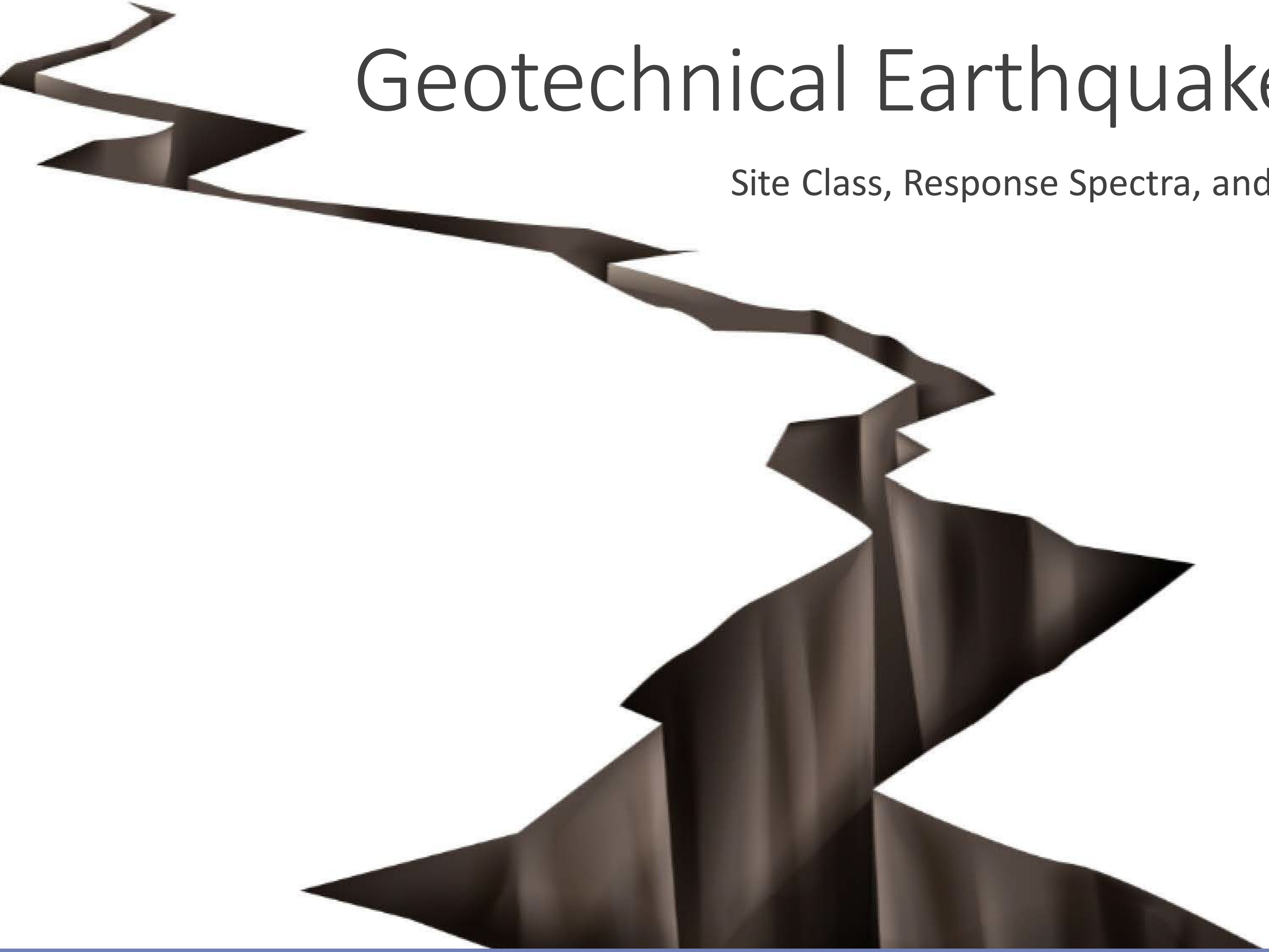
Geotechnical Earthquake Engineering

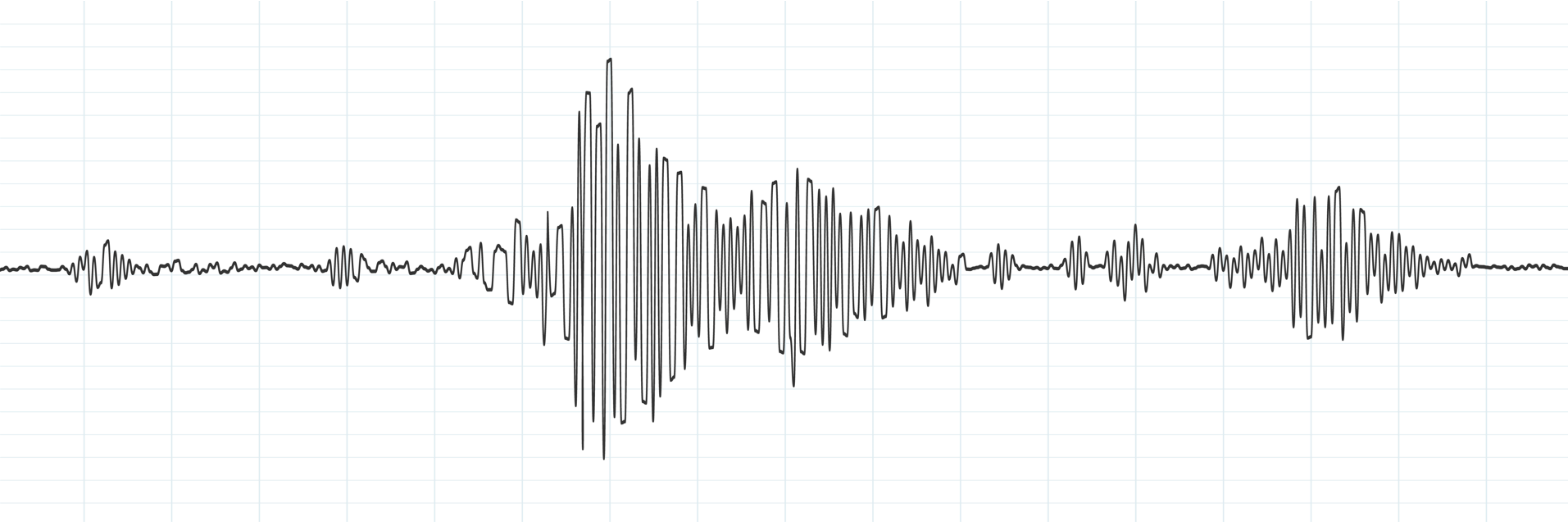
Site Class, Response Spectra, and ASCE 7-22

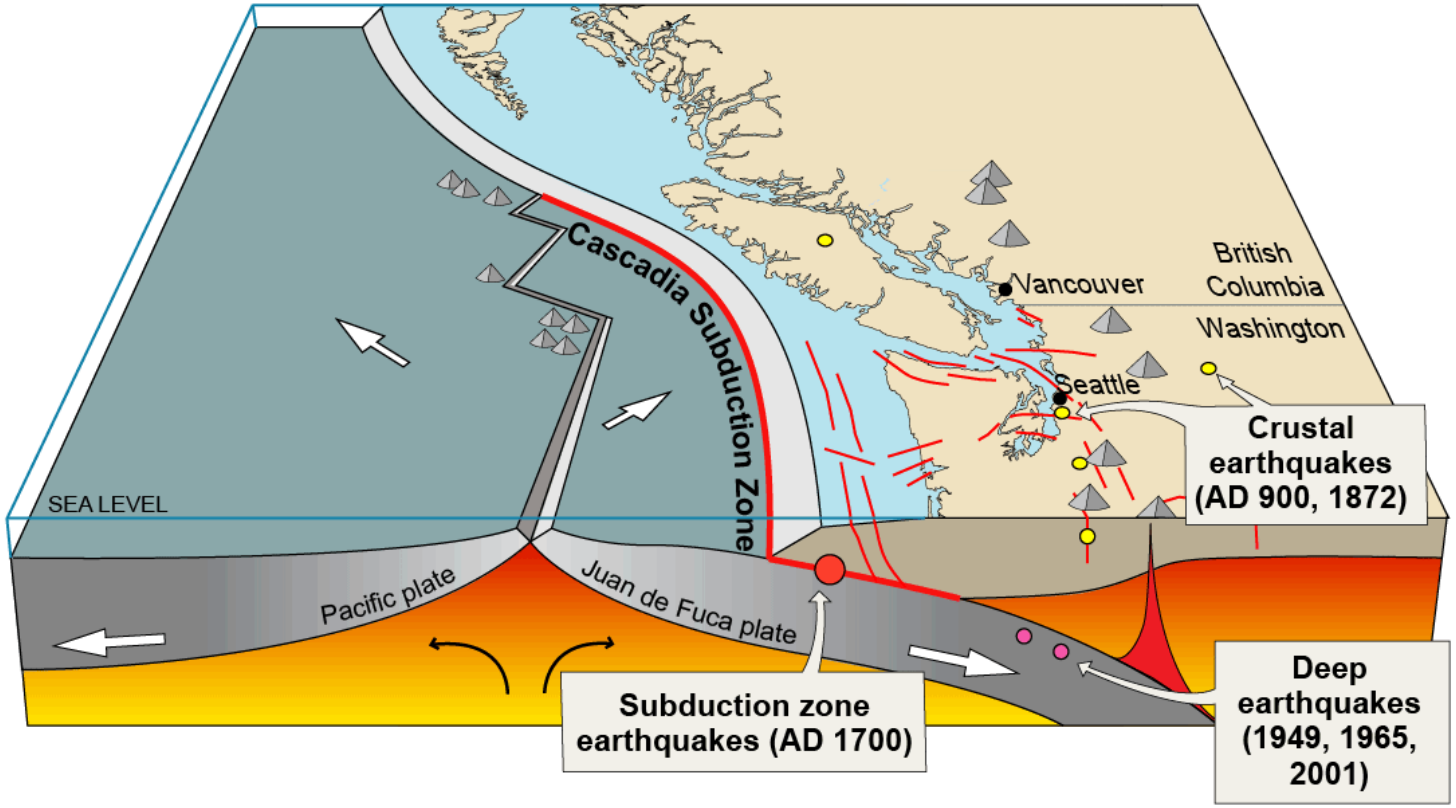


AESI

Associated Earth Sciences, Inc.

Seismology 101





Source	Max. Size	Recurrence
Subduction zone	M 9+	200–600 years
Deep Juan de Fuca plate	M 7+	30–50 years
Crustal faults	M 7+	Hundreds of years?

Volcano

Active crustal fault

Active plate boundary fault

*figure modified from USGS Cascadia earthquake graphics at http://geomaps.wr.usgs.gov/pacnw/pacnweq/index.html

Introduction to Seismology

Seismic waves are mechanical, elastic waves that can be divided into two categories:

Body Waves

- Longitudinal/compressional (P) waves
- Transverse/shear (S) waves

Surface Waves

- Rayleigh waves (compressional + shear)
- Love waves (shear only)

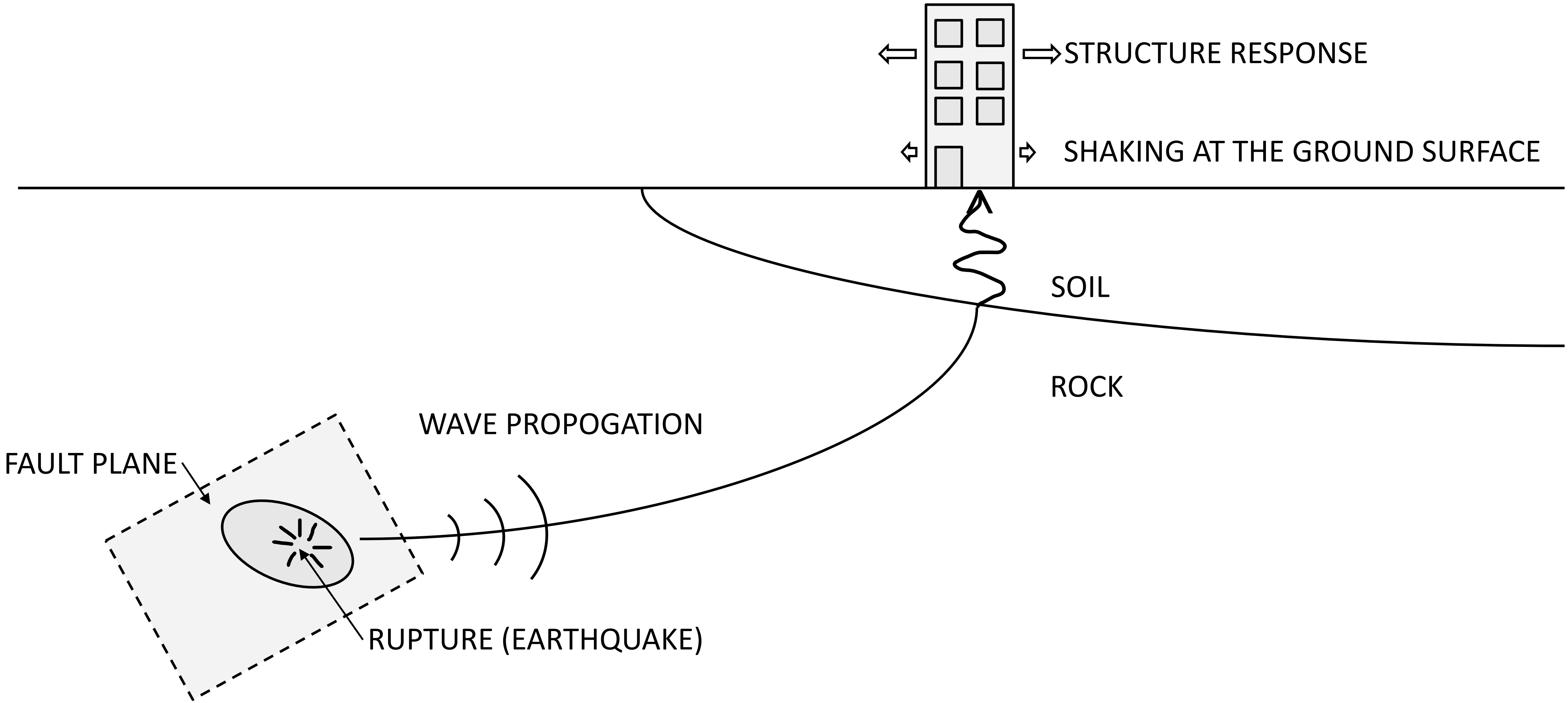


Diagram adapted from lecture notes by Dr. Brett Mauer for Soil Dynamics, Winter 2019, University of Washington

Seismic forces F = ma

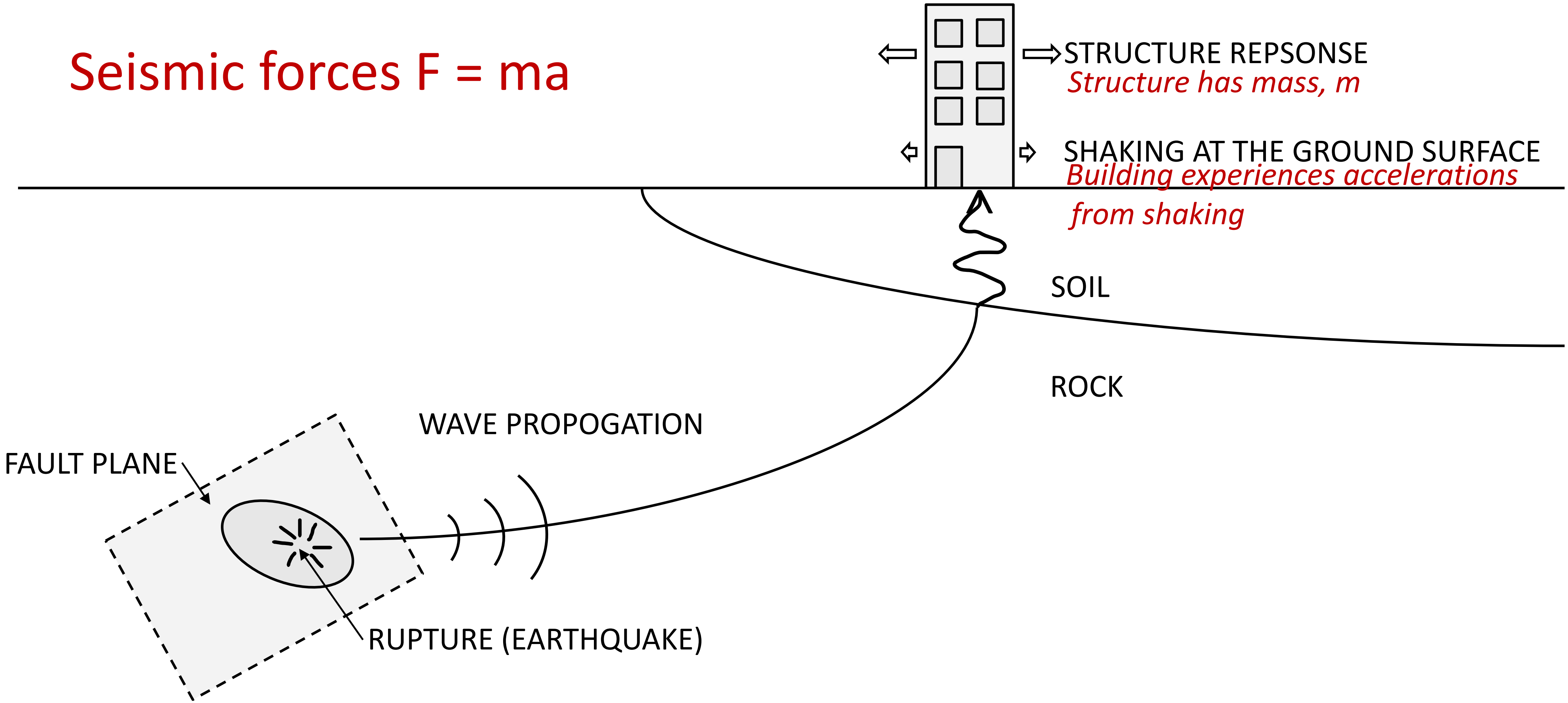
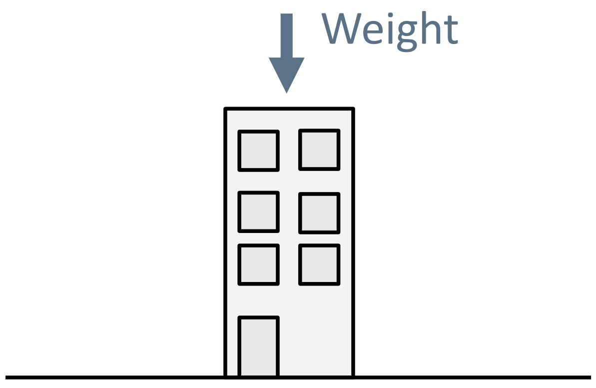
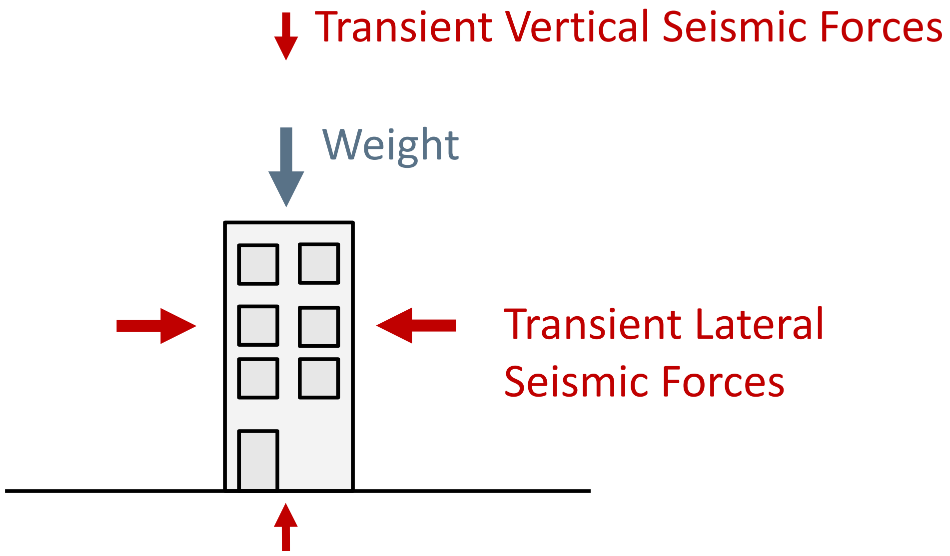


Diagram adapted from lecture notes by Dr. Brett Mauer for Soil Dynamics, Winter 2019, University of Washington



Normal Conditions



Earthquake Conditions

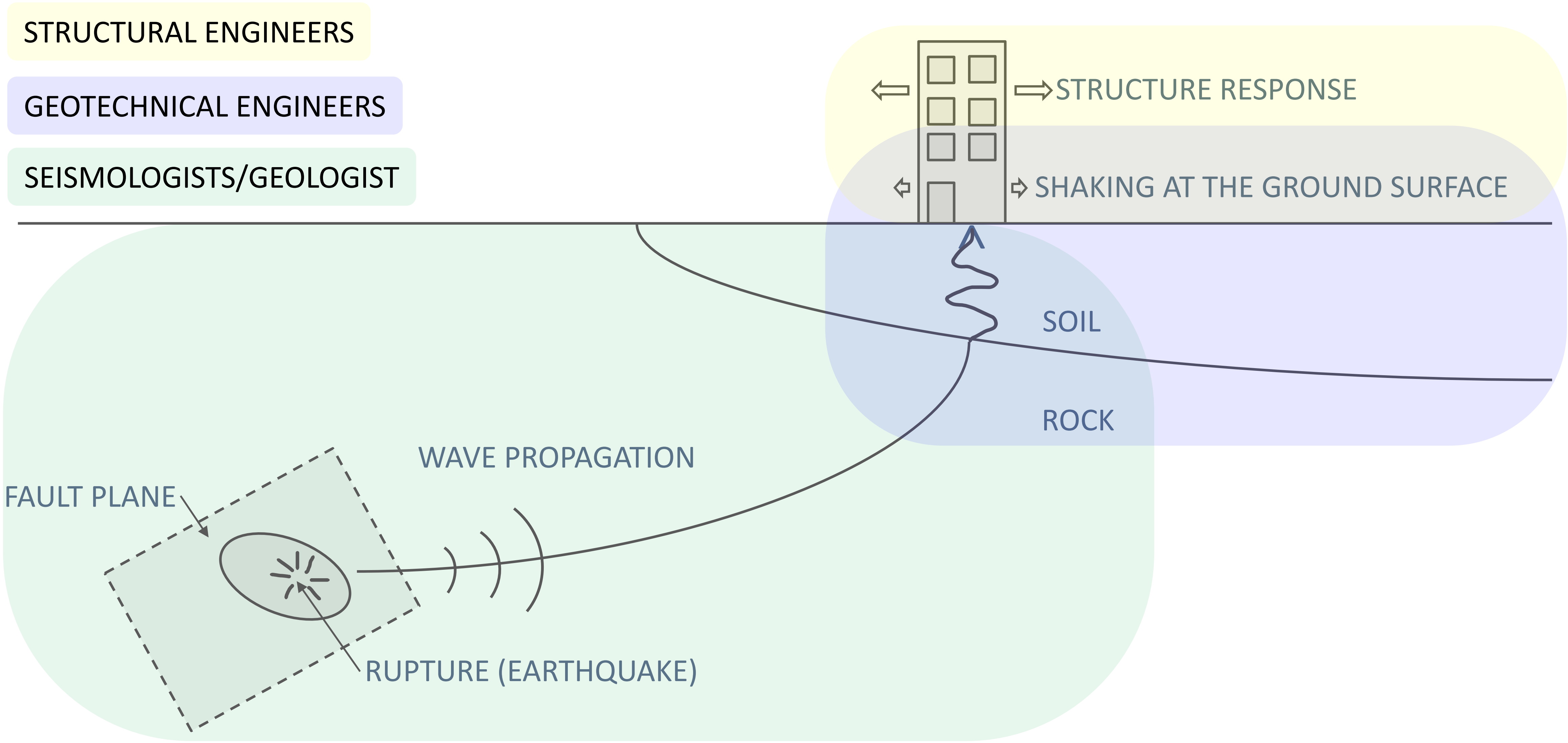
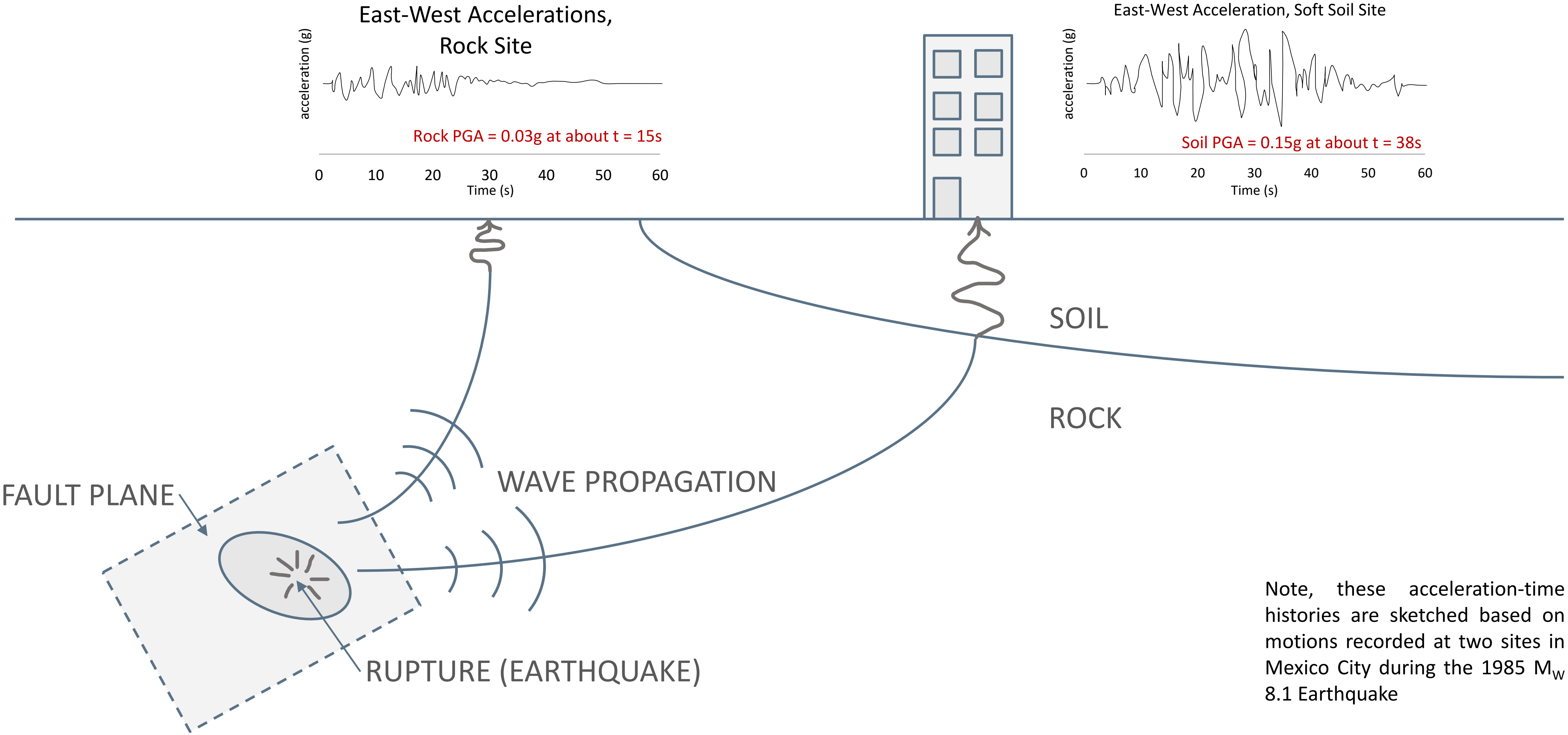


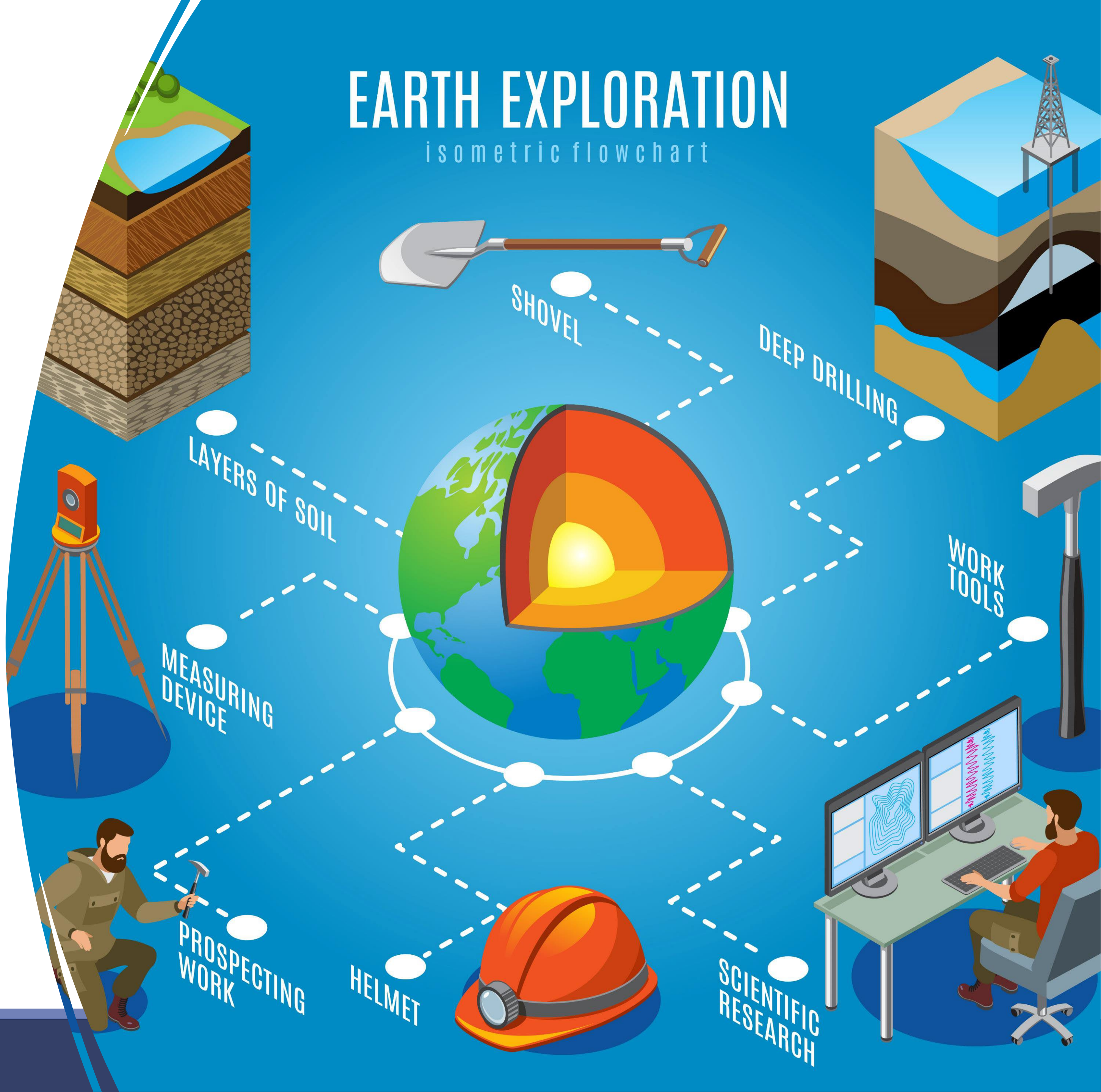
Diagram adapted from lecture notes by Dr. Brett Mauer for Soil Dynamics, Winter 2019, University of Washington

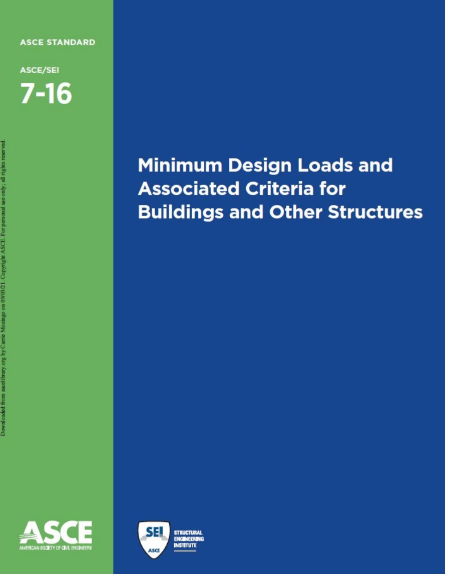


Note, these acceleration-time histories are sketched based on motions recorded at two sites in Mexico City during the 1985 M_W 8.1 Earthquake

Diagram adapted from lecture notes by Dr. Brett Mauer for Soil Dynamics, Winter 2019, University of Washington

Site Characterization and Classification





ASCE 7-16

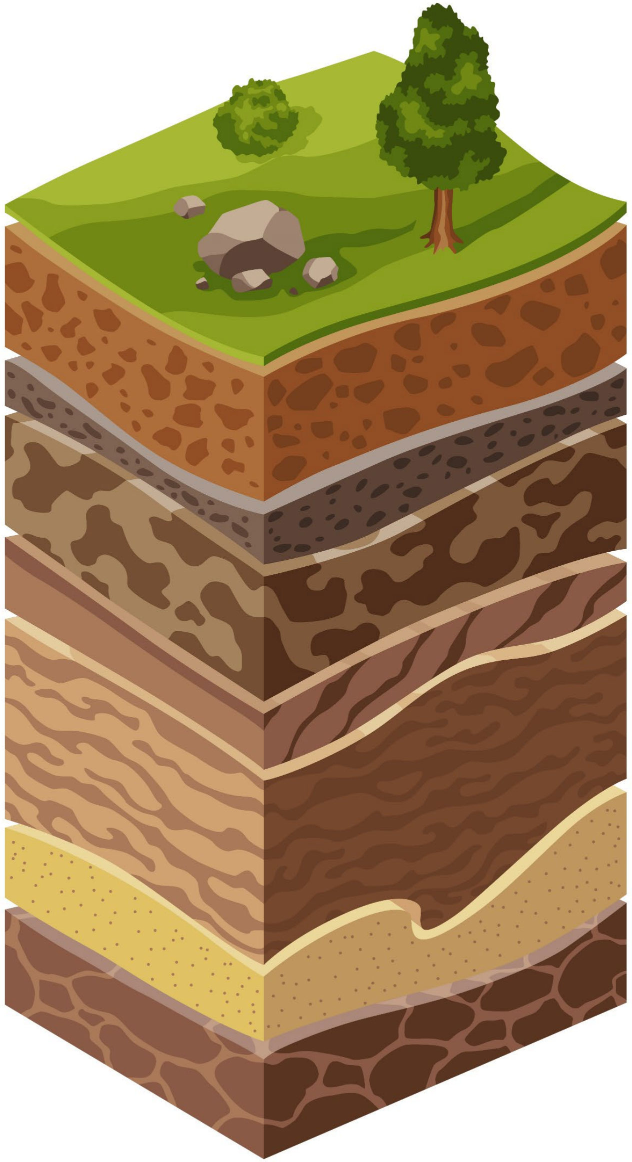
The adopted standard for the 2018 and 2021 Building Codes

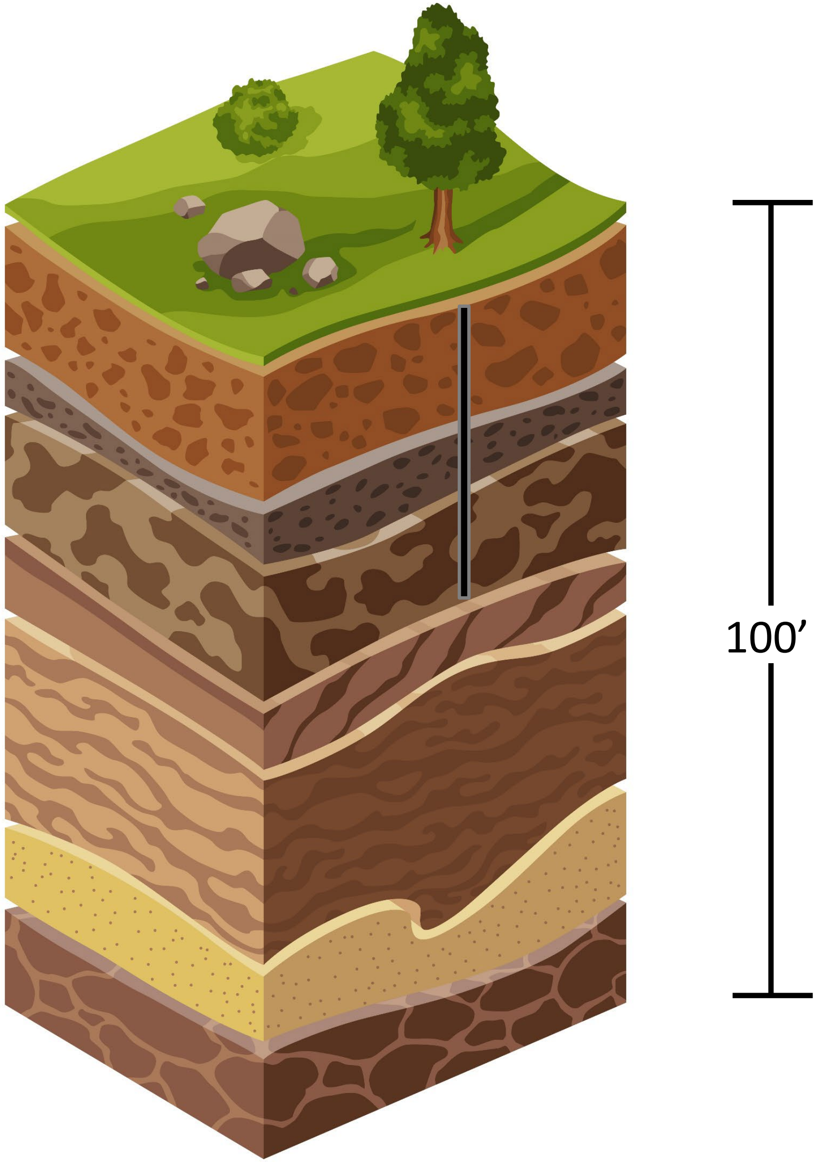
Table 20.3-1 Site Classification

Site Class	$\bar{v}_s$	$\bar{N}$ or $\bar{N}_{ch}$	$\bar{s}_u$
A. Hard rock	>5,000 ft/s	NA	NA
B. Rock	2,500 to 5,000 ft/s	NA	NA
C. Very dense soil and soft rock	1,200 to 2,500 ft/s	>50 blows/ft	>2,000 lb/ft^2
D. Stiff soil	600 to 1,200 ft/s	15 to 50 blows/ft	1,000 to 2,000 lb/ft^2
E. Soft clay soil	<600 ft/s	<15 blows/ft	<1,000 lb/ft^2
	Any profile with more than 10 ft of soil that has the following characteristics: — Plasticity index $PI > 20$, — Moisture content $w \geq 40\%$, — Undrained shear strength $\bar{s}_u < 500$ lb/ft^2		
F. Soils requiring site response analysis in accordance with Section 21.1	See Section 20.3.1		

Note: For SI: 1 ft = 0.3048 m; 1 ft/s = 0.3048 m/s; 1 lb/ft^2 = 0.0479 kN/m^2.

Drilling and the Standard Penetration Test





Soil Borings

A soil boring involves drilling a hole to collect samples of soil and bedrock

A typical soil boring is drilled with a drill rig outfitted with a 6- or 8-inch hollow stem auger

The depth is commonly determined to evaluate the soil profile for engineering purposes, not site class

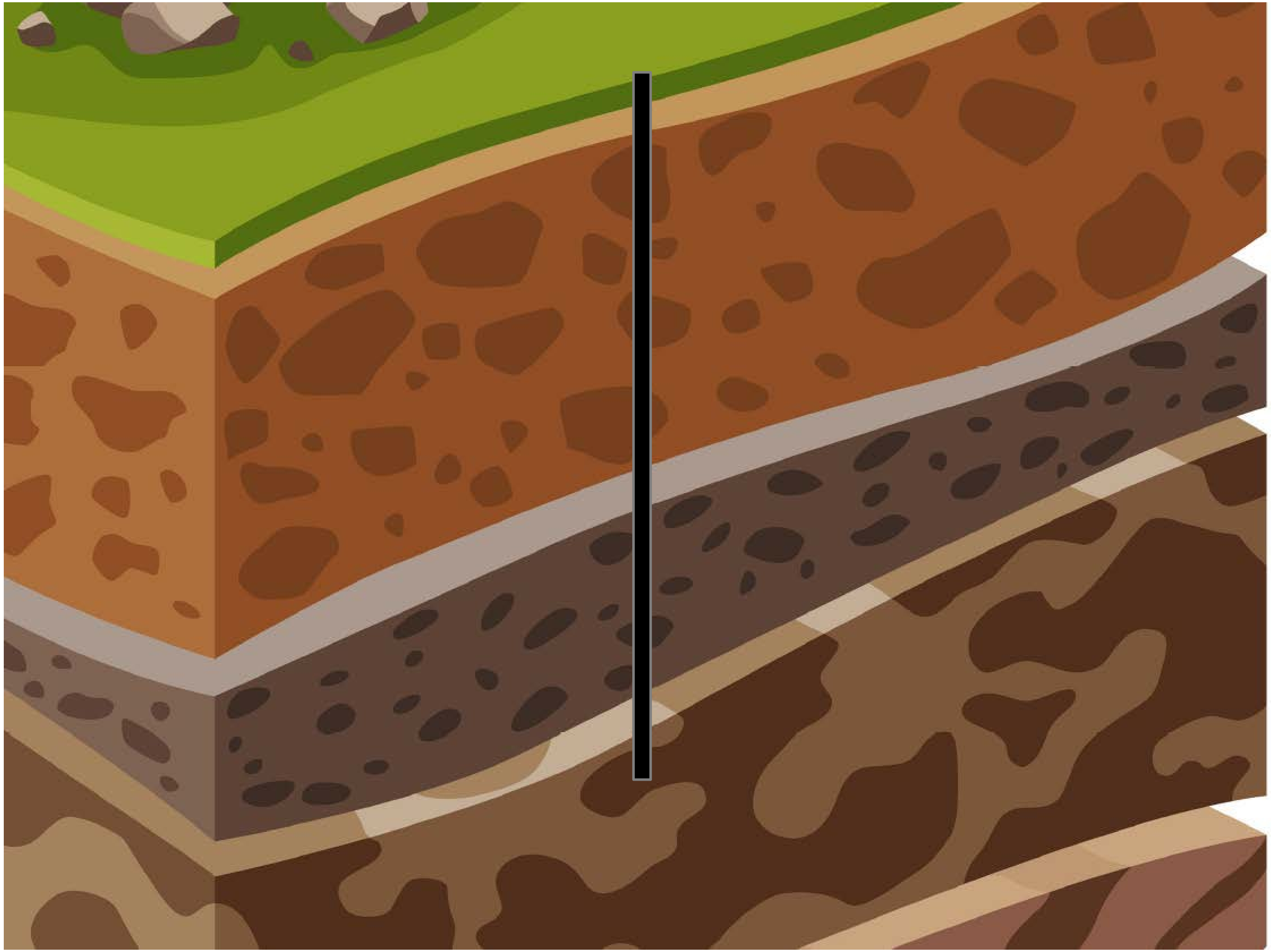
ASCE 7-16 states that the site soil shall be classified based on the upper 100 ft (30 m) of the site profile; in most cases, borings are much shallower

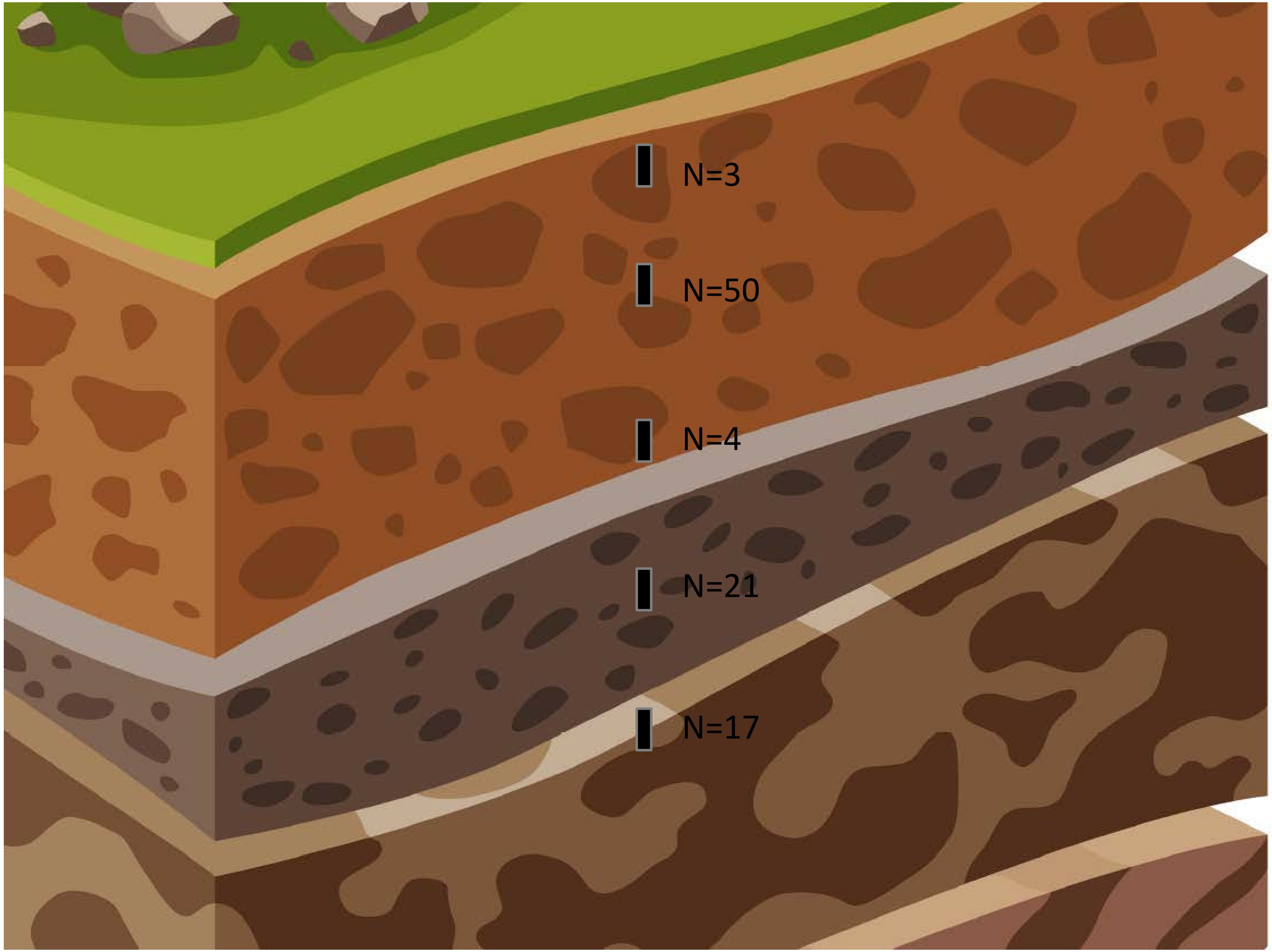
Standard Penetration Test

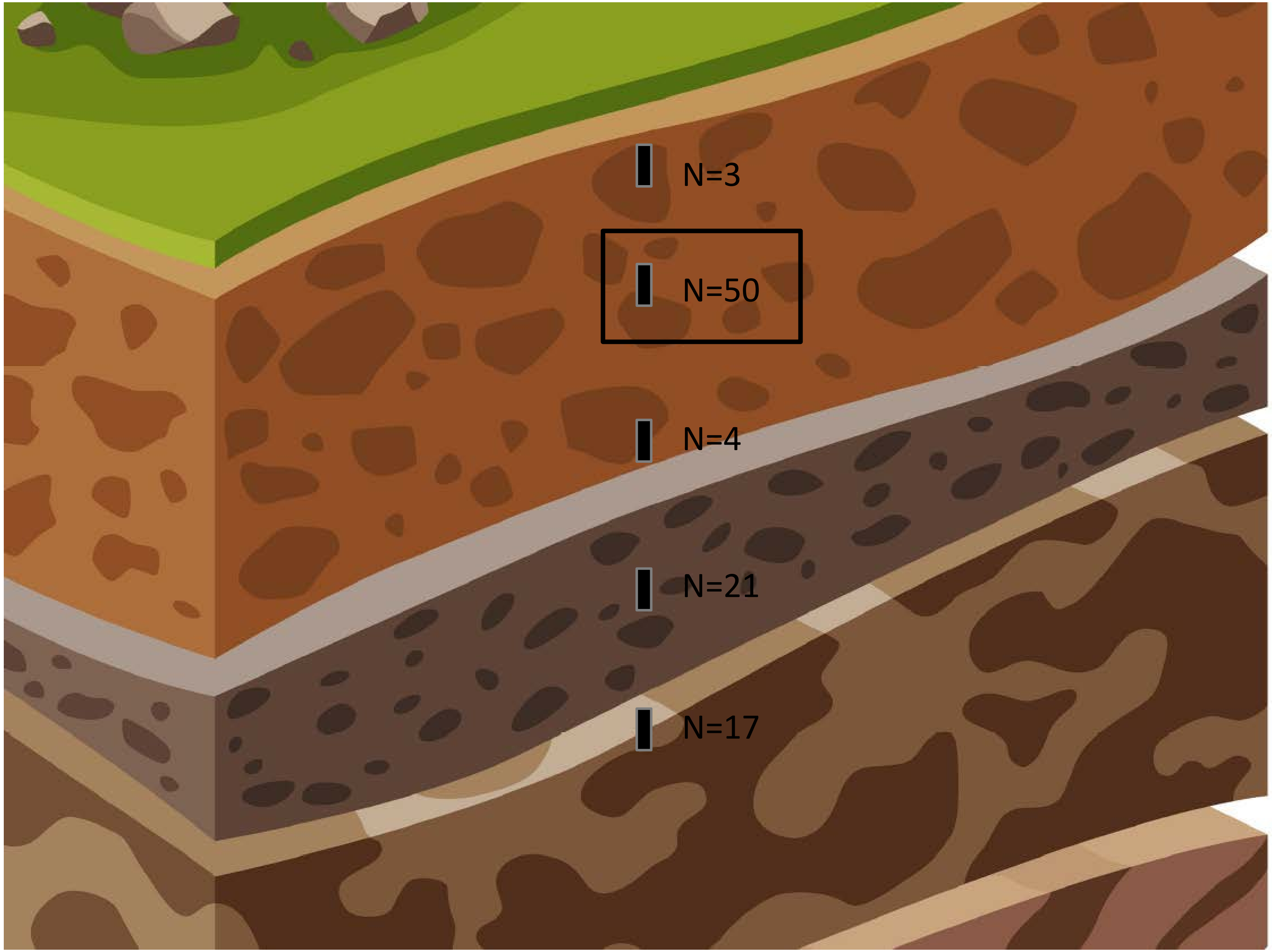
The Standard Penetration Test (SPT) has been the standard practice to characterize and classify most sites

The SPT involves drilling a hole with a 6- or 8-inch auger and sampling with a driven split spoon sampler

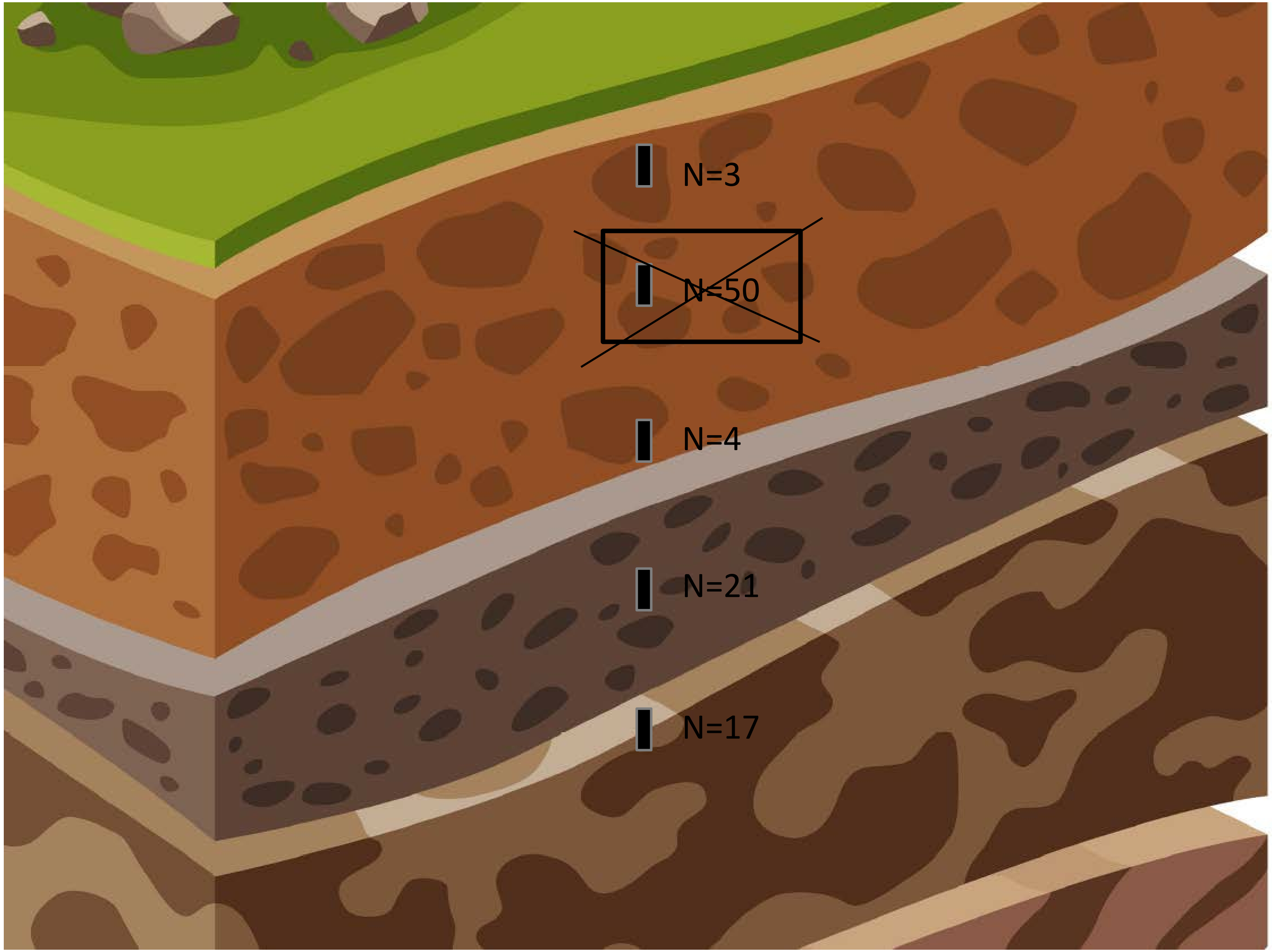
The sample barrel is driven 18-inches with a 140lb hammer falling 30-inches and the number of blows for the final 12 inches are recorded (field N-Value)




N=3
N=50
N=4
N=21
N=17


N=3
N=50
N=4
N=21
N=17


Gravel or heaving sands can
overstate blow counts


N=3
N=50
N=4
N=21
N=17

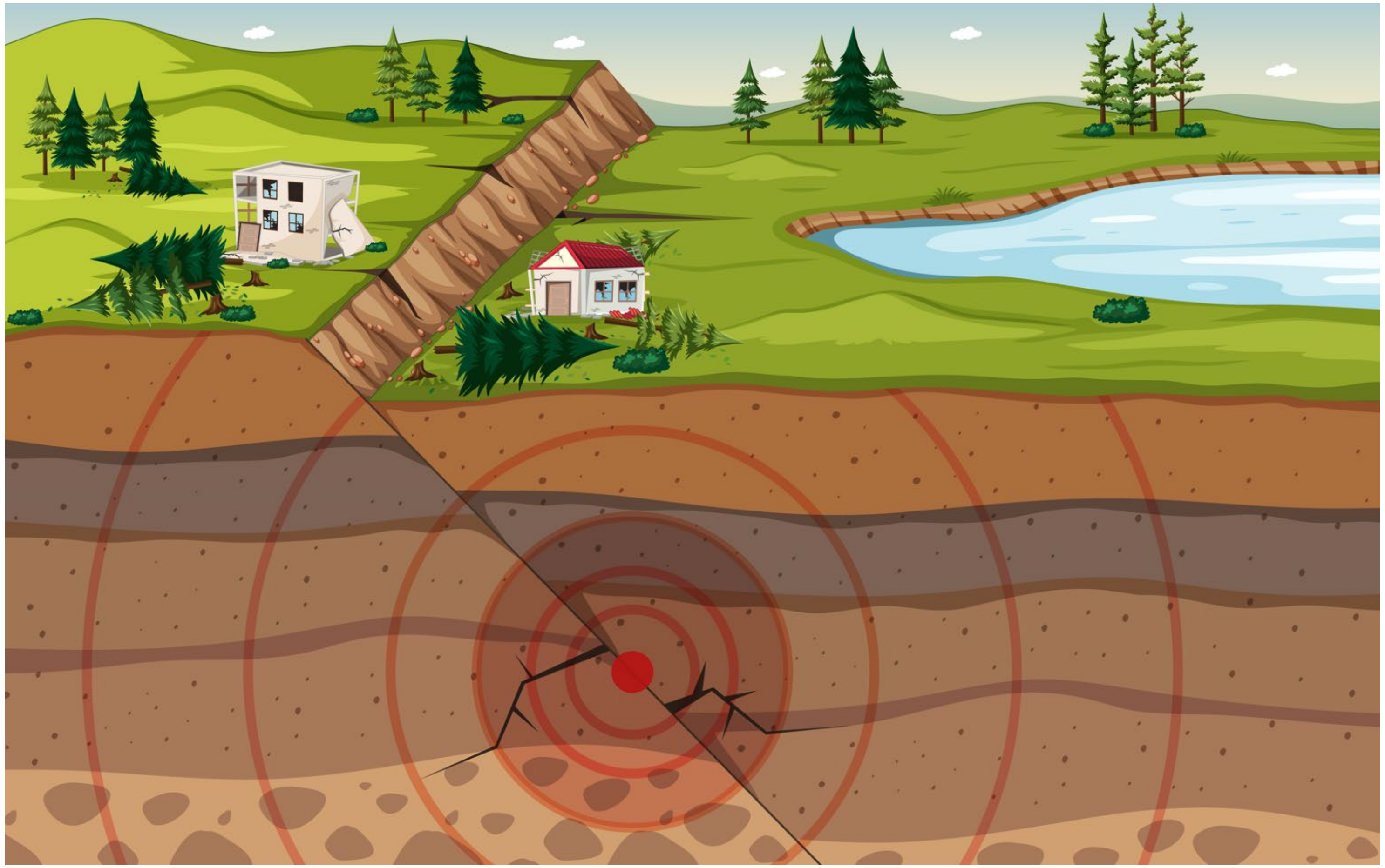
Based on the limited field N-Values, and knowledge of regional geology, an estimation of the average N Value down to 100 feet is made, and a site class is selected

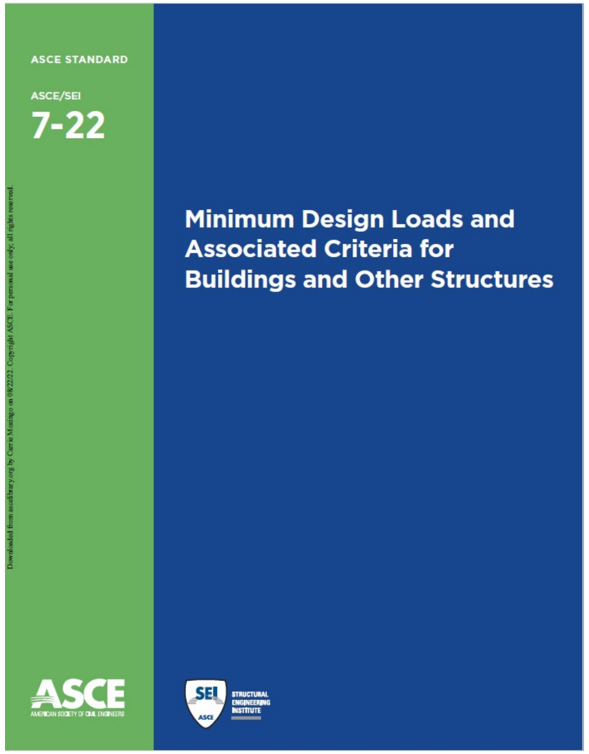
Table 20.3-1 Site Classification

Site Class	$\bar{v}_s$	$\bar{N}$ or $\bar{N}_{ch}$	$\bar{s}_u$
A. Hard rock	>5,000 ft/s	NA	NA
B. Rock	2,500 to 5,000 ft/s	NA	NA
C. Very dense soil and soft rock	1,200 to 2,500 ft/s	>50 blows/ft	>2,000 lb/ft^2
D. Stiff soil	600 to 1,200 ft/s	15 to 50 blows/ft	1,000 to 2,000 lb/ft^2
E. Soft clay soil	<600 ft/s	<15 blows/ft	<1,000 lb/ft^2
	Any profile with more than 10 ft of soil that has the following characteristics: — Plasticity index $PI > 20$, — Moisture content $w \geq 40\%$, — Undrained shear strength $\bar{s}_u < 500$ lb/ft^2		
F. Soils requiring site response analysis in accordance with Section 21.1	See Section 20.3.1		

Note: For SI: 1 ft = 0.3048 m; 1 ft/s = 0.3048 m/s; 1 lb/ft^2 = 0.0479 kN/m^2.

ASCE-7 standards are being modified to limit the assumptions associated with modeling the upper 100 feet of soils



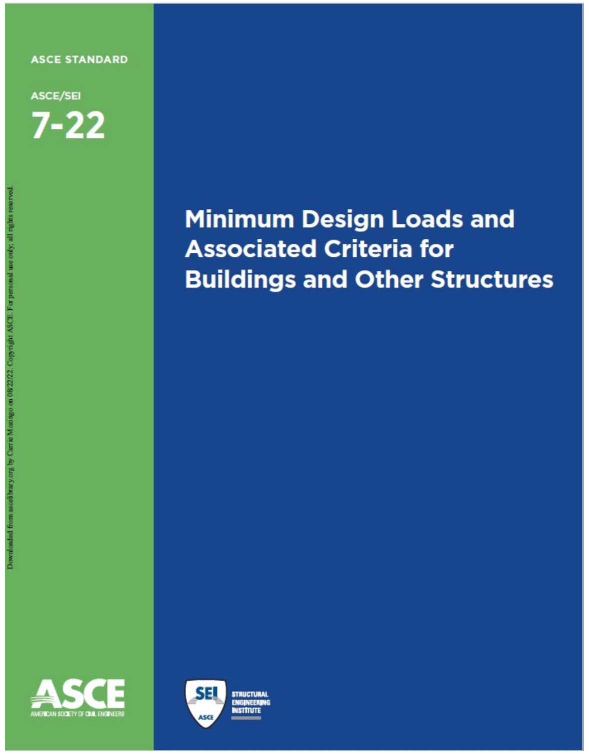


ASCE 7-22

Table 20.2-1. Site Classification.

Site Class	$\bar{v}_s$ Calculated Using Measured or Estimated Shear Wave Velocity Profile (ft/s)
A. Hard rock	>5,000
B. Medium hard rock	>3,000 to 5,000
BC. Soft rock	>2,100 to 3,000
C. Very dense sand or hard clay	>1,450 to 2,100
CD. Dense sand or very stiff clay	>1,000 to 1,450
D. Medium dense sand or stiff clay	>700 to 1,000
DE. Loose sand or medium stiff clay	>500 to 700
E. Very loose sand or soft clay	≥500
F. Soils requiring site response analysis in accordance with Section 21.1	See Section 20.2.1

Note: For SI: 1 ft = 0.3048 m; 1 ft/s = 0.3048 m/s.



ASCE 7-22

Already accepted by local jurisdictions

Likely to be adopted into the 2024 IBC

Adopted by the Washington State Building Code July 1, 2023

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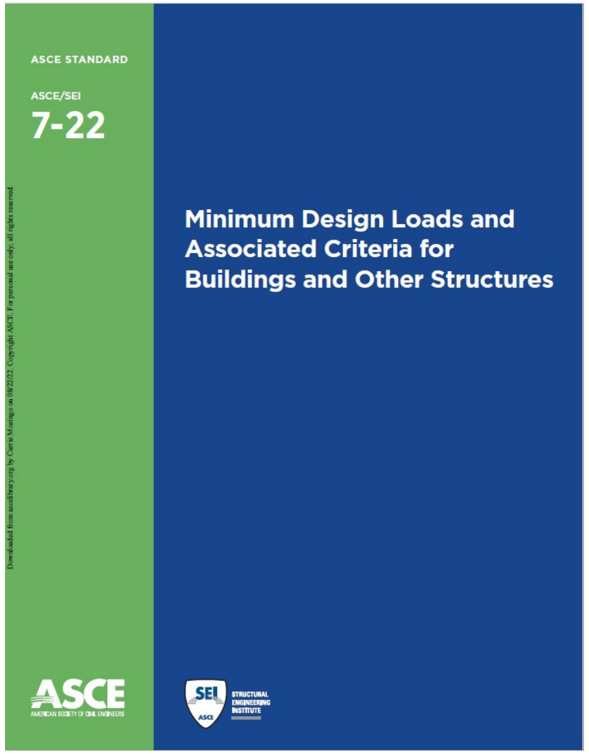

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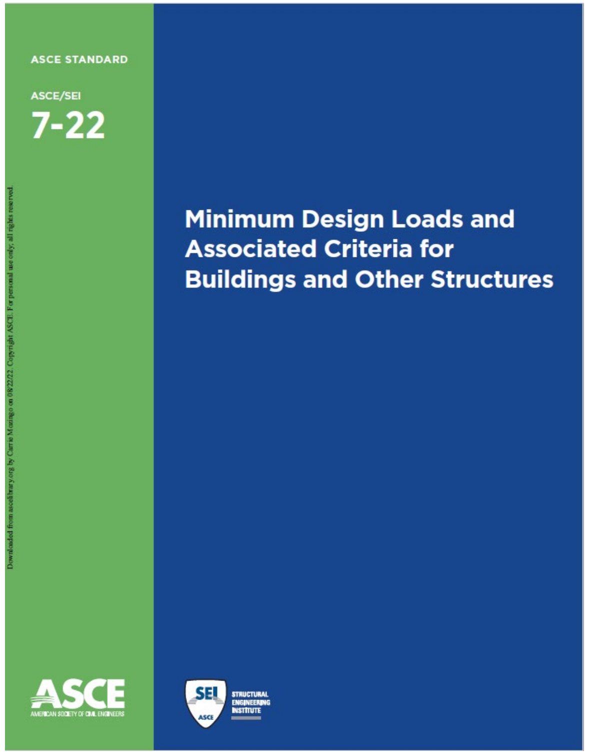

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Note: For SI: 1 ft = 0.3048 m; 1 ft/s = 0.3048 m/s.

Shear Wave Velocity Testing

Shear wave velocity is controlled by the shear modulus (essentially the hardness) and density of soil or rock

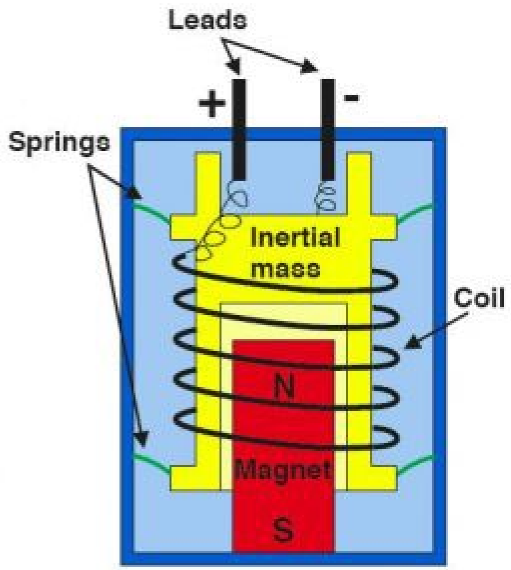
It is a good measure of how much ground shaking will occur in a particular soil or rock type, during an earthquake

Shear Wave Velocity Testing

Multichannel Analysis of Surface Waves (MASW)

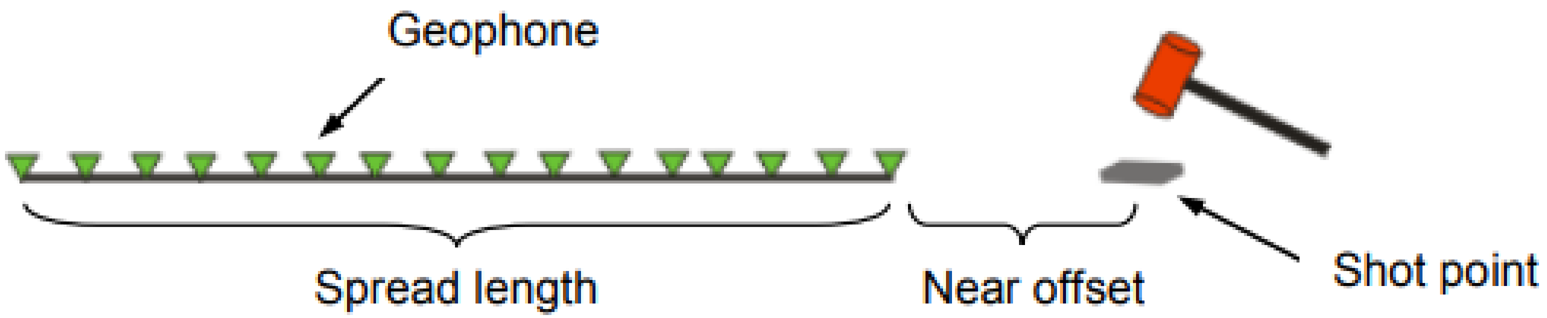
Microtremor Array Measurements (MAM)

Geometrics Geode Geophone system

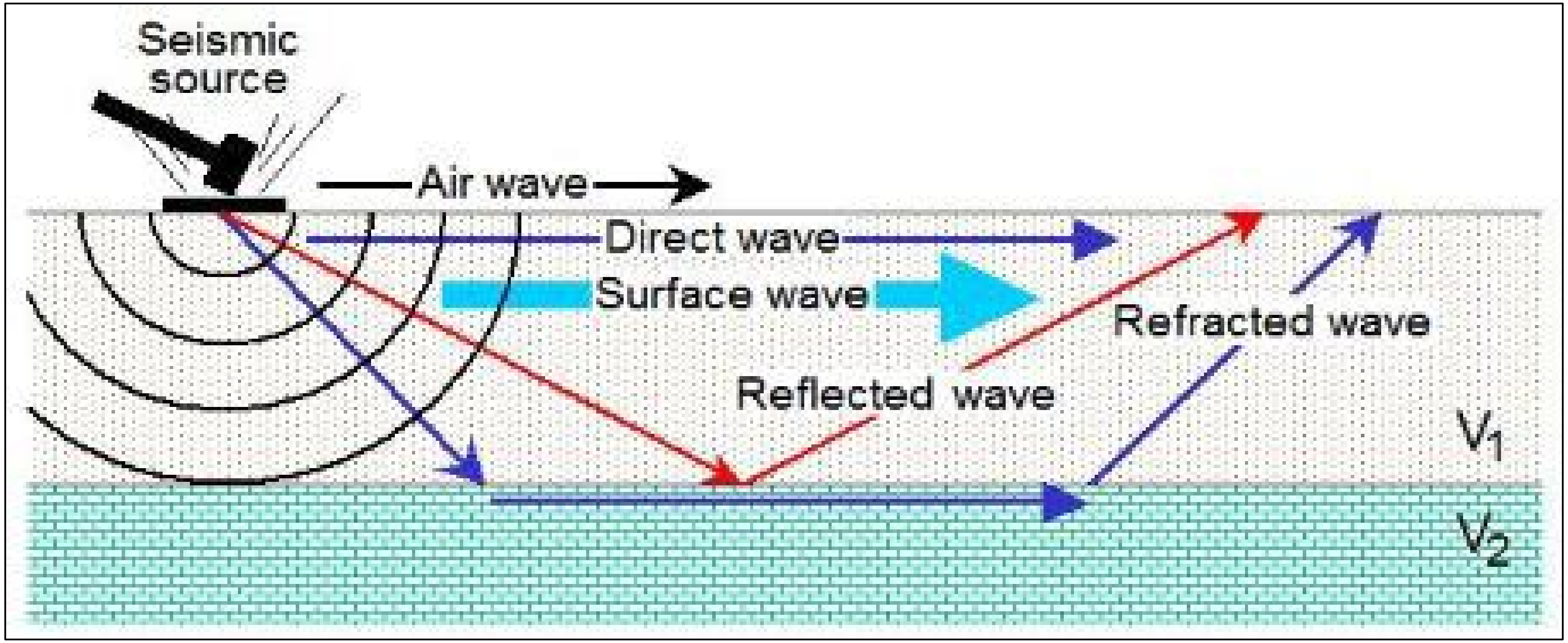


Multichannel Analysis of Surface Waves (MASW)

MASW is an active method where seismic energy is introduced to the Earth and measured with geophones in a linear array some distance away from the source.



These seismic waves travel in all directions and with different frequencies



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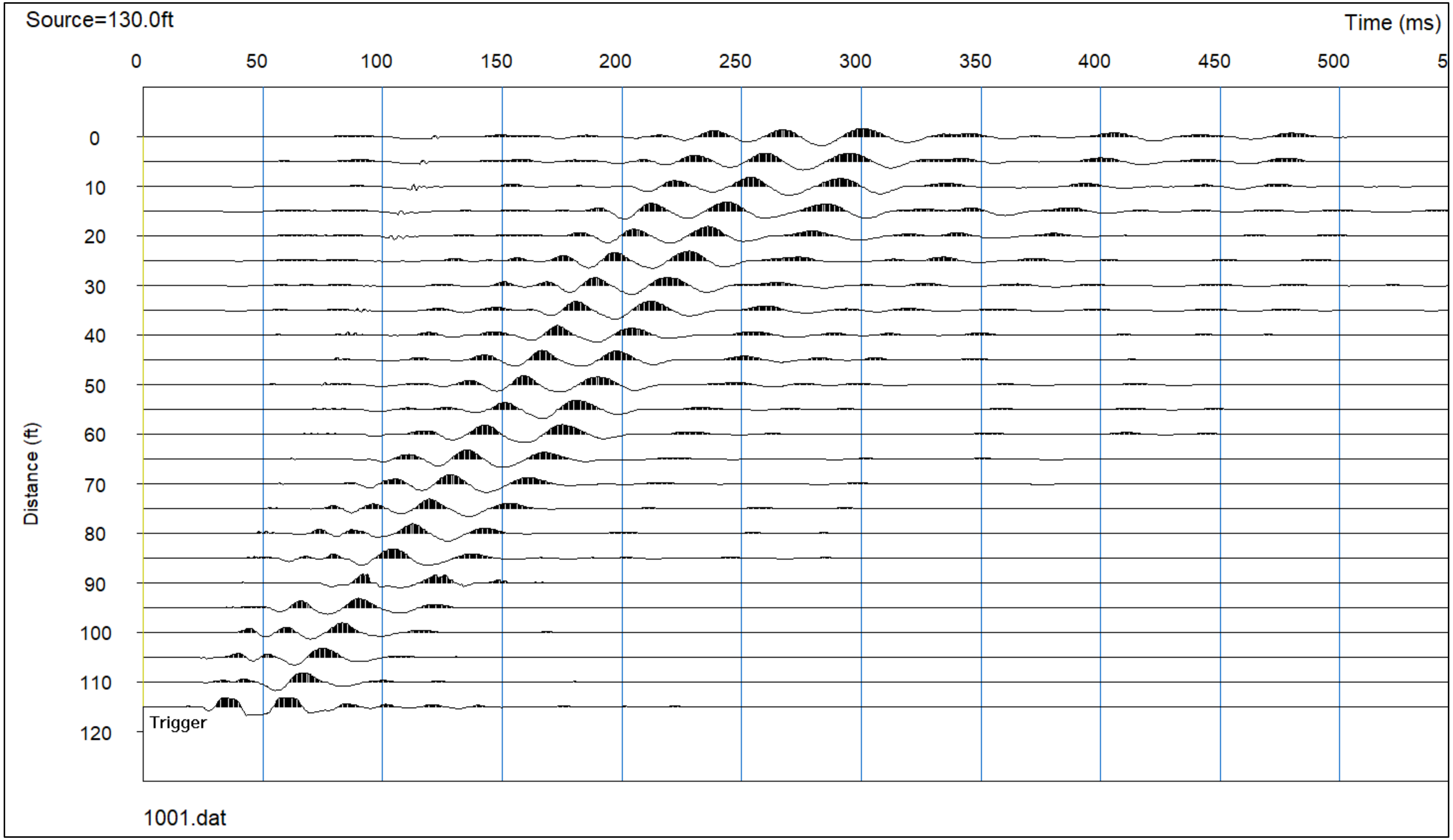
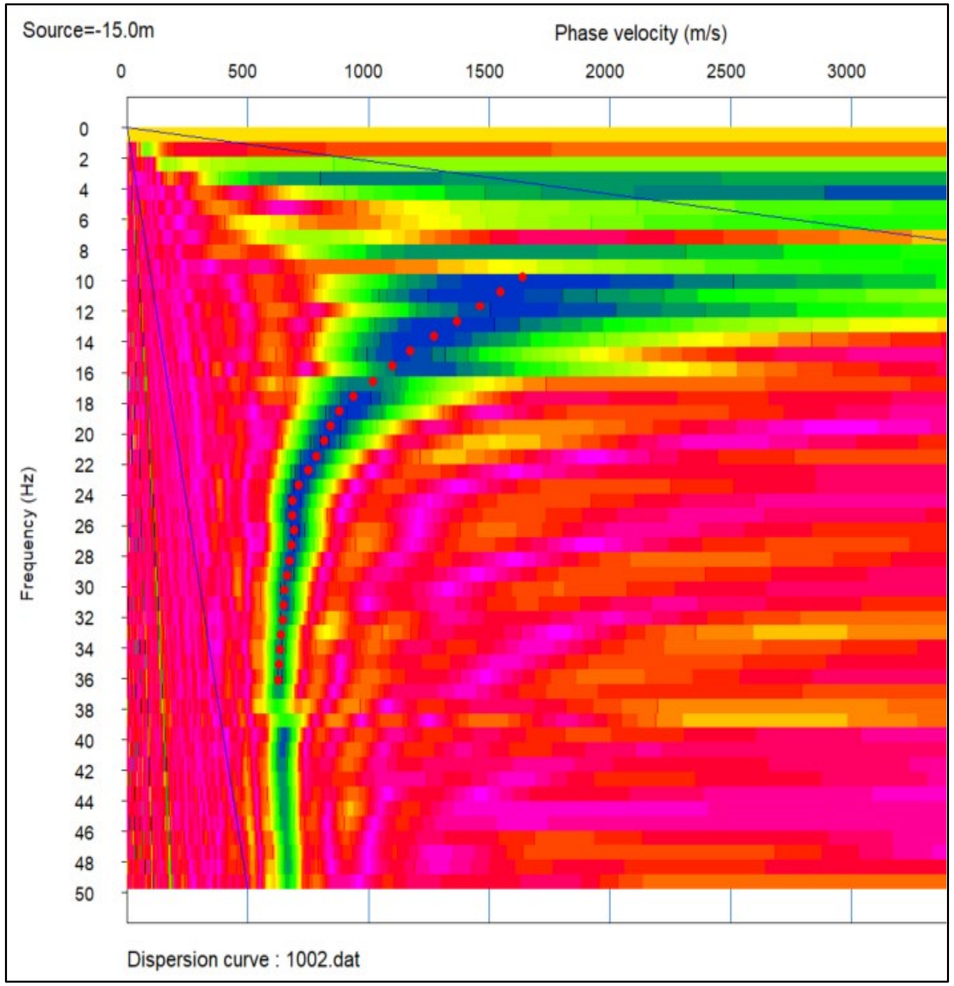
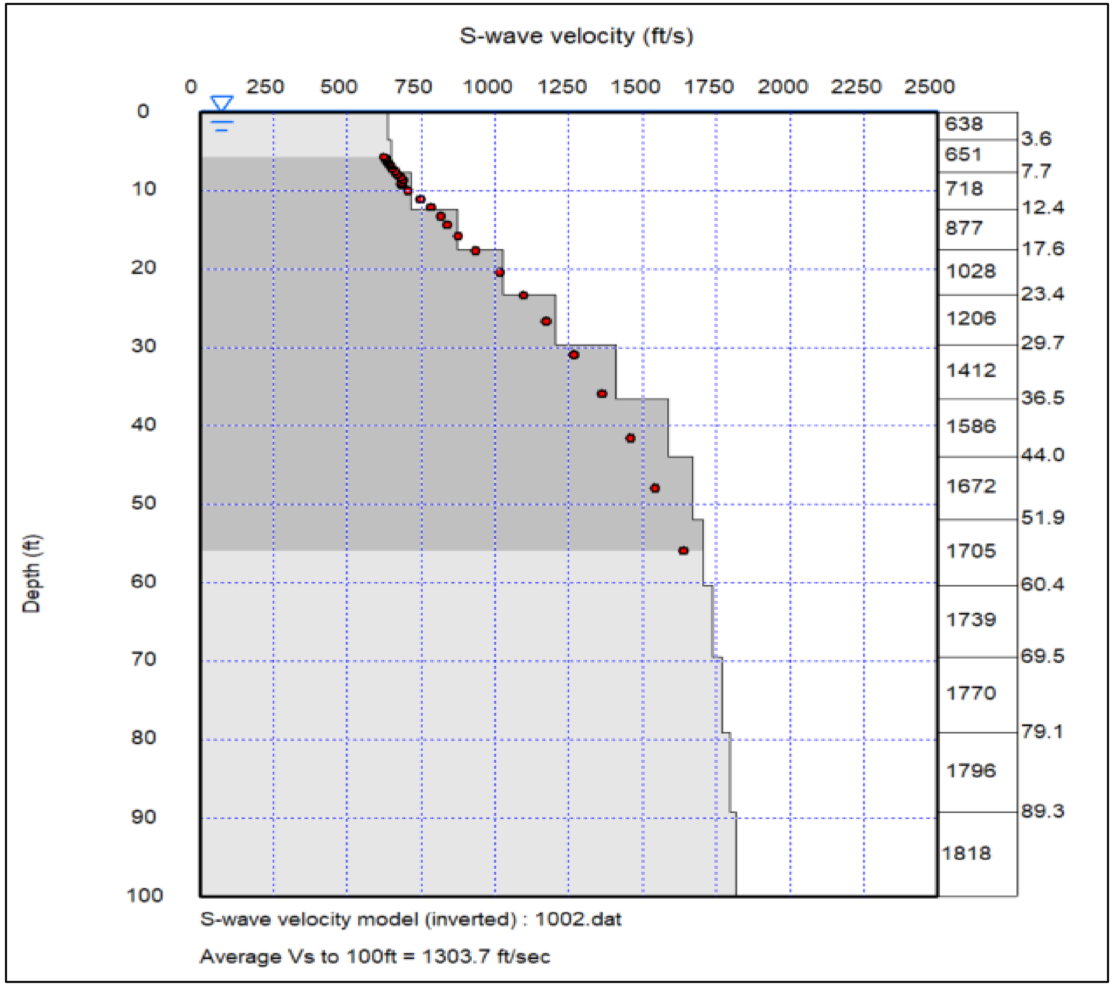

Source=130.0ft
Time (ms)
0
50
100
150
200
250
300
350
400
450
500
Distance (ft)
0
10
20
30
40
50
60
70
80
90
100
110
120
Trigger
1001.dat


Source=-15.0m
Phase velocity (m/s)
0
500
1000
1500
2000
2500
3000
Frequency (Hz)
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
34
36
38
40
42
44
46
48
50
Dispersion curve : 1002.dat


S-wave velocity (ft/s)
0
250
500
750
1000
1250
1500
1750
2000
2250
2500
Depth (ft)
0
10
20
30
40
50
60
70
80
90
100
638
651
718
877
1028
1206
1412
1586
1672
1705
1739
1770
1796
1818
3.6
7.7
12.4
17.6
23.4
29.7
36.5
44.0
51.9
60.4
69.5
79.1
89.3
S-wave velocity model (inverted) : 1002.dat
Average Vs to 100ft = 1303.7 ft/sec

MASW Summary

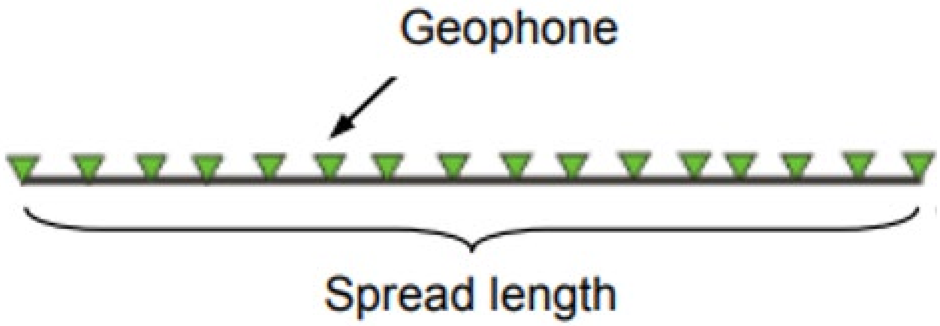
MASW is fast, cost effective & noninvasive technique using an active source to evaluate VS100

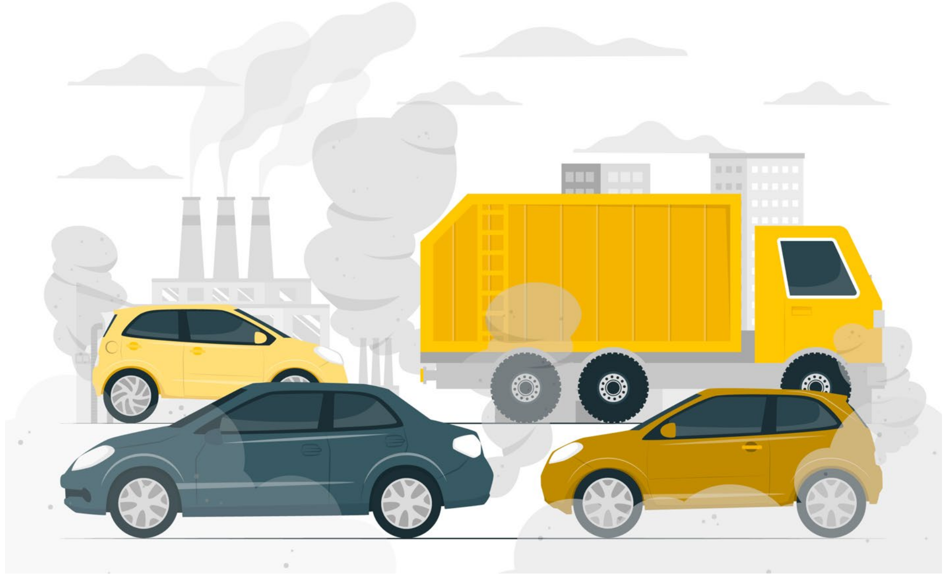
MASW is great for profiling shallow soils

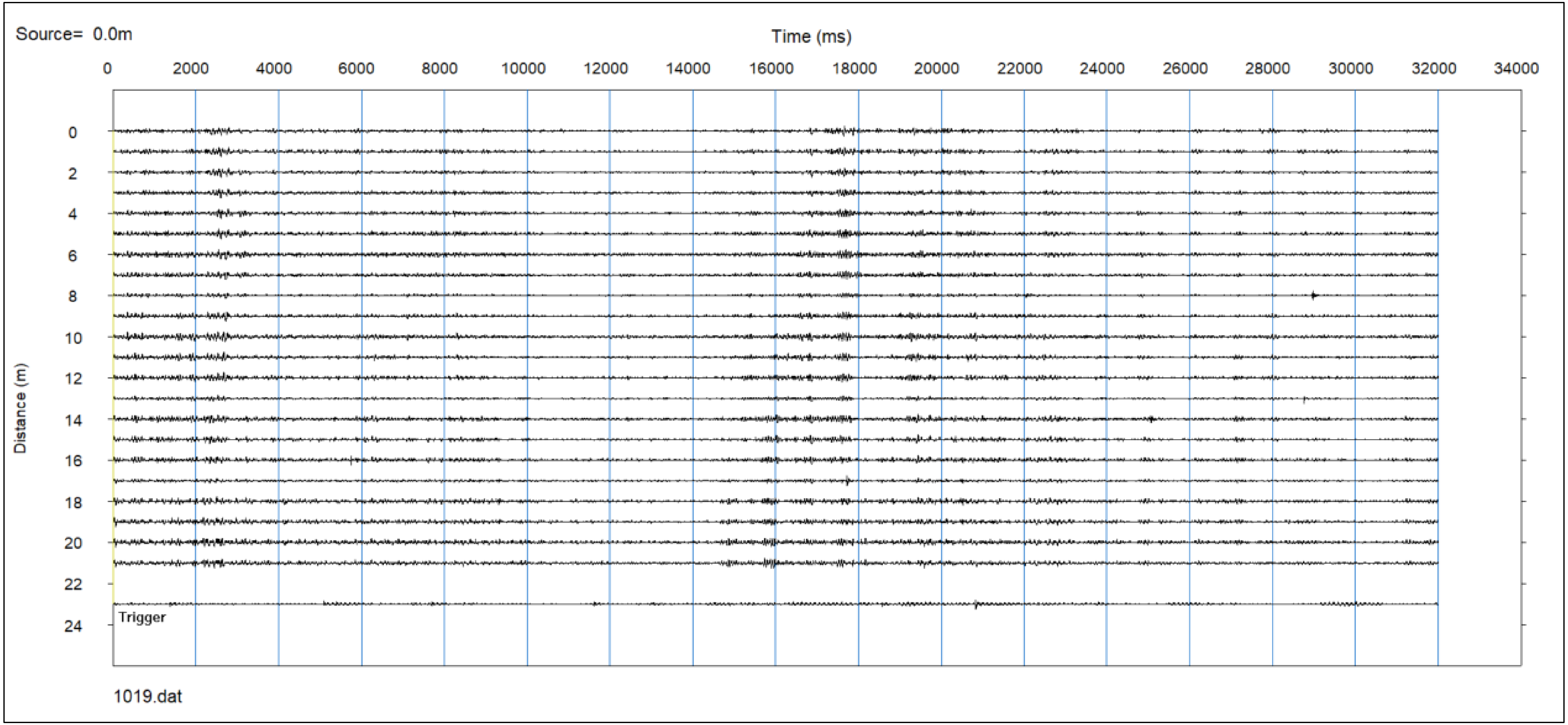
The depth of investigation is limited by availability of low frequency data, typically to 50-100’

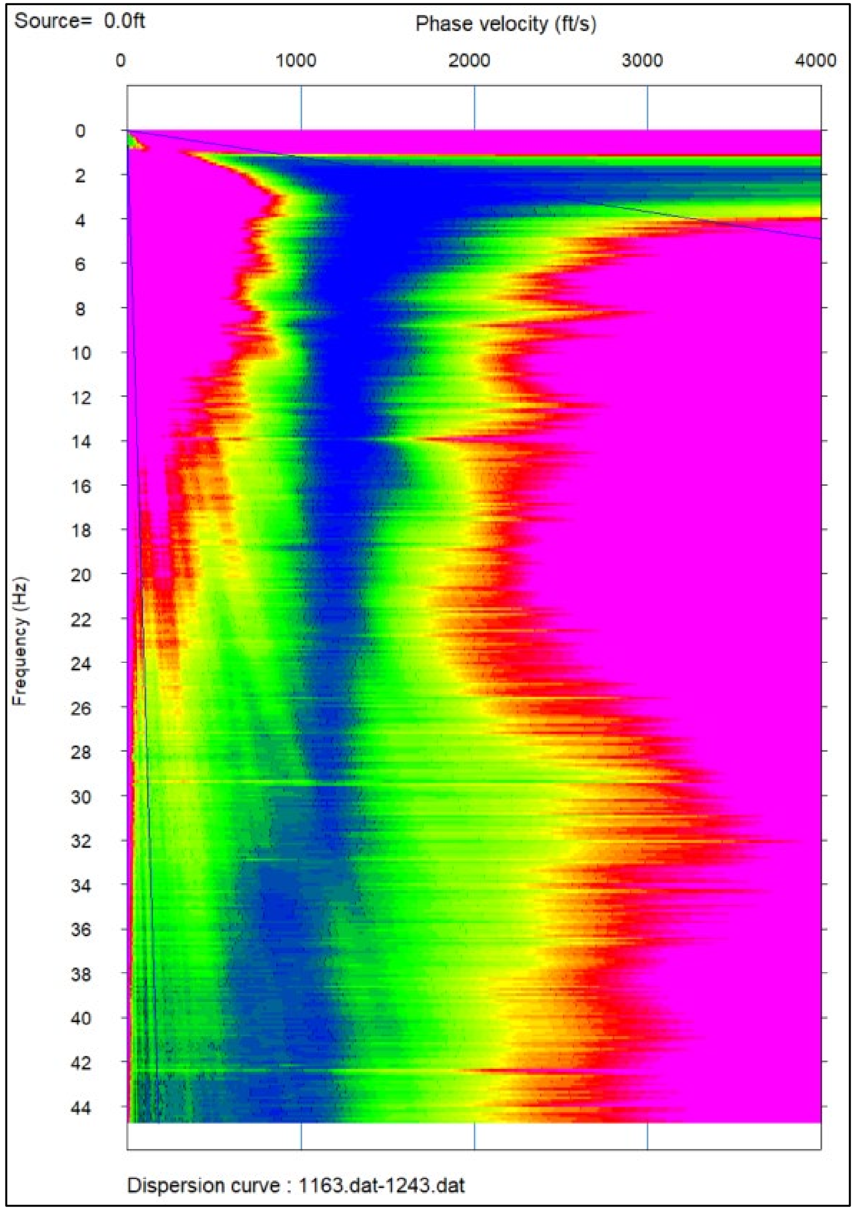
Microtremor Array Measurement (MAM)

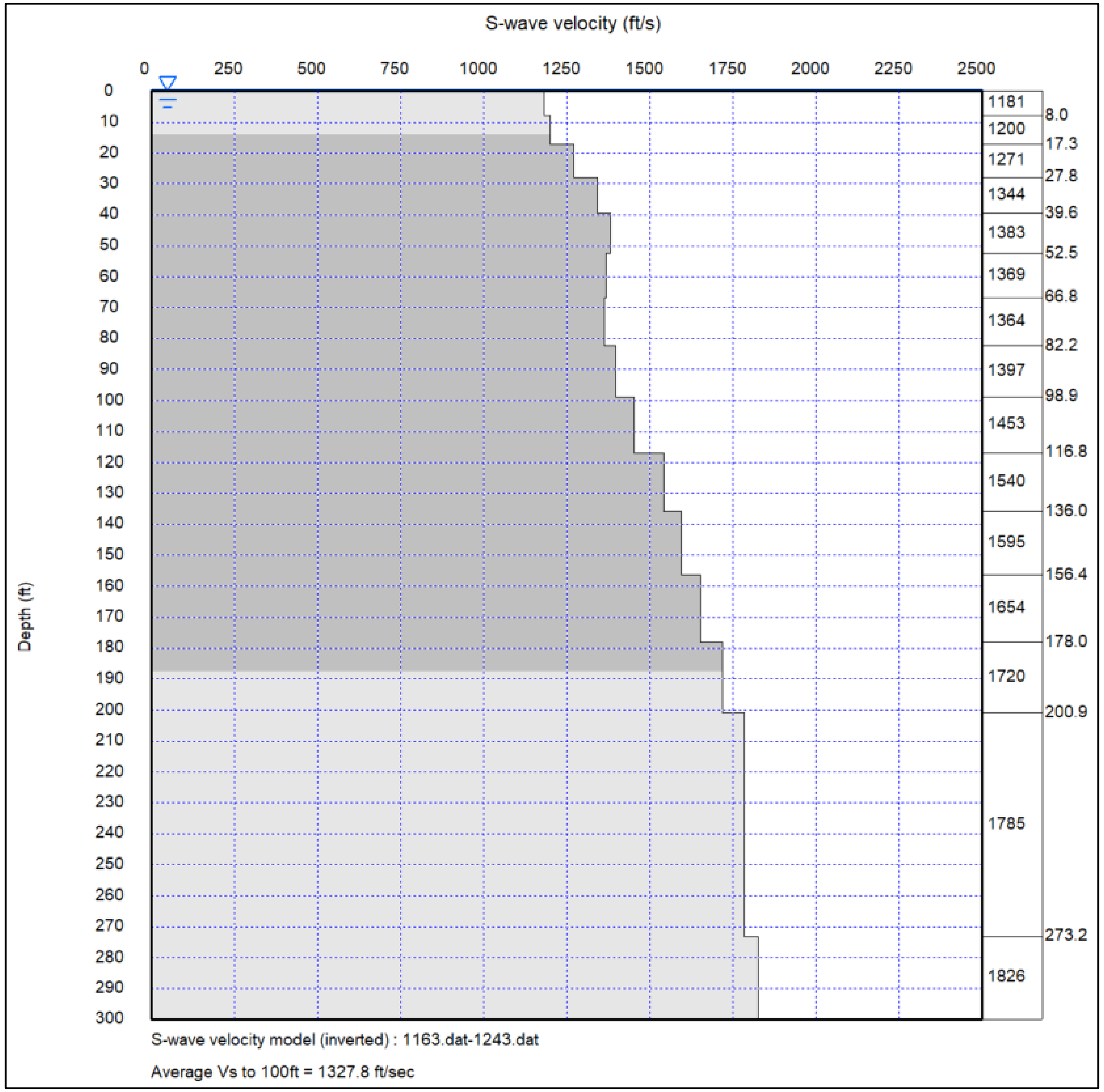
Passive Method where ambient seismic energy (wind, waves, cars, electricity, etc) is recorded over a longer time period






Source= 0.0m
Time (ms)
0
2000
4000
6000
8000
10000
12000
14000
16000
18000
20000
22000
24000
26000
28000
30000
32000
34000
Distance (m)
0
2
4
6
8
10
12
14
16
18
20
22
24
Trigger
1019.dat


Source= 0.0ft
Phase velocity (ft/s)
0
1000
2000
3000
4000
Frequency (Hz)
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
34
36
38
40
42
44
Dispersion curve : 1163.dat-1243.dat


S-wave velocity (ft/s)
0
250
500
750
1000
1250
1500
1750
2000
2250
2500
Depth (ft)
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
200
210
220
230
240
250
260
270
280
290
300
1181
8.0
1200
17.3
1271
27.8
1344
39.6
1383
52.5
1369
66.8
1364
82.2
1397
98.9
1453
116.8
1540
136.0
1595
156.4
1654
178.0
1720
200.9
1785
273.2
1826
S-wave velocity model (inverted) : 1163.dat-1243.dat
Average Vs to 100ft = 1327.8 ft/sec

MAM Summary

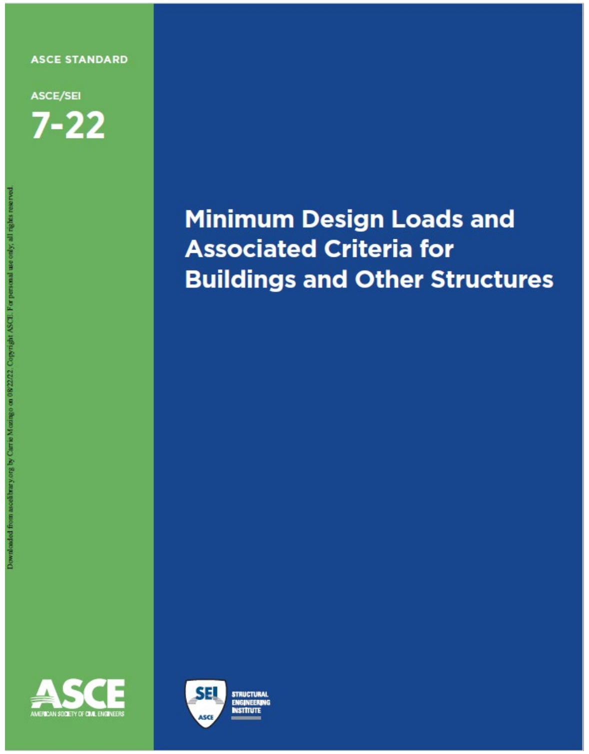
Like MASW, MAM is a fast, cost effective & noninvasive technique to evaluate VS100

Excellent for profiling to depths of much greater than 100 feet

Sensitive to noise – needs some but not too much

Lack of high frequency data can leave gap in shallow Vs data

Can be combined with MASW to give comprehensive VS100 profile



ASCE 7-22

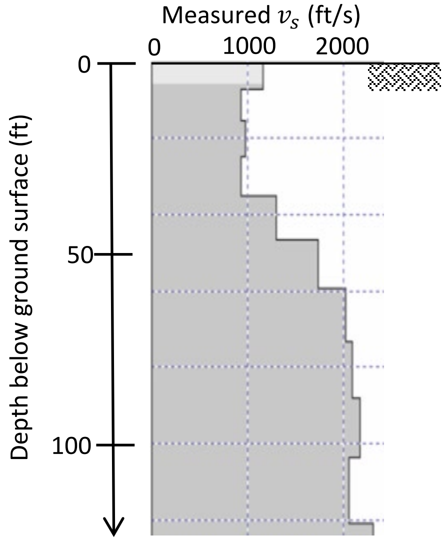
The new standards do allow for correlations

20.3 ESTIMATION OF SHEAR WAVE VELOCITY PROFILES

Where measured shear wave velocity data are not available, shear wave velocity shall be estimated as a function of depth using correlations with suitable geotechnical parameters, including standard penetration test (SPT) blow counts, shear strength, overburden pressure, void ratio, or cone penetration test (CPT) tip resistance, measured at the site.

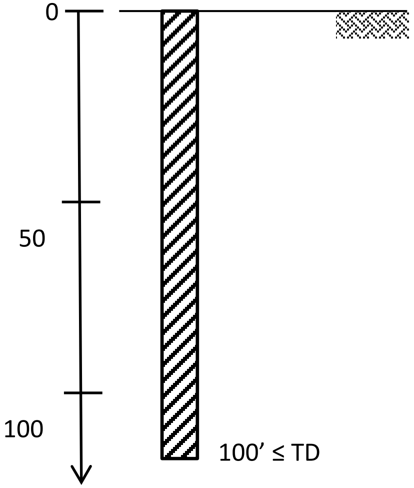
Site class based on estimated values of $\bar{v}_s$ shall be derived using $\bar{v}_s$, $\bar{v}_s/1.3$, and $1.3\bar{v}_s$ when correlation models are used to derive shear wave velocities. Where correlations derived for specific local

$\bar{v}_s$ calculated from measured shear wave velocity profile.



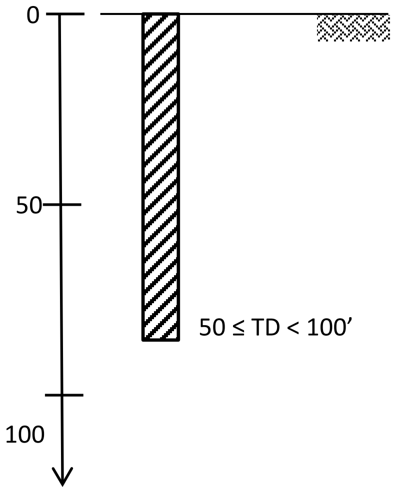
“Gold Standard.” No penalty.

Estimate $\bar{v}_s$ using correlations from blow counts measured in the field.



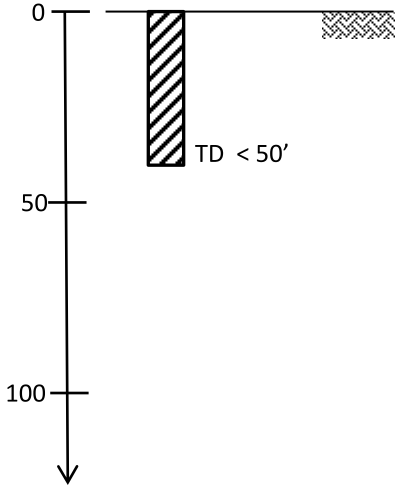
Penalized.
Use the $\bar{v}_s/1.3$ and $\bar{v}_s \times 1.3$ rule.

Estimate $\bar{v}_s$ using correlations from blow counts measured in the field.



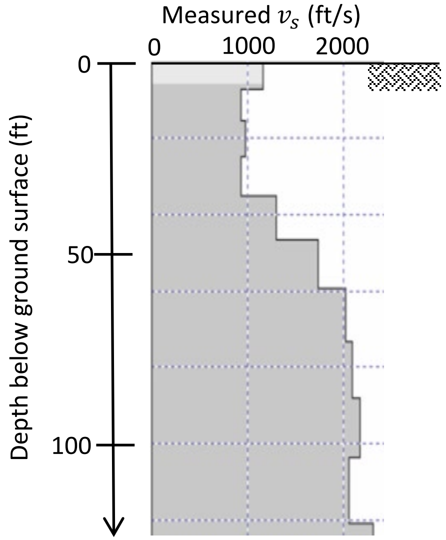
Penalized.
Use the $\bar{v}_s/1.3$ and $\bar{v}_s \times 1.3$ rule

Soil properties not known in sufficient detail to estimate $\bar{v}_s$.



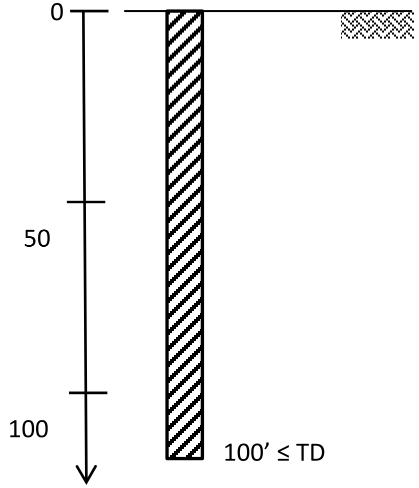
Heavily penalized.
Use “Default” Site Class

$\bar{v}_s$ calculated from measured shear wave velocity profile.



"Gold Standard." No penalty.

Estimate $\bar{v}_s$ using correlations from blow counts measured in the field.



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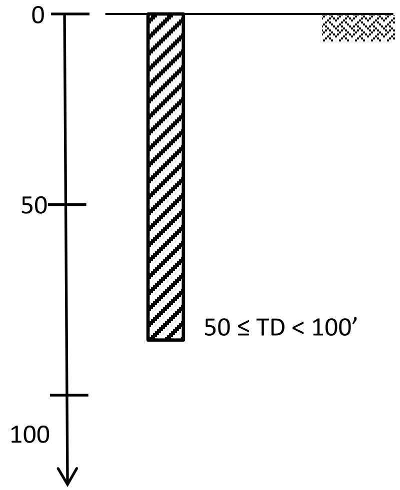

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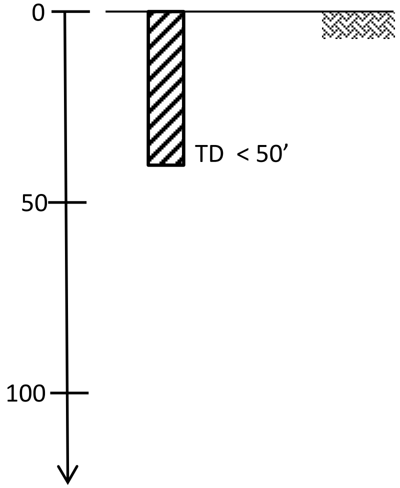

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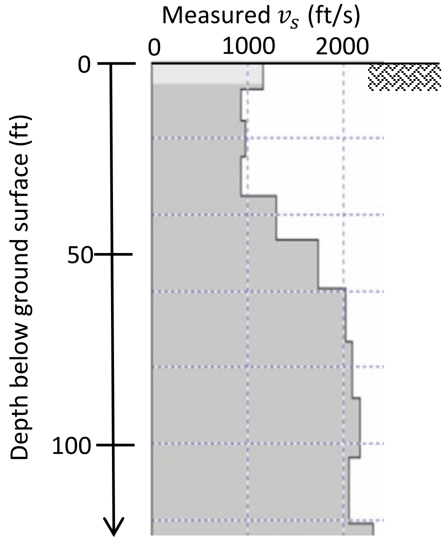

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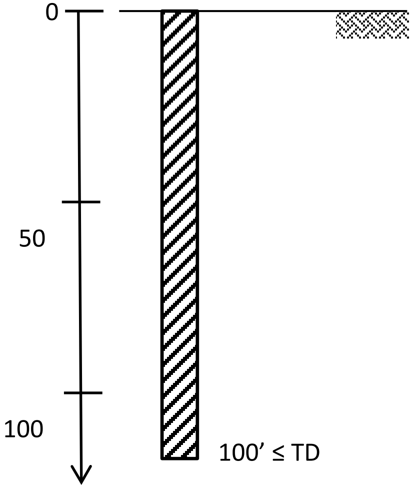

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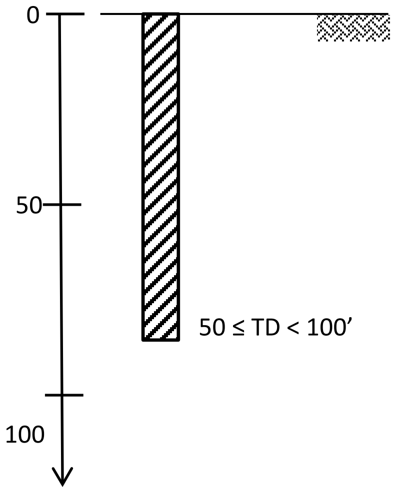

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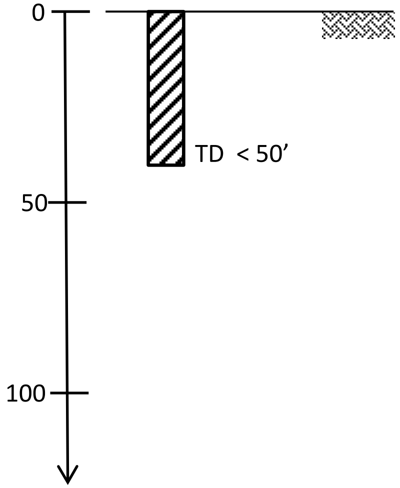

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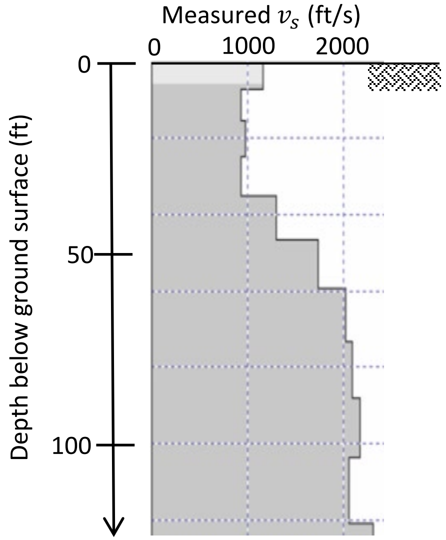

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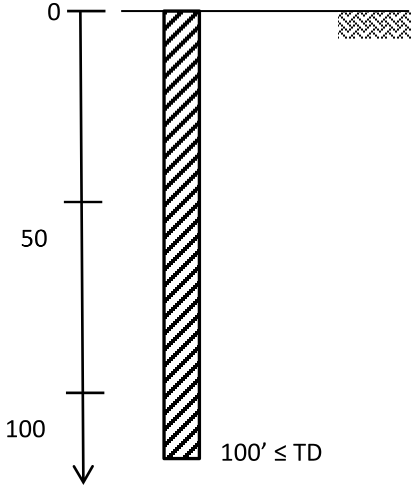

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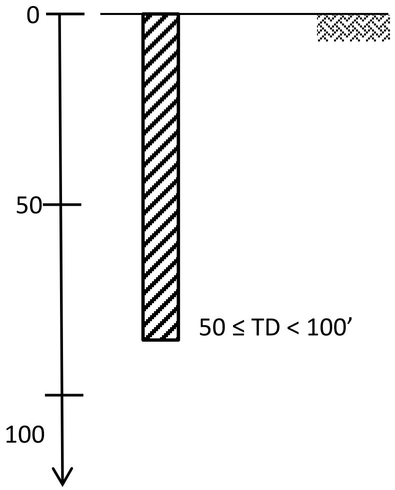

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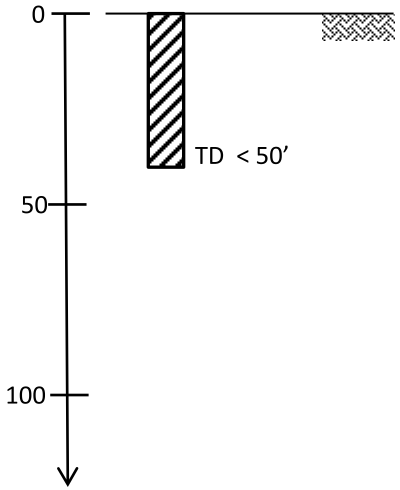

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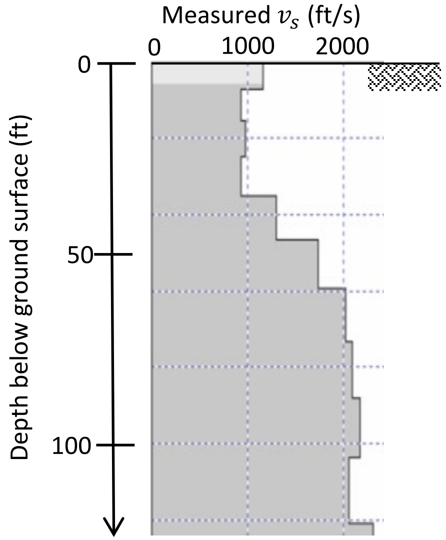

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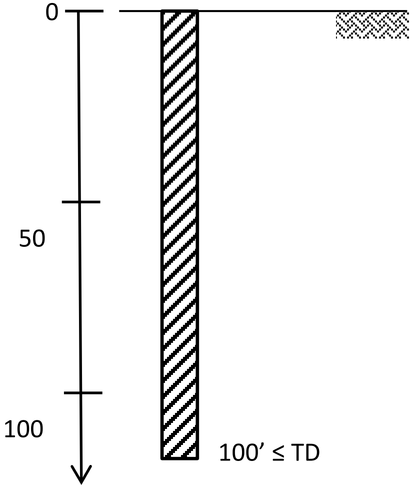

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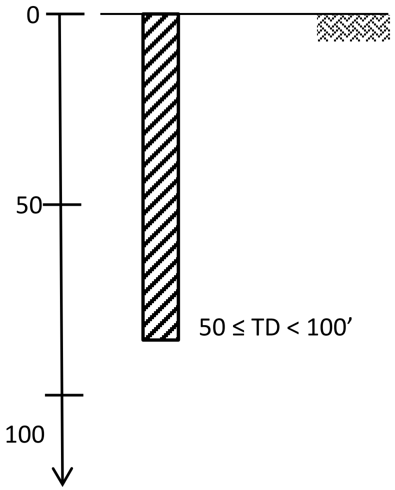

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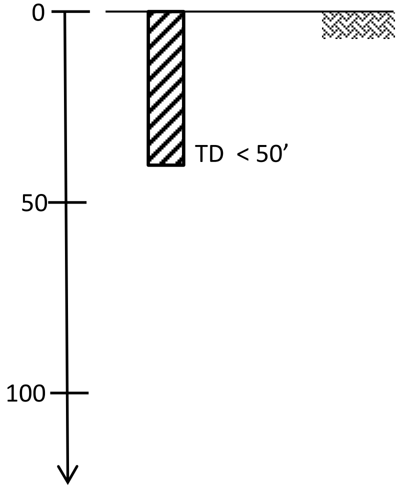

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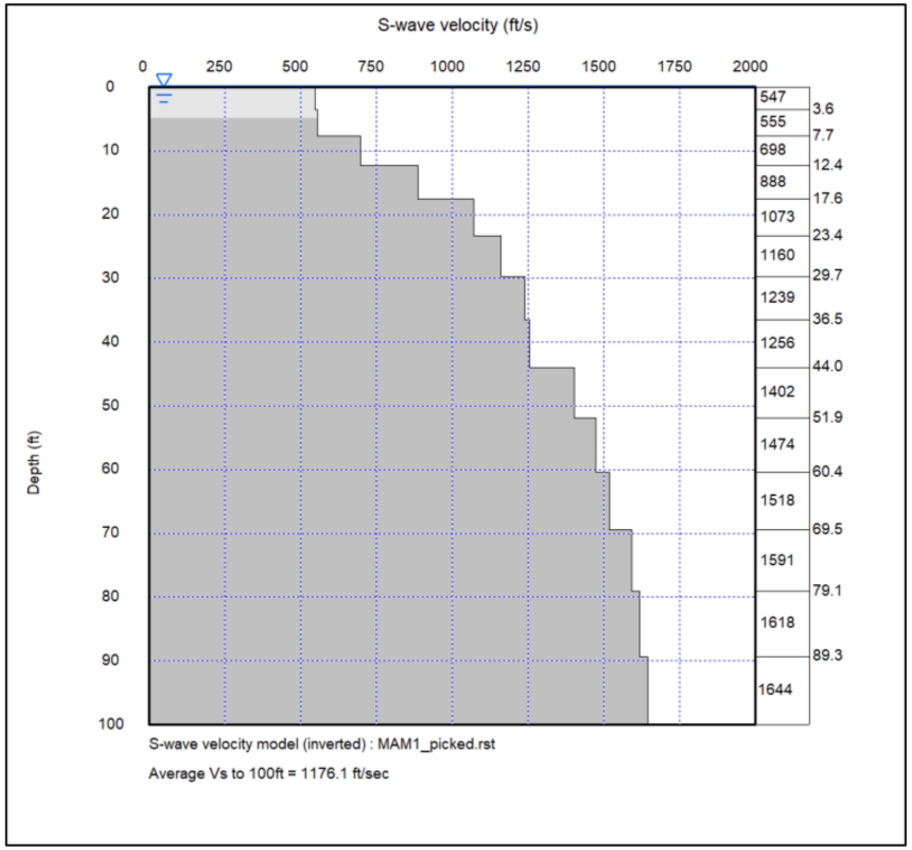
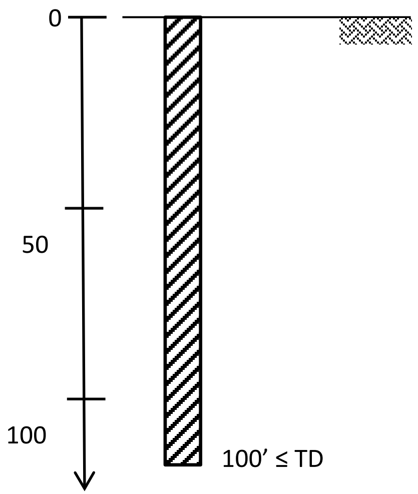


Table 20.2-1. Site Classification.

Site Class	$\bar{v}_s$ Calculated Using Measured or Estimated Shear Wave Velocity Profile (ft/s)
A. Hard rock	>5,000
B. Medium hard rock	>3,000 to 5,000
BC. Soft rock	>2,100 to 3,000
C. Very dense sand or hard clay	>1,450 to 2,100
CD. Dense sand or very stiff clay	>1,000 to 1,450
D. Medium dense sand or stiff clay	>700 to 1,000
DE. Loose sand or medium stiff clay	>500 to 700
E. Very loose sand or soft clay	≥500
F. Soils requiring site response analysis in accordance with Section 21.1	See Section 20.2.1

Note: For SI: 1 ft = 0.3048 m; 1 ft/s = 0.3048 m/s.

$\bar{v}_s$ = 1,176 ft/s



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F. Soils requiring site response analysis in accordance with Section 21.1	See Section 20.2.1

Note: For SI: 1 ft = 0.3048 m; 1 ft/s = 0.3048 m/s.

Use correlations to develop a shear wave velocity profile. Then:

$\bar{v}_s$ = 1,176 fps -> Site Class CD

$\bar{v}_s \div 1.3$ = 904 fps -> Site Class D

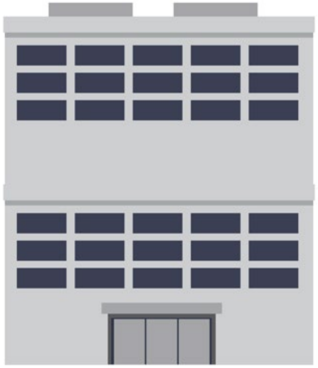
$\bar{v}_s \times 1.3$ = 1,529 fps -> Site Class C

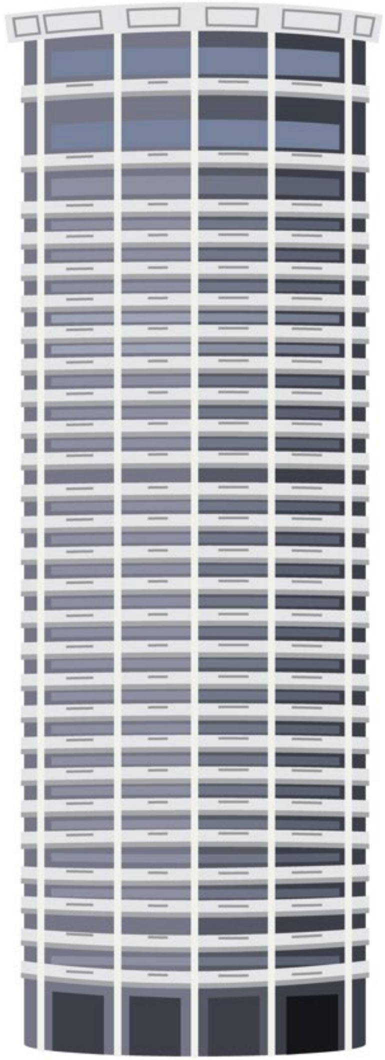
Seismic Design of Structures

Buildings have a natural period (T) which is the time it takes to vibrate back and forth

The natural period is generally a function of height and building stiffness

For many buildings, the period (in seconds) is about a tenth of the number of stories

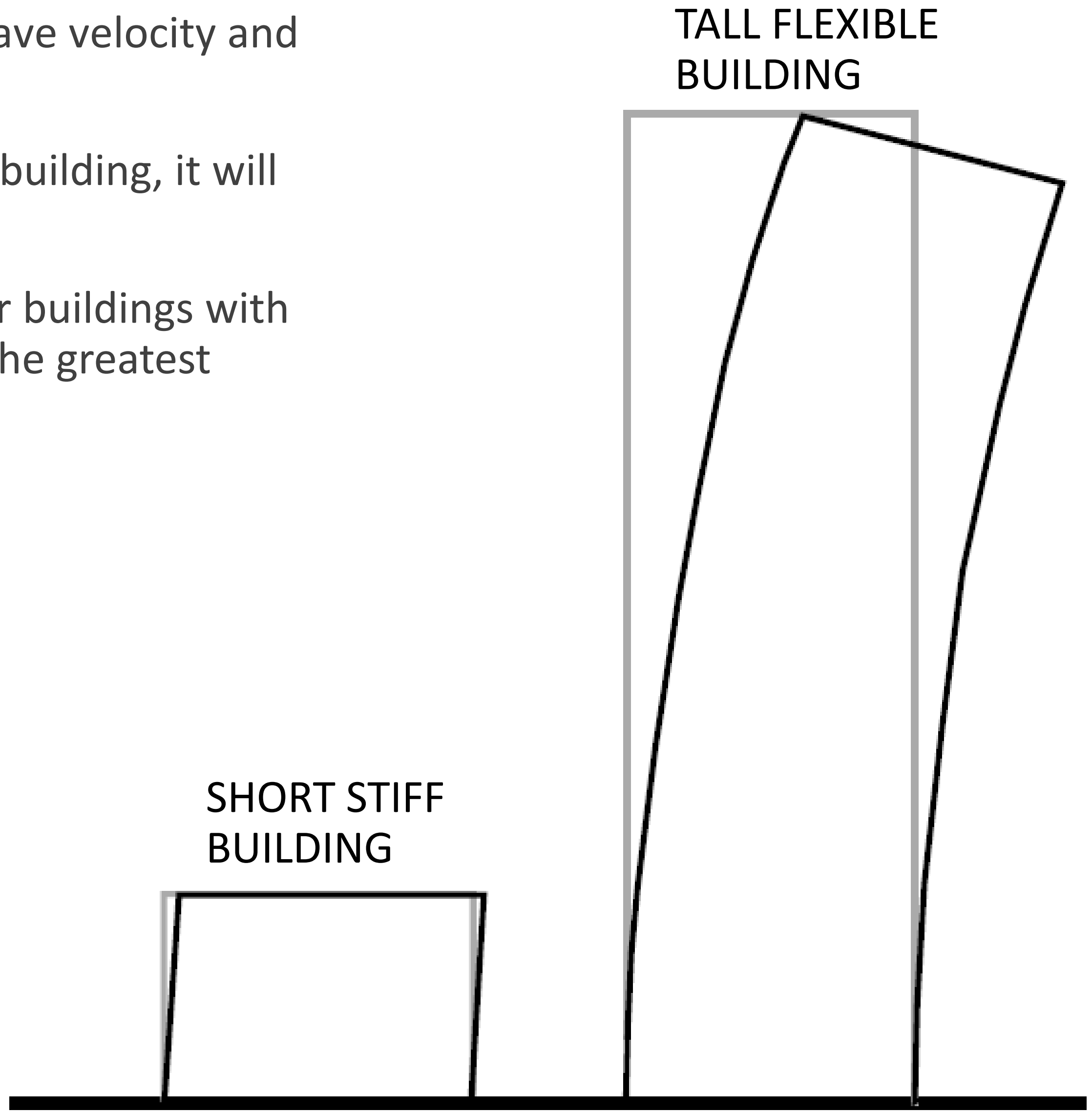




The soil profile has a resonant frequency dependent on its shear wave velocity and thickness

If the period of ground motion matches the natural resonance of a building, it will undergo the greatest oscillations and suffer the greatest damage

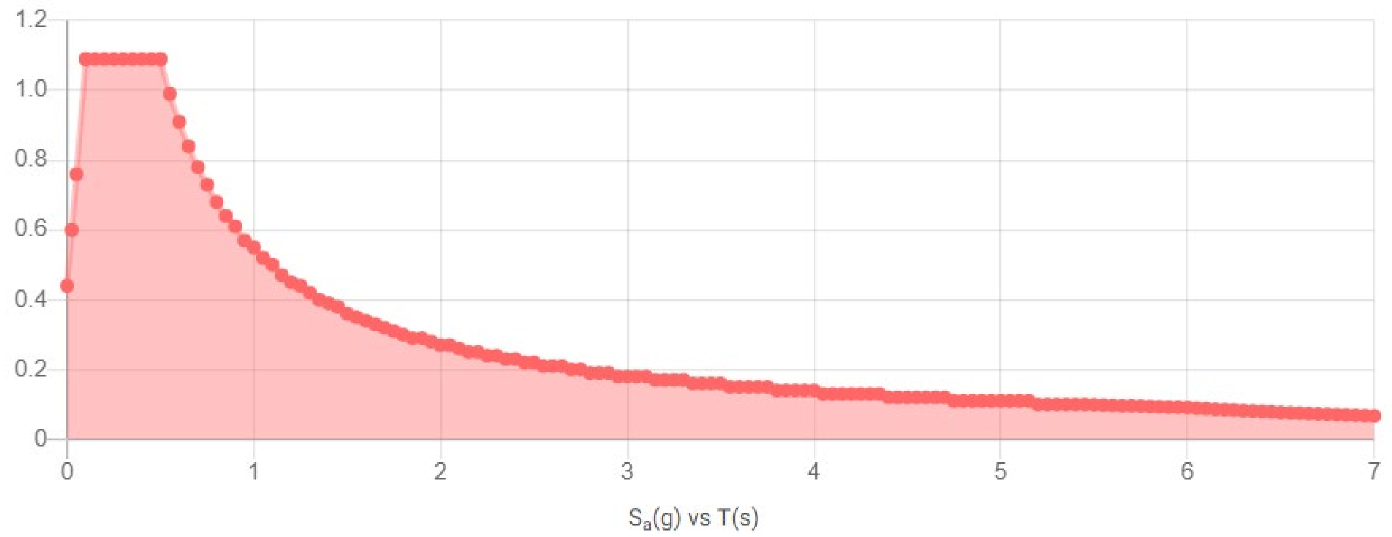
Hard bedrock has higher frequencies and therefore vibrates shorter buildings with short periods and high resonant frequencies while soft soils cause the greatest damage to tall buildings with low resonant frequencies



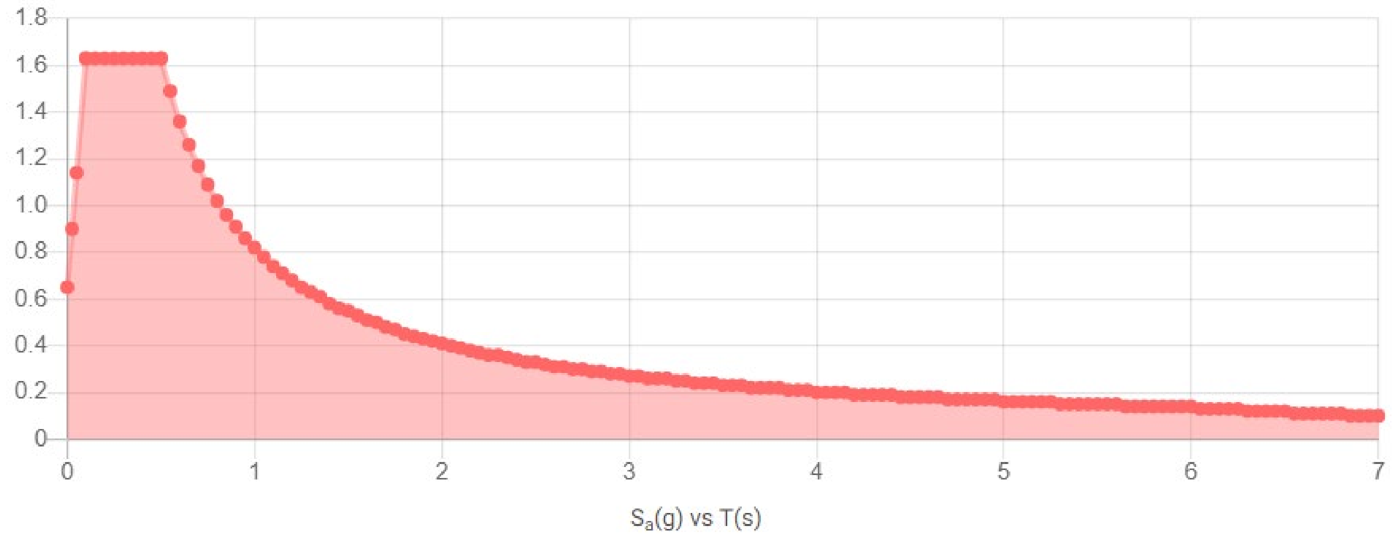
Spectral Acceleration

- During an earthquake, the building oscillations, or vibrations create forces on the structure due to the acceleration and mass of the building (F=MA)
- The top of a building that is oscillating or swaying in an earthquake can develop a greater acceleration than at the base. This is described as spectral acceleration
- Spectral acceleration is the maximum force experienced by a mass on top of a rod having a particular vibration.
- Accelerations from a large earthquake are comparable to what you might feel maneuvering tight turns in a sports car

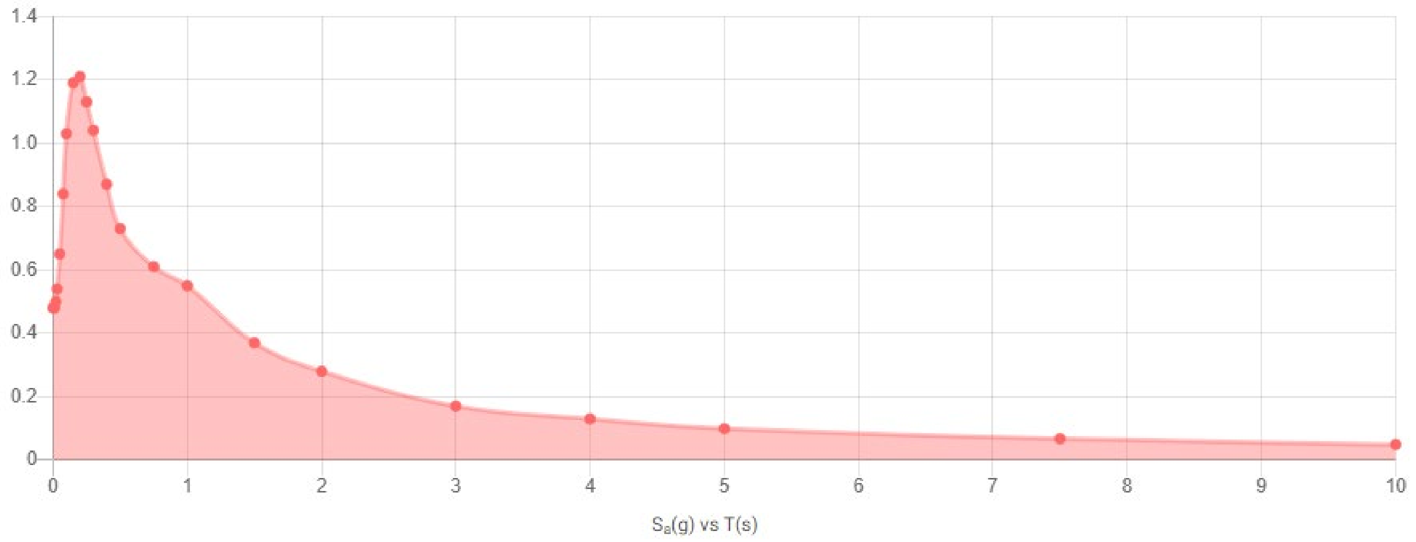
ASCE 7-16 Two-period Design Response Spectrum



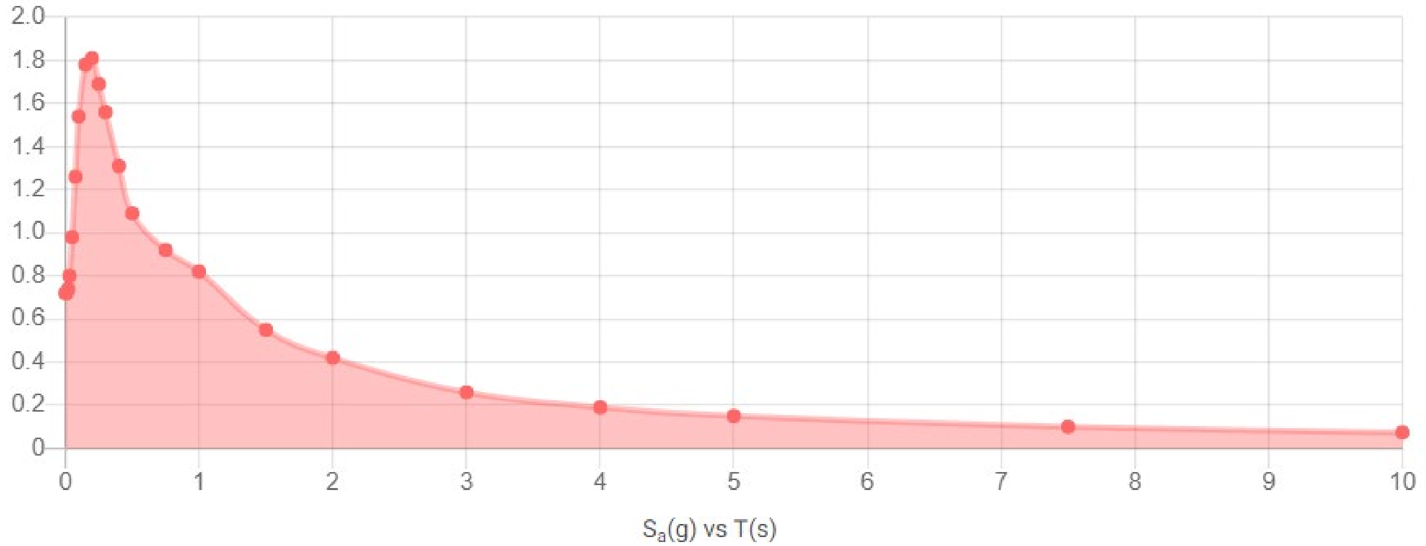
ASCE 7-16 Two-period Risk-Targeted Maximum Considered Earthquake Response (MCE_R) Response Spectrum



ASCE 7-22 Multi-period Design Response Spectrum

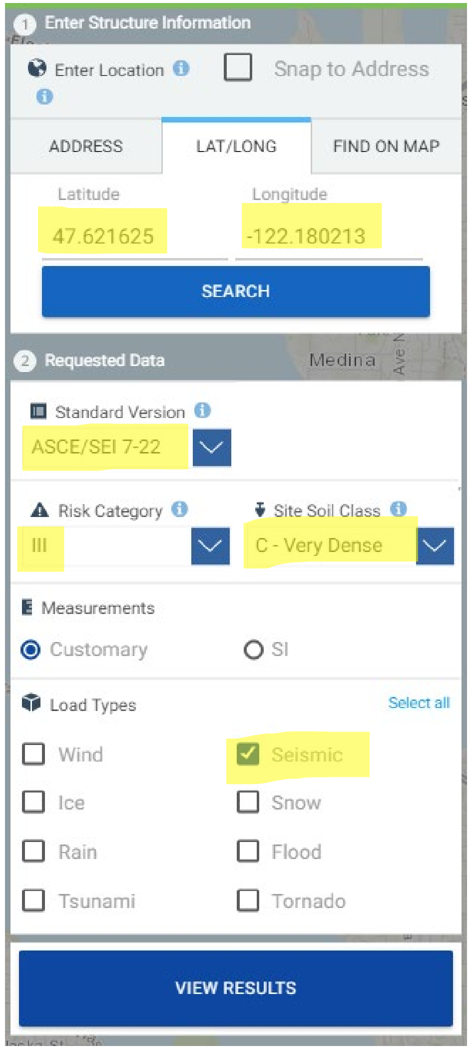


ASCE 7-22 Multi-period Risk-Targeted Maximum Considered Earthquake Response (MCE_R) Response Spectrum

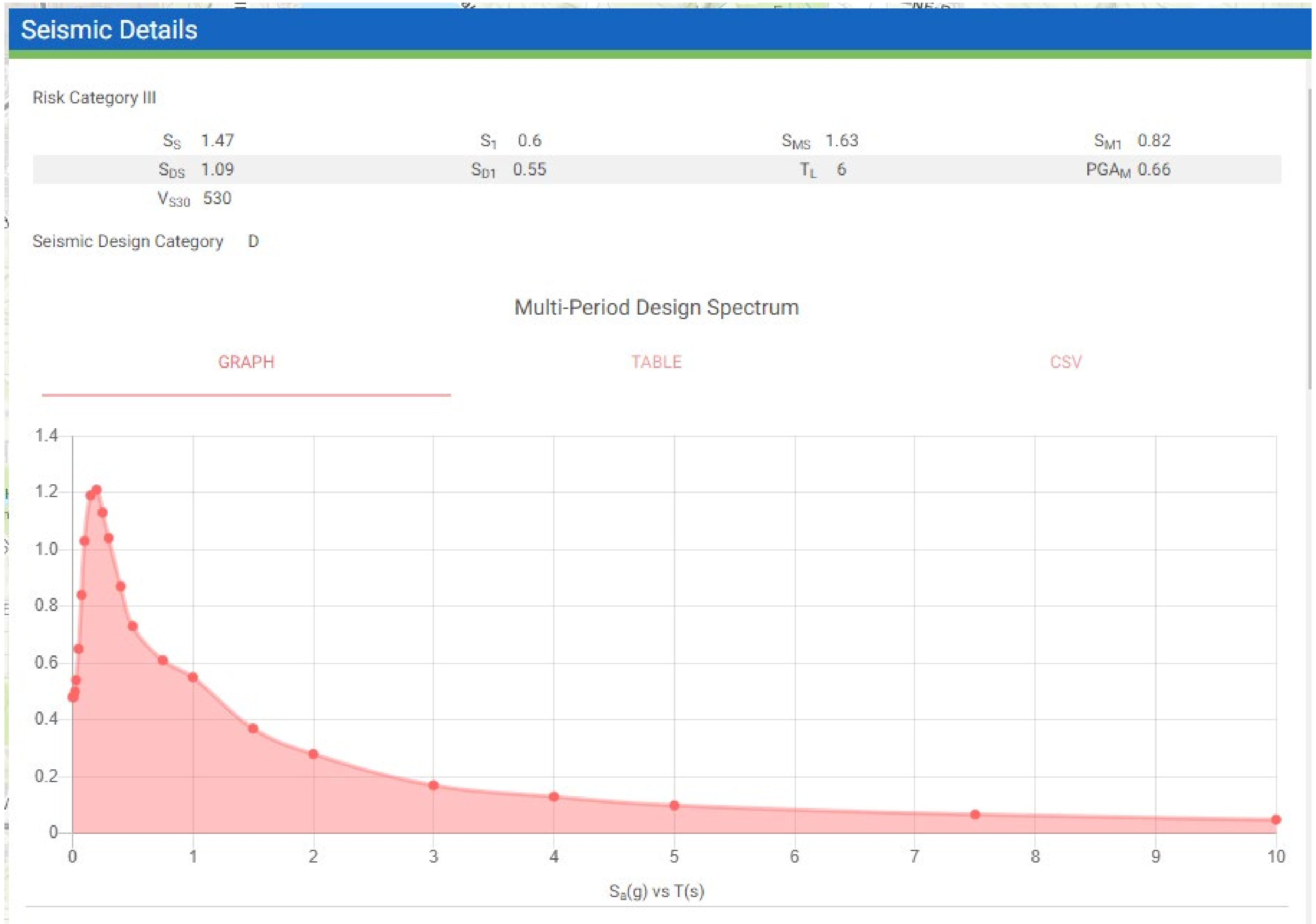


[ASCE 7 Hazard Tool]

ASCE 7-22 Multi-Period Response Spectrum

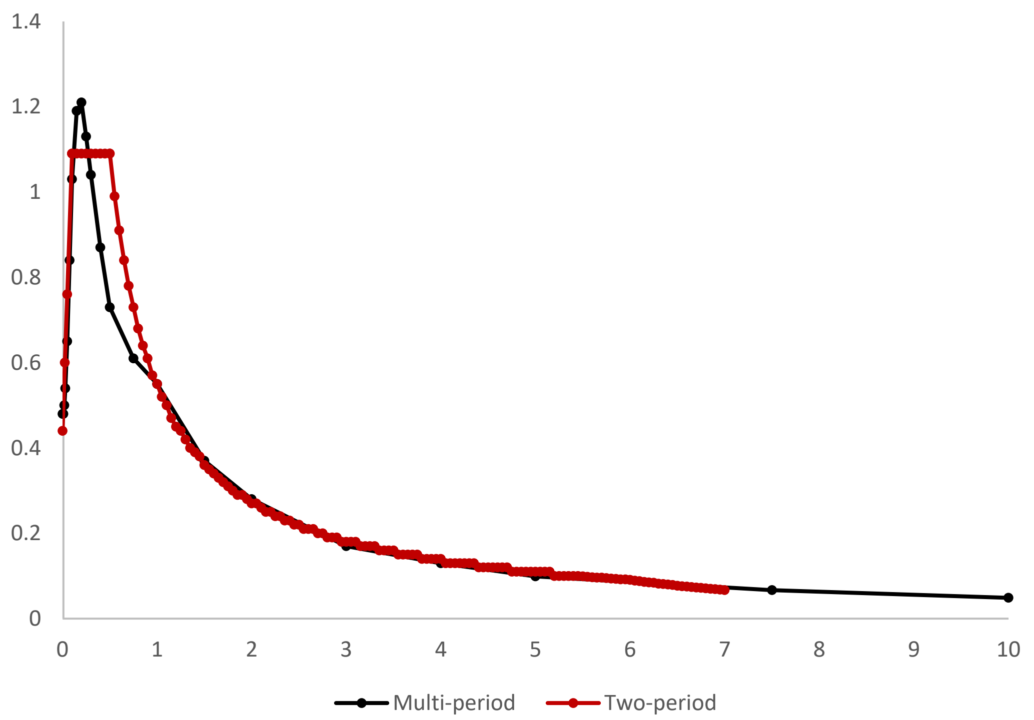


Input

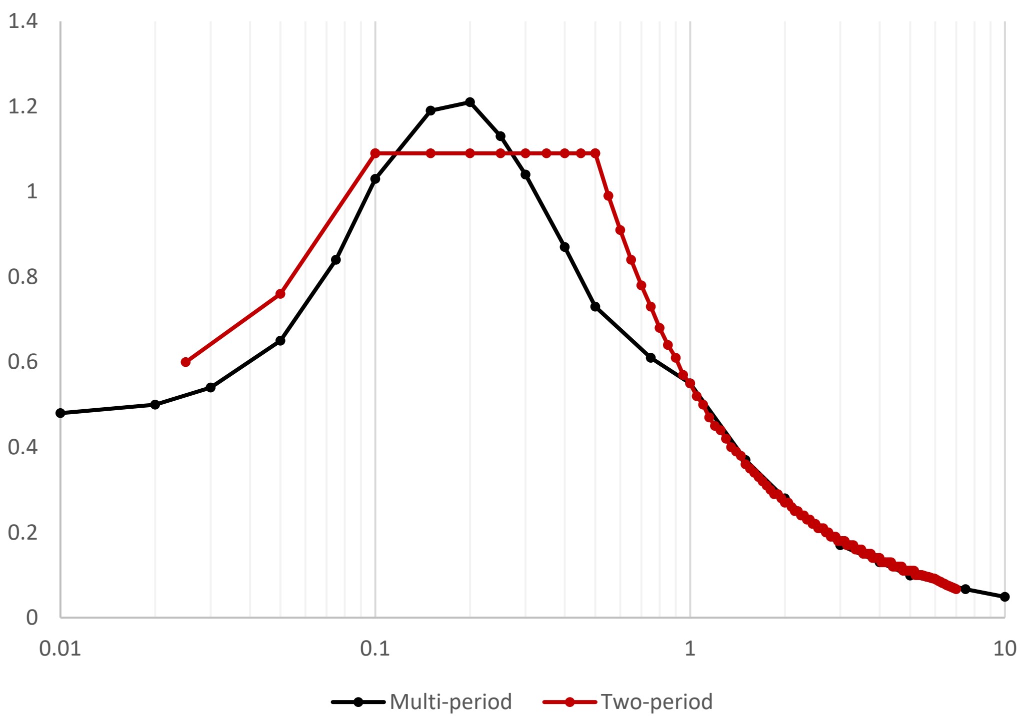


(Part of) Output

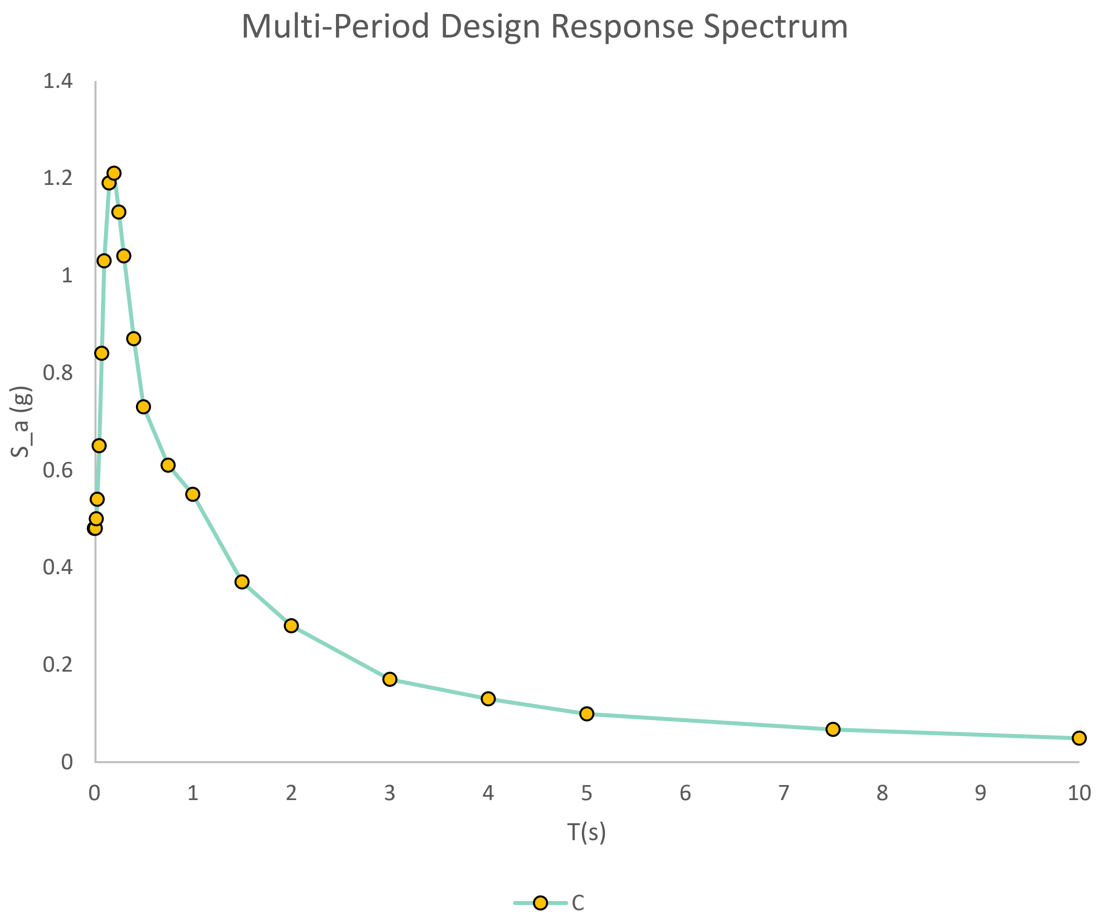
Multi-period and Two-period Design Response Spectra

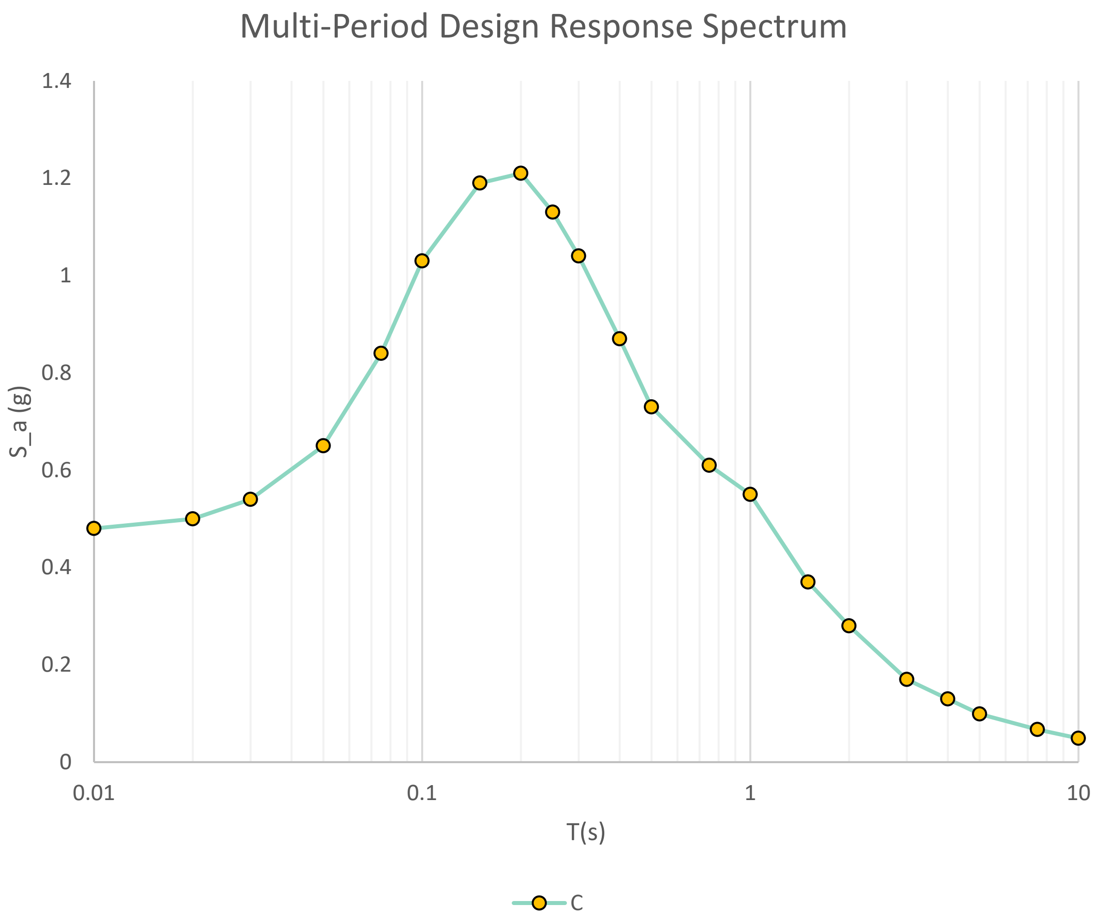


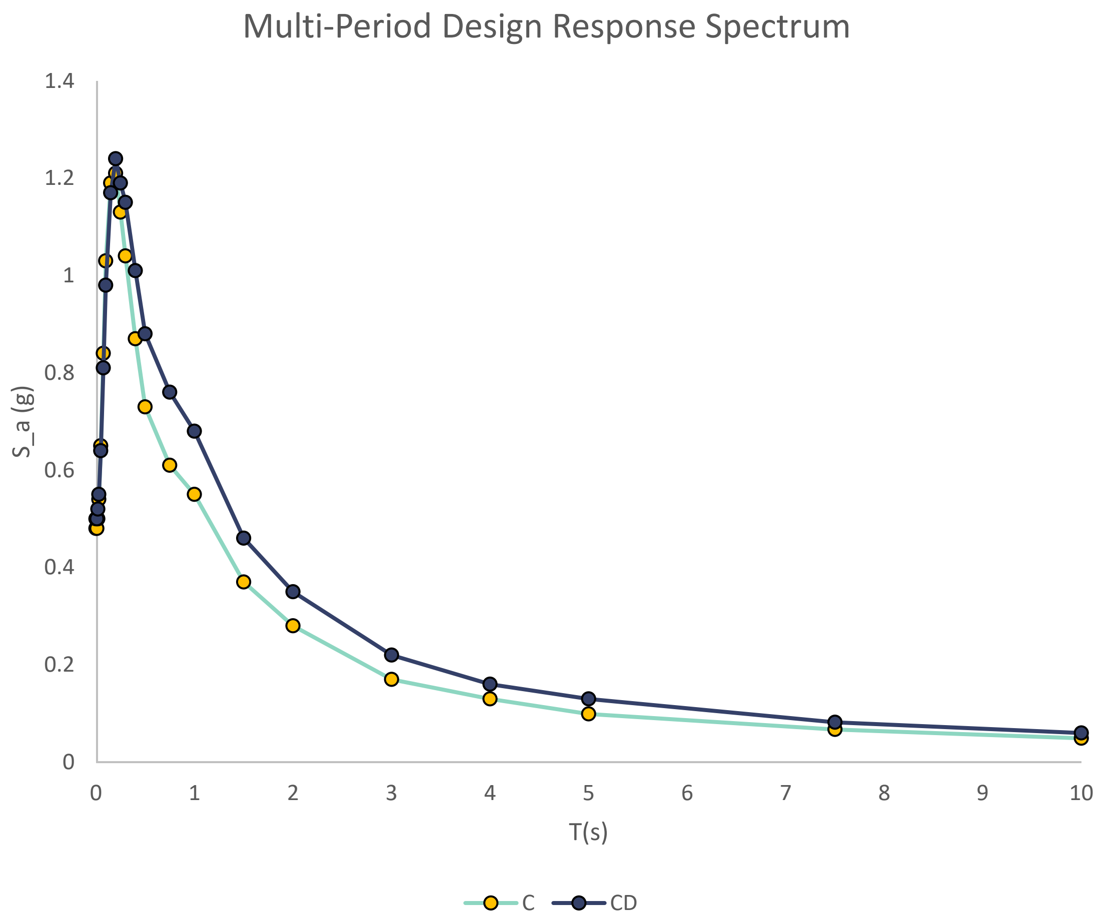
Natural Scale

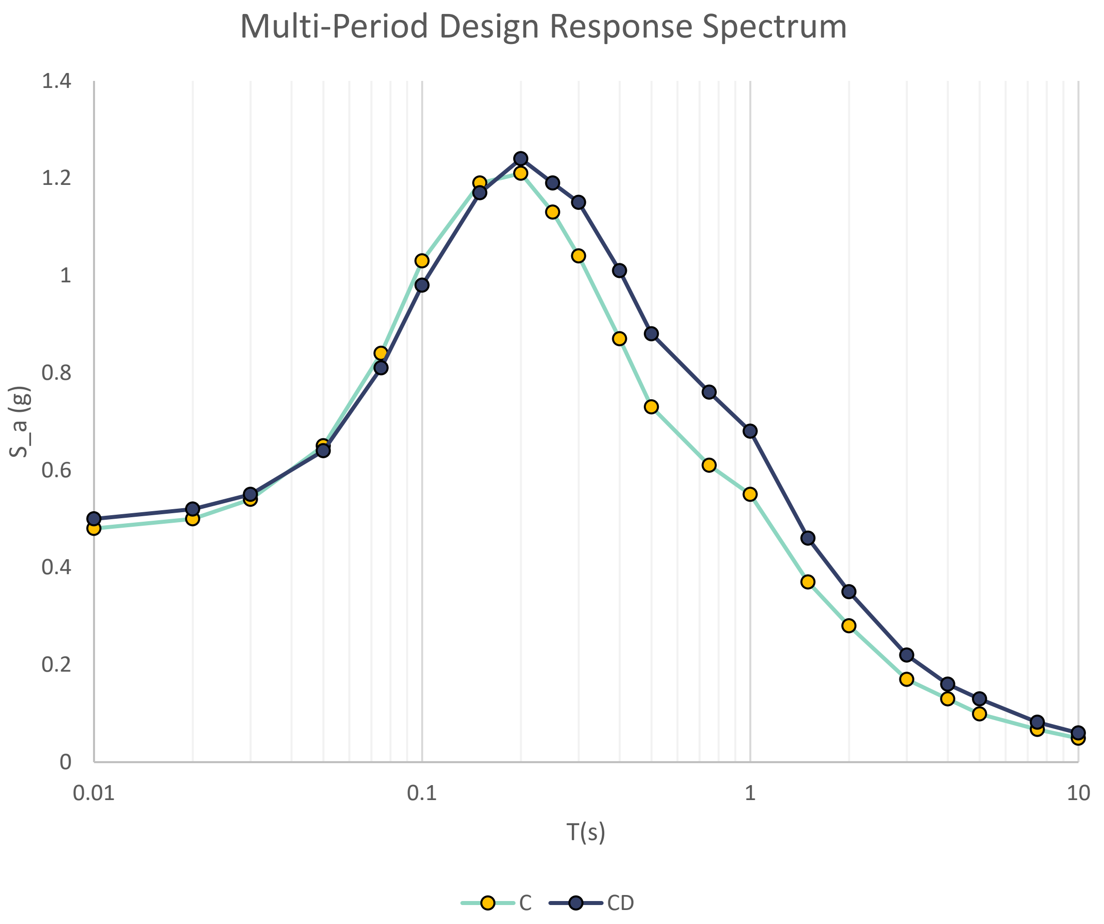


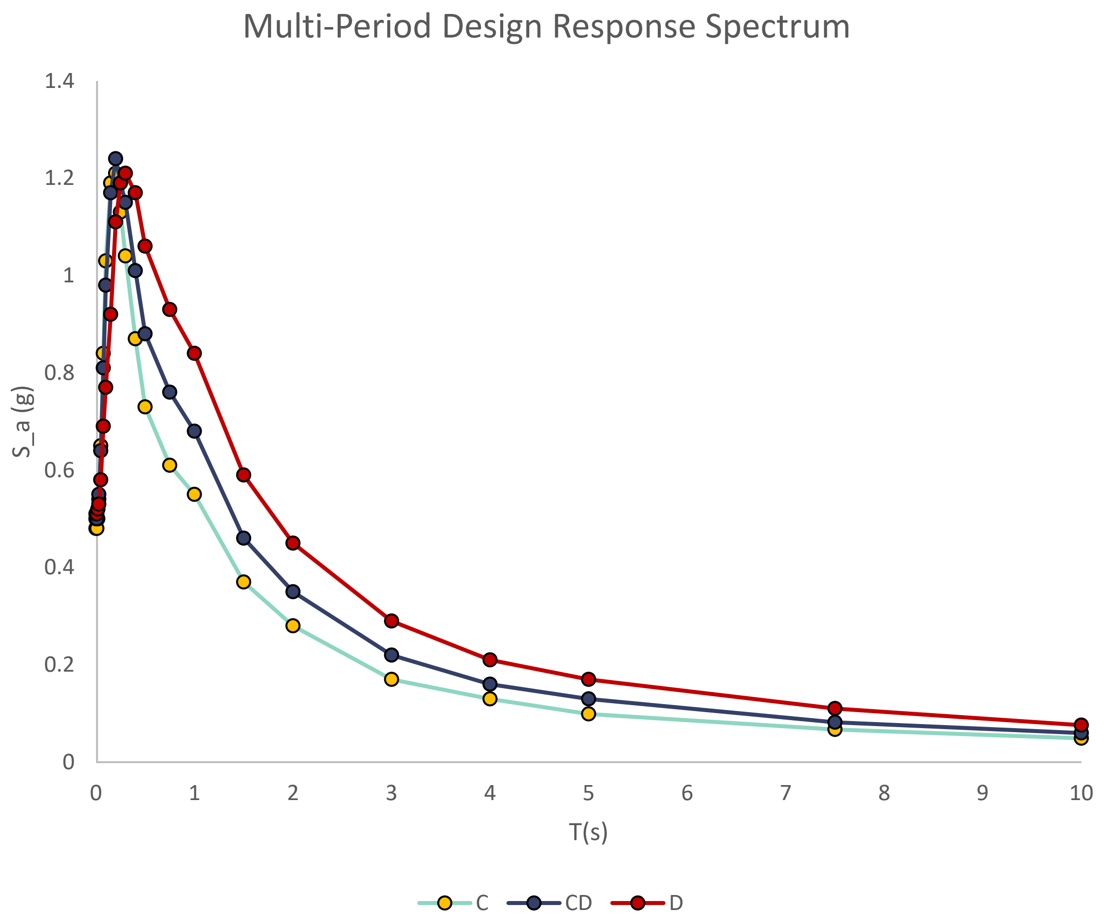
Log Scale

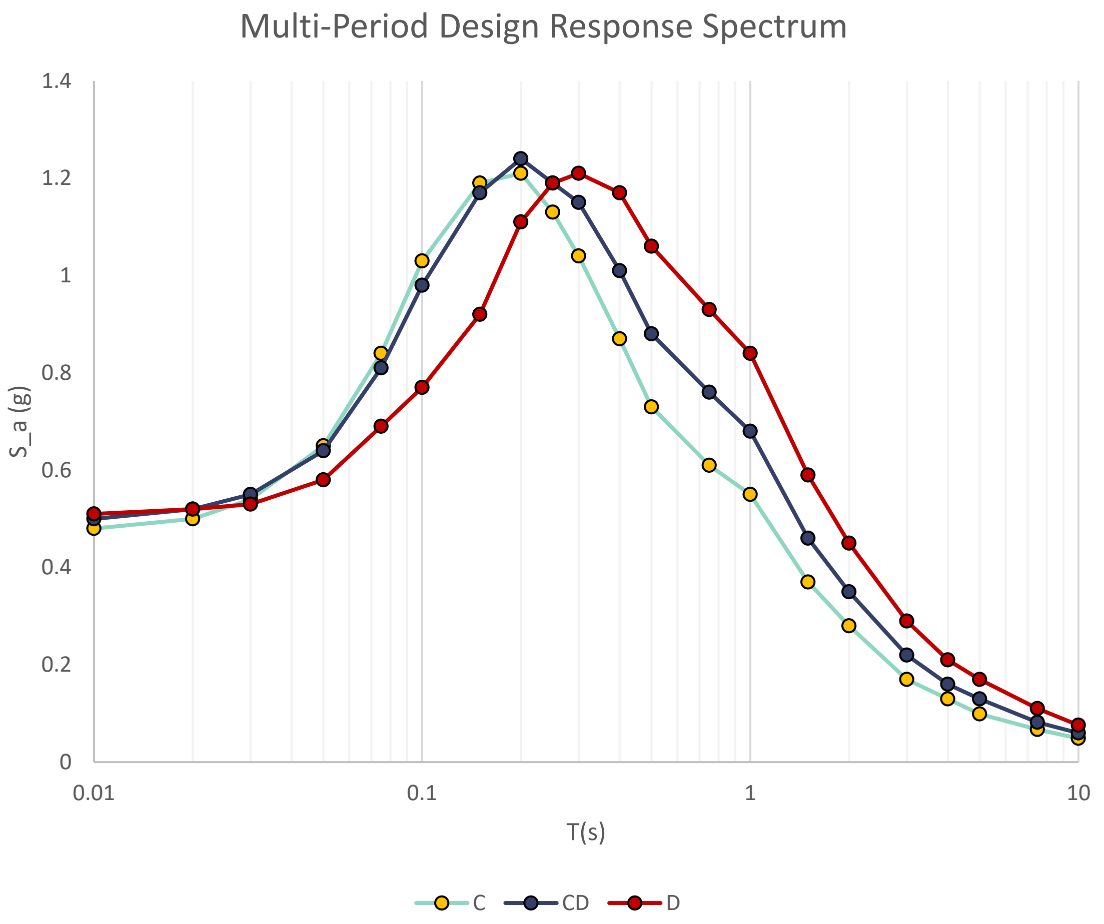

Multi-Period Design Response Spectrum
S_a (g)
T(s)
C

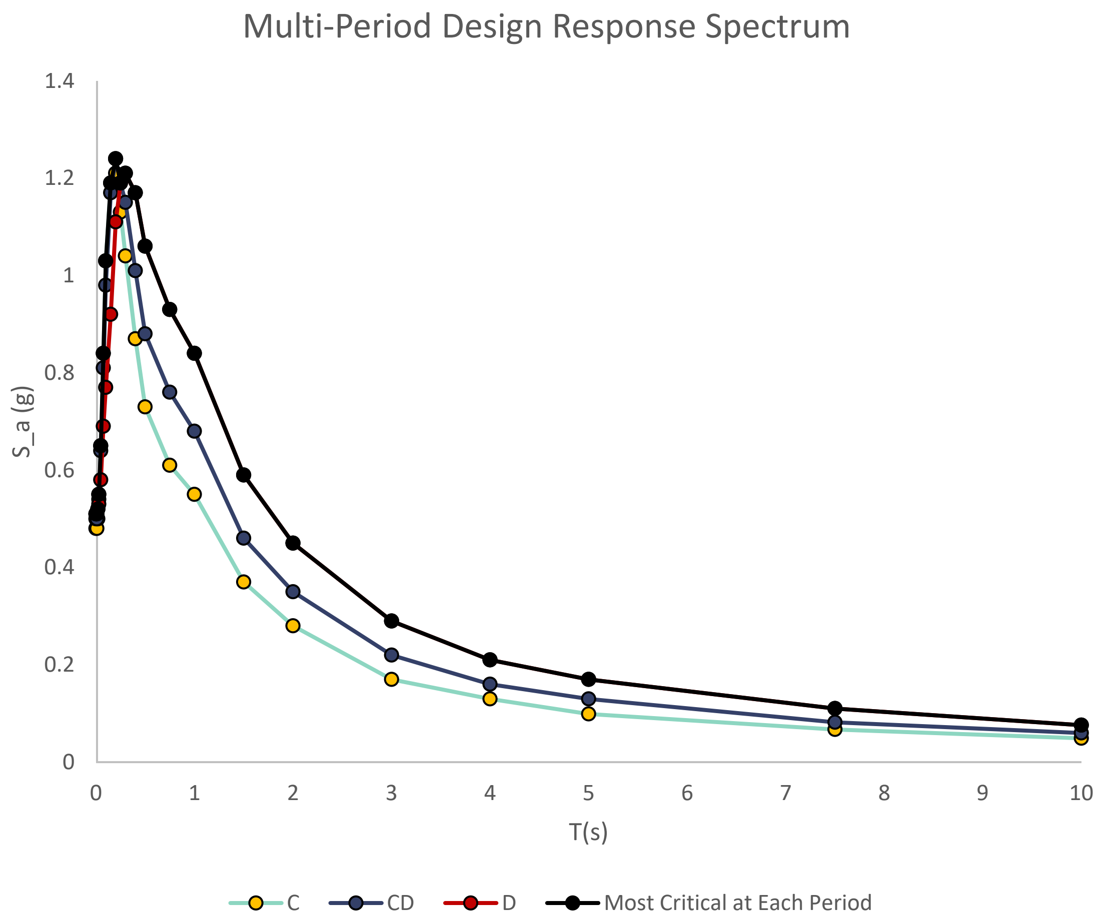

Multi-Period Design Response Spectrum
S_a (g)
T(s)
C


Multi-Period Design Response Spectrum
S_a (g)
T(s)
C
CD

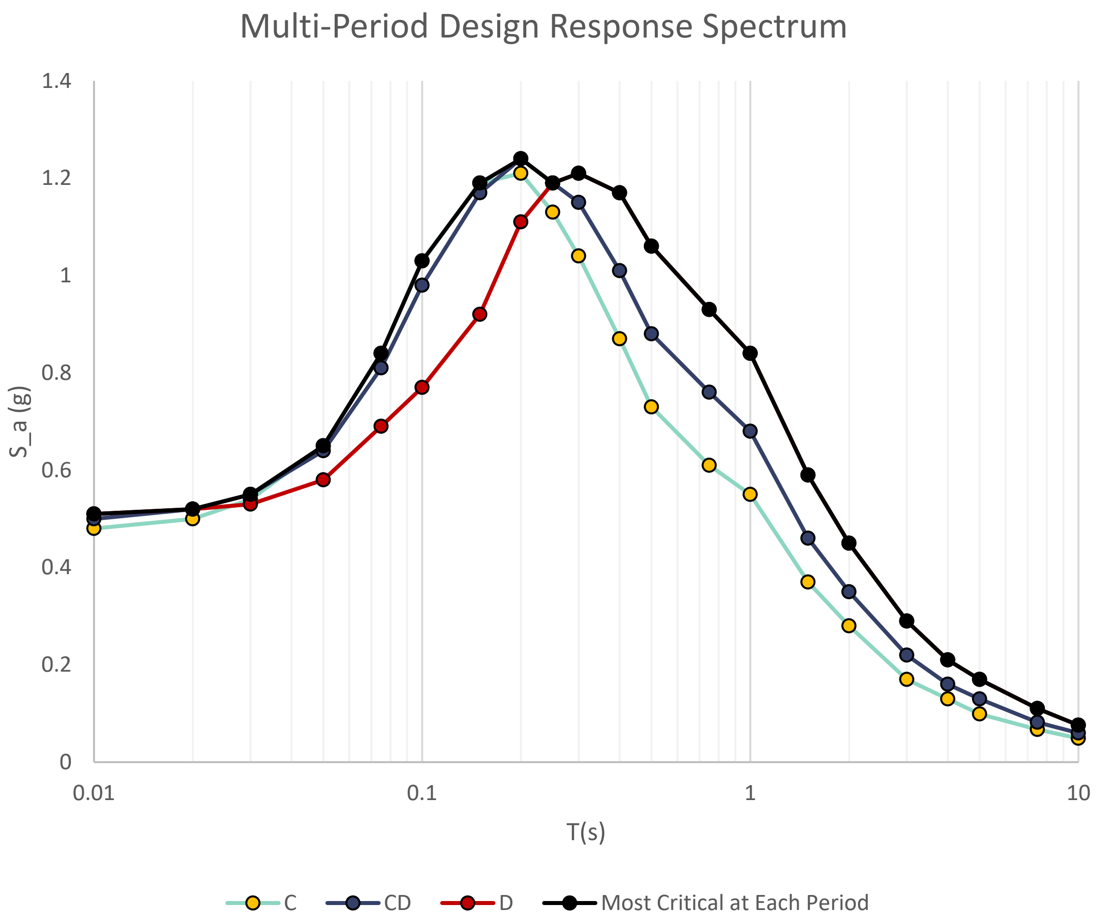

Multi-Period Design Response Spectrum
S_a (g)
T(s)
C
CD


Multi-Period Design Response Spectrum
S_a (g)
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
1
2
3
4
5
6
7
8
9
10
T(s)
C
CD
D

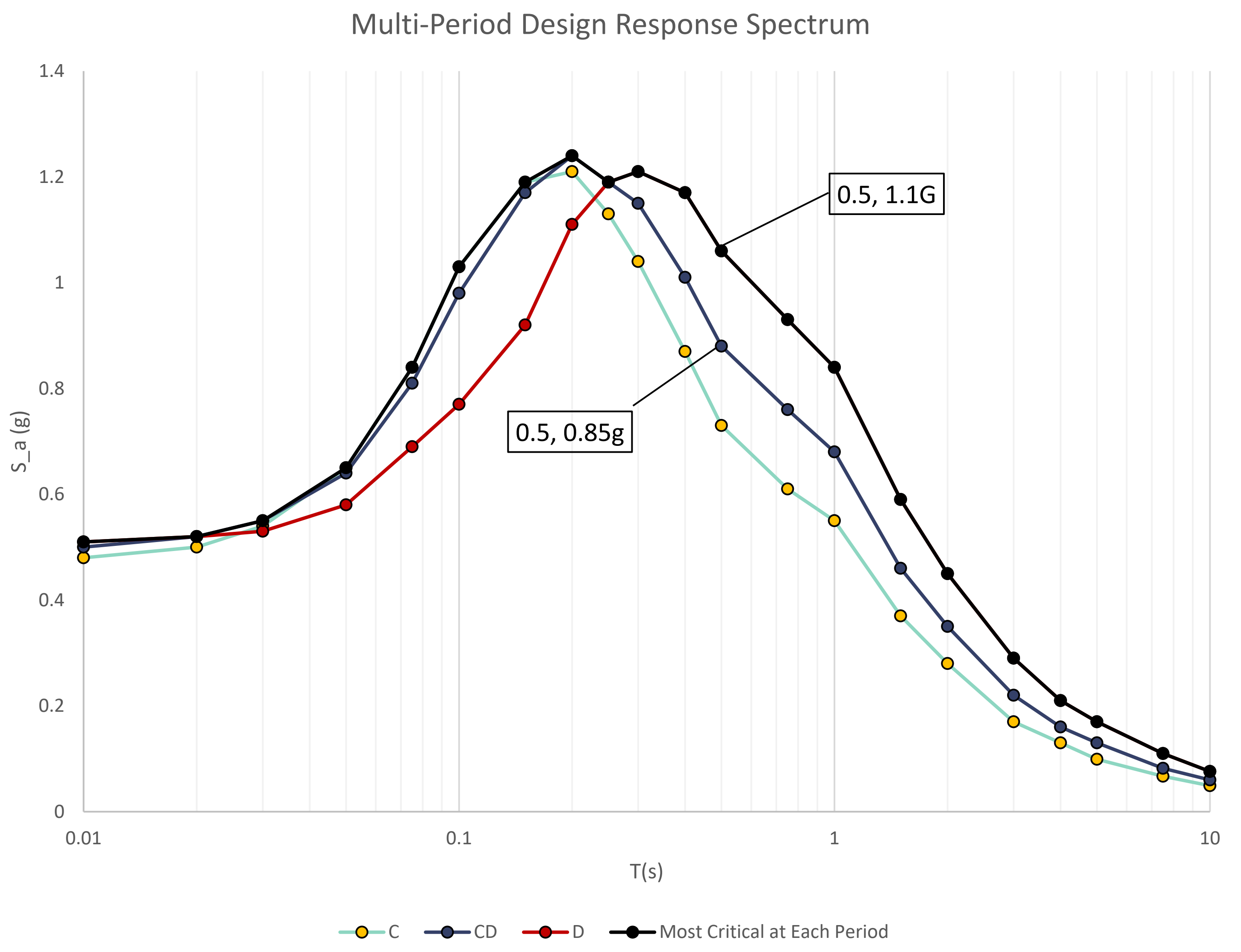

Multi-Period Design Response Spectrum
S_a (g)
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0.01
0.1
1
10
T(s)
C
CD
D



Multi-Period Design Response Spectrum
1.4
1.2
1
0.8
0.6
0.4
0.2
0
S_a (g)
0
1
2
3
4
5
6
7
8
9
10
T(s)
C
CD
D
Most Critical at Each Period



Multi-Period Design Response Spectrum
1.4
1.2
1
0.8
0.6
0.4
0.2
0
S_a (g)
0.01
0.1
1
10
T(s)
C
CD
D
Most Critical at Each Period



Multi-Period Design Response Spectrum
1.4
1.2
1
0.8
0.6
0.4
0.2
0
S_a (g)
0.01
0.1
1
10
T(s)
0.5, 1.1G
0.5, 0.85g
C
CD
D
Most Critical at Each Period

Conclusions

- Western Washington is at risk of large earthquakes
- These earthquakes send seismic waves that amplify in the near surface soft soils
- New building codes and seismic design standards require an in depth look at the upper 100 feet
- Site Classification using shear wave velocity testing is essential
- MAM and MASW methods are fast and cost-effective methods for developing a VS100 profile
- VS100 data can greatly reduce the spectral accelerations used in building design