The Benefits of Site-Specific Seismic Studies for New York City Projects

However; we can save 700 lira and two months by not taking soil tests and call it Site Class “D”.

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Learning Objectives

- Review concepts behind the seismic design provisions
- Review the steps of the Code general procedure
- Review the components of a Site-Specific Seismic Study
- Discuss issues with assessing soil liquefaction potential in the code
- Discuss trends of contemporary standards in seismic design

Presentation Outline

- Overview of Building Code Seismic Design
- Building Code “General Procedure”
- Site-Specific Seismic Studies
- Liquefaction in the Building Code
- Future trends in Seismic Analysis

GENERAL

Disciplines involved in seismic design

- Geologist:
  - Determines active faults, tectonic environment
- Seismologist:
  - Compiles historic seismicity, records Earthquakes, determines fault activity parameters
- Geotechnical Engineer:
  - Determines influence of soil on seismic accelerations
- Structural Engineer:
  - Applies accelerations to design structure

Building Codes, Standards and USGS

USGS 1996

NYCBC (old)

NYCDOT 1998

IBC 2000

ASCE 7-02

USGS 2002

IBC 2003

ASCE 7-05

IBC 2006

USGS 2008

NYCBC (2008)

DRAFT NYCDOT 2008

IBC 2009

ASCE 7-10

IBC 2012

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IBC 2009

ASCE 7-10

IBC 2012

Seismic Design Philosophy

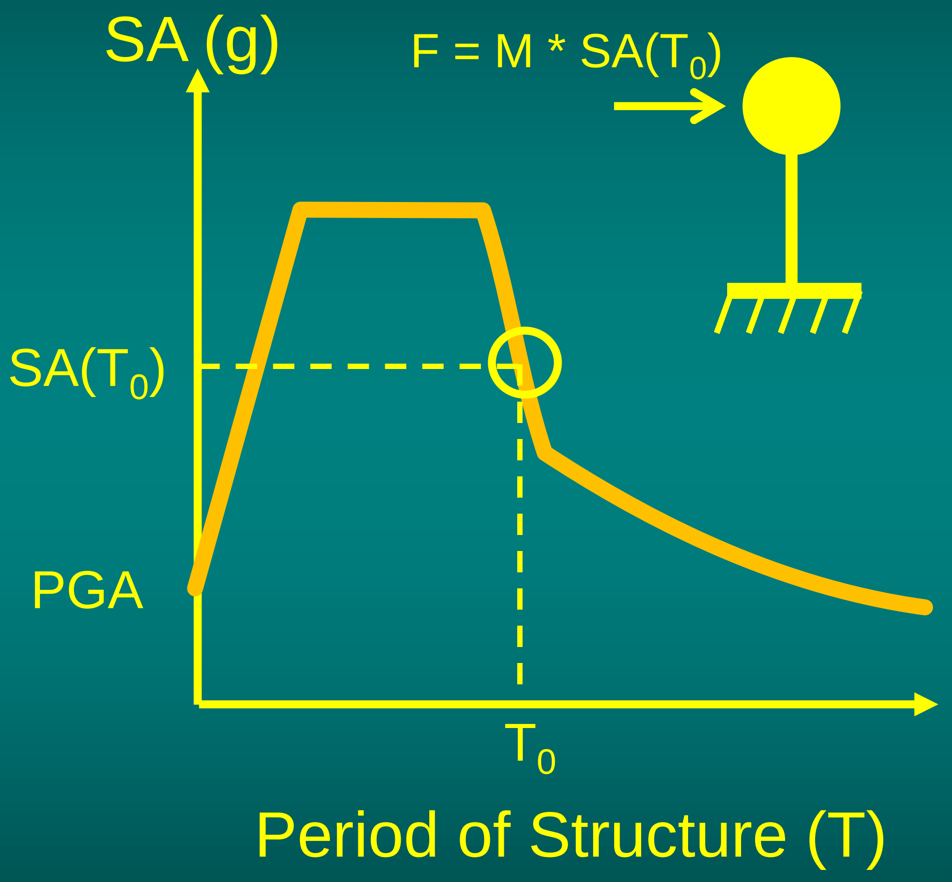
“The design base shear (formula) is the most important and fundamental mathematical expression needed for the design of earthquake-resistant buildings” (IBC commentary)

The design base shear formula uses the “Acceleration Response Spectrum” concept.

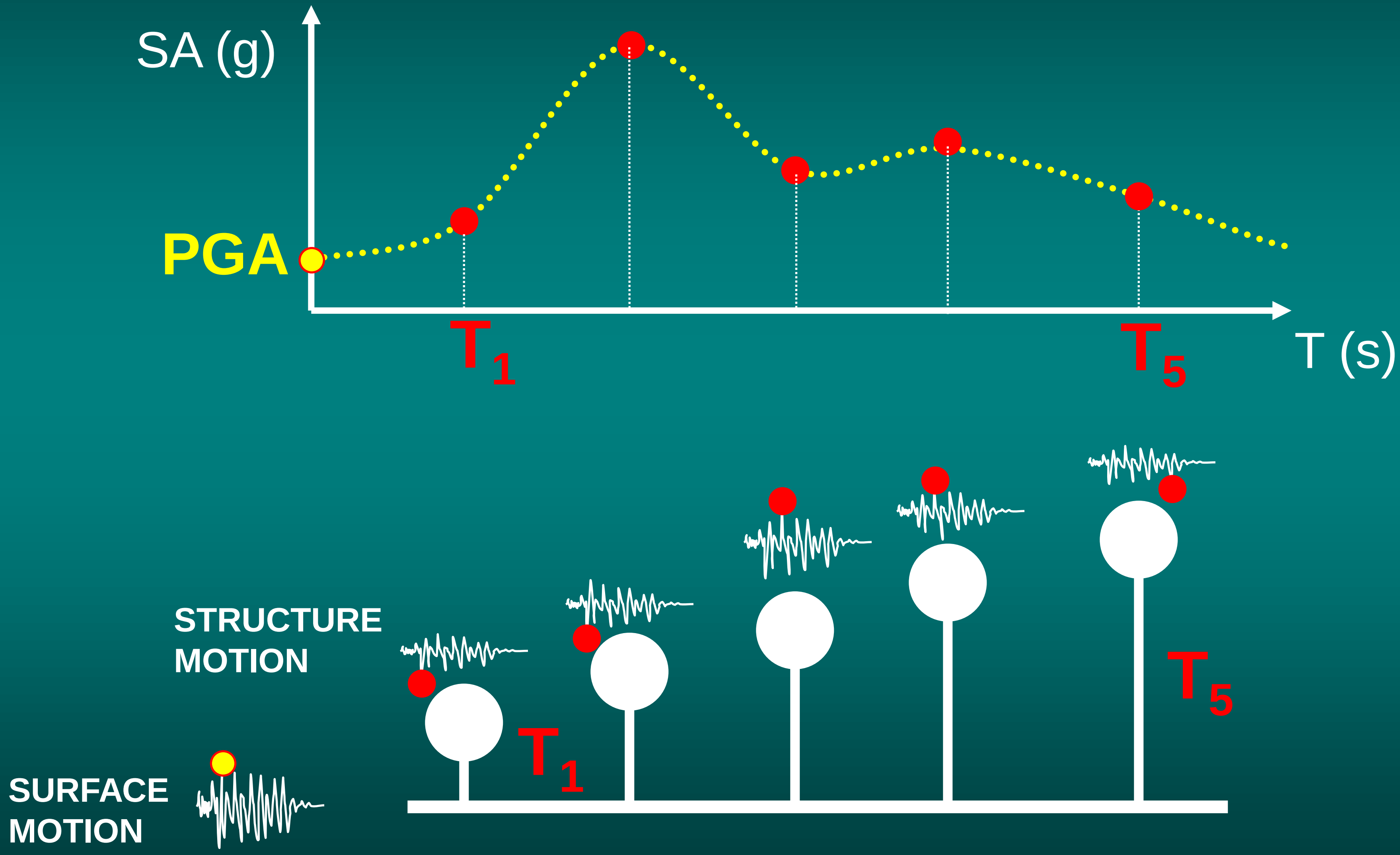
"Smooth" Design Response Spectrum

The Design Spectrum affects

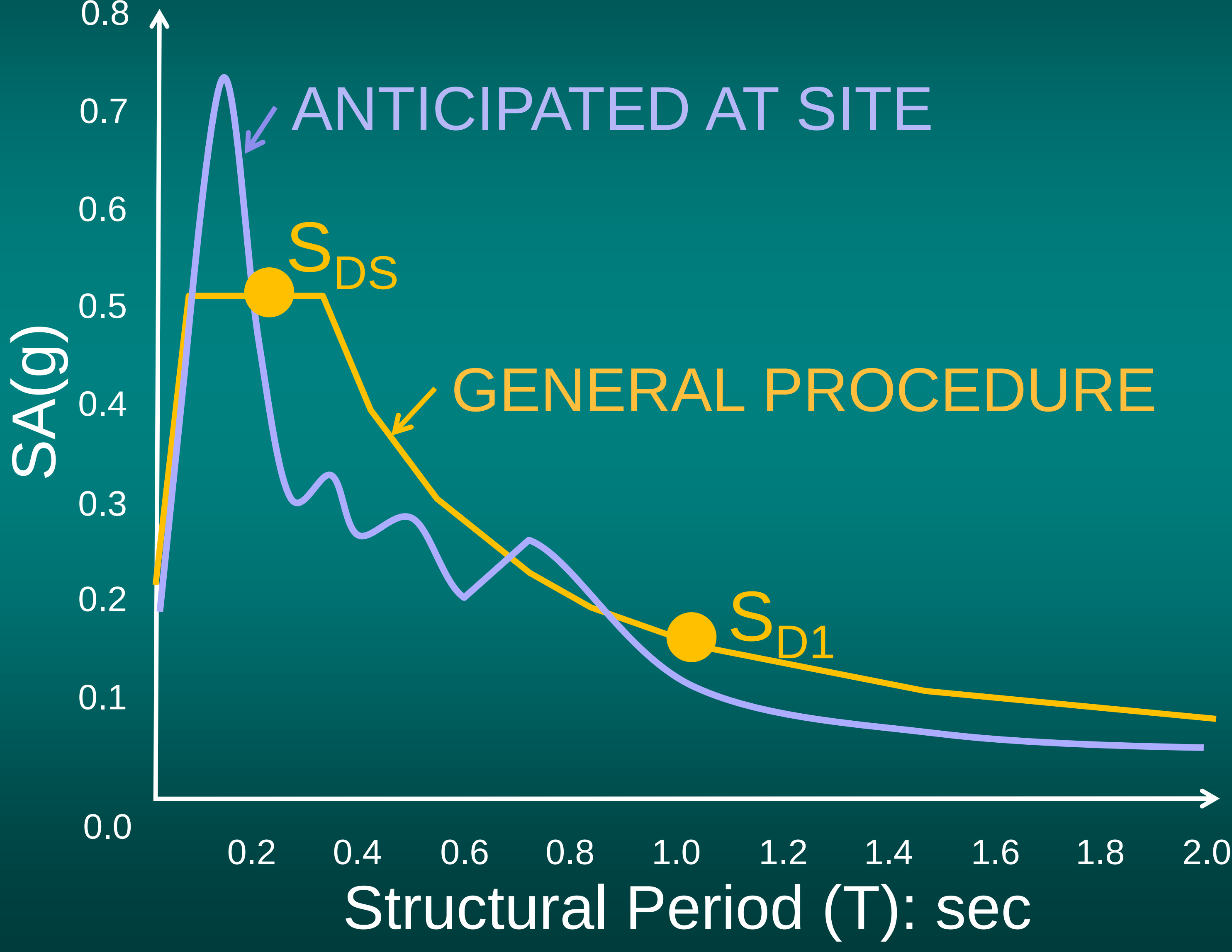
1. Seismic Base Shear
2. Lateral Support System Selection
3. Liquefaction Potential (PGA)



“Actual” Acceleration Response Spectrum



"Actual" Design Response Spectrum



General Procedure

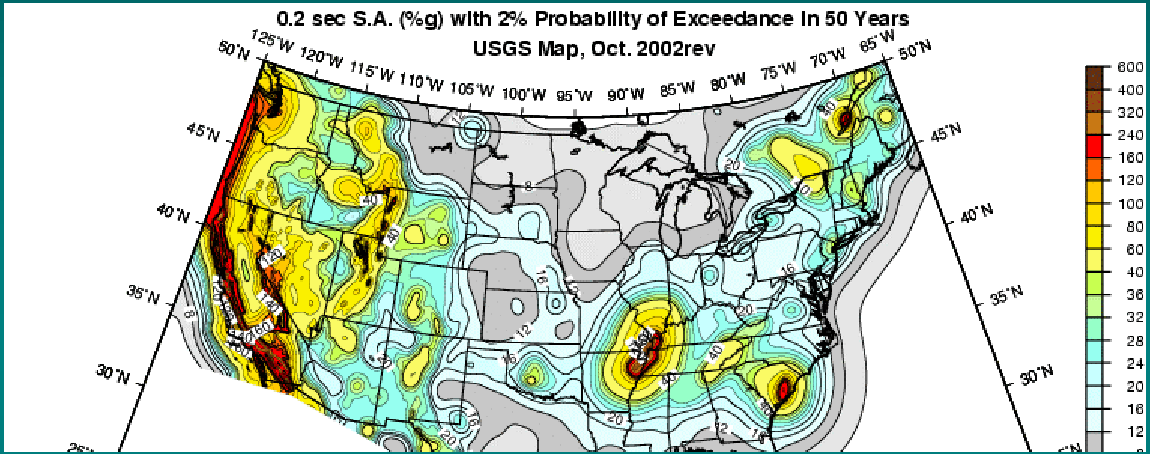
General Procedure (Finding S_{DS})

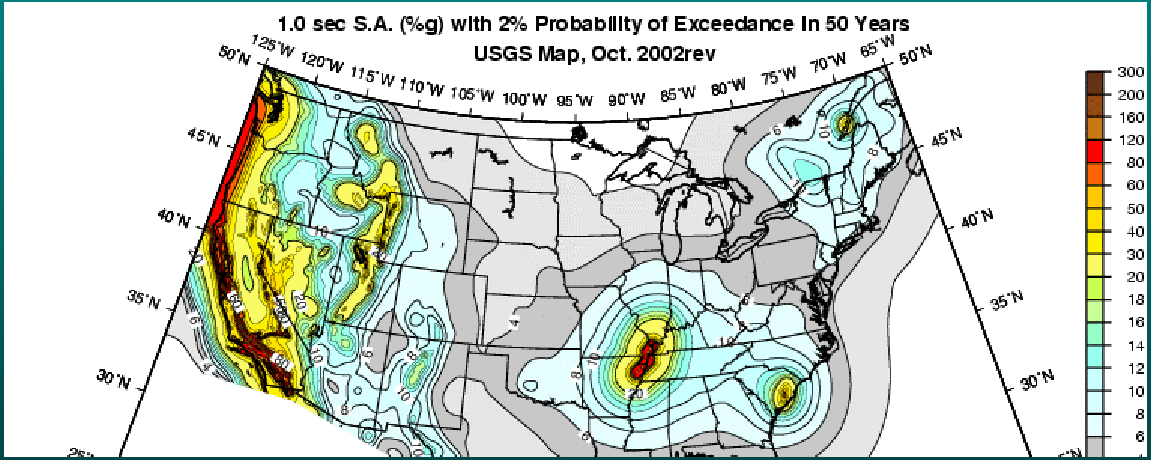
Takes into account

- Geologic & Seismologic Effects
  - Bedrock Accelerations (S_S & S_1)
- Geotechnical Effects
  - Soil/Rock Site Class (A - F)
  - Site Coefficients (F_a & F_v)
  - Ground Surface Accelerations (S_{MS} & S_{M1})
- Structural Needs
  - 2/3 Factor - Design Accelerations (S_{DS} & S_{D1})

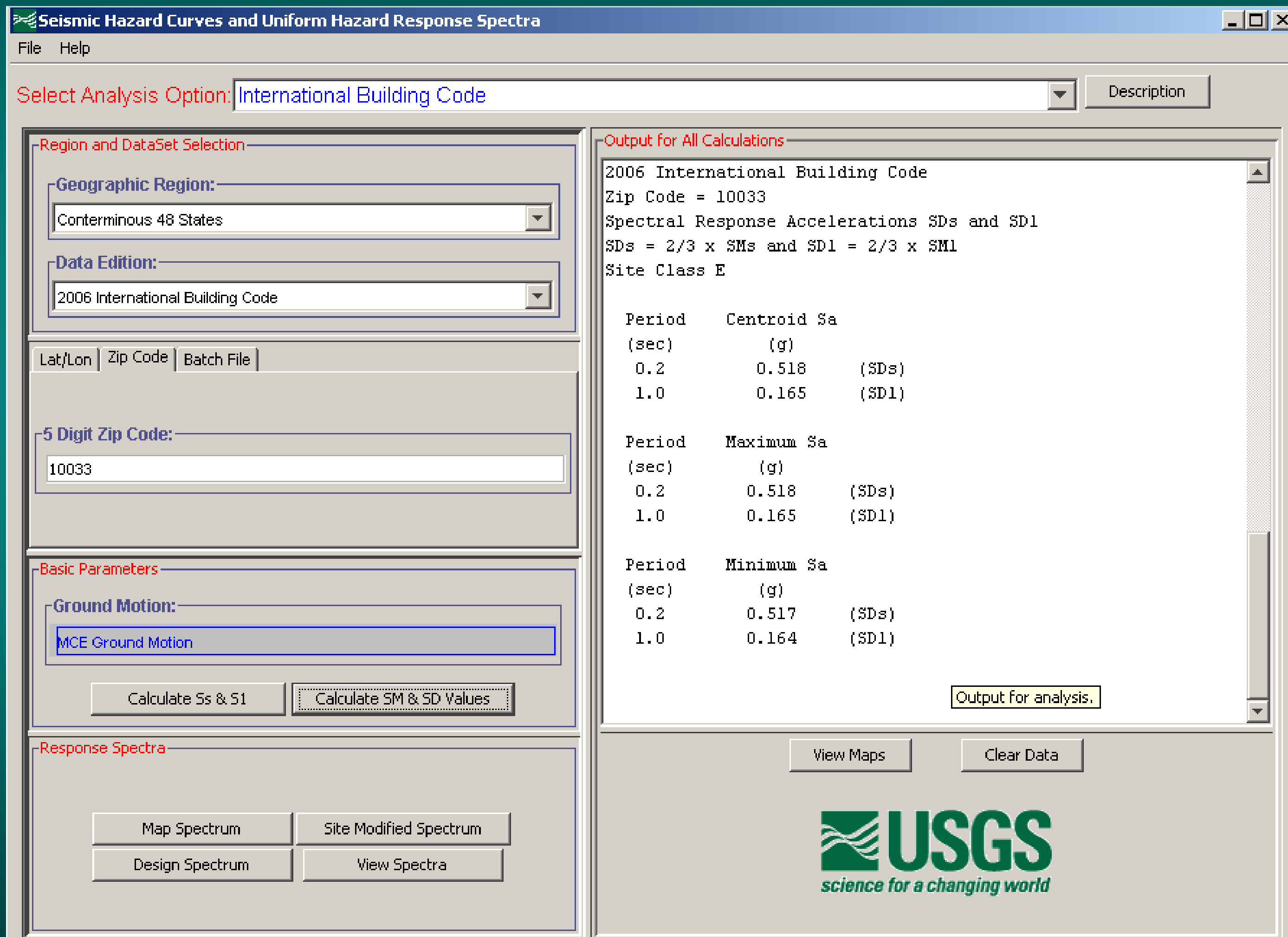
MCE Spectral Accelerations S_S & S_1

Maximum Considered Earthquake – Class B



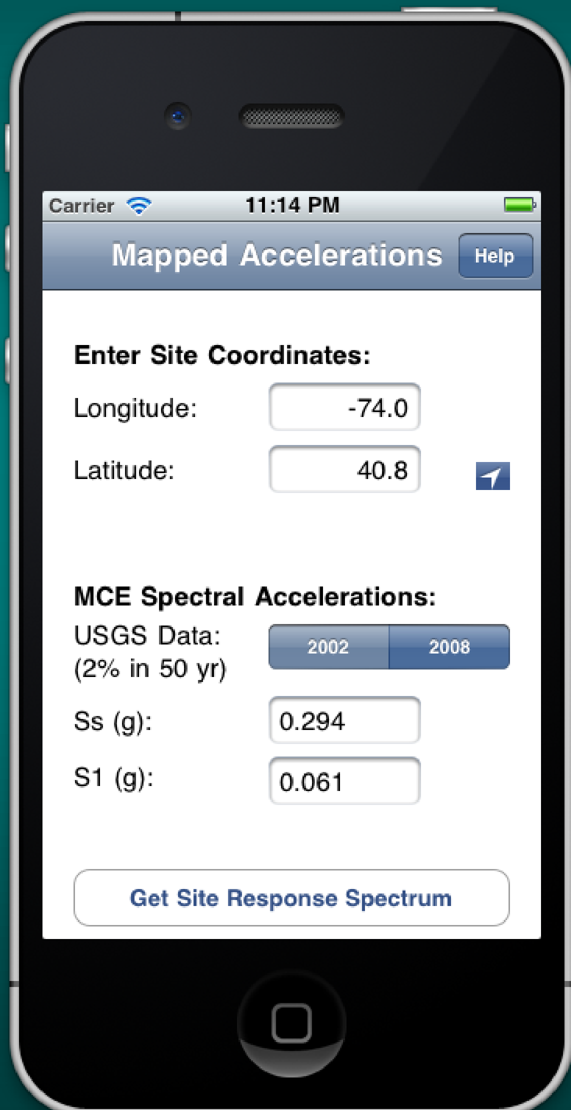


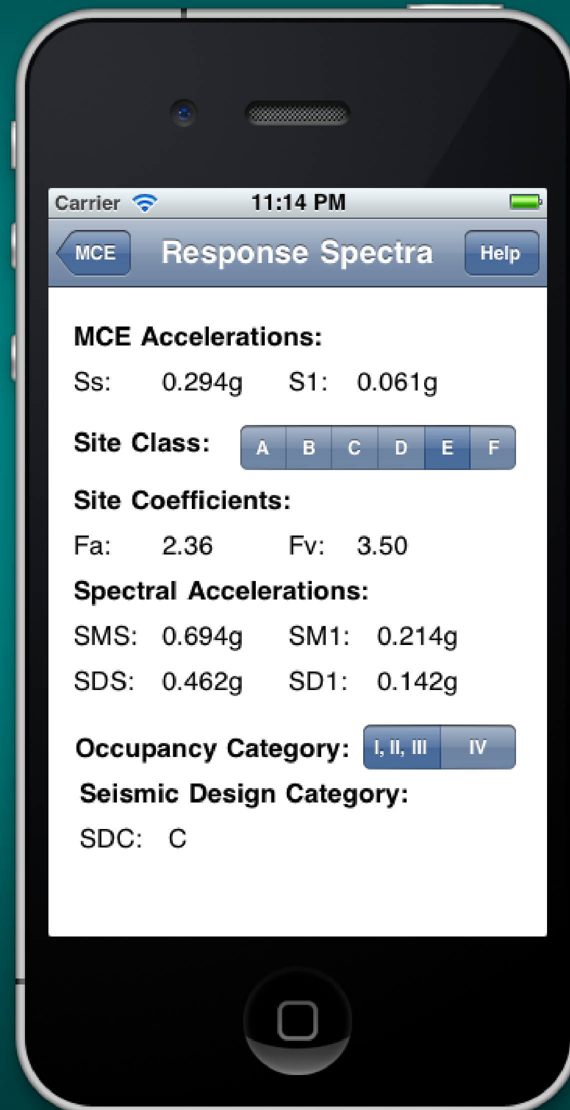
MCE Spectral Accelerations S_S & S_1



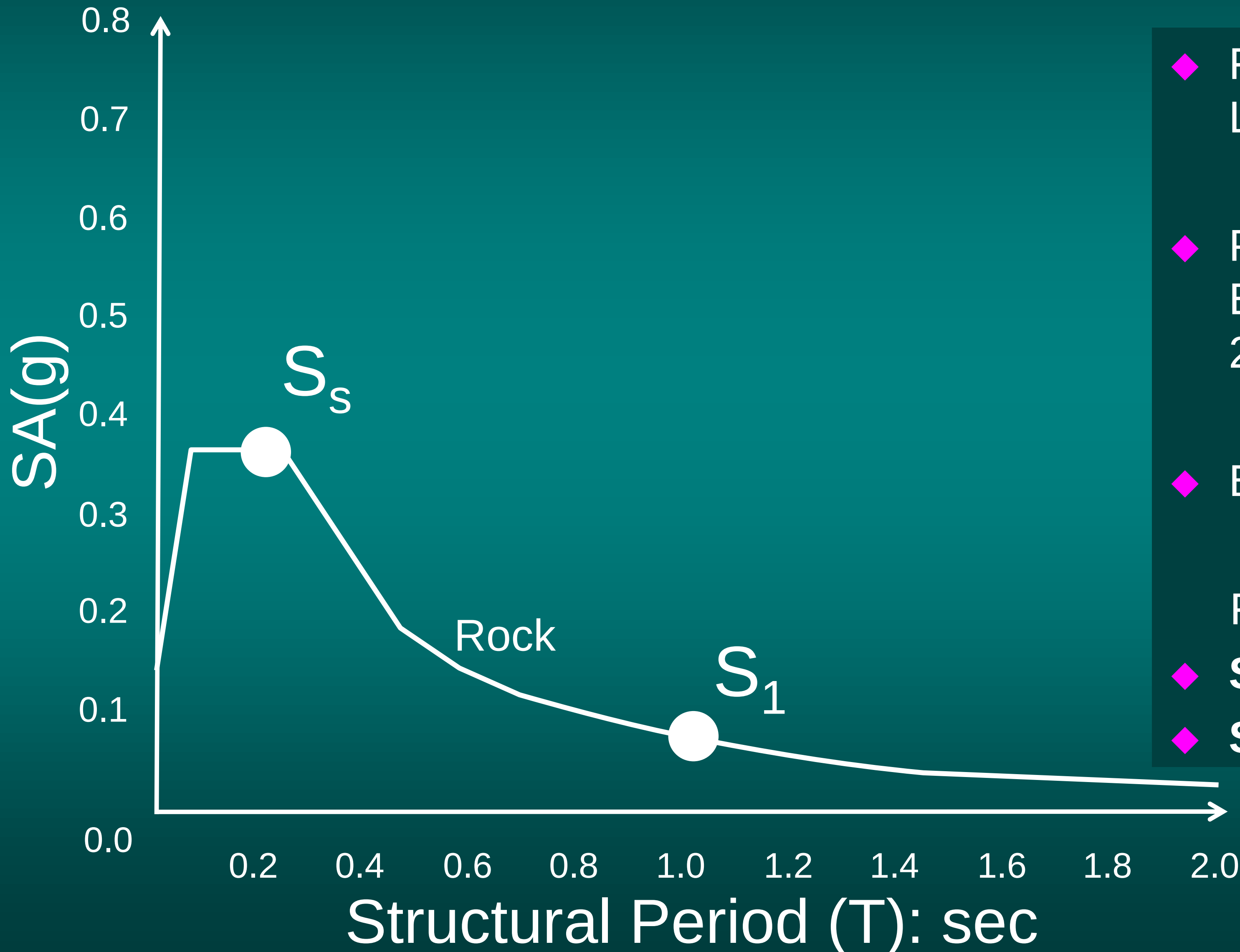
MCE Spectral Accelerations S_S & S_1

SeismicHaz





MCE Spectral Accelerations S_s & S_1



- Function of Location
- Probability of Exceedance 2% in 50y
- B/C Rock

For NYC (§1615.1)

- **S_s = 0.365g**
- **S_1 = 0.071g**

Site Classification

- Site Class "A" through "F"

TABLE 1615.1.1
SITE CLASS DEFINITIONS

SITE CLASS	SOIL PROFILE NAME	AVERAGE PROPERTIES IN TOP 100 feet, AS PER SECTION 1615.1.5		
		Soil shear wave velocity, $\bar{v}_s$, (ft/s)	Standard penetration resistance, $\bar{N}$	Soil undrained shear strength, $\bar{s}_u$, (psf)
A	Hard rock	$\bar{v}_s > 5{,}000$	N/A	N/A
B	Rock	$2{,}500 < \bar{v}_s \leq 5{,}000$	N/A	N/A
C	Very dense soil and soft rock	$1{,}200 < \bar{v}_s \leq 2{,}500$	$\bar{N} > 50$	$\bar{s}_u \geq 2{,}000$
D	Stiff soil profile	$600 \leq \bar{v}_s \leq 1{,}200$	$15 \leq \bar{N} \leq 50$	$1{,}000 \leq \bar{s}_u \leq 2{,}000$
E	Soft soil profile	$\bar{v}_s < 600$	$\bar{N} < 15$	$\bar{s}_u < 1{,}000$
E	—	Any profile with more than 10 feet of soil having the following characteristics: 1. Plasticity index $PI > 20$, 2. Moisture content $w \geq 40\%$, and 3. Undrained shear strength $\bar{s}_u < 500$ psf		
F	—	Any profile containing soils having one or more of the following characteristics: 1. Soils vulnerable to potential failure or collapse under seismic loading such as liquefiable soils, quick and highly sensitive clays, collapsible weakly cemented soils. 2. Peats and/or highly organic clays ($H > 10$ feet of peat and/or highly organic clay where H = thickness of soil) 3. Very high plasticity clays ($H > 25$ feet with plasticity index $PI > 75$) 4. Very thick soft/medium stiff clays ($H > 120$ feet)		

For SI: 1 foot = 304.8 mm, 1 square foot = 0.0929 m^2, 1 pound per square foot = 0.0479 kPa. N/A = Not applicable

Site Coefficients F_a & F_v

TABLE 1615.1.2(1)
VALUES OF SITE COEFFICIENT F_a AS A FUNCTION OF SITE CLASS AND MAPPED SPECTRAL RESPONSE ACCELERATION AT SHORT PERIODS (S_S)[a]

SITE CLASS	MAPPED SPECTRAL RESPONSE ACCELERATION AT SHORT PERIODS				
	$S_S \le 0.25$	$S_S = 0.50$	$S_S = 0.75$	$S_S = 1.00$	$S_S \ge 1.25$
A	0.8	0.8	0.8	0.8	0.8
B	1.0	1.0	1.0	1.0	1.0
C	1.2	1.2	1.1	1.0	1.0
D	1.6	1.4	1.2	1.1	1.0
E	2.5	1.7	1.2	0.9	0.9
F	Note b	Note b	Note b	Note b	Note b

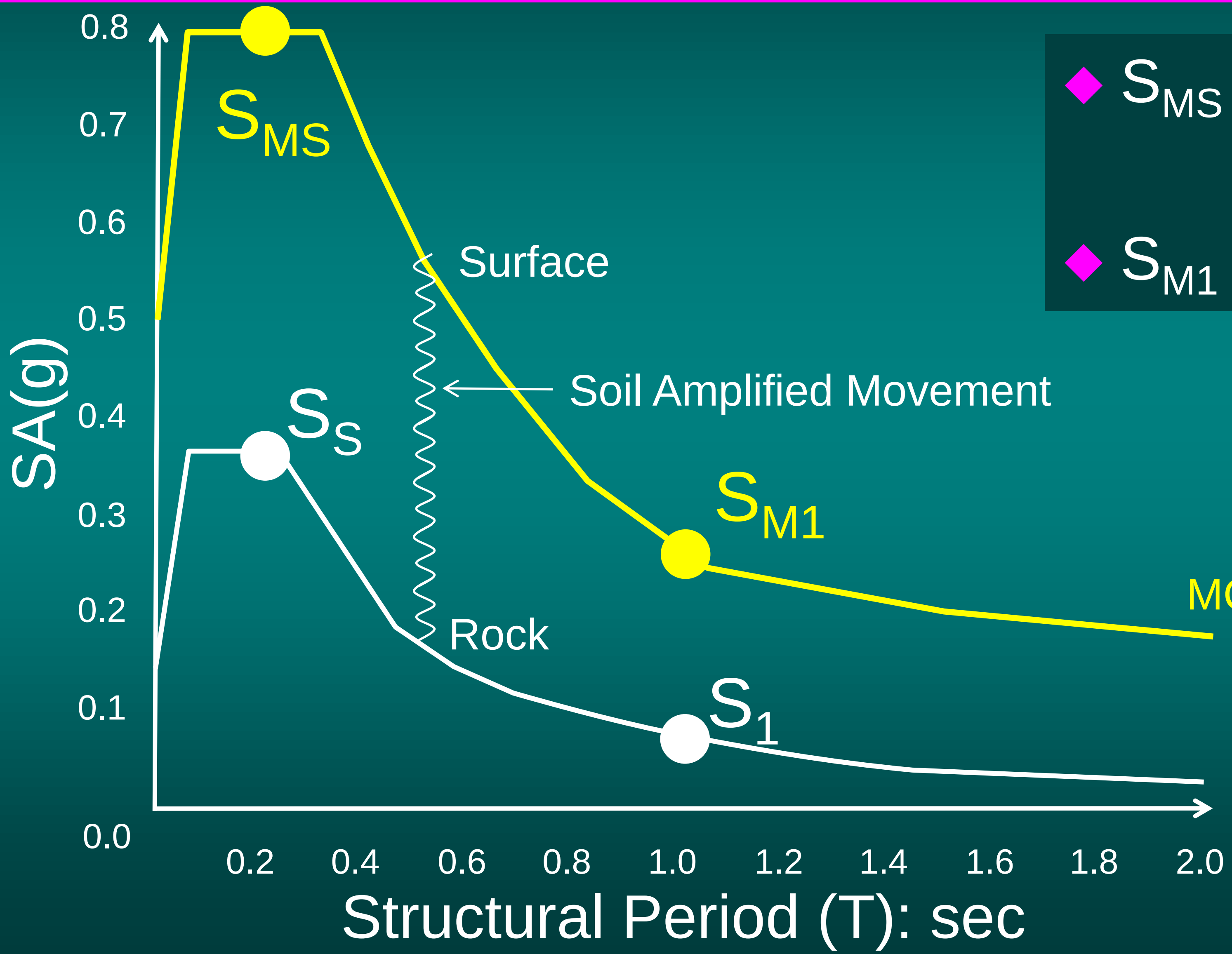
a. Use straight-line interpolation for intermediate values of mapped spectral response acceleration at short period, S_S.
b. Site-specific geotechnical investigation and dynamic site response analyses shall be performed to determine appropriate values, except that for structures with periods of vibration equal to or less than 0.5 second, values of F_a for liquefiable soils are permitted to be taken equal to the values for the site class determined without regard to liquefaction in Section 1615.1.5.1.

TABLE 1615.1.2(2)
VALUES OF SITE COEFFICIENT F_V AS A FUNCTION OF SITE CLASS AND MAPPED SPECTRAL RESPONSE ACCELERATION AT 1-SECOND PERIOD (S_1)[a]

SITE CLASS	MAPPED SPECTRAL RESPONSE ACCELERATION AT SHORT PERIODS				
	$S_1 \le 0.1$	$S_1 = 0.2$	$S_1 = 0.3$	$S_1 = 0.4$	$S_1 \ge 0.5$
A	0.8	0.8	0.8	0.8	0.8
B	1.0	1.0	1.0	1.0	1.0
C	1.7	1.6	1.5	1.4	1.3
D	2.4	2.0	1.8	1.6	1.5
E	3.5	3.2	2.8	2.4	2.4
F	Note b	Note b	Note b	Note b	Note b

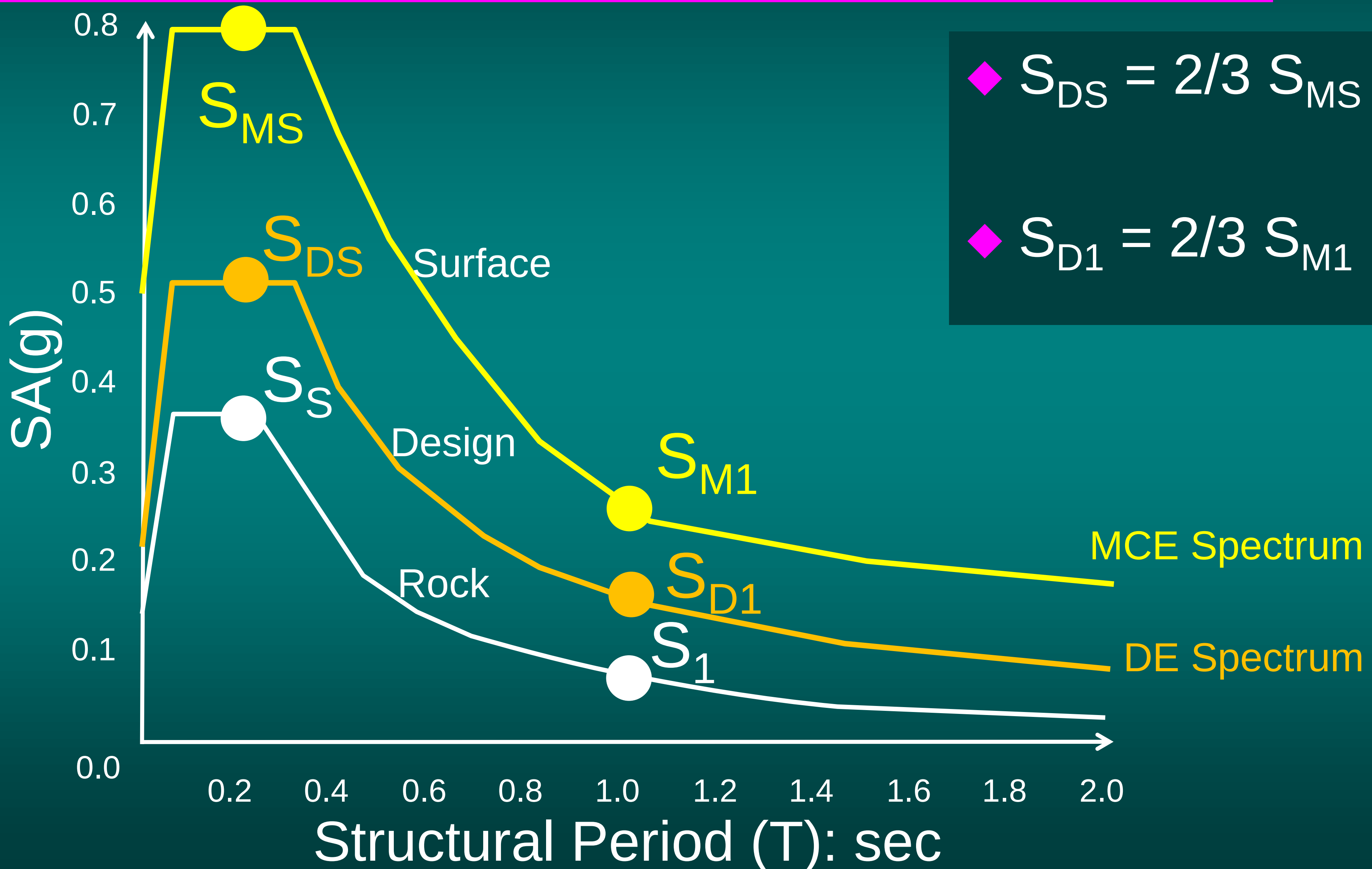
a. Use straight-line interpolation for intermediate values of mapped spectral response acceleration at 1-second period, S_1.
b. Site-specific geotechnical investigation and dynamic site response analyses shall be performed to determine appropriate values, except that for structures with periods of vibration equal to or less than 0.5 second, values of F_v for liquefiable soils are permitted to be taken equal to the values for the site class determined without regard to liquefaction in Section 1615.1.5.1.

Site Coefficients F_a & F_v



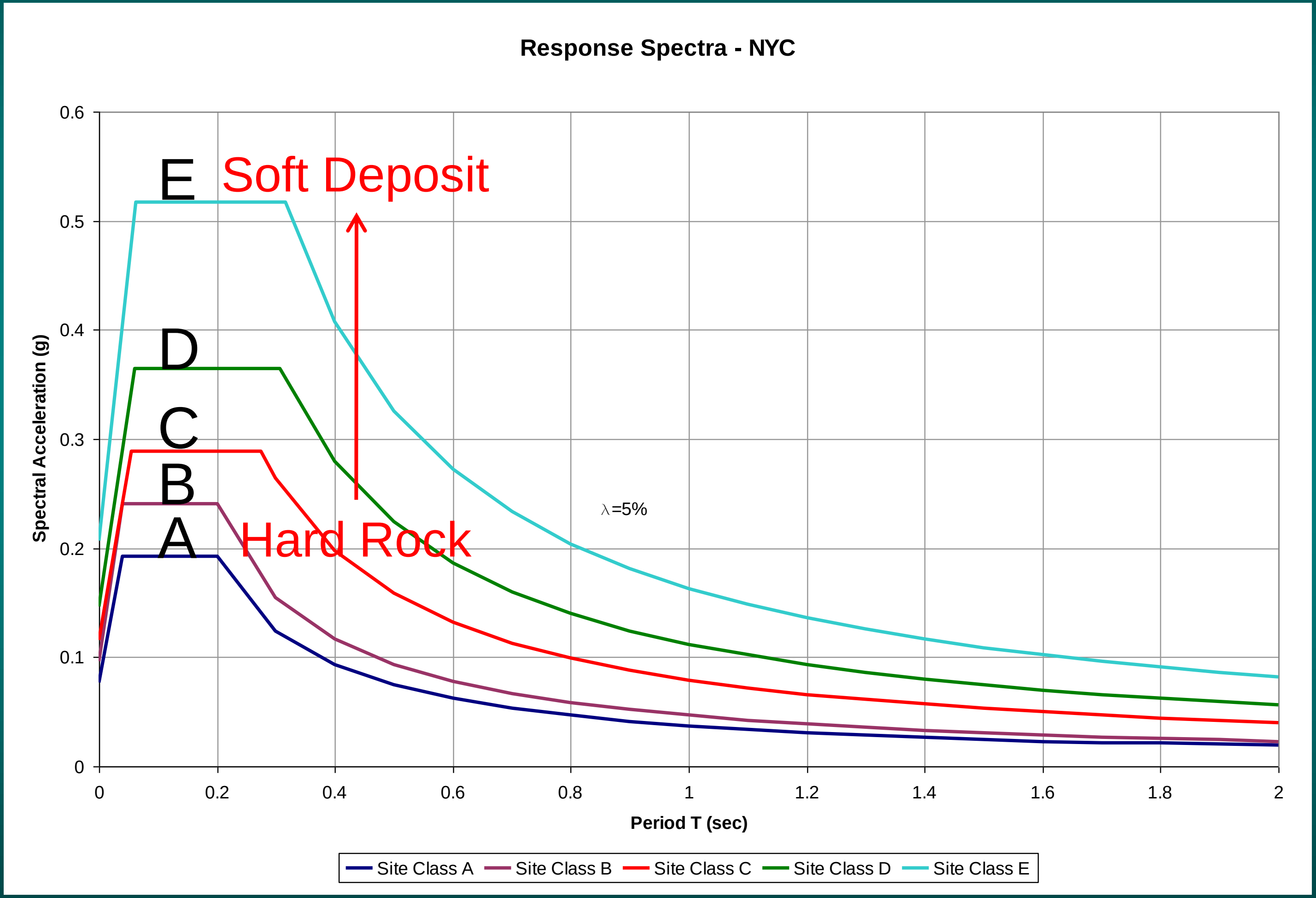
- $S_{MS} = F_a\, S_S$
- $S_{M1} = F_v\, S_1$

General Procedure Design Spectrum



- $S_{DS} = 2/3\ S_{MS}$
- $S_{D1} = 2/3\ S_{M1}$

General Procedure Design Spectrum



Implications of S_{DS} & S_{D1}

It Affects

- Design Base Shear
- Seismic Design Category
- Liquefaction

Base Shear: Analysis Procedures

Simple

- Simplified Procedure

(NYCBC/ASCE 7-02-§9.5.2.5.1, ASCE 7-05-§12.14)

- Equivalent Lateral Force (ELF)

(NYCBC/ASCE 7-02-§9.5.5, ASCE 7-05-§12.8)

- Modal Analysis

(NYCBC/ASCE 7-02-§9.5.5, ASCE 7-05-§12.9)

- Linear Response History Analysis

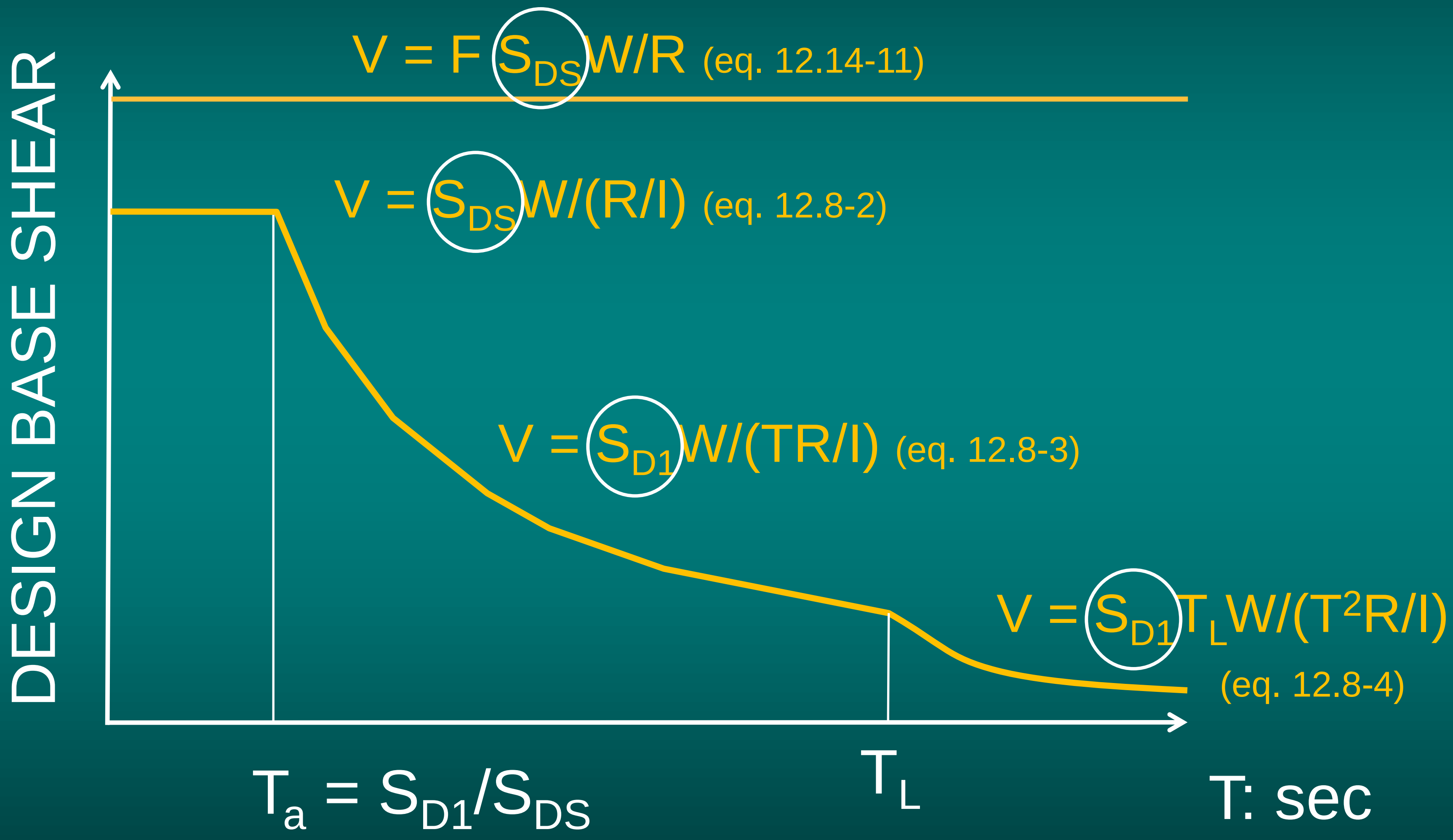
(NYCBC/ASCE 7-02-§9.5.7, ASCE 7-05-§16.1)

- Non-Linear Response History Analysis

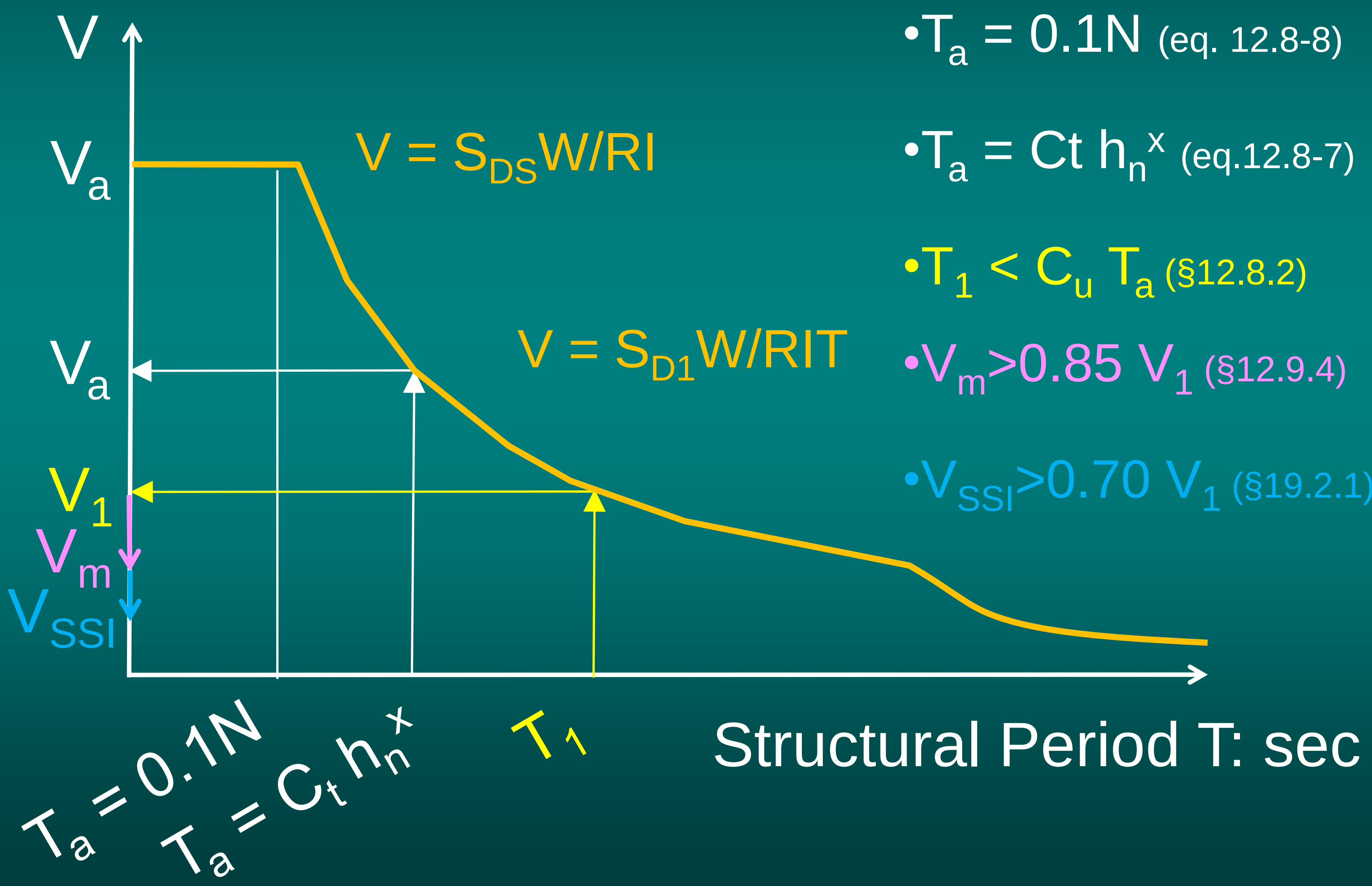
(NYCBC/ASCE 7-02-§9.5.8, ASCE 7-05-§16.2)

Complex

Design Base Shear (IBC 2006/ ASCE 7-05)



Design Base Shear V (ASCE 7-05)



- $T_a = 0.1N$ (eq. 12.8-8)
- $T_a = Ct\ h_n^x$ (eq.12.8-7)
- $T_1 < C_u\ T_a$ (§12.8.2)
- $V_m > 0.85\ V_1$ (§12.9.4)
- $V_{SSI} > 0.70\ V_1$ (§19.2.1)

Effect of S_{DS}&S_{D1} on Seismic Design Category

It affects

- Lateral Support System
- Structural Detailing
- MEP special bracing

TABLE 11.6-1 SEISMIC DESIGN CATEGORY BASED ON SHORT PERIOD RESPONSE ACCELERATION PARAMETER

Value of S_{DS}	Occupancy Category I or II	Occupancy Category III	Occupancy Category IV
$S_{DS} < 0.167$	A	A	A
$0.167 \leq S_{DS} < 0.33$	B	B	C
$0.33 \leq S_{DS} < 0.50$	C	C	D
$0.50 \leq S_{DS}$	D	D	D

TABLE 11.6-2 SEISMIC DESIGN CATEGORY BASED ON 1-S PERIOD RESPONSE ACCELERATION PARAMETER

Value of S_{D1}	OCCUPANCY CATEGORY I or II	OCCUPANCY CATEGORY III	OCCUPANCY CATEGORY IV
$S_{D1} < 0.067$	A	A	A
$0.067 \leq S_{D1} < 0.133$	B	B	C
$0.133 \leq S_{D1} < 0.20$	C	C	D
$0.20 \leq S_{D1}$	D	D	D

Effect of S_{DS} on Liquefaction Assessment

- S_{DS} correlated to ground accelerations
  $PGA = 0.4S_{DS}$ (NYCBC, NEHRP 2003, §C7)
  $PGA = 0.4S_{S}$ (ASCE 7-05, §11.8.3.2) (NYC $0.27\text{-}0.4S_{DS}$)
- NYCBC Screening Chart based on $0.4S_{DS}$
- Factor of safety against liquefaction inversely proportional to S_{DS}

Site-Specific Seismic Studies

Site-Specific Seismic Studies

- Seismic Hazard
- Ground Response
- Ground Motion
- Soil-Foundation-Structure-Interaction

S_{DS} and Site-Specific Seismic Study

Typically S.S. study lowers the S_{DS}, S_{D1}

(NYC, site class D, E, F)

- Lower Design Base Shear
- Lower Seismic Design Category
- Higher F.o.S. against liquefaction

Minimum Site-Specific S_{DS}

1. The Seismic Site-Specific Analysis is allowed for Site Class A, B, C, D, E and is required for Site Class F

   (NYCBC-§1615.1, ASCE 7-05-§11.4.7, NEHRP 2003-§3.2.2)

2. For Site Class A, B, C, D, E
   Minimum Site-Specific S_a = 80% of general procedure S_a
   (NYCBC-§1615.2.4, ASCE 7-05-§21.3)

3. For Site Class F
   Minimum Site-Specific S_a = 80% of Site Class E gen proc S_a (ASCE 7-05-§21.3)

Minimum Site Specific S_{DS}

For Site Class "E" or "F"

(NYCBC-§1615.2.4, ASCE 7-05-§21.3)

- Min $S_{DS,SS} = 0.8\ S_{DS,E}$
- Min $S_{DS,S1} = 0.8\ S_{D1,E}$

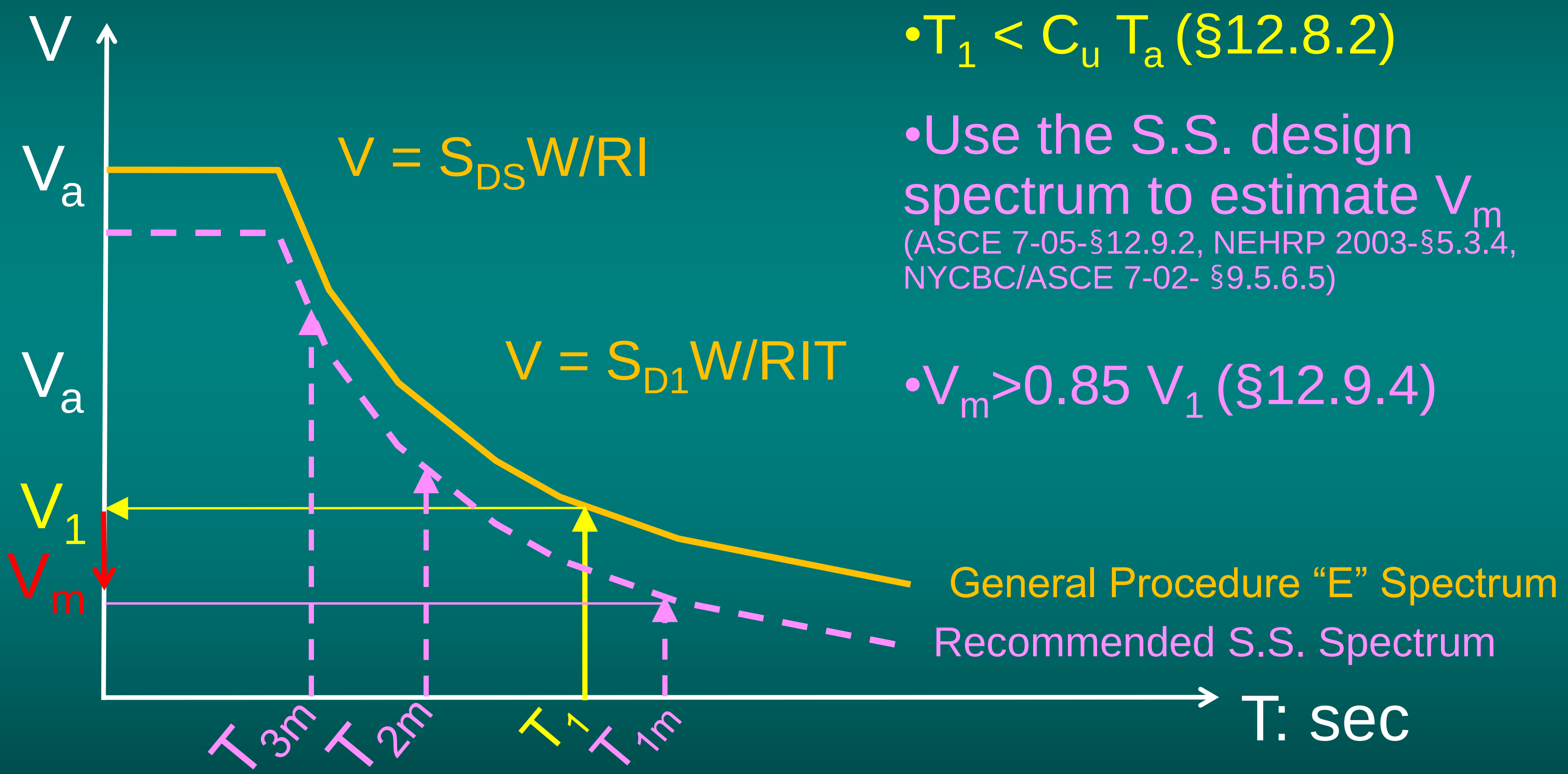
Design Base Shear and S.S. Spectrum

1. For modal analysis the site-specific design spectrum can be used in lieu of the general procedure design spectrum (ASCE 7-05-§12.9.2, NEHRP 2003-§5.3.4, NYCBC/ASCE 7-02- §9.5.6.5)

2. The site-specific spectrum and the modal analysis are, both, more accurate than the general procedure spectrum and ELF, however

3. ASCE 7-05 and NEHRP 2003 imply that the site-specific spectrum should not be used with the ELF procedure. (Therefore the maximum reduction factor in the design base shear should only be 0.85 instead of 0.80 * 0.85 = 0.68)

Design Base Shear and S.S. Spectrum



- $T_1 < C_u\ T_a$ (§12.8.2)
- Use the S.S. design spectrum to estimate V_m
  (ASCE 7-05-§12.9.2, NEHRP 2003-§5.3.4, NYCBC/ASCE 7-02- §9.5.6.5)
- $V_m > 0.85\ V_1$ (§12.9.4)

Potential Cost Savings with S.S. Study

- Lower Seismic Design Category (as much as <u>20% reduction</u> in S_{DS}, S_{D1} which can result adjusting from SDC "D" to "C")

- Lower Seismic Design Base Shear
(as much as <u>15% total reduction with modal analysis</u>)

- Further lower Seismic Base Shear
(as much as <u>30% total reduction with SSI analysis</u>)

- Increase Factor of Safety against liquefaction
(can demonstrate no liquefaction risk which implies no remediation costs or increased foundation lateral resistance)

So, what if the S_{DS} seems high at first?

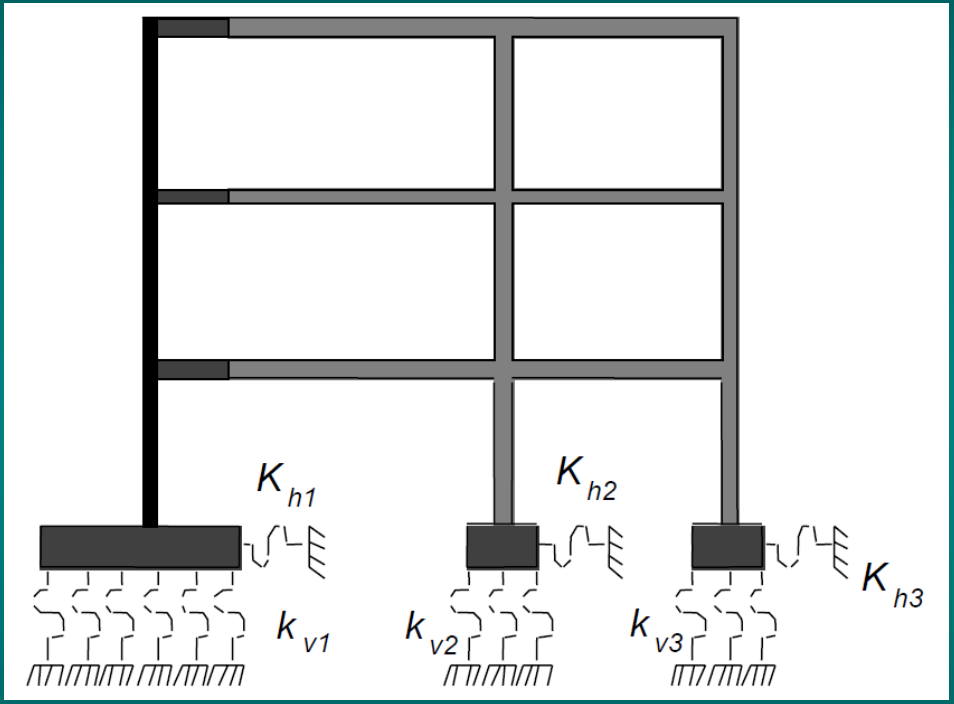
- Perform a more detailed soil investigation
  (invest to find V_s instead of using N, S_u to estimate the Site Class, focus on soft layer properties >10 ft thick)
- Perform a soil amplification analysis
  (invest to find site-specific soil amplification factors F_a, F_v)
- Perform a seismic hazard analysis
  (invest to estimate S_s and S_1, or the surface response spectrum)
- Soil-Structure Interaction and Ground Motion analysis
  (invest to estimate foundation compliance and FIM)

SSI: When is more applicable

- Rigid Building (T<1 sec),

  and

- Soft soil (Site Class D, E)
- h/(V_s T) > 0.1 (Stewart et al 1999)
- FEMA 356, FEMA 440, ASCE/SEI 41-06

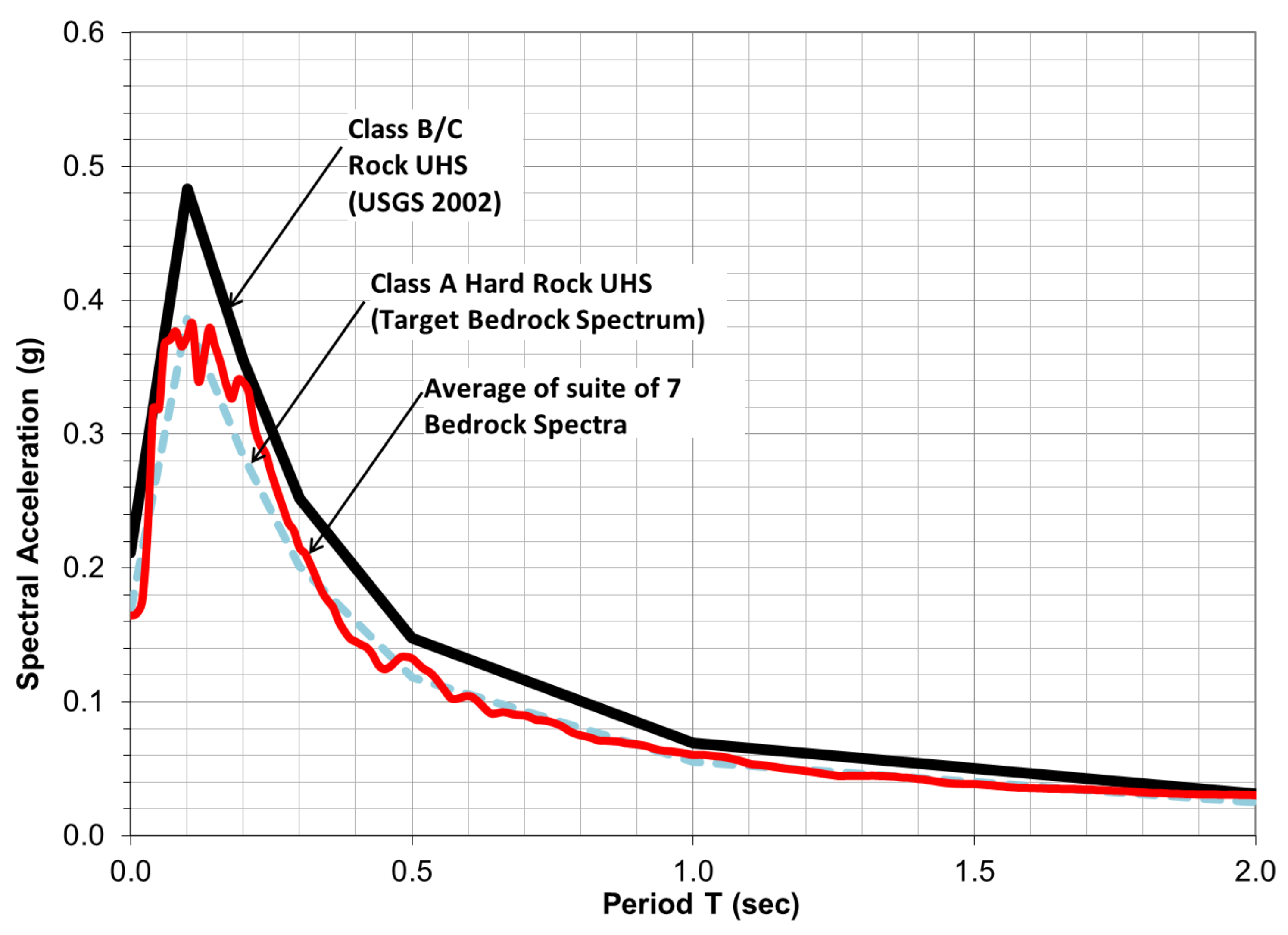


(Mike Mahoney, FEMA)

Typical “Quick” NYC S.S. Study

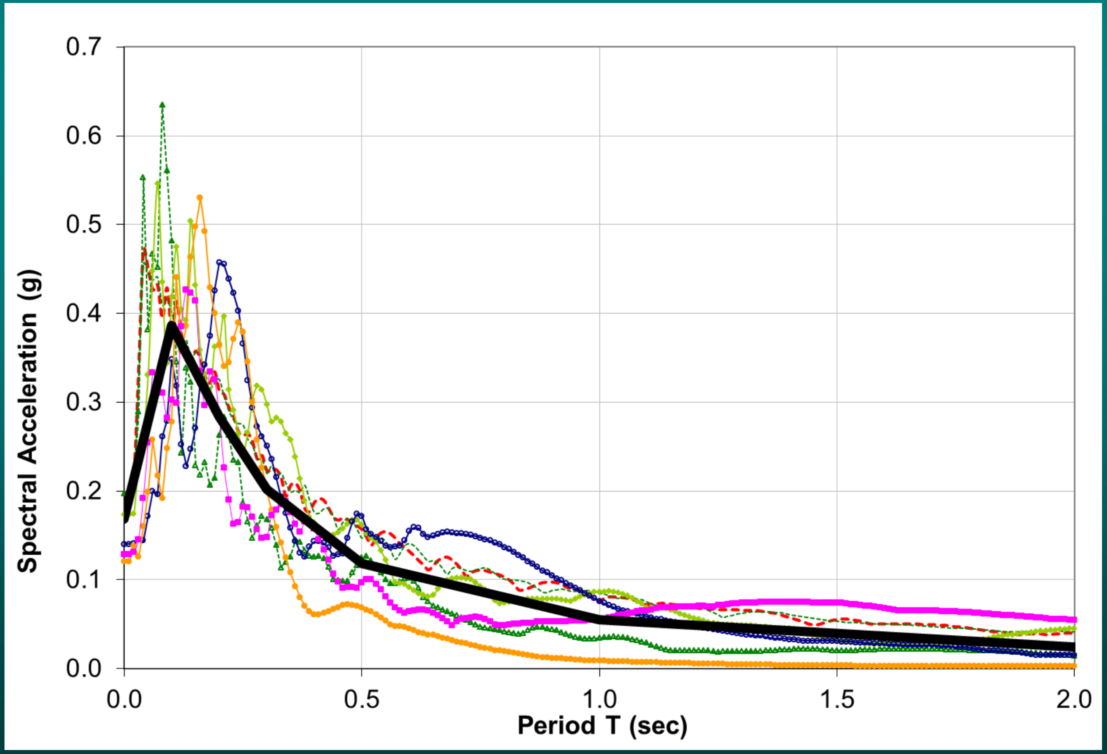
- Seismic Hazard Assessment
  - Available information from the USGS to estimate $S_s$and S_1
- Soil Properties Assessment
  - Perform in-situ and ex-situ tests (V_s, PI, S_u, etc)
- Soil Amplification Analysis
  - Desk Study to estimate F_a, F_v
- Site-Specific Design Response Spectrum
  - Evaluate S_{DS}, S_{D1}, SDC, PGA

Determination of Rock Spectrum



Selection of input time-histories

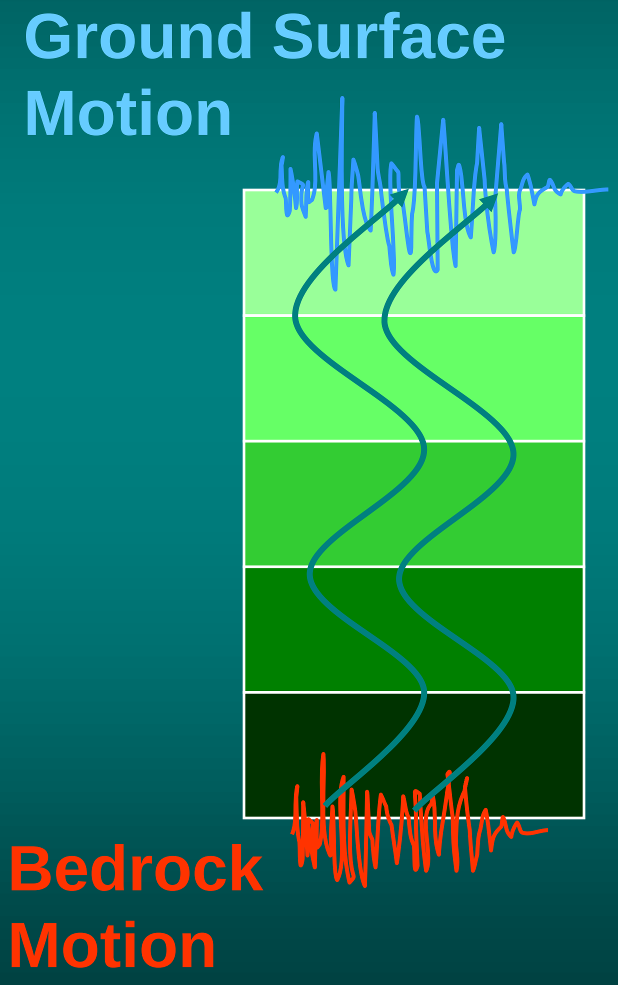
- Select a series of acceleration time-histories that approximate on average the target spectrum
- The acceleration time histories can be
  - Matched
  - Scaled
  - Synthetic



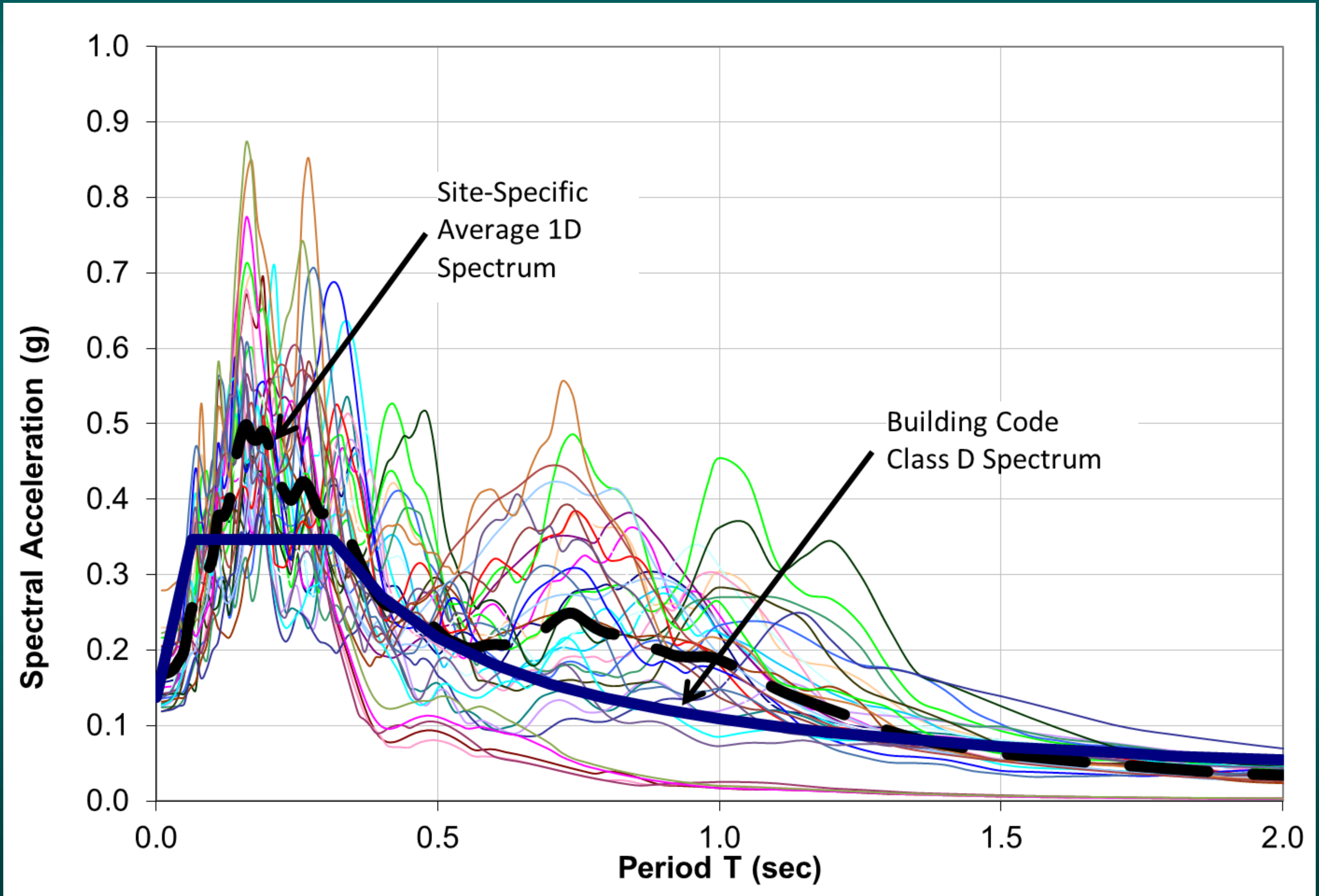
Soil Amplification Analyses

Typical NYC Site

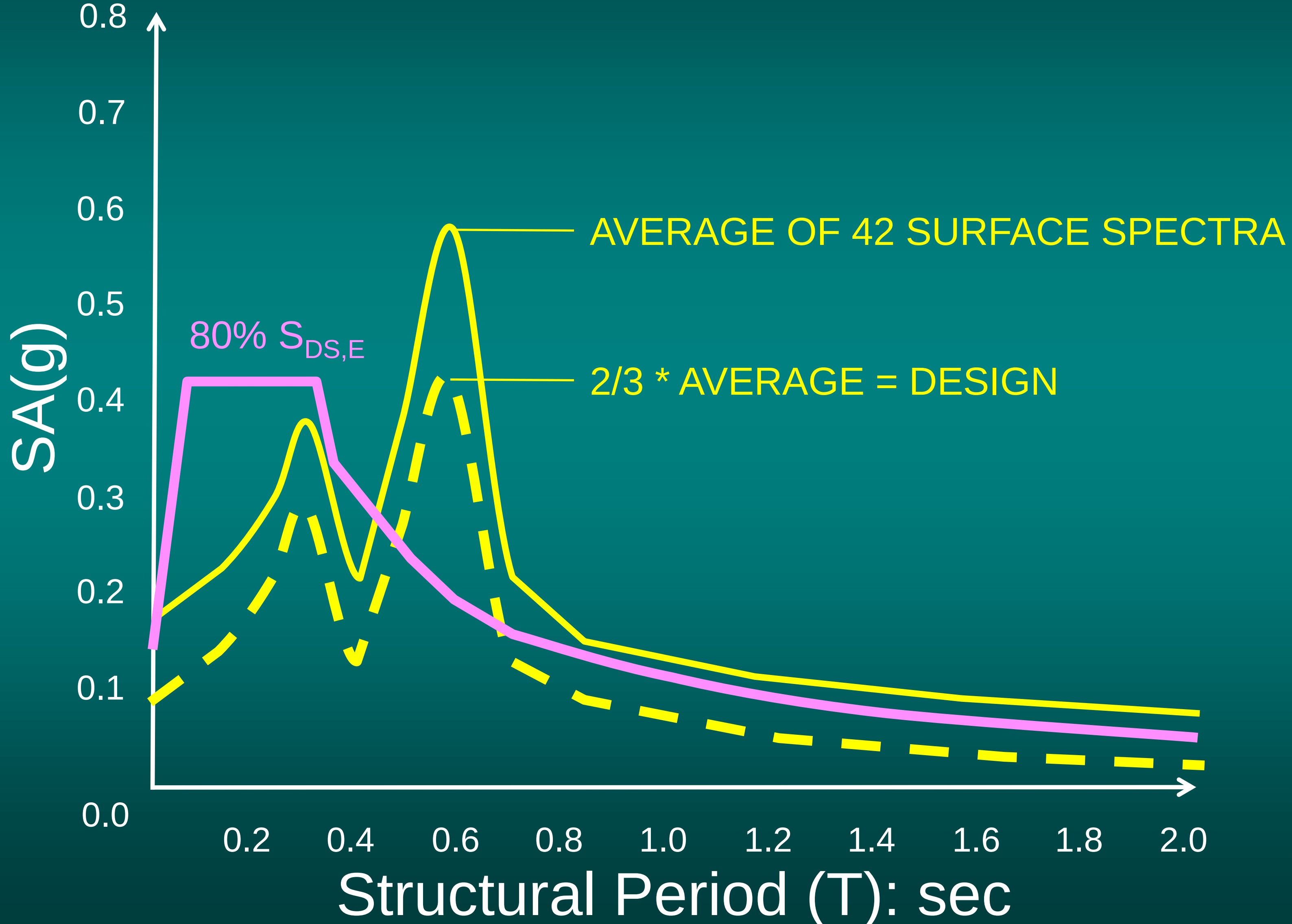
- 3-6 Soil Columns
- 7 Bedrock Motions
- 21-42 Surface Spectra



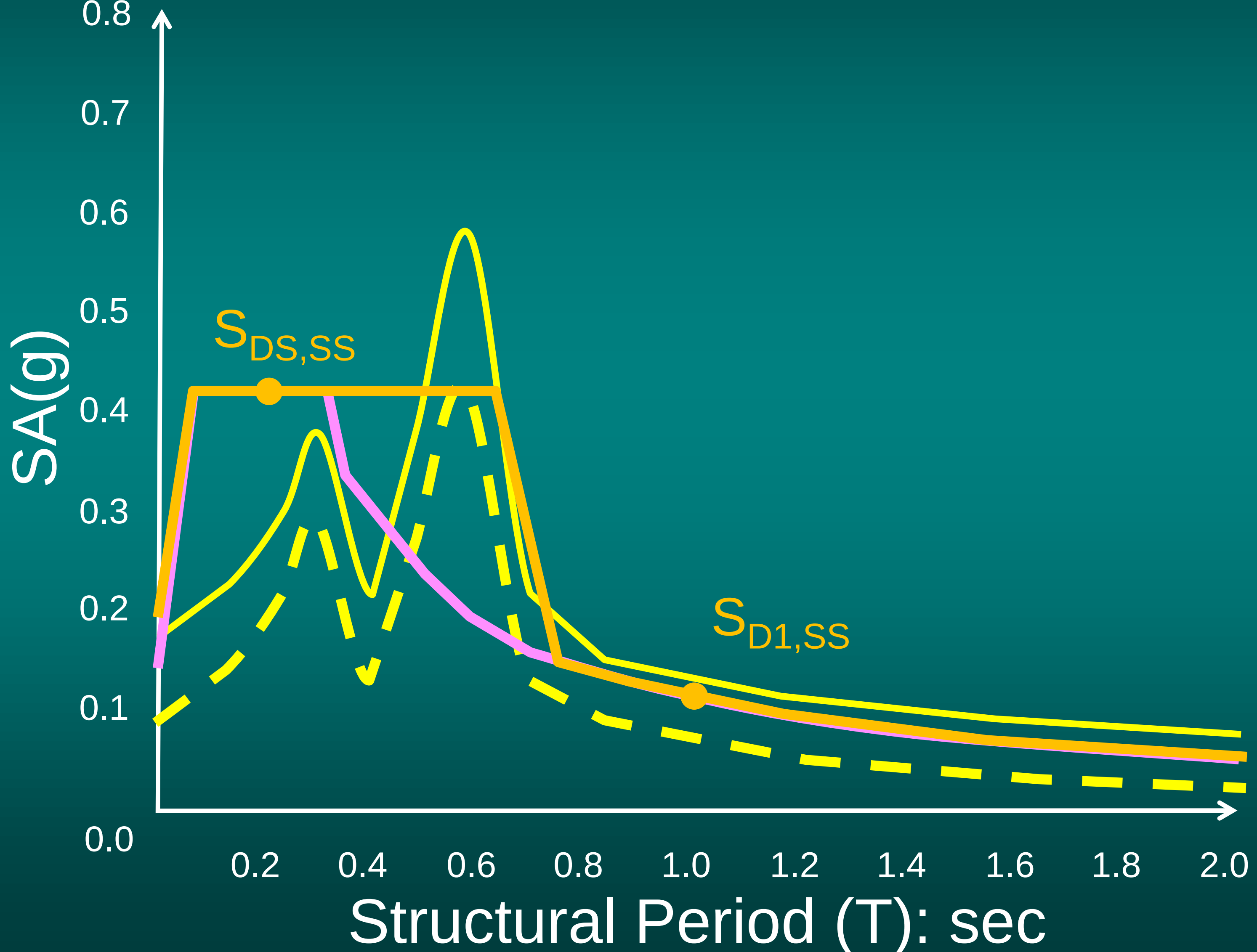
Determination of Surface Spectrum



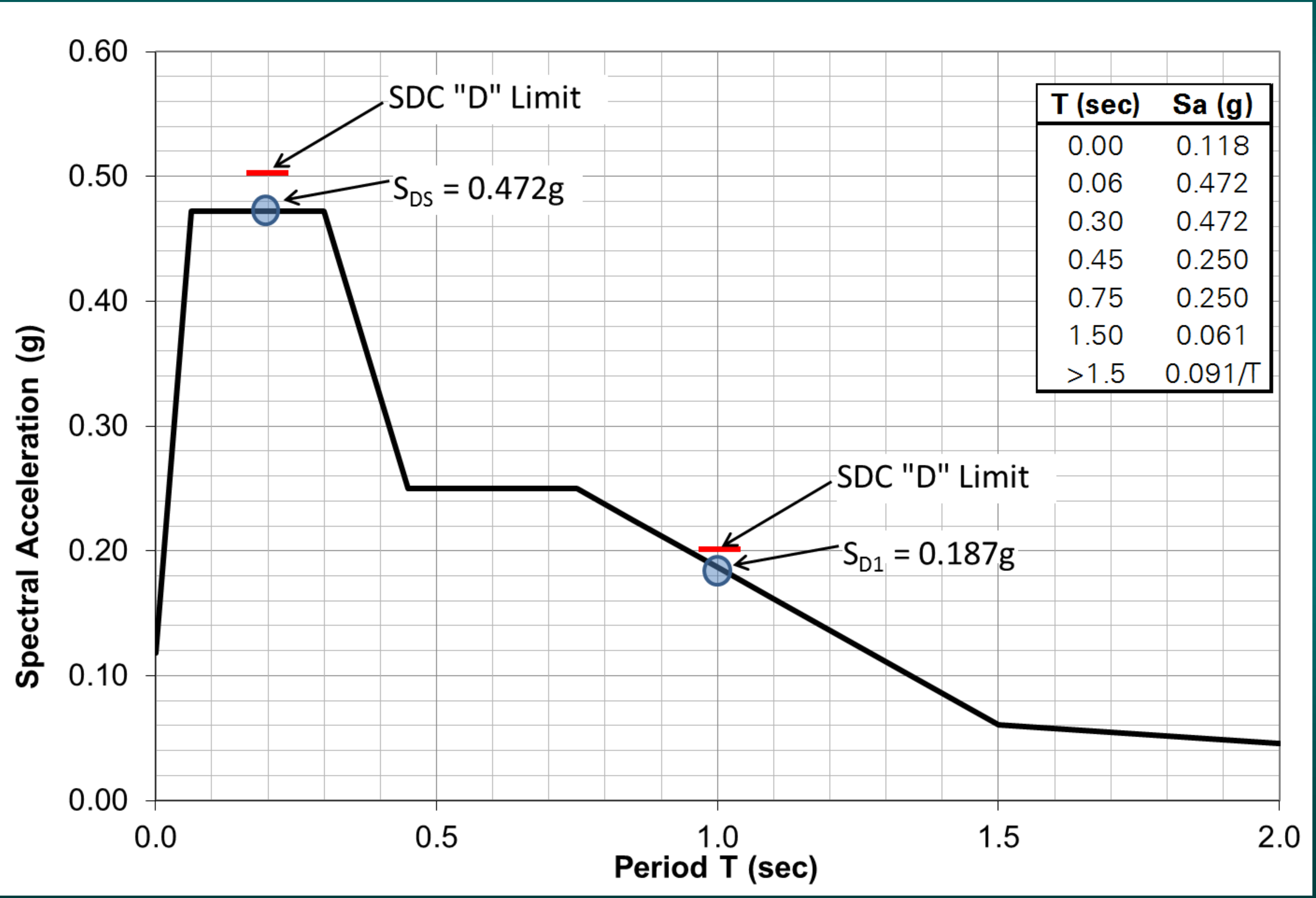
Determination of S.S. Design Spectrum



Determination of S.S. Design Spectrum



Final Site-Specific Design Spectrum



T (sec)	Sa (g)
0.00	0.118
0.06	0.472
0.30	0.472
0.45	0.250
0.75	0.250
1.50	0.061
>1.5	0.091/T

Earthquake Hazards - Liquefaction

Kobe Japan (1995)

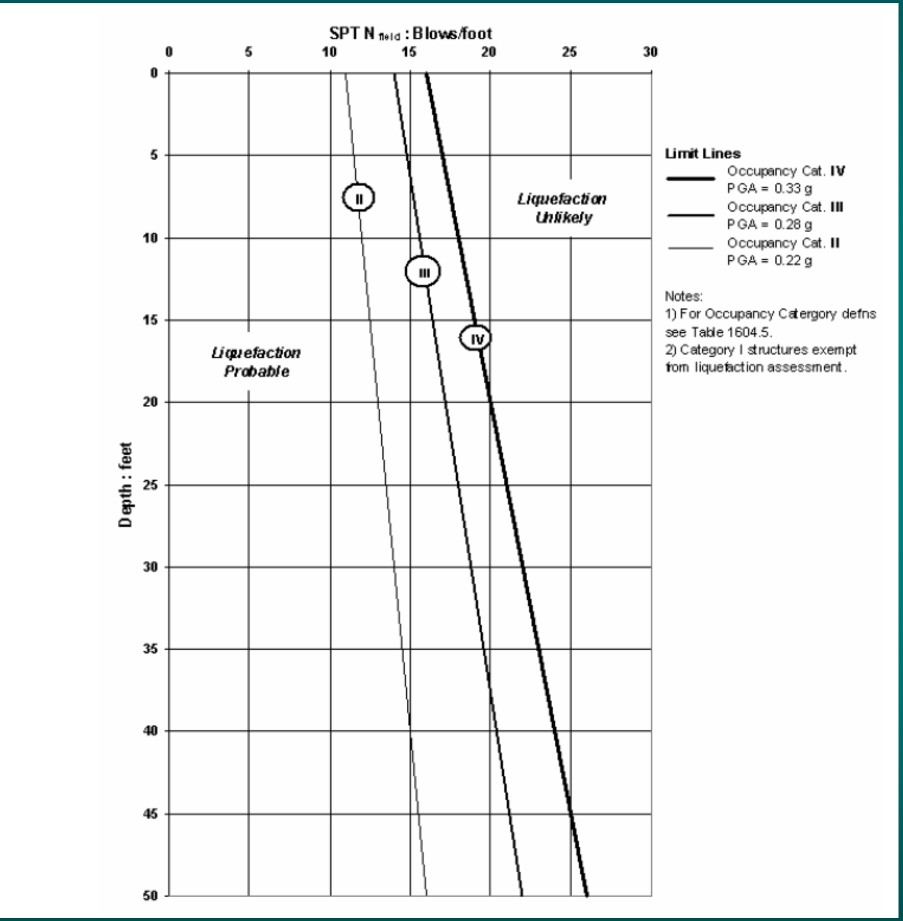
Liquefaction implications in design

- Loss of lateral support (NYCBC § 1813.4)
- Soil Remediation or Foundation Strengthening (NYCBC §1813.3)
- Structural strengthening

Liquefaction and Building Codes

- Screening Chart to Determine triggering
  (NYC Figure 1813.1)
- Empirical Methods using SPT or CPT
- Site Specific Study
  - Empirical Methods + Soil Amplification Study
  - Advanced Numerical Modeling

Liquefaction Screening Chart (NYC Figure 1813.1)

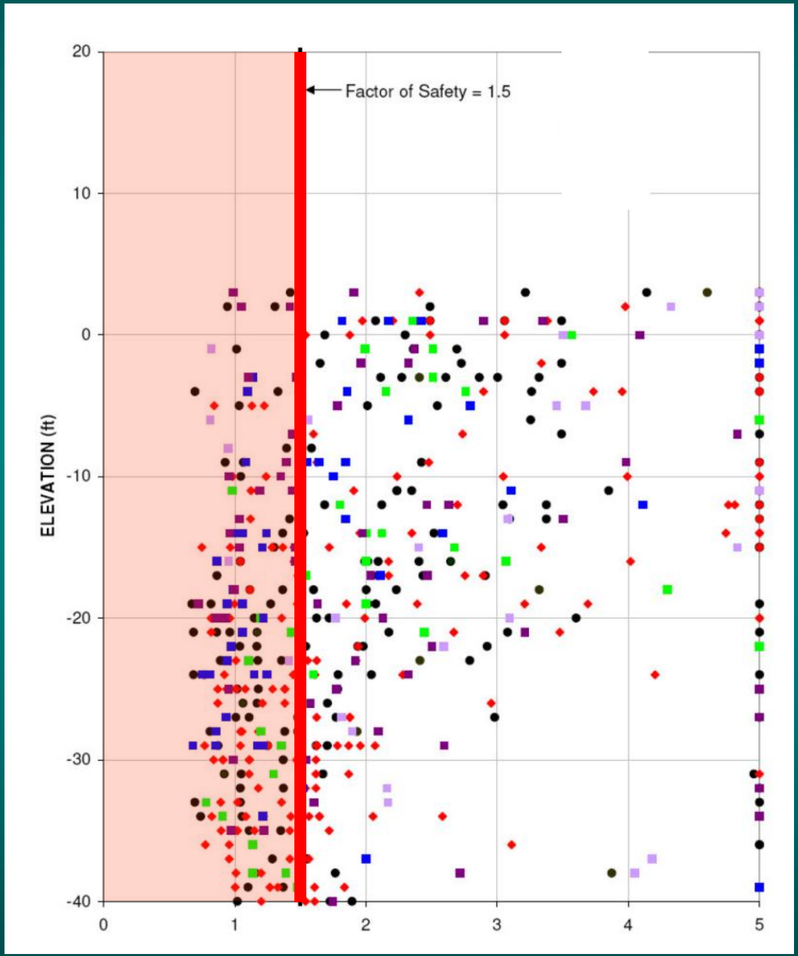


Assessment performed for non-cohesive soils below the ground water table and less than 50 feet below the ground surface

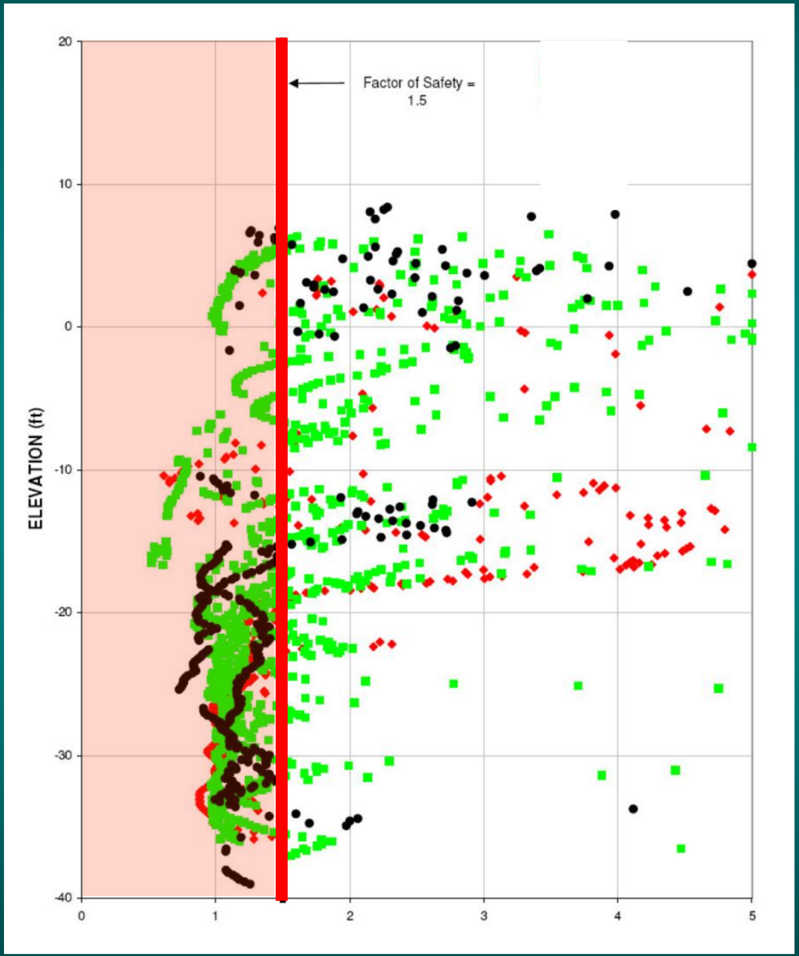
Liquefaction - Empirical Methods

- Youd et al. (2001 - Current State-of-Practice: Recommended by NEHRP 2003)
- Cetin et al. (2004), Moss et al. (2006)
- Idriss and Boulanger (EERI 2008)

Factor of Safety Against Liquefaction



SPT



CPT

Factor of Safety	Remarks
FS <0.9	Requires Remediation
0.9 < FS < 1.25	Questionable - use advanced analyses
1.25 < FS < 1.4	Likely acceptable - check consequences
FS > 1.4	Acceptable

Liquefaction – Factor of Safety

(RESISTANCE)

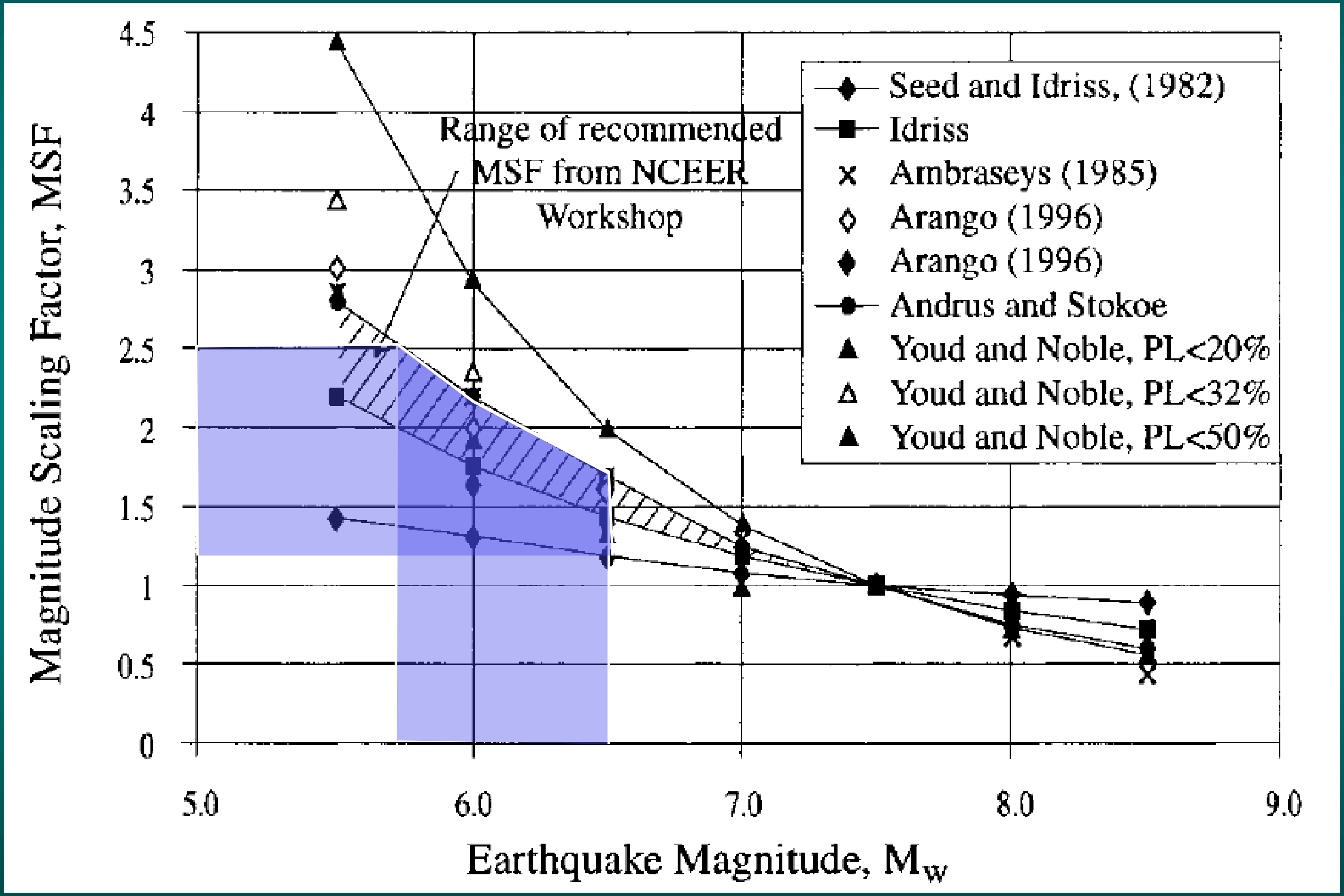
$$FS = \frac{CRR_{7.5}}{CSR} * MSF$$

(DEMAND)

Liquefaction – MSF from Empirical Methods

NYC

- **M_w: 5.7 – 6.5**
- **MSF: 1.2 – 2.5**
- **F.o.S.: 1.0 – 2.0**



Youd et al. (2001)

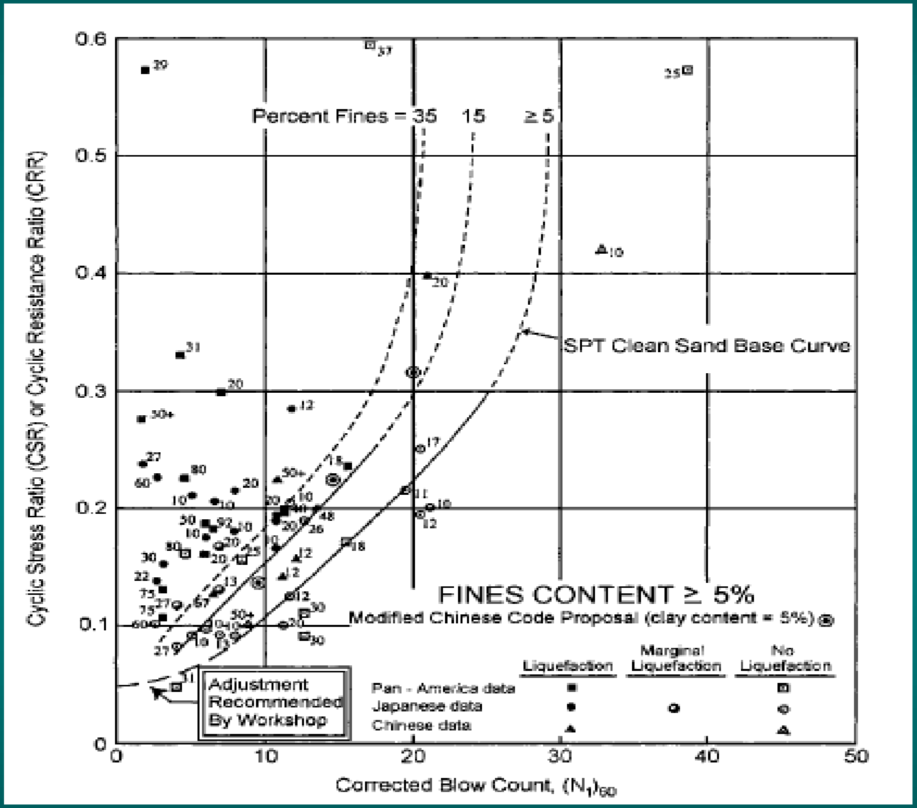
Liquefaction – Resistance (CRR)

Two approaches

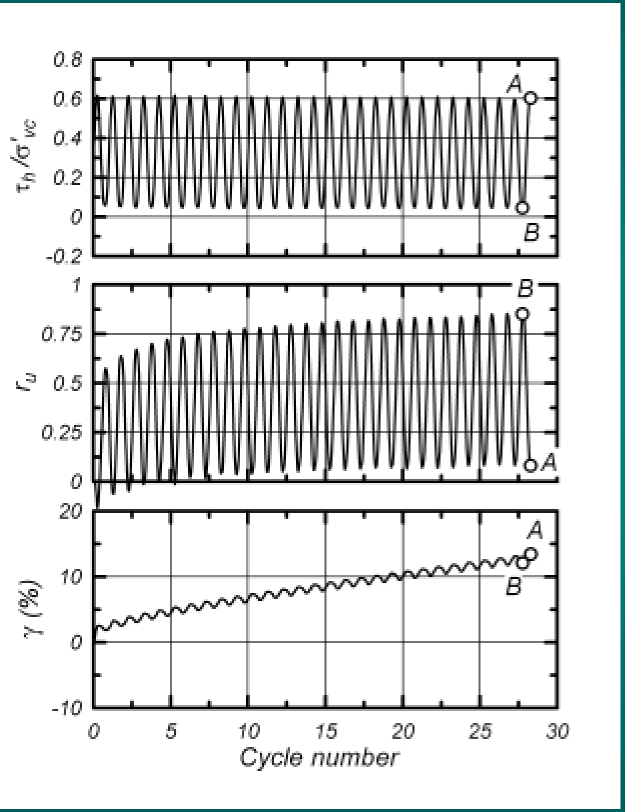
- Empirical relationships with SPT, CPT (CRR vs. N or CRR vs. q)

- Laboratory testing on "undisturbed" samples (rare, site specific approach)

CRR Evaluation



Youd et al. (2001)



Boulanger et al. (1991)

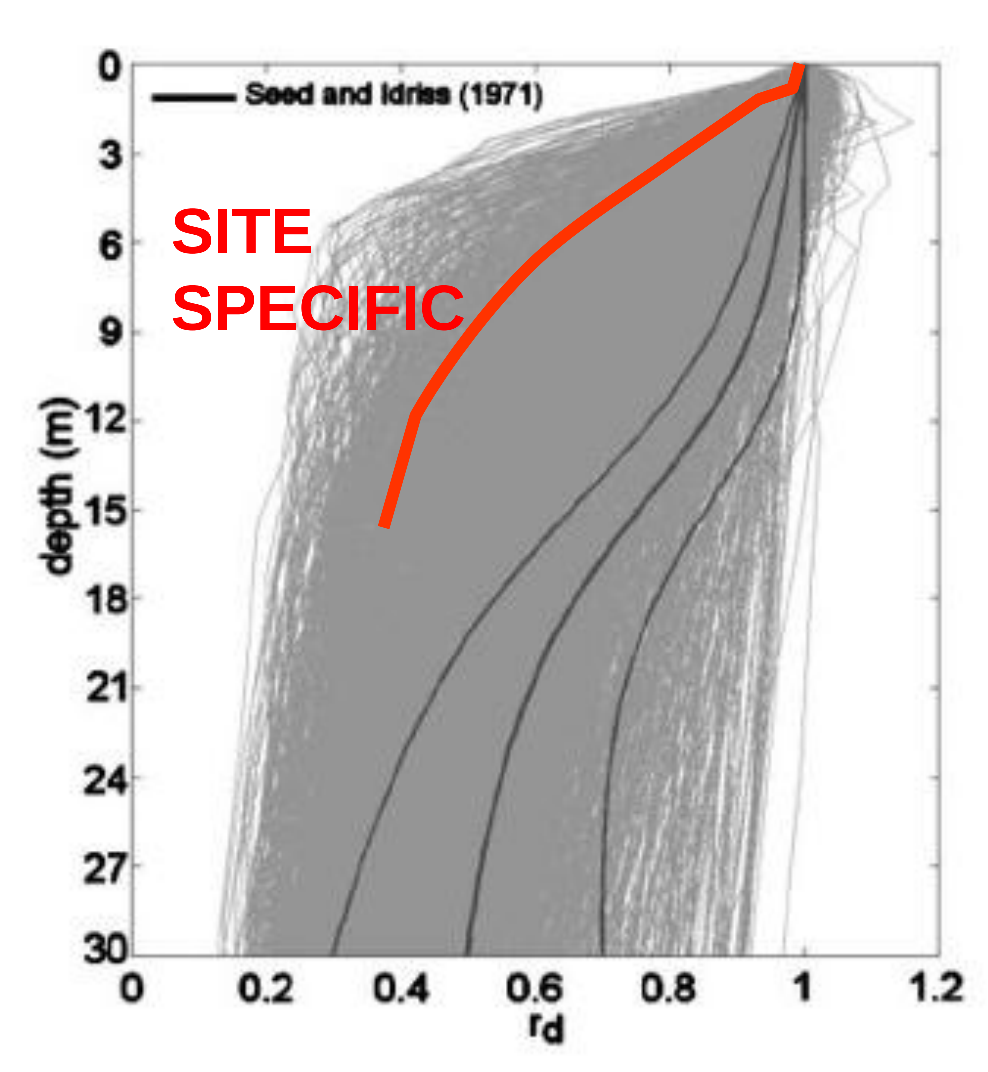
Liquefaction – Demand (CSR)

$$CSR = 0.65 * a_{\max} * \frac{\sigma_{vo}}{\sigma'_{vo}} * r_d$$

- $a_{max} = S_{DS}/2.5$ (NYCBC 2008 §1802.2.3)
- r_d = stress reduction coefficient

Liquefaction – Demand (CSR), r_d

- r_d ranges widely
- r_d can be estimated with Site-Specific Analysis but should be checked if applicable with simplified method.



Liquefaction – Factor of Safety

$$FS = \frac{CRR_{7.5}}{CSR} * MSF$$

(RESISTANCE)

(DEMAND)

- MSF: up to 200%
- CRR: Method dependant
- CSR: Varies widely (PGA, r_d)

So, what if the site Liquefies per NYCBC?

Simple → Complex

- Perform an analysis using an Empirical Method (typically Youd et al 2001) with SPT
- Use an empirical method with CPT and V_s data
- Estimate Settlements
- Use an empirical method with a soil-amplification S.S. study results
- Perform a soil-amplification S.S. study incorporating pore water pressure buildup to model liquefaction.

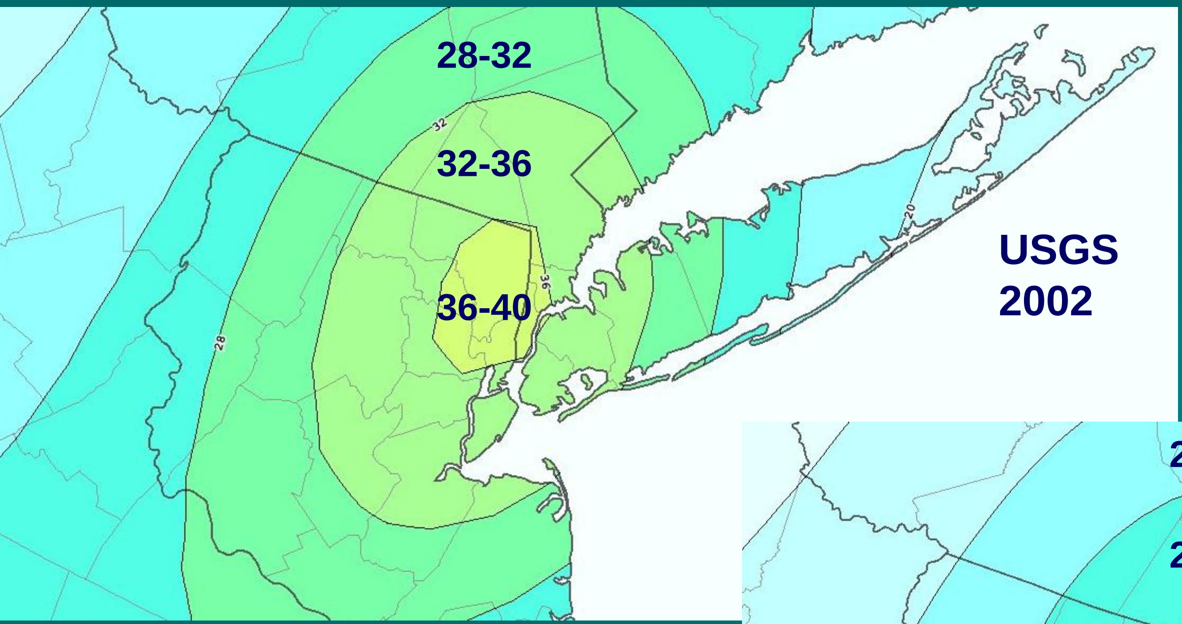
FUTURE TRENDS IN SEISMIC DESIGN

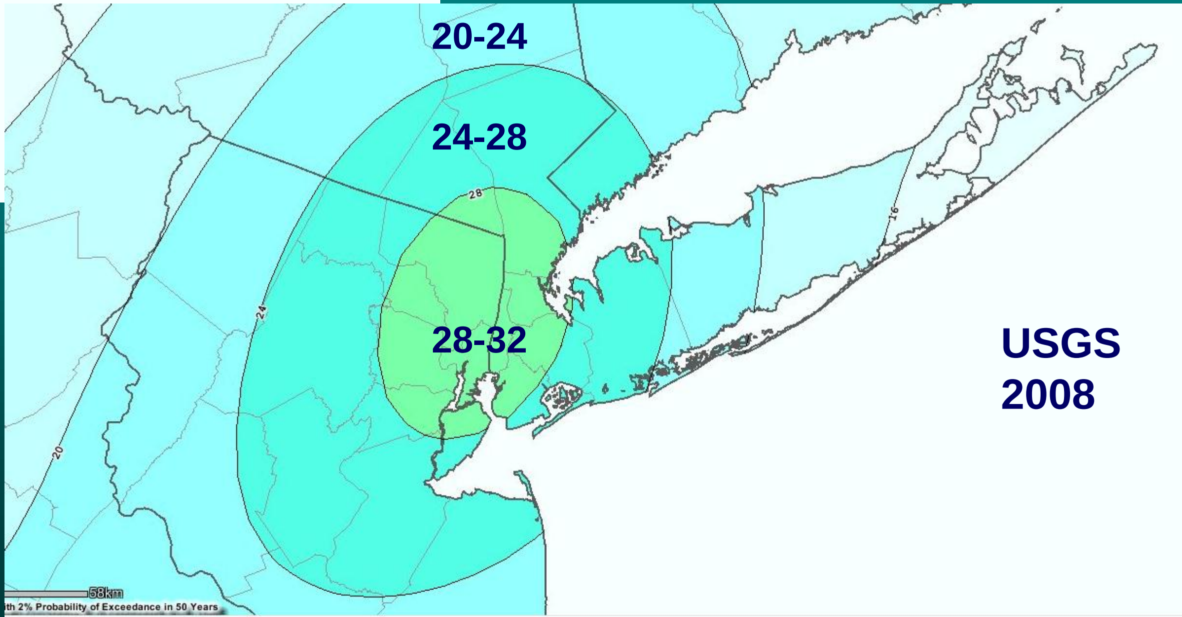
ASCE 7-10

- Changes in the USGS 2008 Maps (direction of maximum horizontal response, risk coefficients)
- Changes in the seismic response history procedures
- Liquefaction triggering with maximum considered earthquake PGA (resulting to a 150% increase in demand)

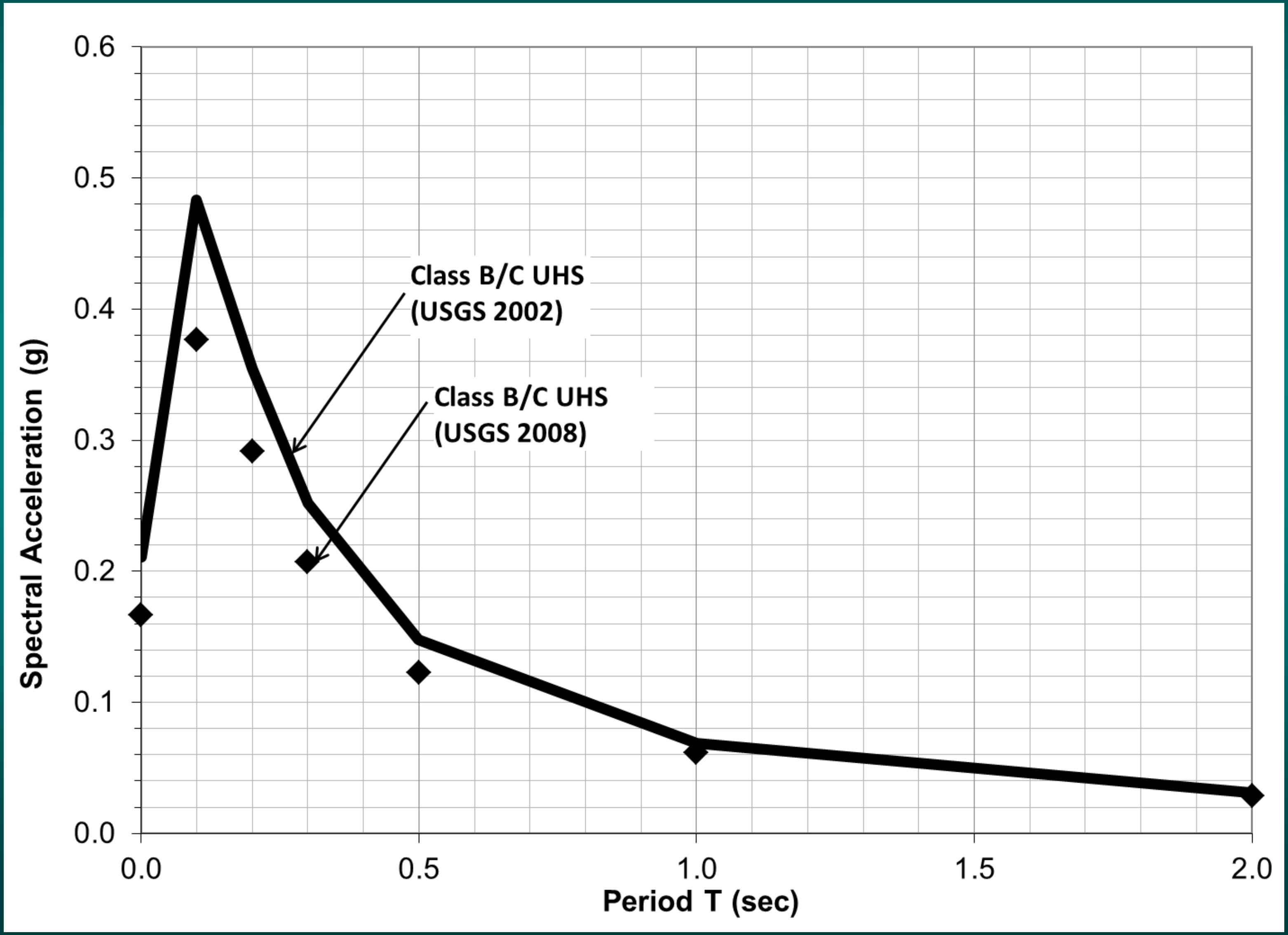
MCE Spectral Acceleration S_S (%g)

USGS 2002 and 2008 Maximum Considered Earthquake – Class B

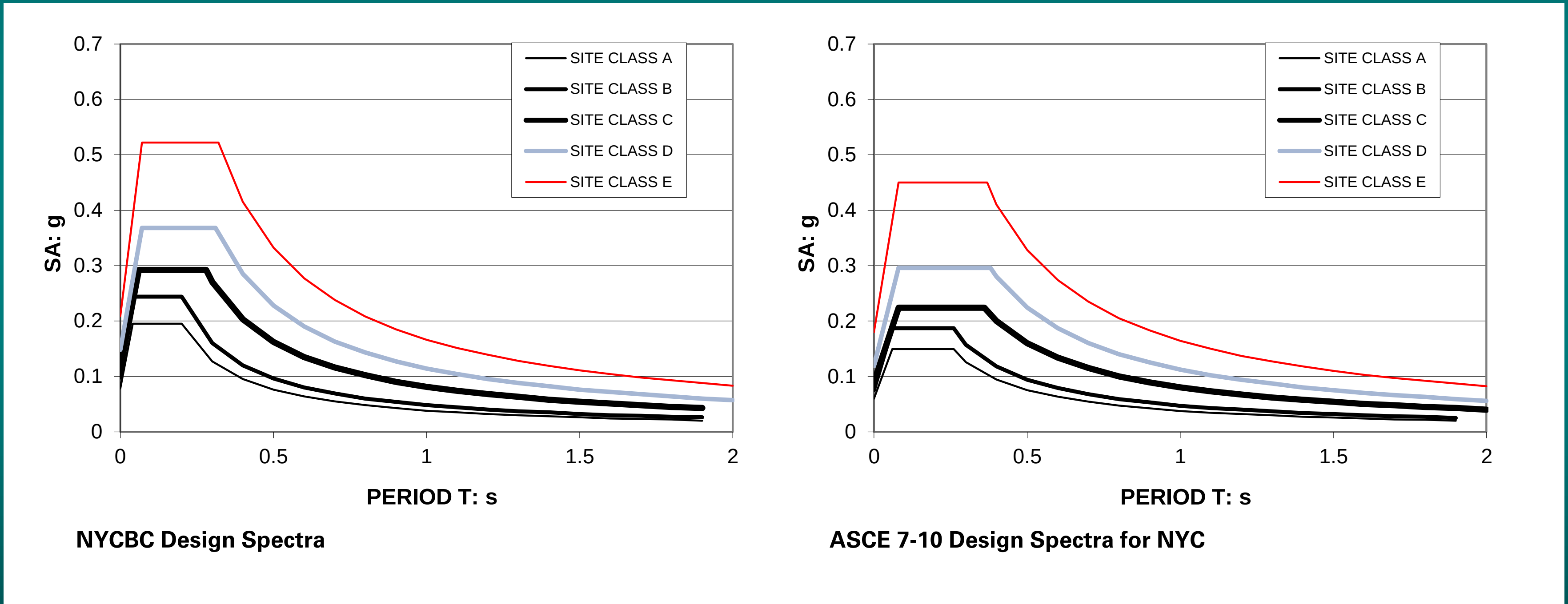




NYCBC vs. ASCE 7-10 Bedrock Spectra



NYCBC vs. ASCE 7-10 Design Spectra

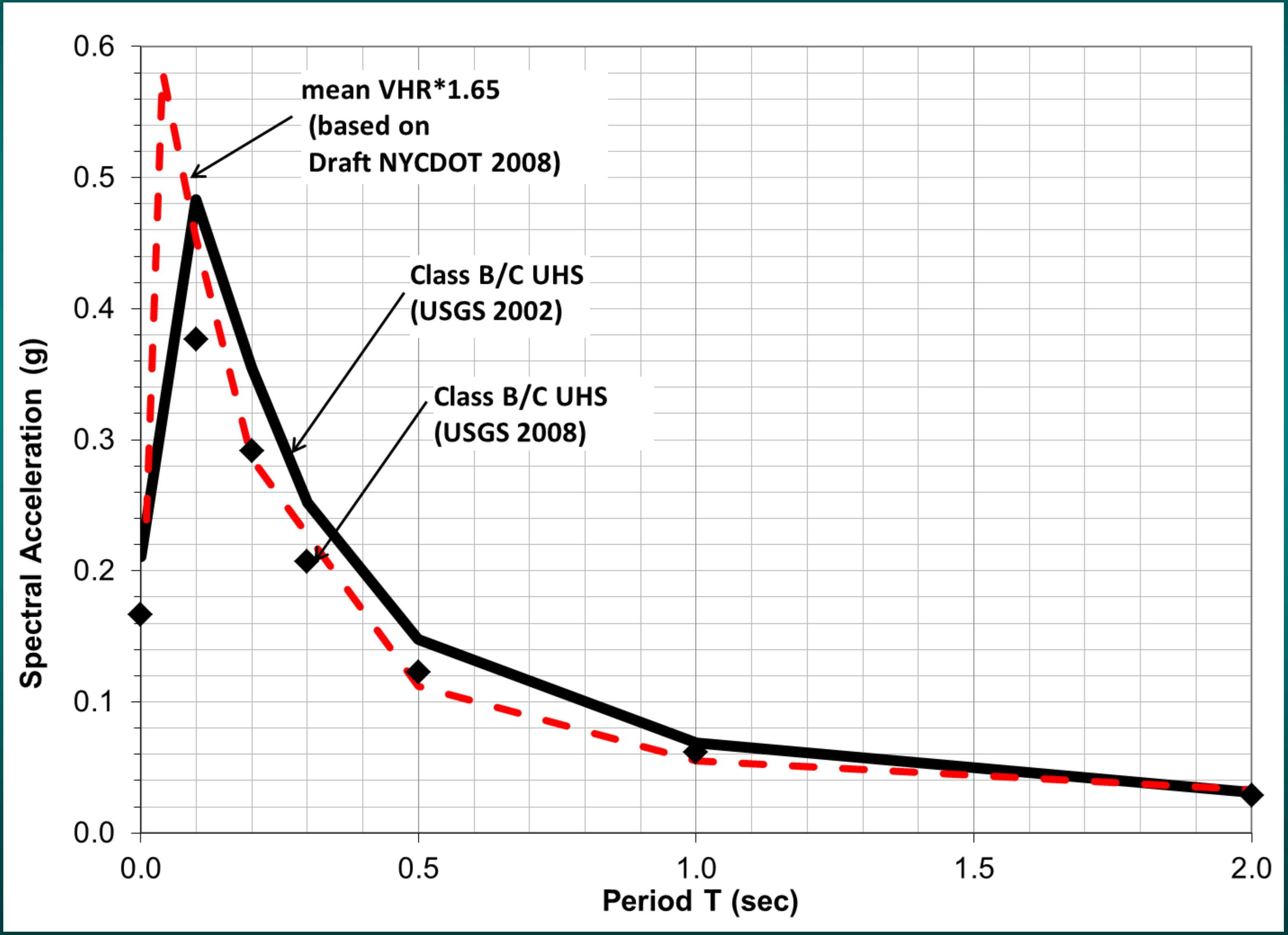


NYCBC to ASCE 7-10: 14%-20% DECREASE

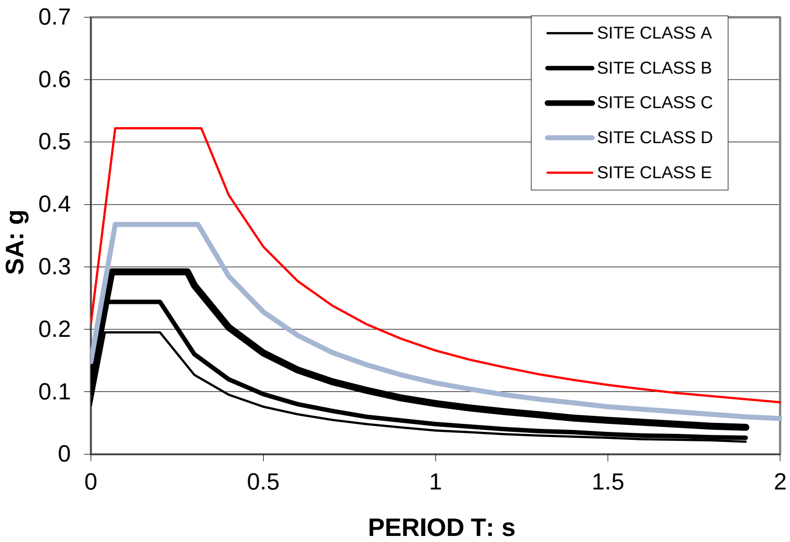
DRAFT NYCDOT Guidelines

- Changes in site classification (“Very Hard Rock”)
- Considerations of depth to rock<100 ft
- Liquefaction triggering with maximum considered earthquake PGA

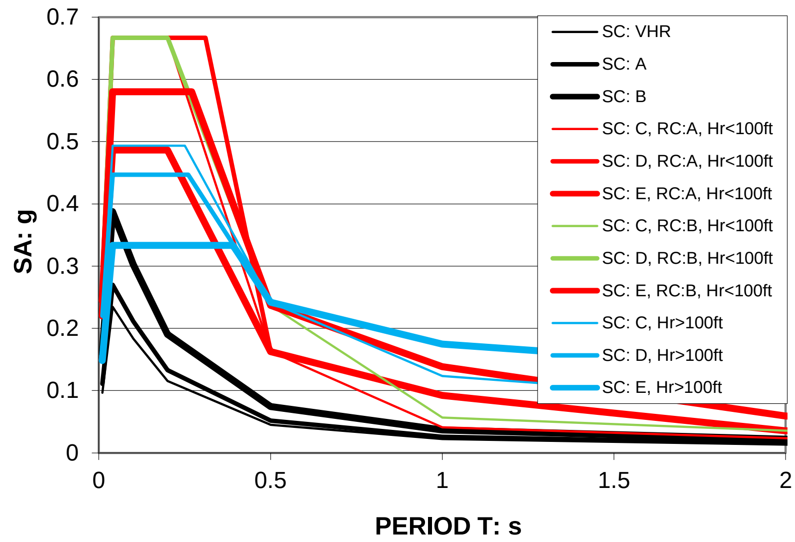
NYCBC vs. DRAFT NYCDOT Bedrock Spectra



NYCBC vs. interpreted Draft NYCDOT Spectra



NYCBC Design Spectra



Possible Design Spectra based on values by the Draft NYCDOT Guidelines

- NYCBC to “NYCDOT”
- SC “E”: 36% decrease to 11% Increase
- SC “D”: 20% to 80% Increase
- SC “C”: 70% to 128% Increase

Conclusions and Recommendations

- Site-specific approach doesn’t necessarily result in lower seismic demand
- Depending on the needs, a site-specific study can vary from a site class evaluation to modeling liquefaction, developing a.t.h. and modeling SSI.
- When lower demand is obtained, cost savings can be significant (lower SDC, decreased design base shear, increased F.o.S. against liquefaction)
- The Seismic community in NYC should reach a consensus regarding seismic demand (NYCDOT vs. ASCE 7-10)

Thank you for your time!

QUESTIONS??

This concludes The American Institute of Architects Continuing Education Systems Program

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