profiles were derived using correletions with Standard Penetration Tests (SPT) and from geophysical testing information. The SPT blow counts were correlated with V_s using the Seed et al (1986) correlation for sands, the Seed & Idriss (1970) correlation for clays as well as the generic Sykora (1987) correlations. For sites 6 and 10, we used direct results from crosshole testing that were available. The average V_s profiles are shown in Figure 5. The shear wave velocity in the bedrock is assumed to range between 2 to 2.5 km/sec for all profiles. The fundamental natural period of the profiles ranges between about 0.5 to 1.4 seconds, except for the shallow profiles that have periods between 0.2 and 0.25 seconds. Tabulated properties and code classification are summarized in Table I.

Table I. Summary of properties of soil profiles.

Profile No.	Depth to Rock (m)	Aver. $V_{s,30\,m}$ (m/s)	Period $T^{\dagger}$ (sec)	NYC Class	NYCDOT Class
1	51	202	0.72	S_3	D
2	10	210	0.20	S_3	$D^{\ddagger}$
3	15	224	0.25	S_2	$D^{\ddagger}$
4	55	250	0.69	S_2	D
5	31	255	0.44	S_2	D
6	40	230	0.69	S_3	D
7	60	303	0.66	S_3	D
8	90	275	0.85	S_3	D
9	200	228	1.39	S_2/S_3	D
10	250	250	1.41	S_2/S_3	D

† period calculations based on a 500-year event

‡ classification based on average velocity

Earthquake Motions

Two sets of input motions, each consisting of three time histories, were used in the analyses. The two sets have rock outcrop response spectra equivalent to the 500 and 2,500-year hard rock design spectra of the NYCDOT Guidelines. The shape of the code spectra and their values for selected periods are shown in Figure 2.

The motions were selected from a set of time histories developed by Risk Engineering, Inc. for the NYCDOT study. They are based on real motions with characteristics derived by de-aggregation of the hazard in the area for the two return periods. The deaggregation indicated that the dominant pair of magnitude M and distance R for the 2,500-year event is equal to $M = 6.5$ and $R = 22.5\ km$ for a period of 1 sec and $M = 5.2$ and $R = 12.5\ km$ for PGA. For the 500-year event the most significant contribution of M/R values in the hazard was found equal to $M = 6$ and $R = 22.5\ km$ (T=1 sec) and $M = 5.1$, $R = 18\ km$ (PGA). The motions developed are artificial, based

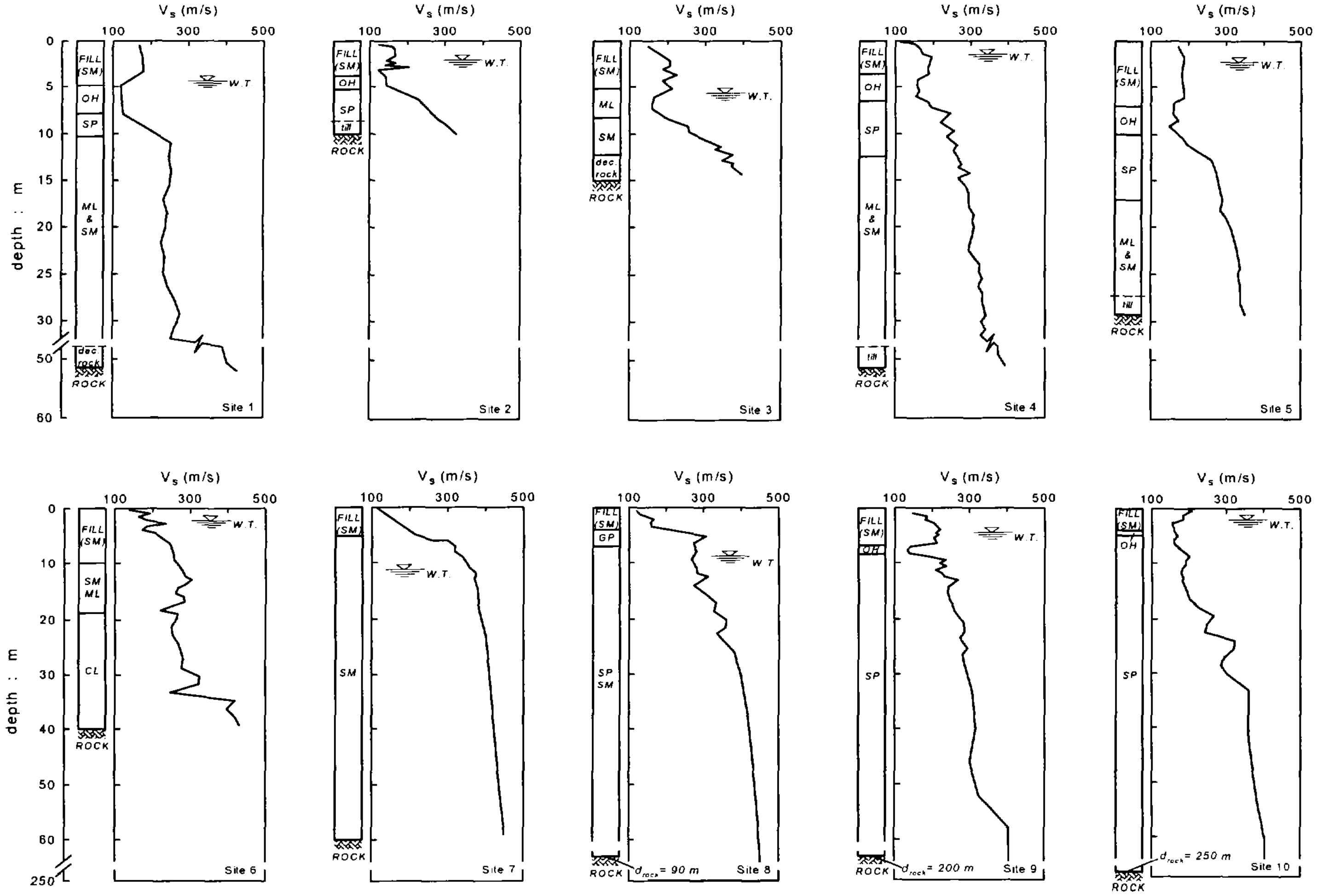

Fig 5. Soil strata description, and mean shear wave velocity V_s profiles used in the analyses. The V_s for Sites 6 and 10 were measured directly, using the crosshole technique.

on recorded ground motions with similar *M/R* pairs, and response spectral shapes resembling the probabilistic rock spectra.

Parameter analyses

One-dimensional wave propagation analyses using SHAKE (Schnabel et al 1972) were performed to derive surface motions for the selected soil profiles. It was assumed that the rock motions consist exclusively of vertically propagating S waves specified at the surface of outcropping bedrock. Ten (10) soil profiles with three (3) different stiffness variations (average, upper and lower bounds) and six (6) motions per profile were used. Hence, a total of 10×3×6 = 180 cases were investigated. Variations in soil shear modulus and material damping with increasing strain were modeled using the generic Vucetic & Dobry (1991) and Seed & Idriss (1970) curves, based on the plasticity indices of the strata. Statistical analyses of the results were performed for the surface response spectra and the surface-to-rock amplification ratios of response spectra (RRS). It should be noted here that the RRS results presented have been normalized to a ratio with respect to class "B" rock, in order to be directly comparable to the NYCDOT and the NYC Seismic Code site coefficients.

RESULTS

The mean and mean plus one standard deviation RRS for the 500-year return period are plotted in Figure 6. Corresponding spectra and RRS for the NYC Seismic Code and the NYCDOT guidelines are shown for comparison. Average amplification values of the order of 1.5 to 3 are observed. The results show that the NYCDOT RRS are more conservative than the average computed curve for periods larger than about 0.75 seconds; but they are unconservative at smaller periods. In contrast, the amplification factors of the NYC Seismic Code are much smaller and unconservative at all periods. These trends are stronger when the two shallow profiles, Nos. 2 and 3, are included in the statistics. This is a predictable behavior given the short natural periods of these profiles that tend to produce strong amplification at short periods, yet drop more quickly at long periods. Note that the mean+σ values of RRS

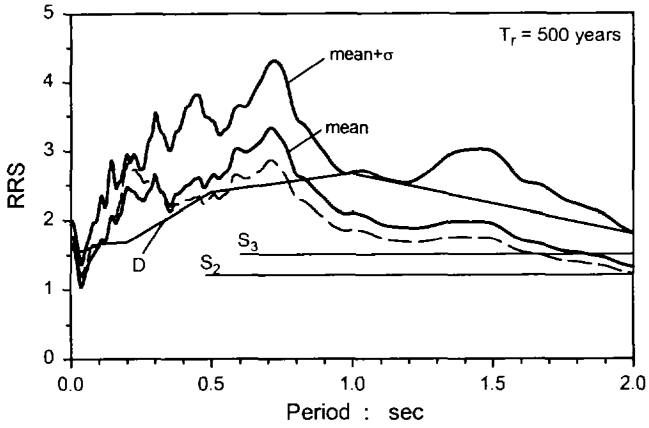

Fig 6. Response spectra ratios (RRS) for T_r=500 years, ξ=5%, V_{rock}=2.5 km/s. The dashed line corresponds to results from all sites and solid lines exclude results from shallow profiles.

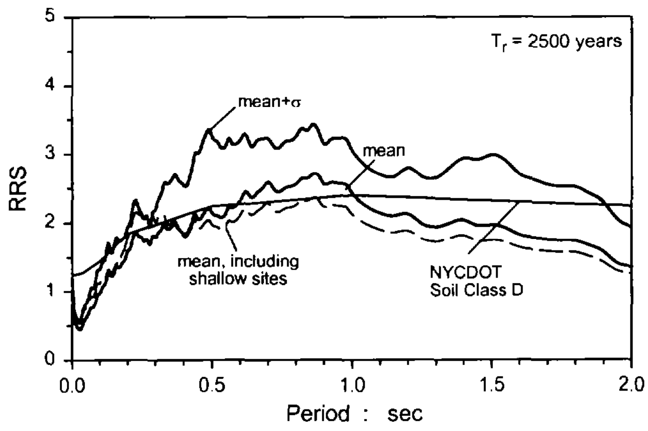

Fig 7. Mean and mean+σ response spectra ratios for the 2500-year event for 5% damping and V_{rock}=2.5 km/s.

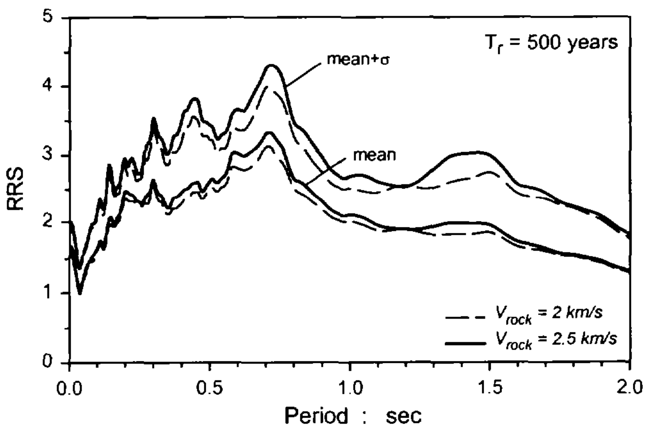

Fig 8. Mean and mean+σ response spectra ratios (RRS) for the 500-year event and two rock shear wave velocities V_{rock}.

are higher than the RRS values of the two codes throughout the period range examined.

Corresponding results for the 2500-year return period are shown in Figure 7. The amplification values are smaller that those in the previous figure, because of the higher damping in the soil. Peak computed RRS do not exceed 2.5, while deamplification, RRS < 1, develops at periods smaller than 0.15 seconds. These reductions are reflected in the NYC code factors, as discussed by Dobry (1998) and Dobry et al (2000).

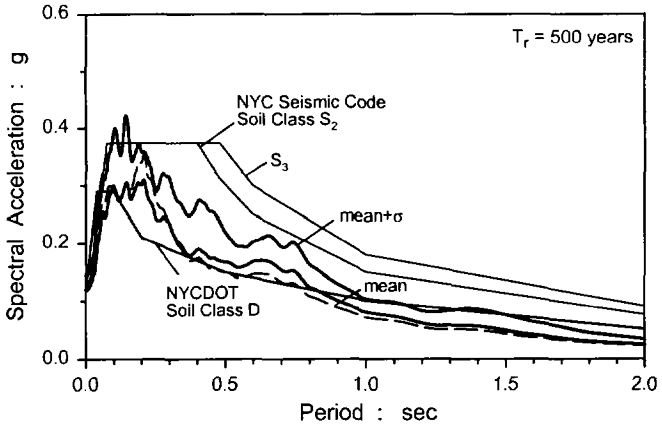

Fig 9. Surface response spectra for T_r=500 years, ξ=5%, V_{rock}=2.5 km/s. The dashed line corresponds to results from all sites and solid lines exclude results from shallow profiles.

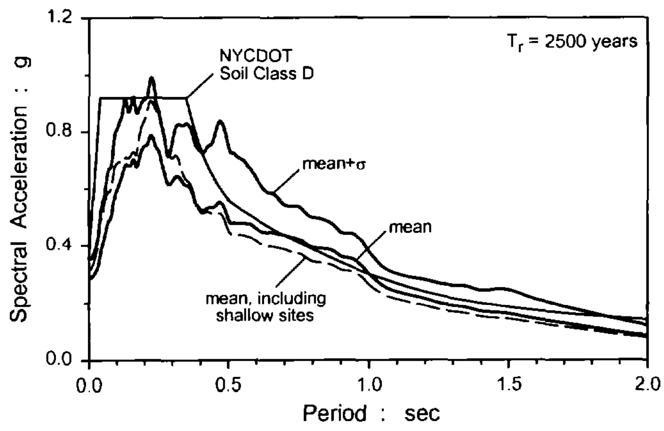

Fig 10. Mean and mean+σ surface response spectra for the 2500-year event for 5% damping and V_{rock}=2.5 km/s.

The effect of the impedance contrast between rock and soil is depicted in Figure 8 for a return period of 500 years. It is seen that an increase in the shear wave velocity of the rock from 2 km/s to 2.5 km/sec leads to an increase in RRS of the order of 5 to 15 percent. This effect, which is not considered in the NYC Code or the NYCDOT guidelines, demonstrates the desirability of accurate field measurements of rock velocities in engineering applications.

Figure 9 compares the 500-year surface response spectrum obtained from this study with the spectra defined in the NYCDOT guidelines and the NYC Seismic Code. The NYCDOT spectrum appears to be conservative at periods smaller than 0.2 seconds and larger than 0.8 seconds, but it is unconservative at intermediate periods. In contrast, and despite the small amplifications for the S_2 and S_3 profiles indicated in Figure 6, the ordinates of the NYC Code spectrum are always higher than the NYCDOT and the computed ones. This results from the conservative bedrock spectrum and the high PGA of 0.15g adopted in the NYC Code as opposed to 0.13g of the present study and 0.12g in the NYCDOT guidelines.

Corresponding 2500-year spectra are shown in Figure 10. The NYCDOT spectrum is slightly higher than the mean computed curve, which is in agreement with the RRS results of Figure 7. The corresponding PGA values in the two spectra are 0.32g and 0.37g, respectively. The $m+\sigma$ computed curve, however, is somewhat higher than the DOT spectrum beyond about 0.4 seconds. Note that the NYC code does not define a spectrum for this return period.

CONCLUSIONS

A parameter study for site factors applicable to typical New York City soil profiles is summarized herein. SHAKE site response analyses were performed using ten (10) local soil profiles corresponding to site profiles S_2 and S_3 of the NYC Seismic Code and site profile D of the NYCDOT guidelines, and three (3) different rock motions compatible with the 500- and 2500-year probabilistic response spectra. Average site factors and associated elastic design spectra were derived and compared with existing code spectra. The main conclusions from the study are:

(1) The NYC Seismic Code provides conservative design response spectra for the 500-year event. However, this is a result of a conservative design bedrock spectrum that is much higher than the NYCDOT seismic uniform hazard spectrum for a 500-year return period. The site factors assigned to the soil profiles S_2 and S_3 defined in the Code are lower than the amplifications computed for realistic earthquakes.

(2) Comparison of average computed amplified spectra with soil category D NYCDOT spectra show that the latter may be unconservative at small periods ($T < 0.5$ sec), but conservative at long periods. The trend is more pronounced in the 500-year spectrum

(3) An increase in the impedance contrast between soil and rock by 25% was found to increase the amplification factors by about 5 to 15%. This indicates that accurate field measurements of the rock shear modulus are desirable, especially in shallow and soft sites

(4) A more up-to-date definition of the design earthquake for the New York City Seismic Code may be desirable

(5) Site factors for shallow profiles with soil thickness less than 30 meters need to be studied

Future research is needed to examine the response of deep, soft soil profiles in New York City. Also, additional studies of all types of profiles for each category, and non-linear inelastic computer analyses to complement the equivalent-linear SHAKE analyses would be useful for defining Code criteria.

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