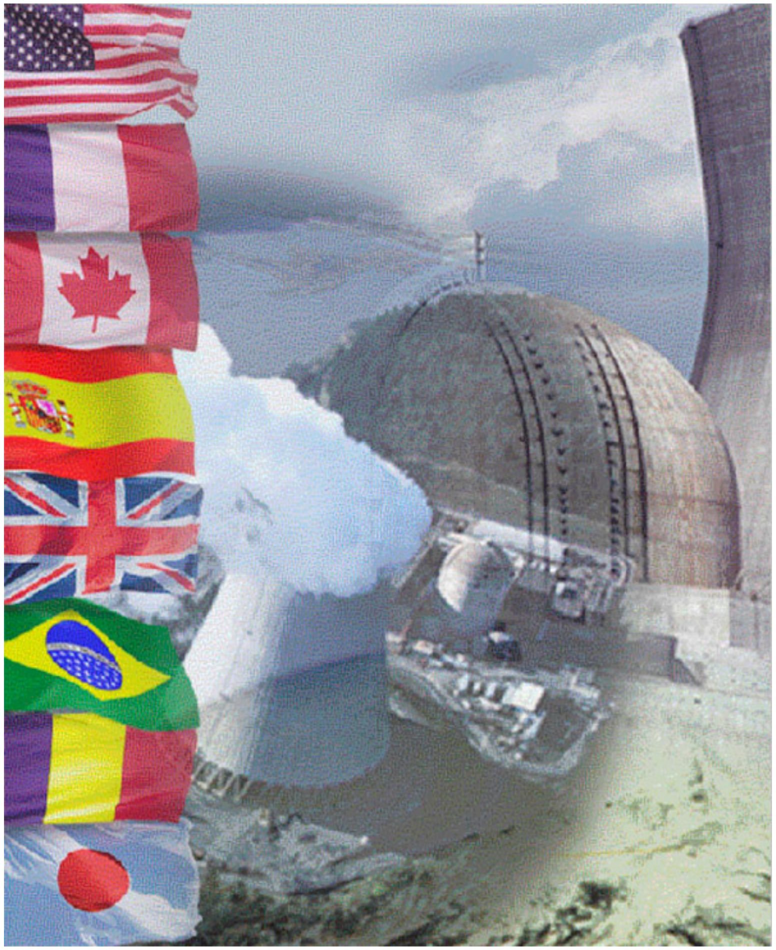


New Plant Seismic Issues Resolution Program

Task S2.1 – Effect of Seismic Wave Incoherence on Foundation and Building Response

Greg Hardy/Steve Short
Norm Abrahamson
Jim Johnson

October 2005

S2.1 Items for Discussion

- **Greg Hardy (ARES)**
  - Background
  - Objectives
  - Status and Required Studies
- **Norm Abrahamson (Consultant)**
  - Coherency Function Development
- **Jim Johnson (Consultant)**
  - Project Approach
  - Benchmark Problem Comparison
  - S2.1 Results

Motivation for S2.1 Task

- **Background**
  - Observations have shown that effective input motion to structures accounts for the averaging or integrating effects of the foundation especially for structures with large, relatively rigid foundations such as those at NPPs
  - Phenomenon was recognized early, but the lack of extensive recorded data prevented the incorporation of the effect into the dynamic analysis of NPP structures
- **Prior High Frequency Response Considerations Used Early (limited) Incoherence Data**
- **New research effort required to properly address incoherency**
  - Generate new coherency function based on all current applicable data
  - Objective of this study is to systematically study the ground motion incoherency effects on structures/foundations similar to those being considered for Advanced Reactor designs

Past NRC Acceptance – Diablo Canyon

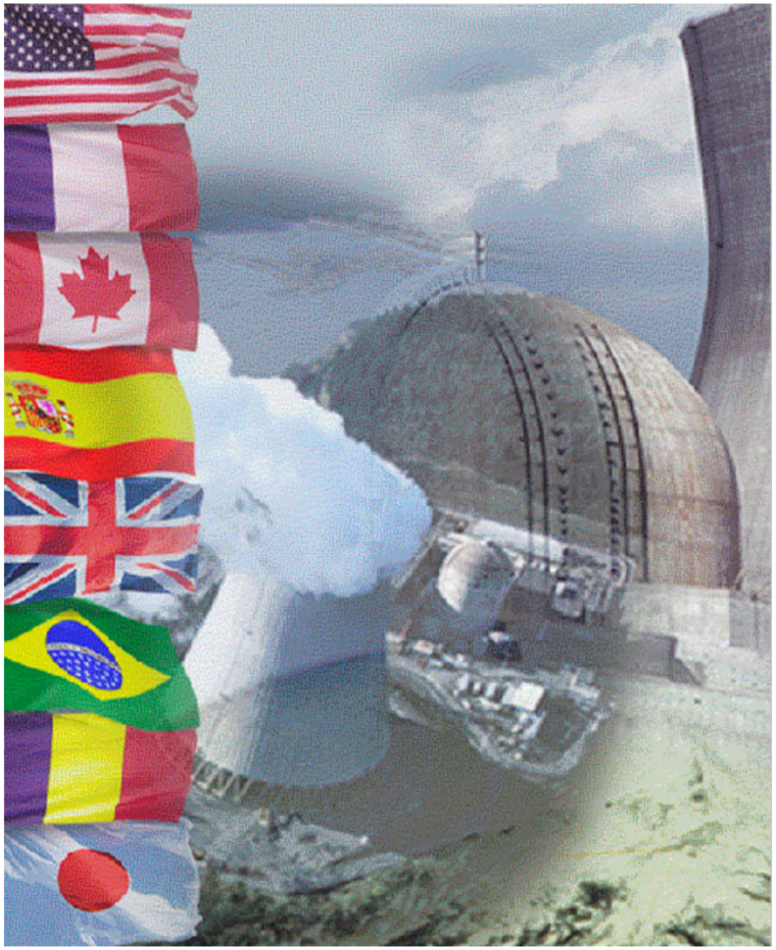
- Ground motion incoherency was considered using CLASSI for the Diablo Canyon Long Term Seismic Program (1988)
- Site-specific spatial incoherence functions were developed at Diablo Canyon
  - Developed from small earthquake recordings, dynamite explosions in boreholes, and air gun shots fired at sea
- The results of analyses performed show that the spatial incoherence of ground motion generally results in reductions in the soil/structure interaction responses
- The NRC addressed the LTSP SSI including incoherency in Safety Evaluation Report, NUREG-0675, Supplement No. 34
  - "The SSI analysis provides acceptable plant seismic responses"
  - NRC audit by Costantino and Veletsos
- LTSP re-analyses using CLASSI & coherency models from the Lotung array developed by Abrahamson (1991)
  - Greater effects of incoherency from Lotung than from Diablo Canyon site-specific measurements

S2.1 Task Objectives

- Develop a state-of-the-art representation of the coherency function based on the most applicable data available (Dr. Norm Abrahamson)
- Develop coherency transfer functions to be applied to the seismologically defined seismic ground motion to account for the effects of incoherence on NPP structures/foundations as a function of foundation size, site conditions, and other relevant parameters (ARES)
- The modified Fourier amplitude spectra and the original Fourier phase spectra will be used to develop new input ground motion time histories that account for incoherency
- Validate coherency transfer functions and their implementation:
  - CLASSI (ARES)
  - SASSI (Bechtel)
- Verify that the approach gives accurate and reasonable seismic response

S2.1 Task Results

- **Benchmark Problem Comparison - The effect of incoherent ground motion has been evaluated by:**
  - 2 different programs; CLASSI and SASSI
  - 2 different algorithms; CLASSI-stochastic method and SASSI eigen decomposition method
  - 2 different analytical approaches; RVT by CLASSI; time history by SASSI
- **Excellent agreement is obtained for both coherency transfer functions and spectra reductions**
  - Verification Completed for Application Methodology Given Incoherence Function
- **Reductions for Foundations Significant and Relevant to Address High Frequency Issue**



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Coherency Function

Abrahamson Coherency Function

$$\gamma_{PW} = \left[1+\left(\frac{f\,Tanh(a_3\xi)}{a_1 f_c}\right)^{n1}\right]^{-1/2}\left[1+\left(\frac{f\,Tanh(a_3\xi)}{a_2 f_c}\right)^{n2}\right]^{-1/2}$$

$$\gamma = |\gamma_{PW}|\left[\cos(2\pi f\xi_R s) + i\sin(2\pi f\xi_R s)\right] = |\gamma_{PW}|e^{i2\pi f\xi_R s}$$

- where γ is the total coherency function and γ_{PW} is the plane wave coherency function
- For horizontal ground motion : a_1=1.647; a_2=1.01; a_3=0.4; n1=7.02; n2=5.1-0.51ln(ξ+10); s=0.00025 s/m (c=4000 m/s);

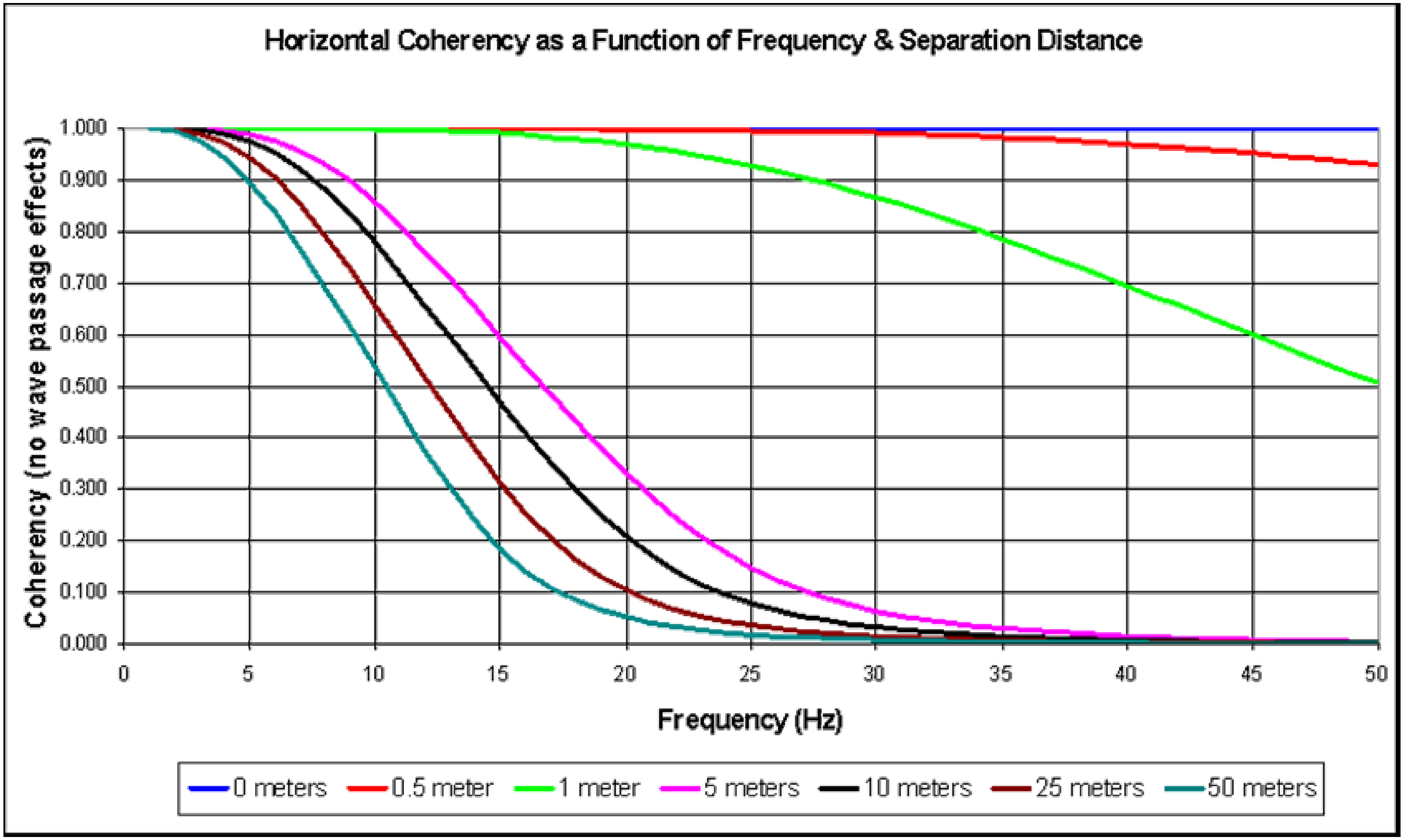
  f_c=-1.886+2.221ln(4000/(ξ+1)+1.5)
- For vertical ground motion : a_1=3.15; a_2=1.0; a_3=0.4; n1=4.95; n2=1.685; s=0.00025 s/m (c=4000 m/s);

  f_c=exp(2.43-0.025 ln(ξ+1)-0.048 (ln(ξ+1))^2)

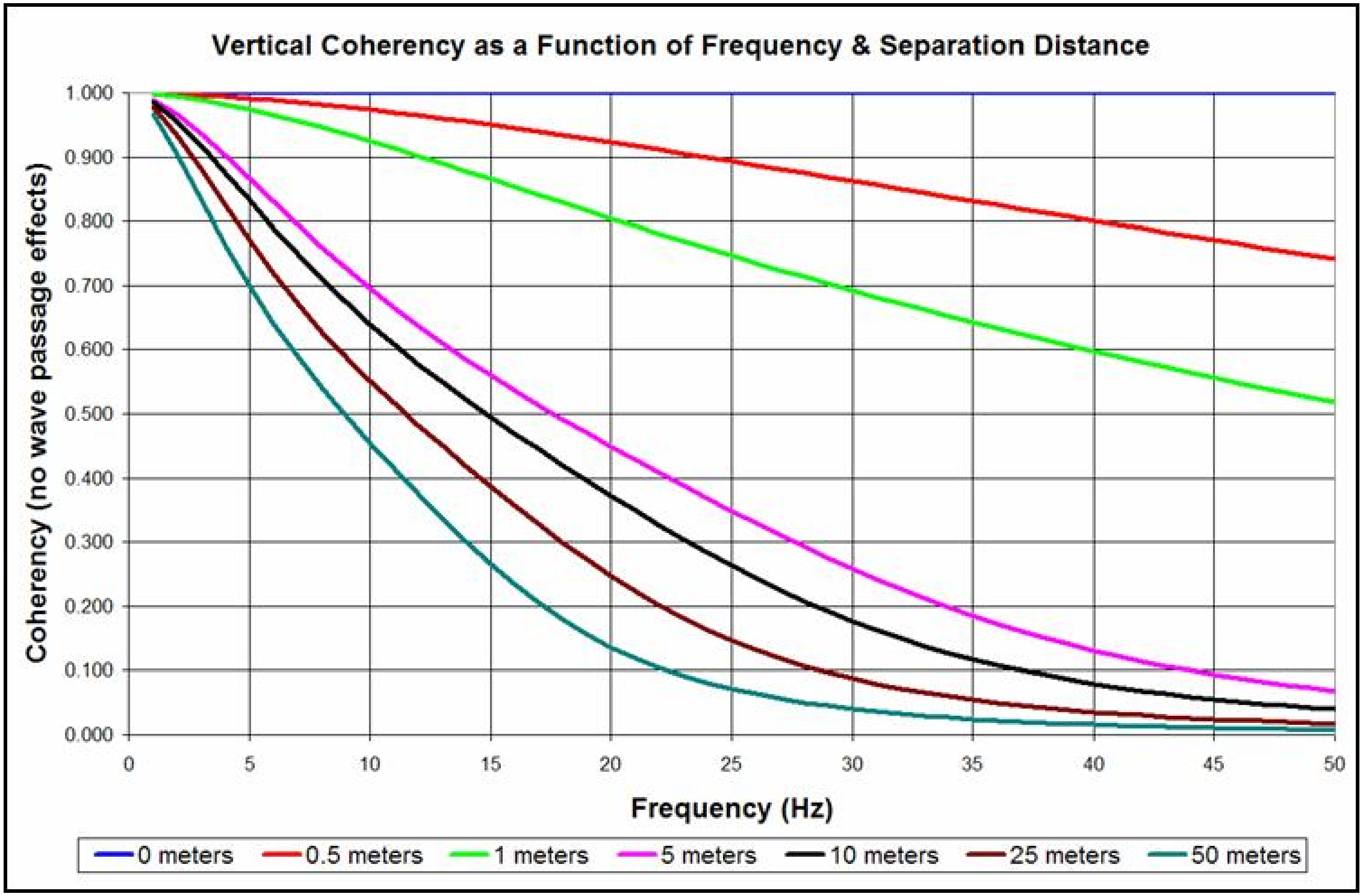
Wave Passage Effects

- The Abrahamson coherency function accounts for both wave passage effects and random spatial variation
- For this project, only random spatial variation of ground motion will be considered
  - Random spatial variation results in large reductions in foundation motion
  - Wave passage effects produce minimal further reductions
  - Assigning an appropriate apparent wave velocity for wave passage effects may be controversial

Coherency for Horizontal Motion



Coherency for Vertical Motion



Spatial Coherency

- Describes the similarity of the phase angles between two locations
  - Amplitude variations have no effect on coherency
- Phase Differences
  - Random differences
  - Systematic differences over a frequency band
    - Wave-passage effect

Spatial Coherency Measures

- Lagged coherency
  - Removes systematic phase differences due to wave-passage effect
  - No consistency in wave-speed required between different frequency bands
  - Bias due to finite number of frequencies smoothed (e.g. white noise has non-zero lagged coherency)
- Unlagged coherency
  - Includes both random and systematic phase differences
  - Wave-passage effects are included in the unlagged coherency
- Plane-wave coherency
  - Removes systematic phase differences associated with a single wave-passage effect (wave speed) at all frequencies
  - Removes bias (white noise has zero coherency)

Estimation of Coherency

- Empirically Based
  - Requires dense array recordings
- Select a time window that includes the strong shaking (S-wave window)
  - Window lengths are typically 2-5 seconds

Dense Array Characteristics

Array	Location	Site Class	Surface Stations	Spacing (m)
EPRI LSST	Taiwan	Soil	15	3-85
EPRI Parkfield	CA	Rock	13	10-191
Chiba	Japan	Soil	15	5-319
USGS Parkfield	CA	Rock	14	25-952
Imperial Valley Diff	CA	Soil	5	18-213
Hollister Diff	CA	Soil	4	61-256
Stanford (temp)	CA	Soil	4	32-185
Coalinga (temp)	CA	Rock	7	48-313
UCSC ZIYA (temp)	CA	Rock	6	25-300
Pinyon Flat (temp)	CA	Rock	58	7-340

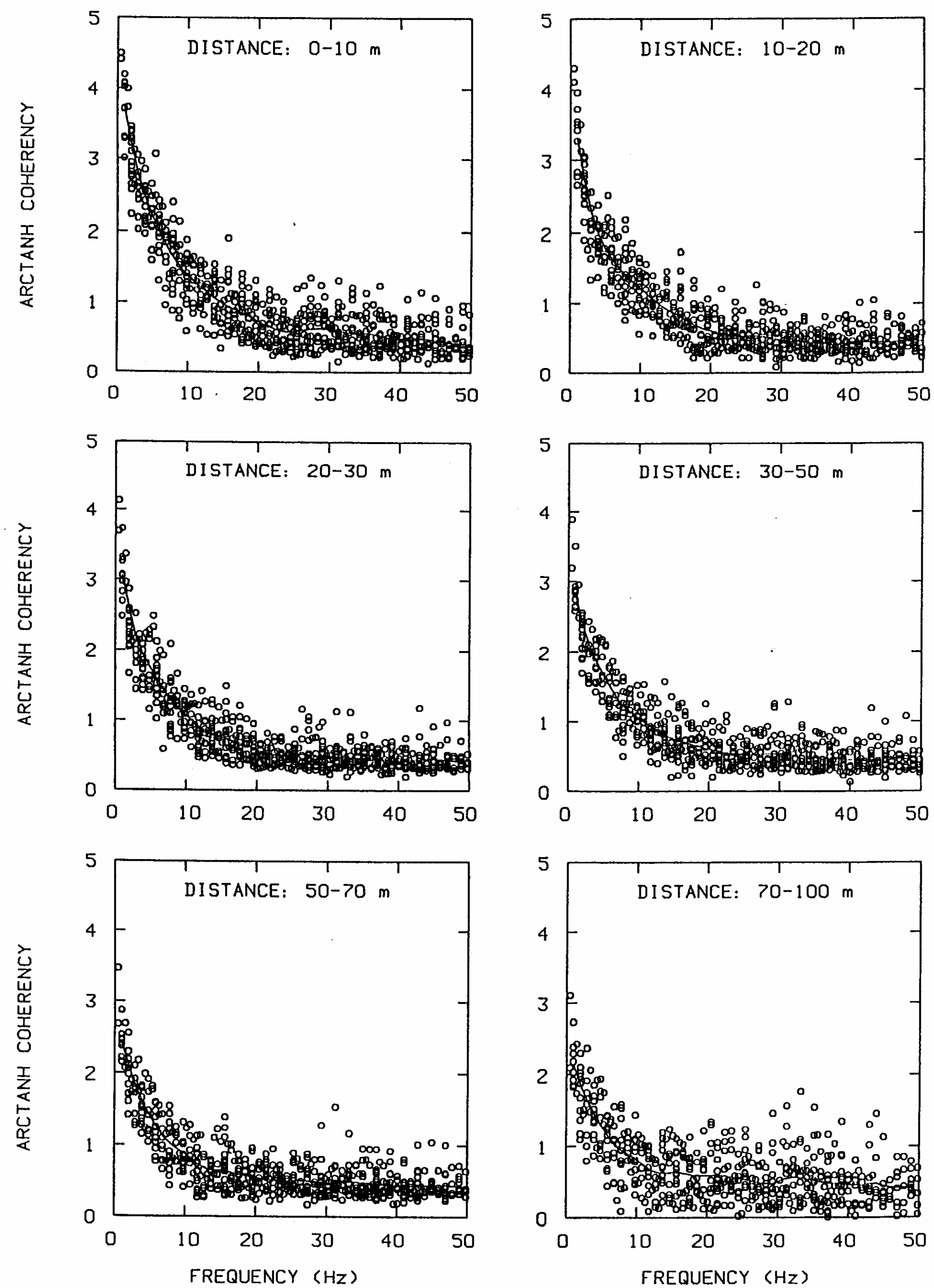
Dense Array Data Sets

Array	Number of Eqks	Mag	Dist (km)	Max PGA(g)
EPRI LSST	15	3.0-7.8	5-113	0.26
EPRI Parkfield	2	3.0-3.9	13-15	0.04
Chiba	9	4.8-6.7	61-105	0.41
USGS Parkfield	9	2.2-3.5	18-45	0.04
Imperial Valley Diff	2	5.1-6.5	4-14	0.89
Hollister Diff	1	5.3	17	0.20
Stanford (temp)	4	3.5-4.5	~40	0.007
Coalinga (temp)	6	2.3-5.2	10-15	0.21
UCSC ZIYA (temp)	3	2.3-3.0	9-19	-
Pinyon Flat (temp)	6	2.0-3.6	14-39	-

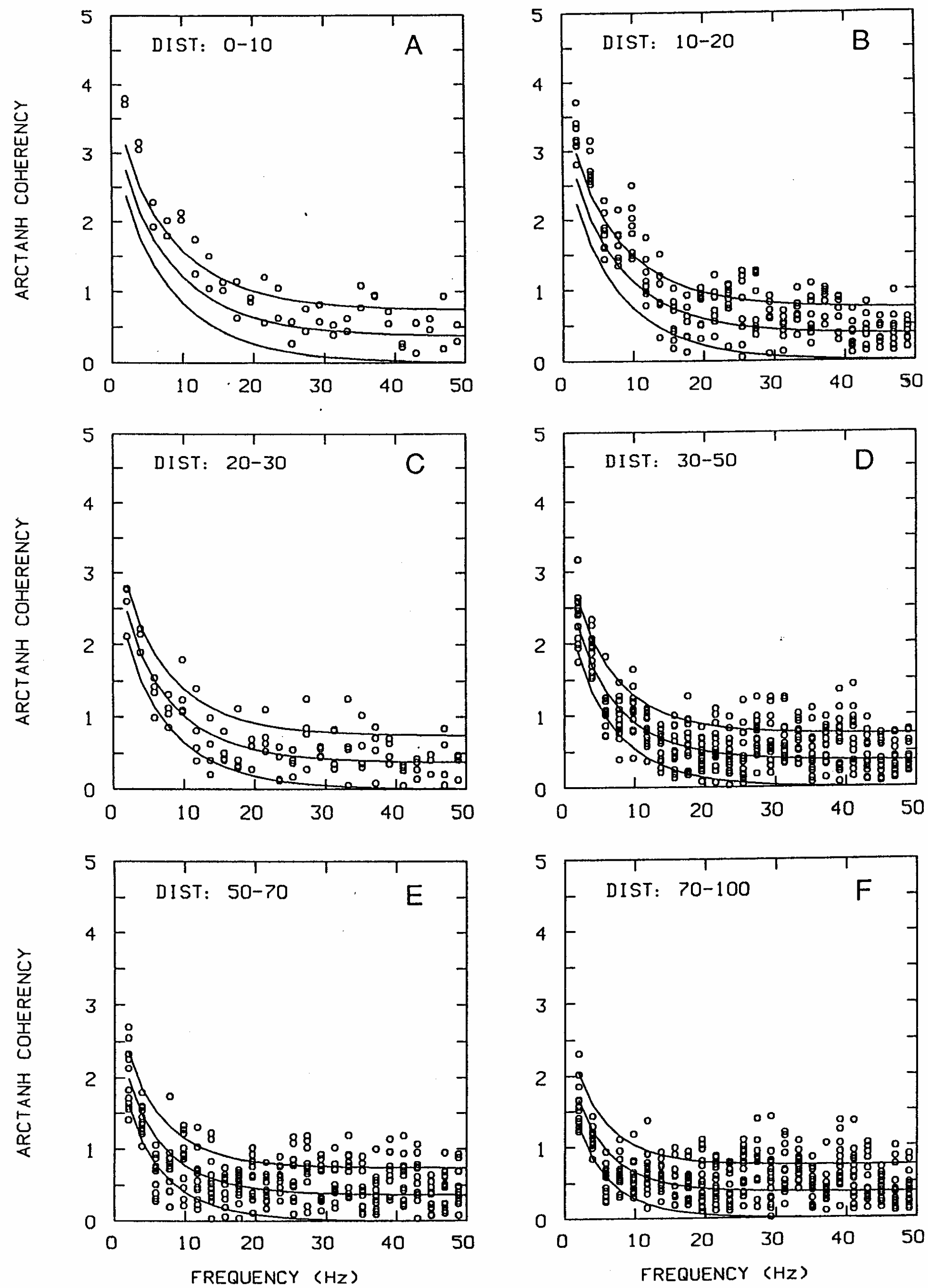
Site Dependence

- Most of the dense array data is from soil sites
  - Best data sets are from Taiwan
- Does the coherency from Taiwan apply to other regions?
  - Compare with coherency from CA and Japan
- Does the spatial coherency change for rock sites?
  - Compare with coherency for rock sites

Lagged Coherency From the EPRI LSST Array

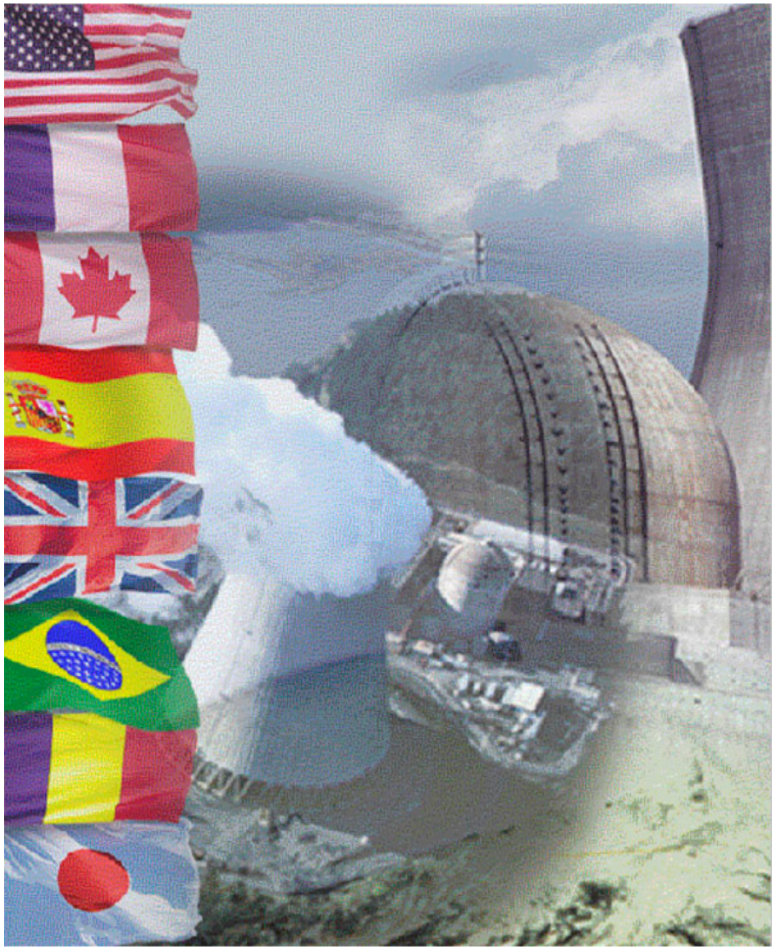


Comparison of EPRI Parkfield (Rock site) with the LSST Coherency Model



Coherency Observations/Conclusions

- Coherency functions are appropriate for all frequencies (including above 20 Hz)
  - Data analyzed for f<20 Hz, but trends should extrapolate to higher frequencies
- For the purposes of this Task S2.1 study, Dr. Norm Abrahamson concluded:
  - Coherency does not vary as a function of site Vs, but strongly affected by topography
  - Coherency does not vary as a function of earthquake magnitude (for magnitudes of interest, greater than 4.5 to 5)
  - Each component of earthquake input can be treated as uncorrelated (coherency of cross-components is near zero)
- Mean input ground motion is the goal and mean coherency will be used. In the future, consideration of uncertainty in coherency is planned.
  - Abrahamson models give the median coherency
  - Median coherency is slightly larger than mean coherency (only a few percent difference)



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S2.1 Approach and Results

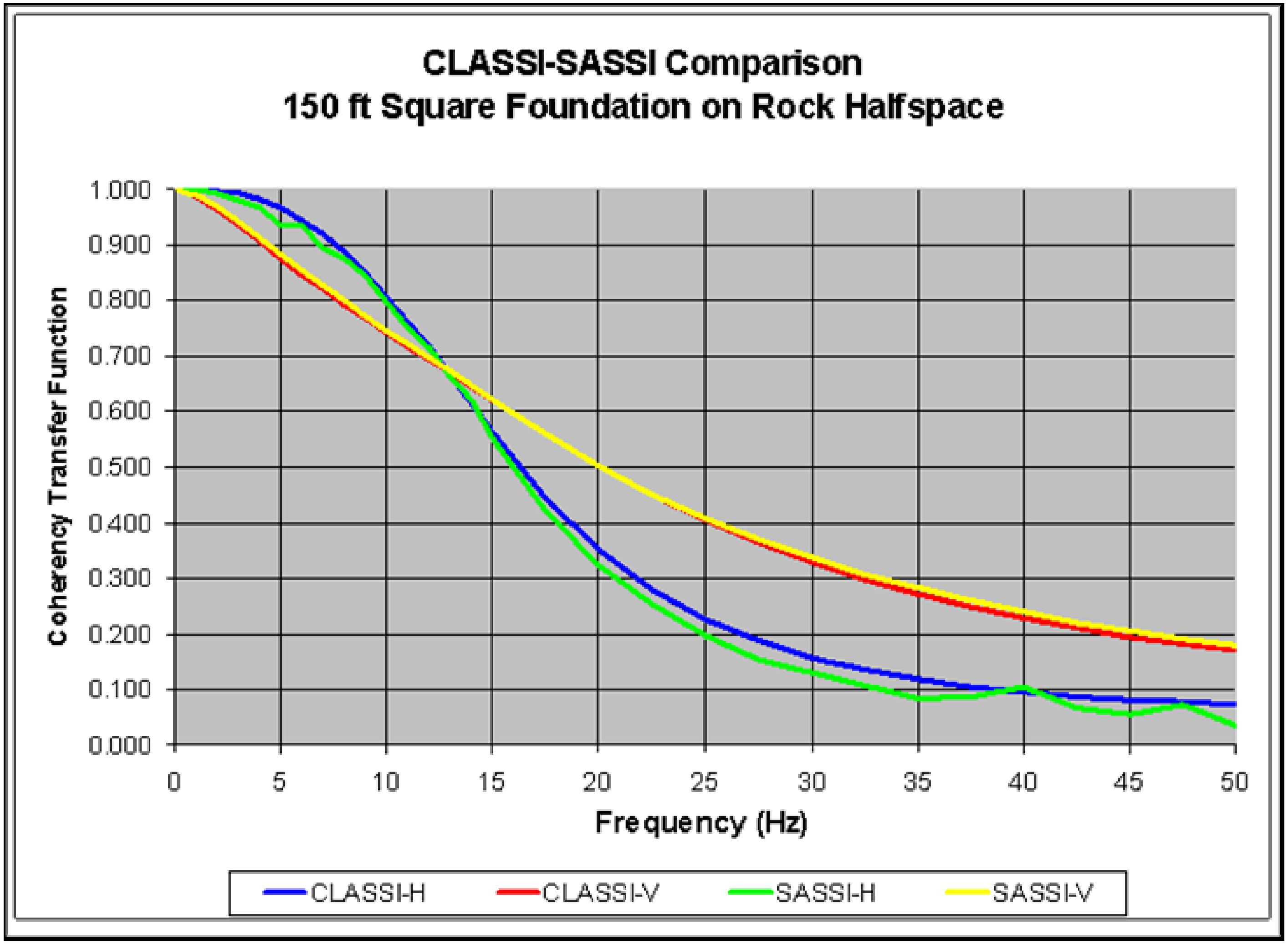
Technical Approach

- Stochastic Approach
  - Coherency transfer function developed for rigid massless, foundation & validated to be appropriate by evaluating structure response for a typical NPP structure
  - Random Vibration Theory (RVT) to convert response spectra to PSD and PSD to response spectra to determine spectra reductions
- Coherency as a function of separation distance, frequency, apparent wave velocity, and direction of motion from Dr. Norm Abrahamson
- Coherency transfer function and spectra reductions generated for rigid, massless foundation using CLASSI
  - Intent is to apply the coherency transfer function to Fourier amplitude spectra in the free-field -- the end result being an engineering modified motion accounting for incoherency effects and to be used in subsequent SSI analyses to generate structure response
- Coherency transfer function and spectra reductions validated for complete SSI using CLASSI

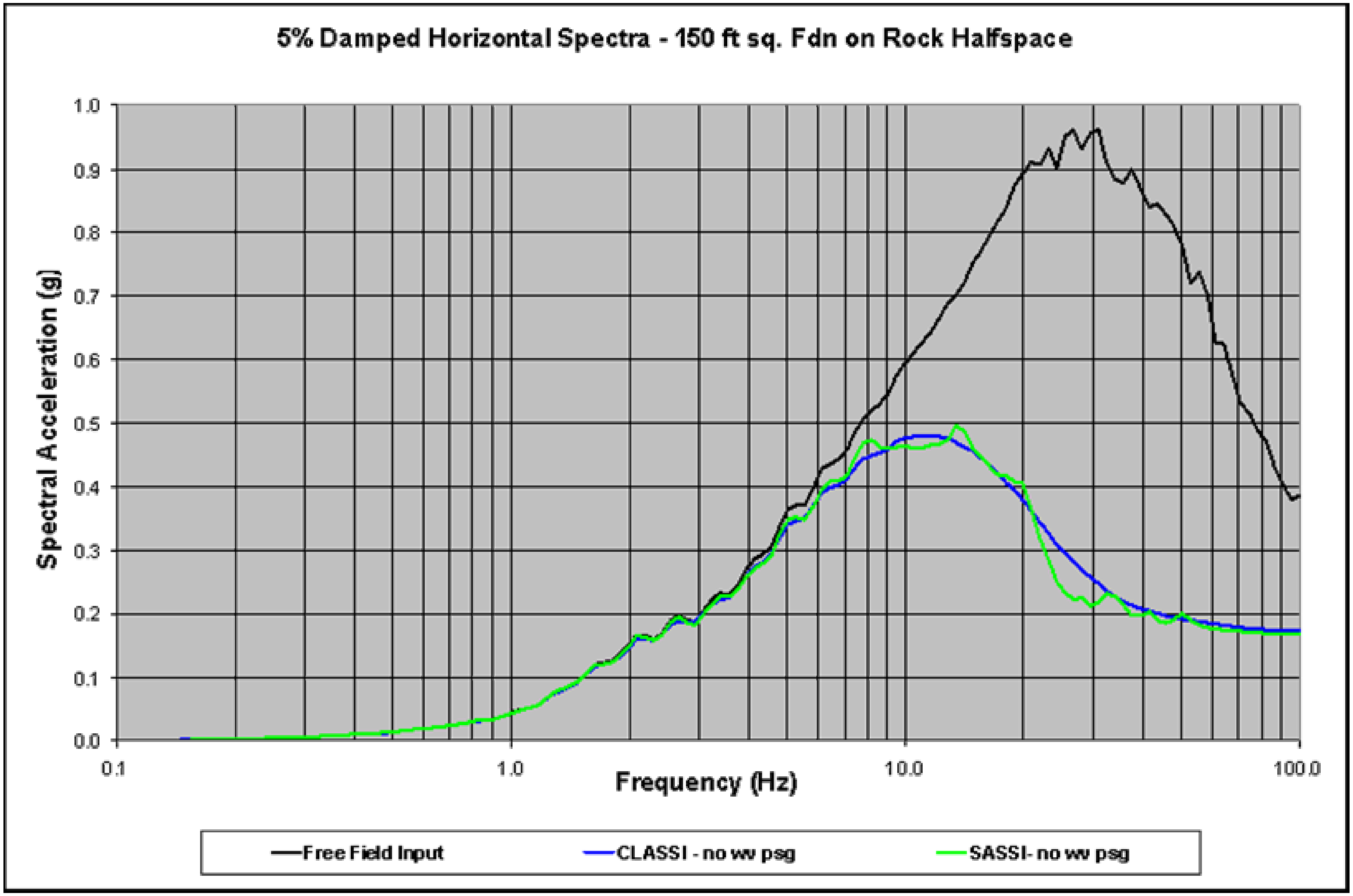
Benchmark Problem Comparison

- The effect of incoherent ground motion has been evaluated by:
  - 2 different programs; CLASSI and SASSI
  - 2 different algorithms; CLASSI-stochastic method and SASSI eigen decomposition method
  - 2 different analytical approaches; RVT by CLASSI; time history by SASSI
- Determine motion of a rigid, massless foundation on a rock halfspace
  - 150 x 150 ft square foundation footprint
  - 6300 fps rock
- Excellent agreement is obtained for both coherency transfer functions and spectra reductions on the foundation; structure response comparisons in progress

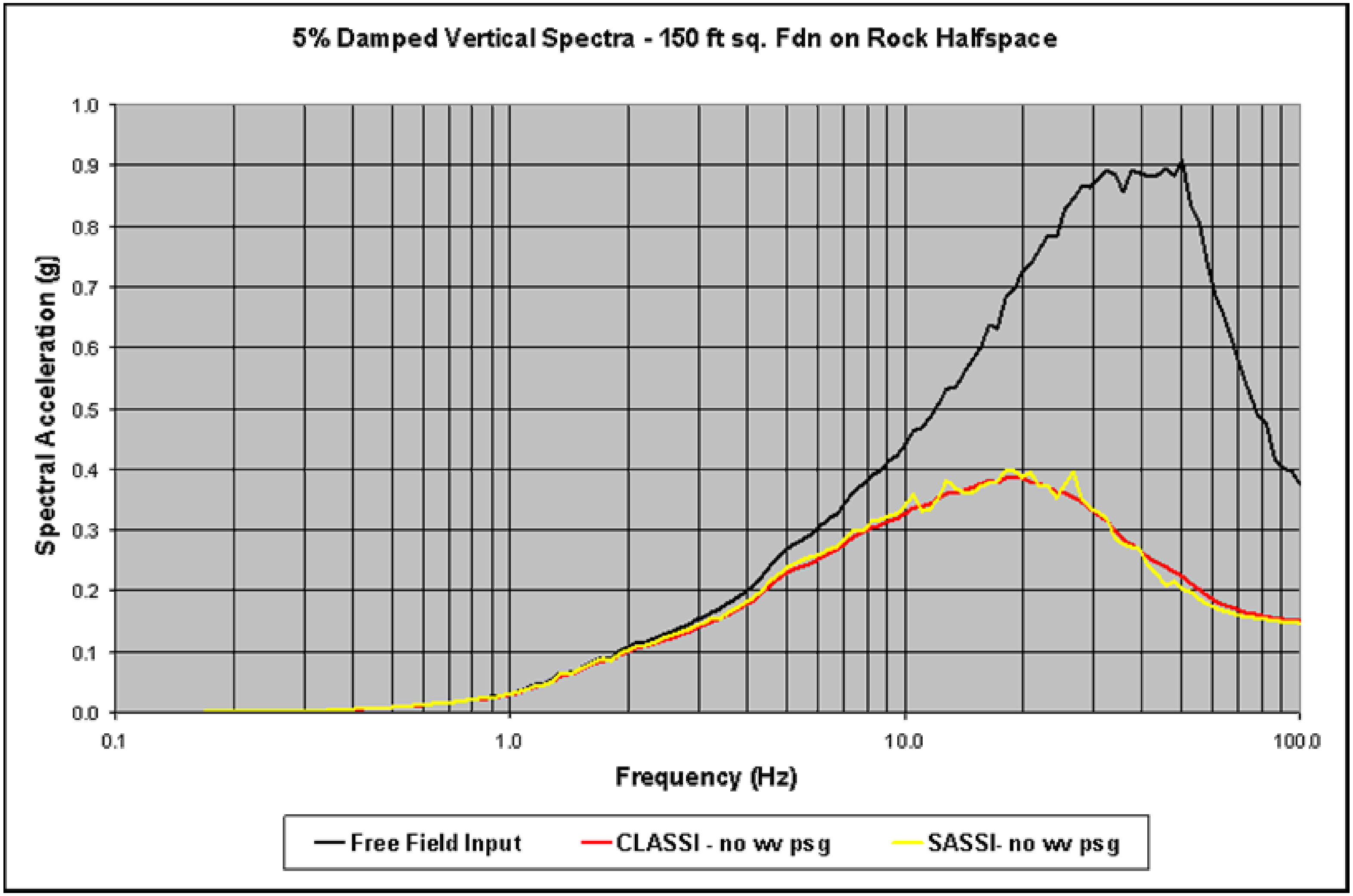
Coherency Transfer Function Comparison



Spectra Reduction Comparison-Horizontal



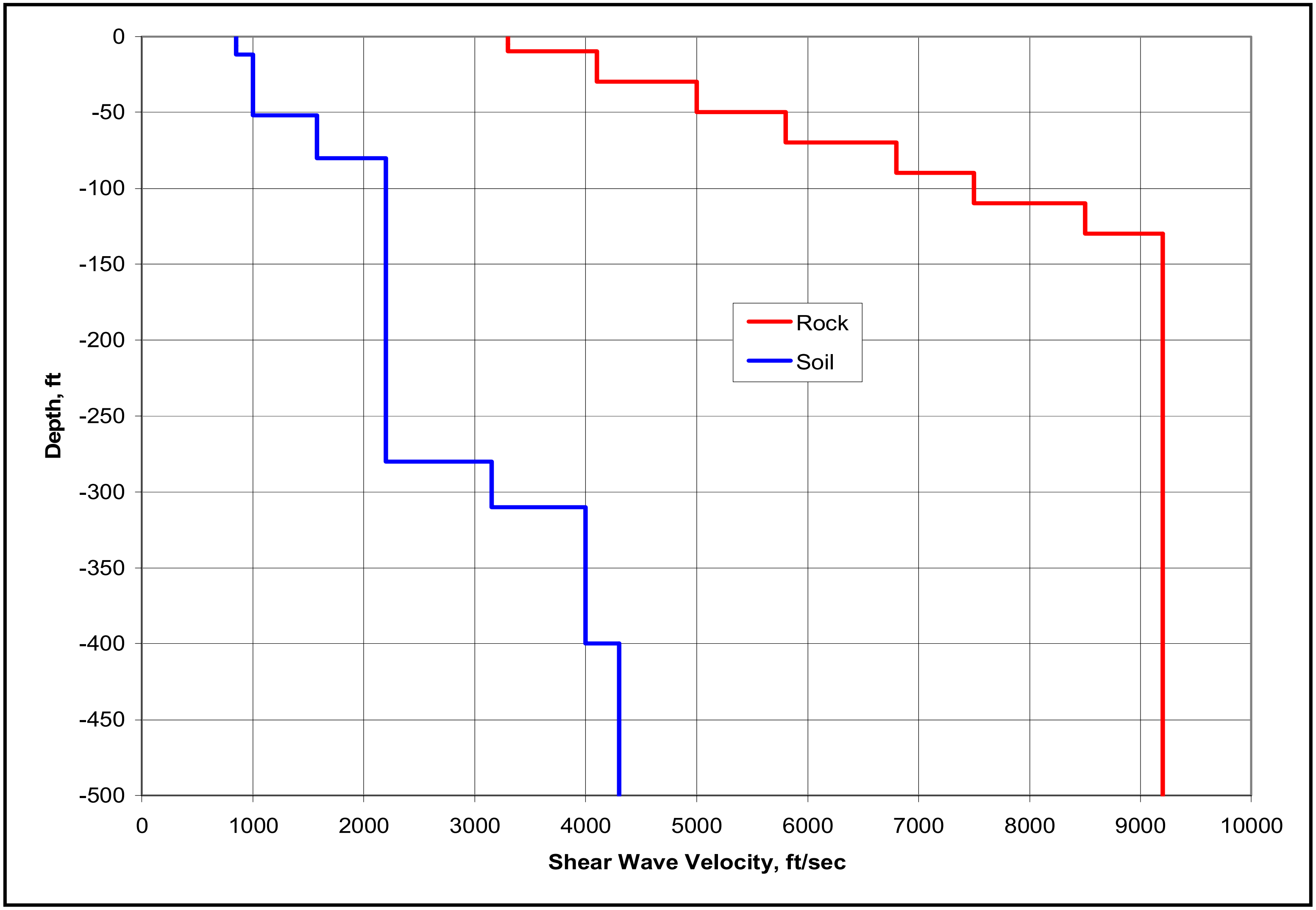
Spectra Reduction Comparison-Vertical



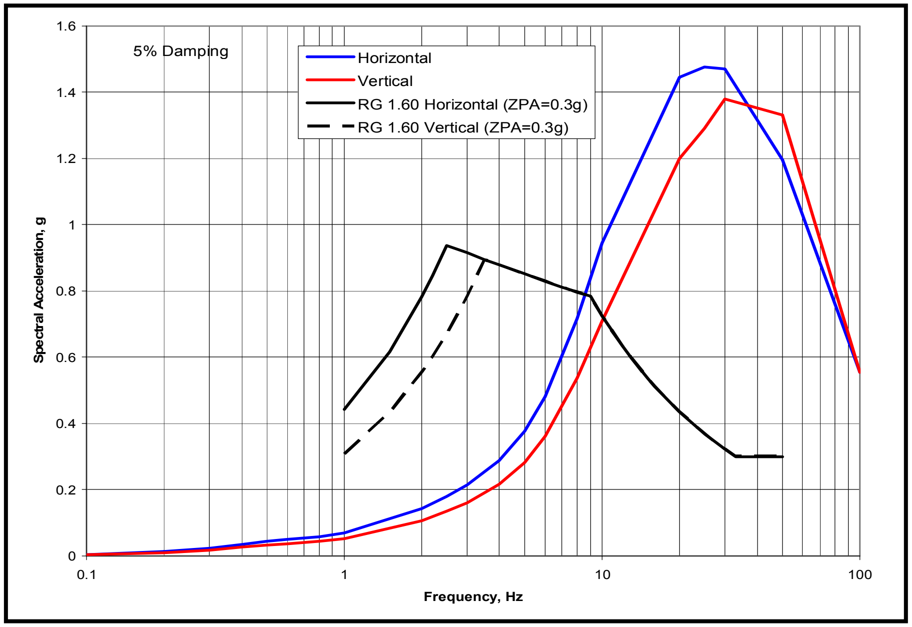
S2.1 Foundation Response: Analysis Cases/Sensitivity Studies

- Parameters
  - Rock Site Profile and High Frequency Spectra
  - Soil Site Profile and Lower Frequency Spectra
  - Foundation Shape, Constant Area
    - 150 foot square footprint
    - 100x225 ft rectangle footprint
  - Foundation Size
    - 75 foot square footprint
    - 150 foot square footprint
    - 300 foot square footprint
  - Coherency Transfer Function and Spectra Reduction

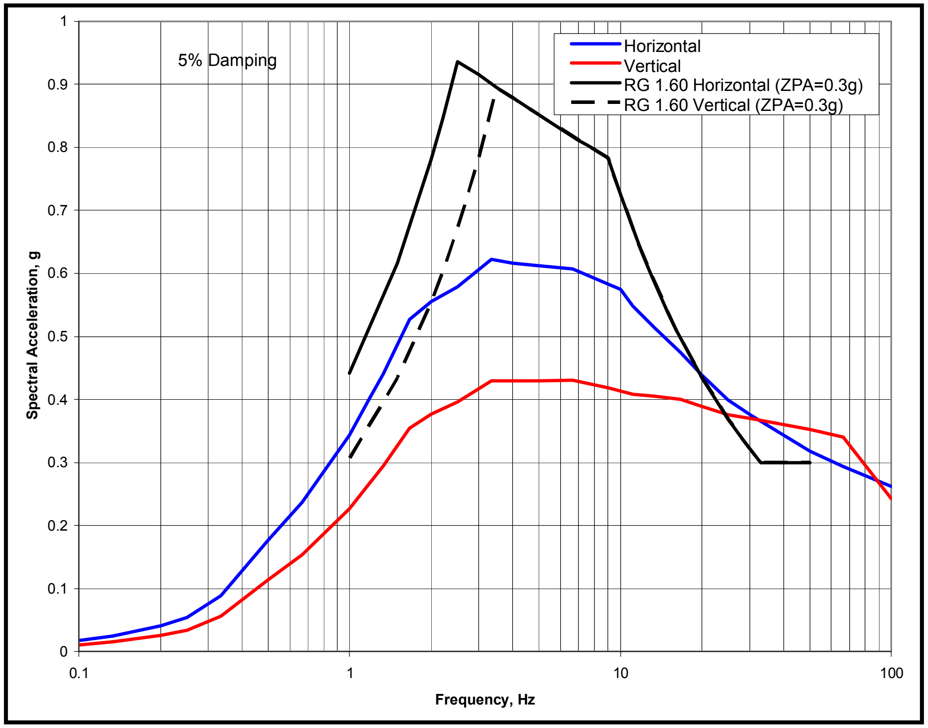
Rock and Soil Profiles within 500 feet of Surface



S2.1 Ground Response Spectra

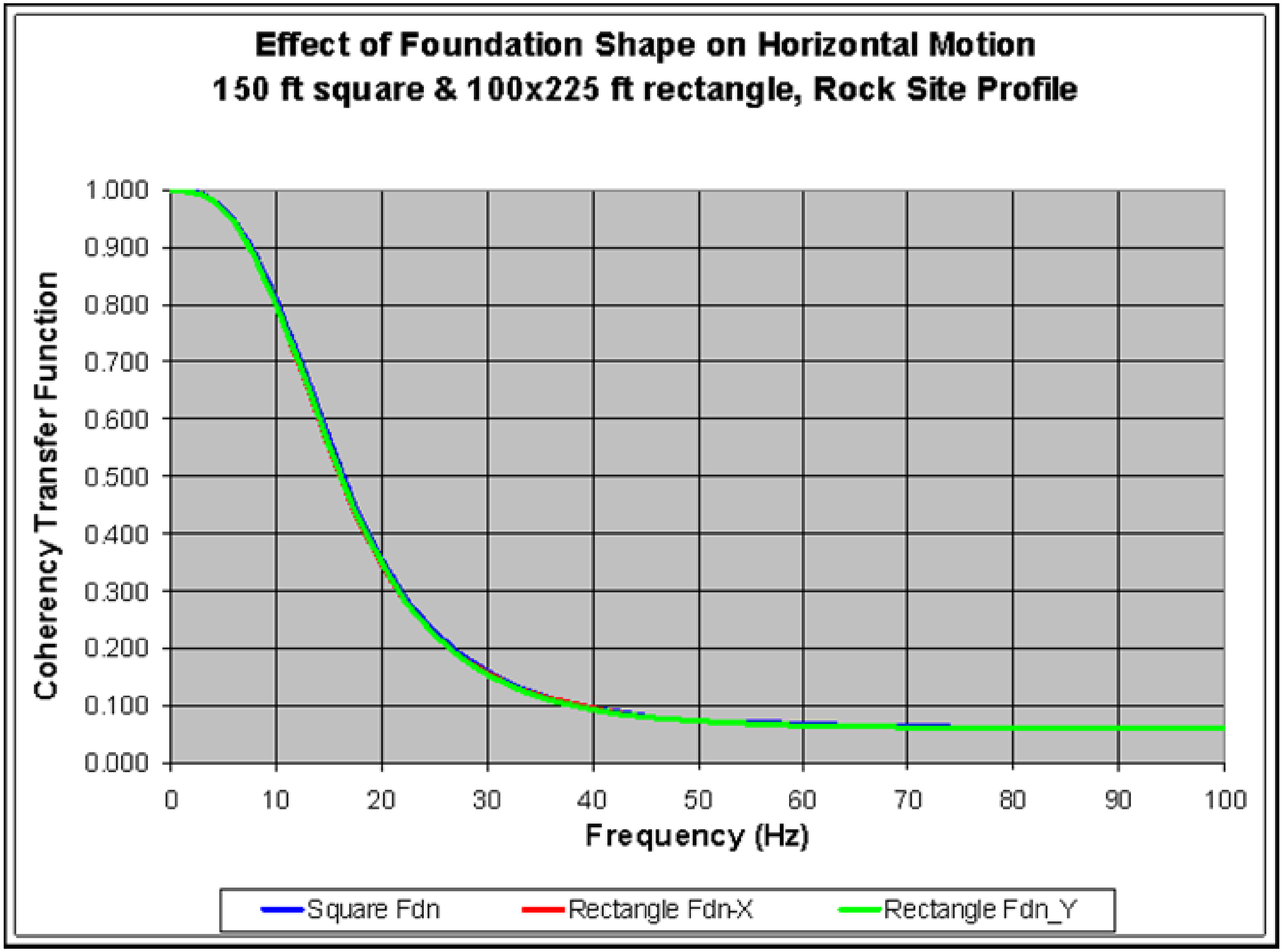


Site specific response spectra for Rock Site

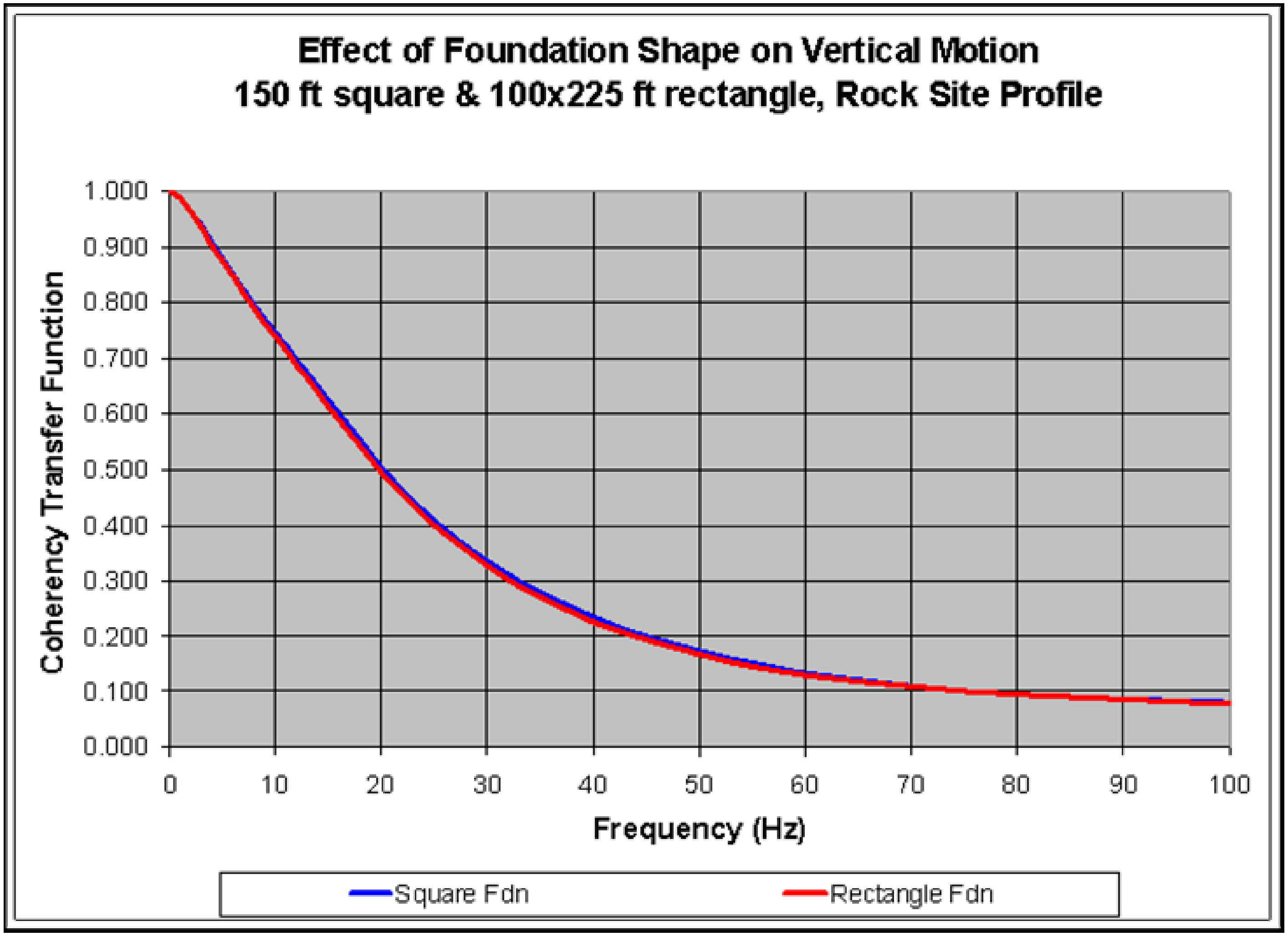


Site specific response spectra for Soil Site

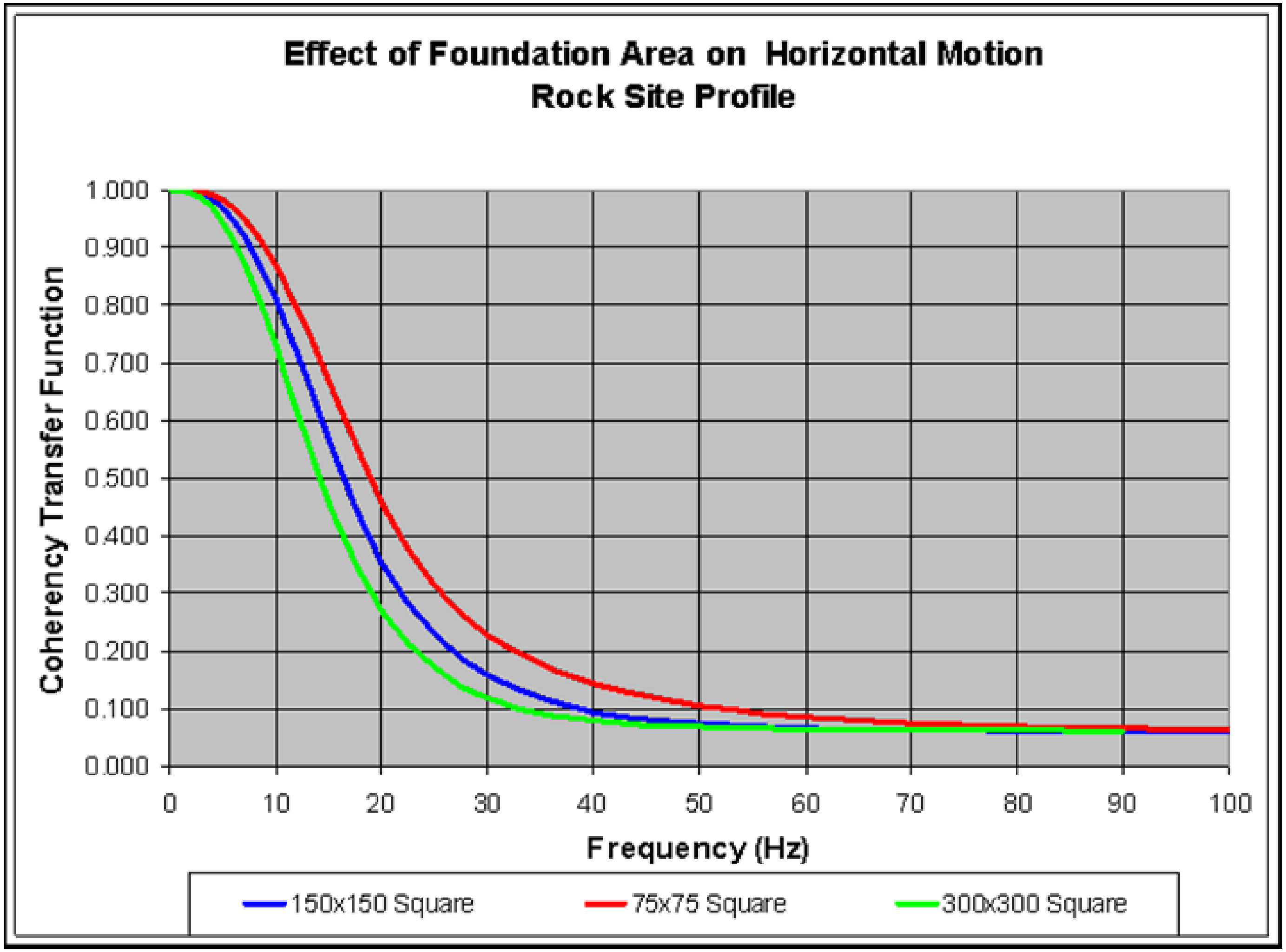
S2.1 Effect of Foundation Shape: Rock Site/Horizontal Motion



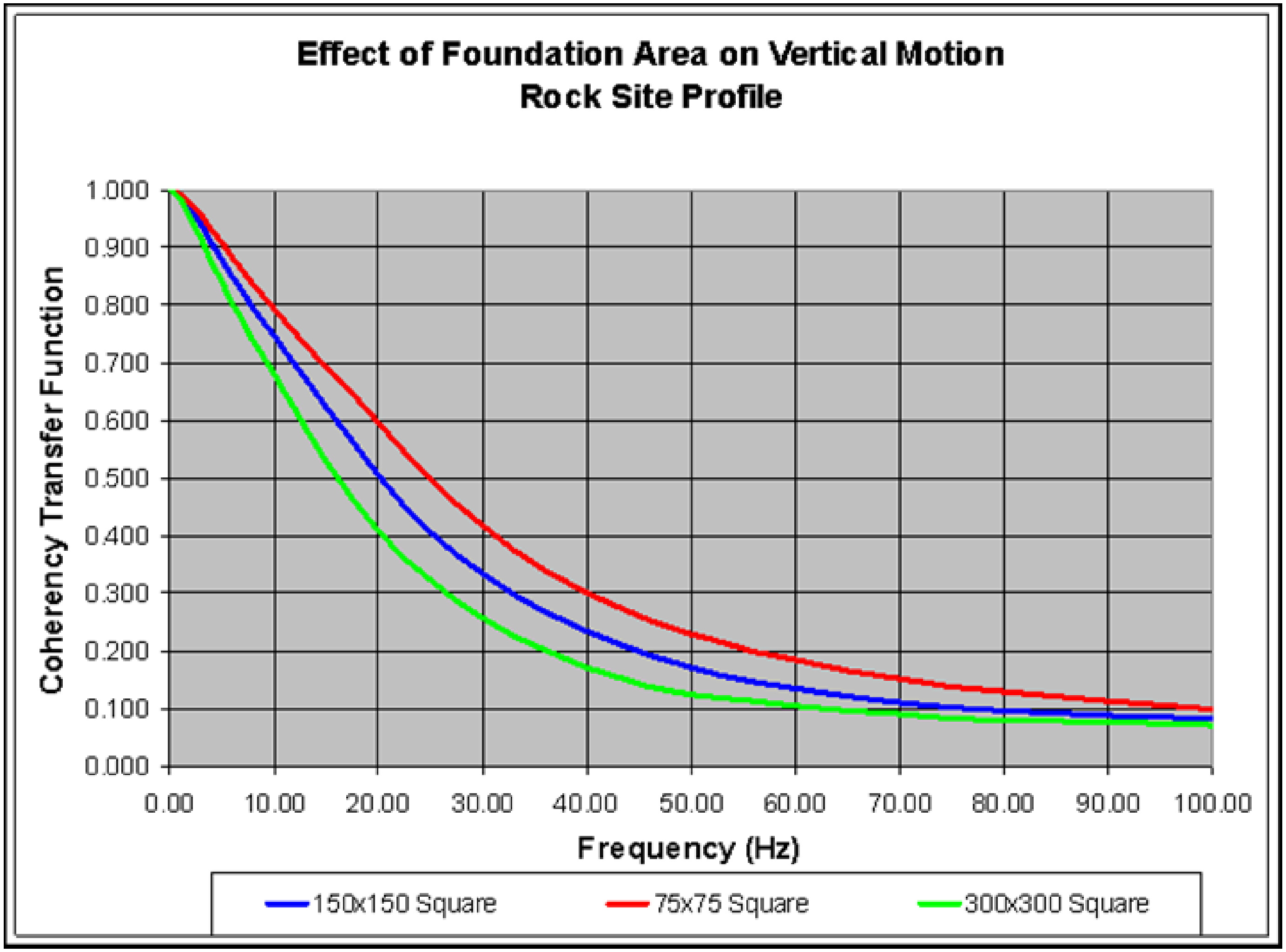
S2.1 Effect of Foundation Shape: Rock Site/Vertical Motion



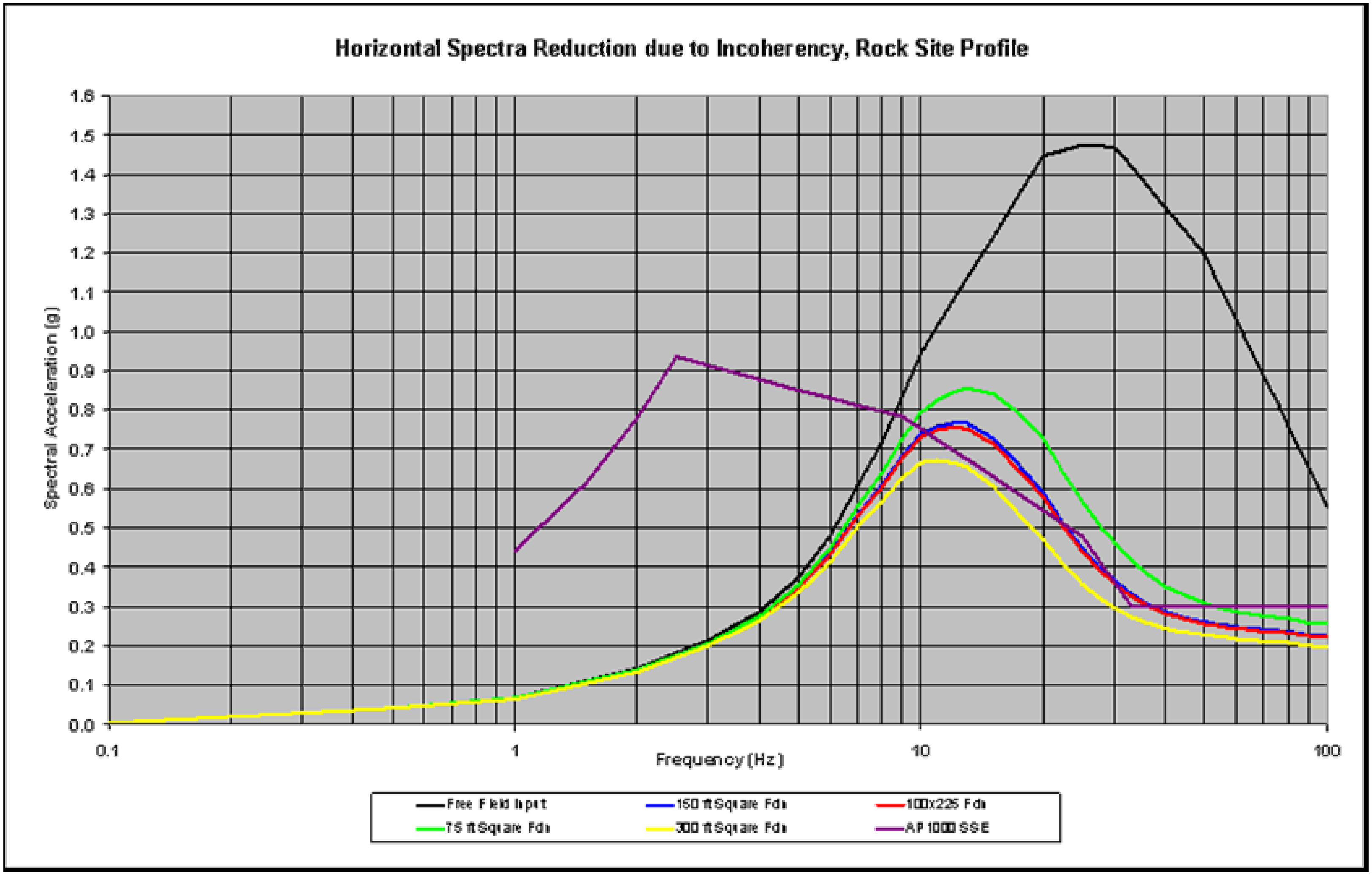
S2.1 Effect of Foundation Area: Rock Site/Horizontal Motion



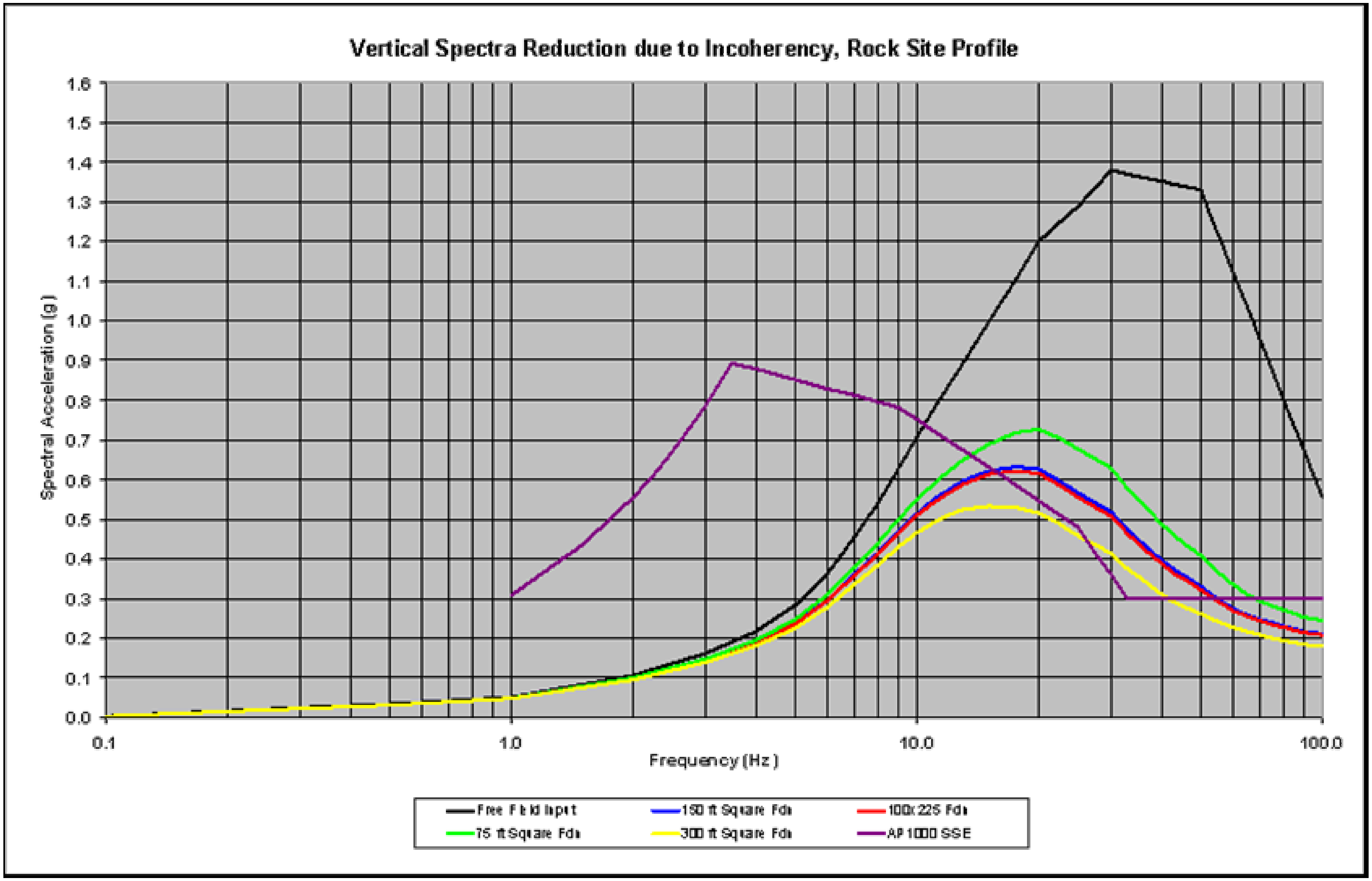
S2.1 Effect of Foundation Area: Rock Site/Vertical Motion



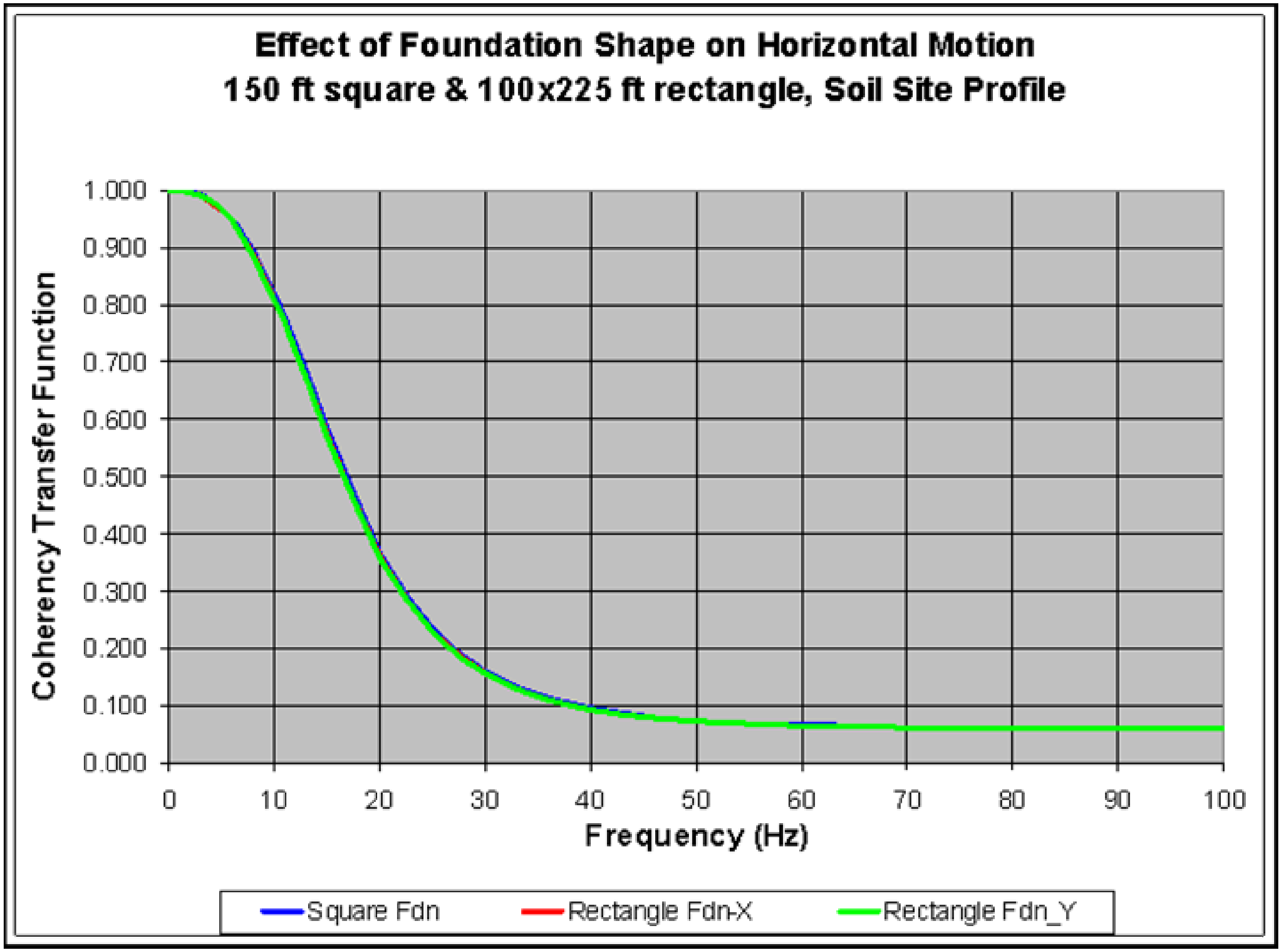
S2.1 Effect of Foundation Area & Shape: Rock Site/Horizontal Motion



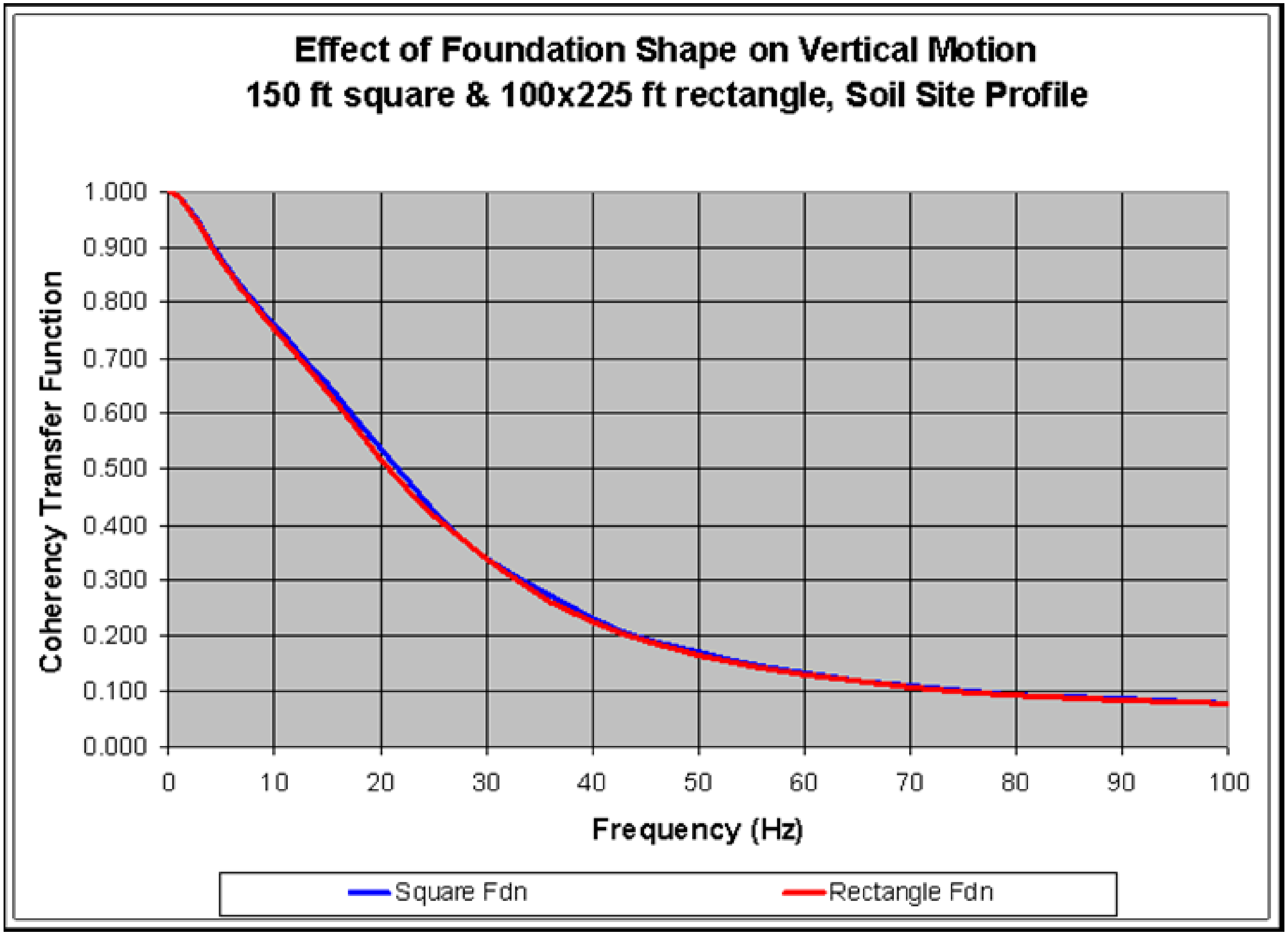
S2.1 Effect of Foundation Area & Shape: Rock Site/Vertical Motion



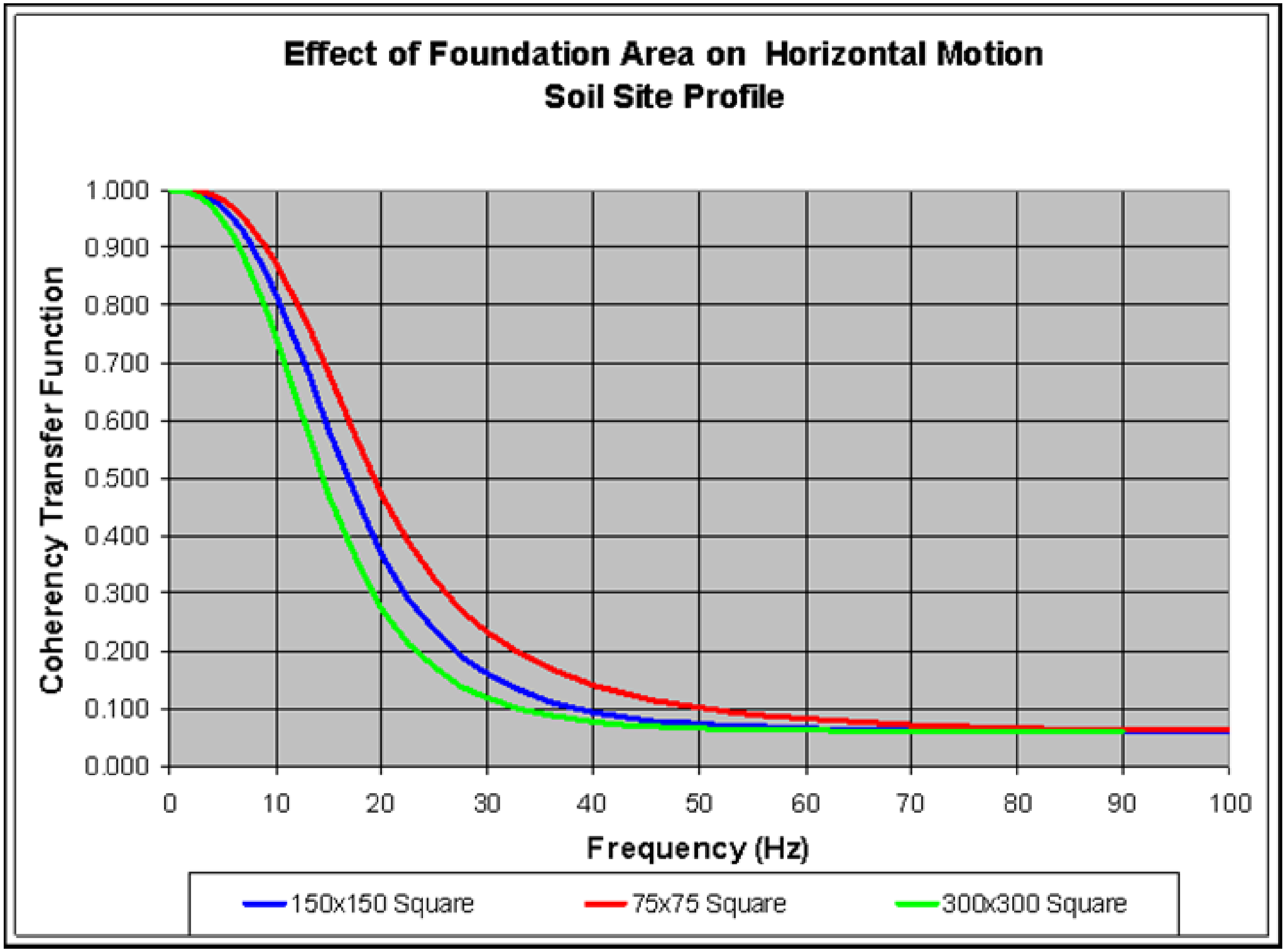
S2.1 Effect of Foundation Shape: Rock Site/Horizontal Motion



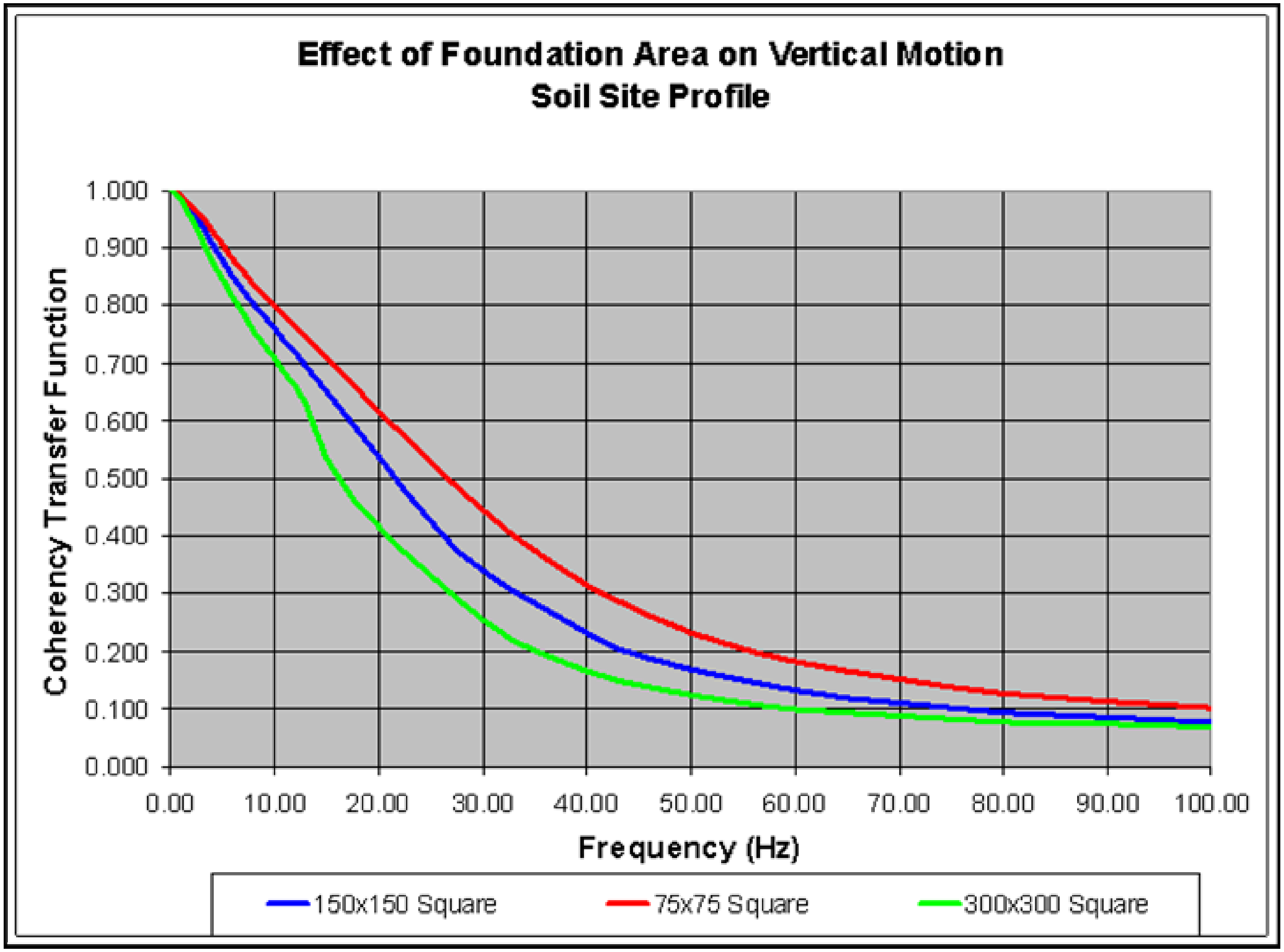
S2.1 Effect of Foundation Shape: Rock Site/Vertical Motion



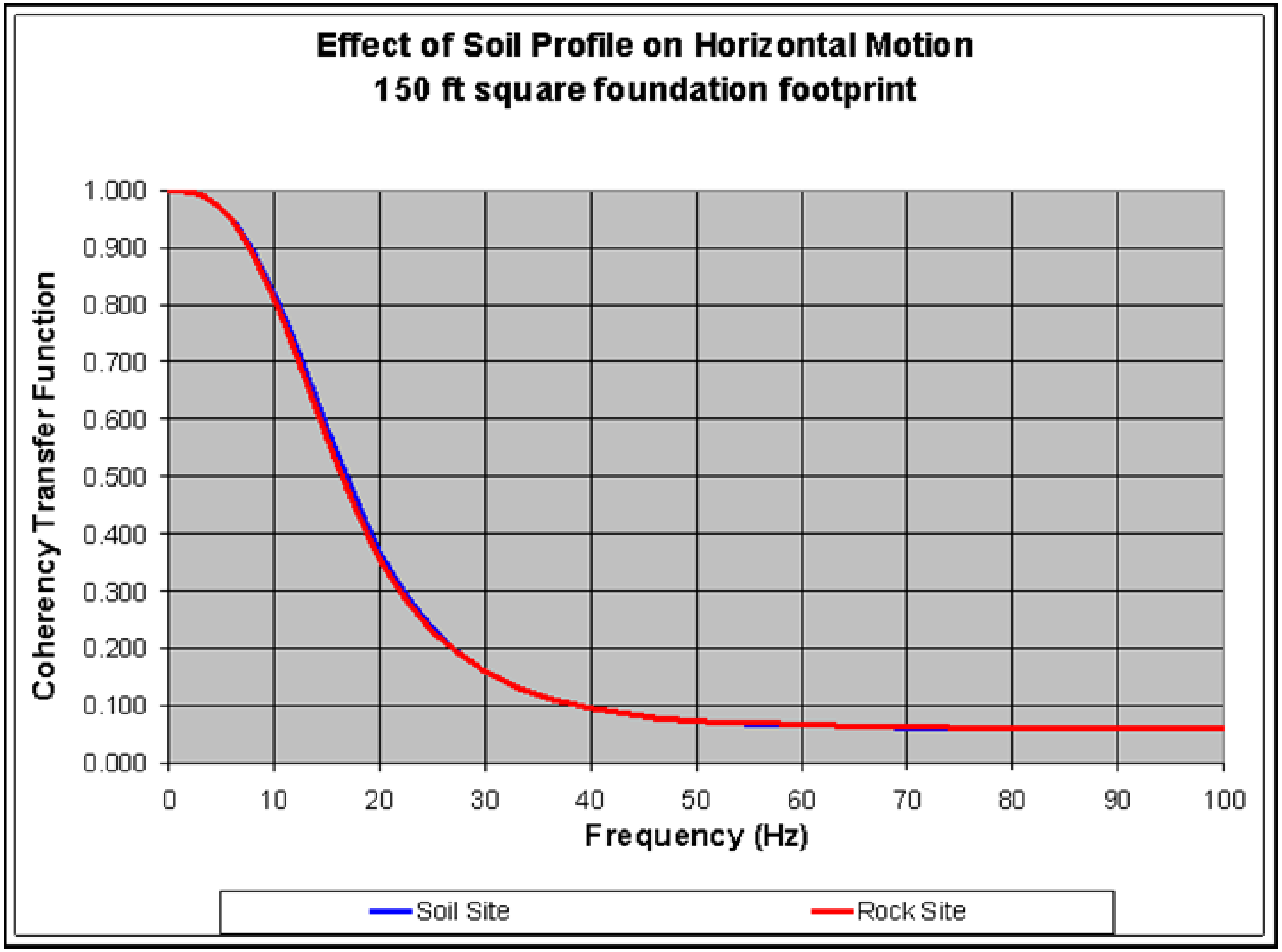
S2.1 Effect of Foundation Area: Soil Site/Horizontal Motion



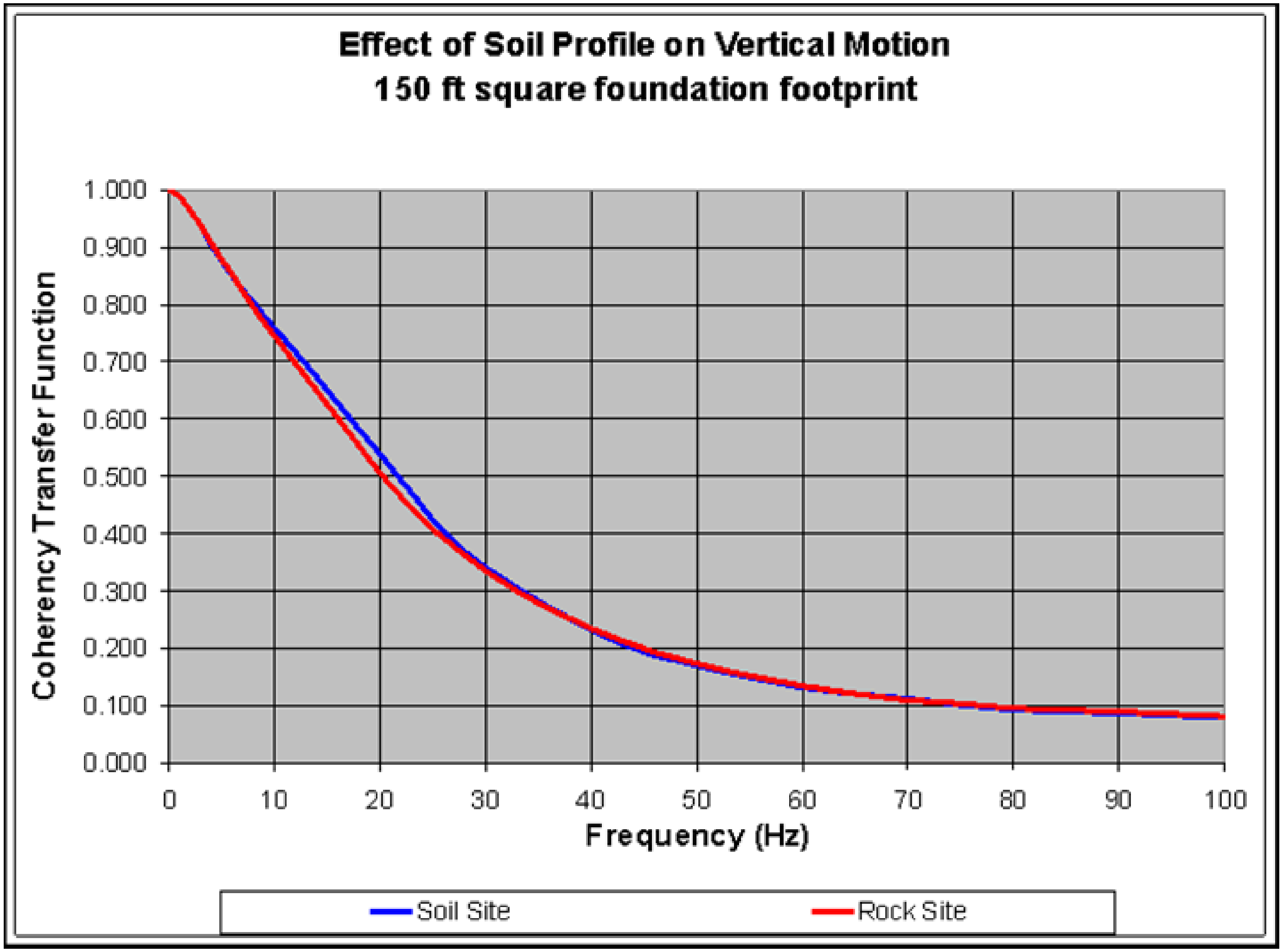
S2.1 Effect of Foundation Area: Soil Site/Vertical Motion



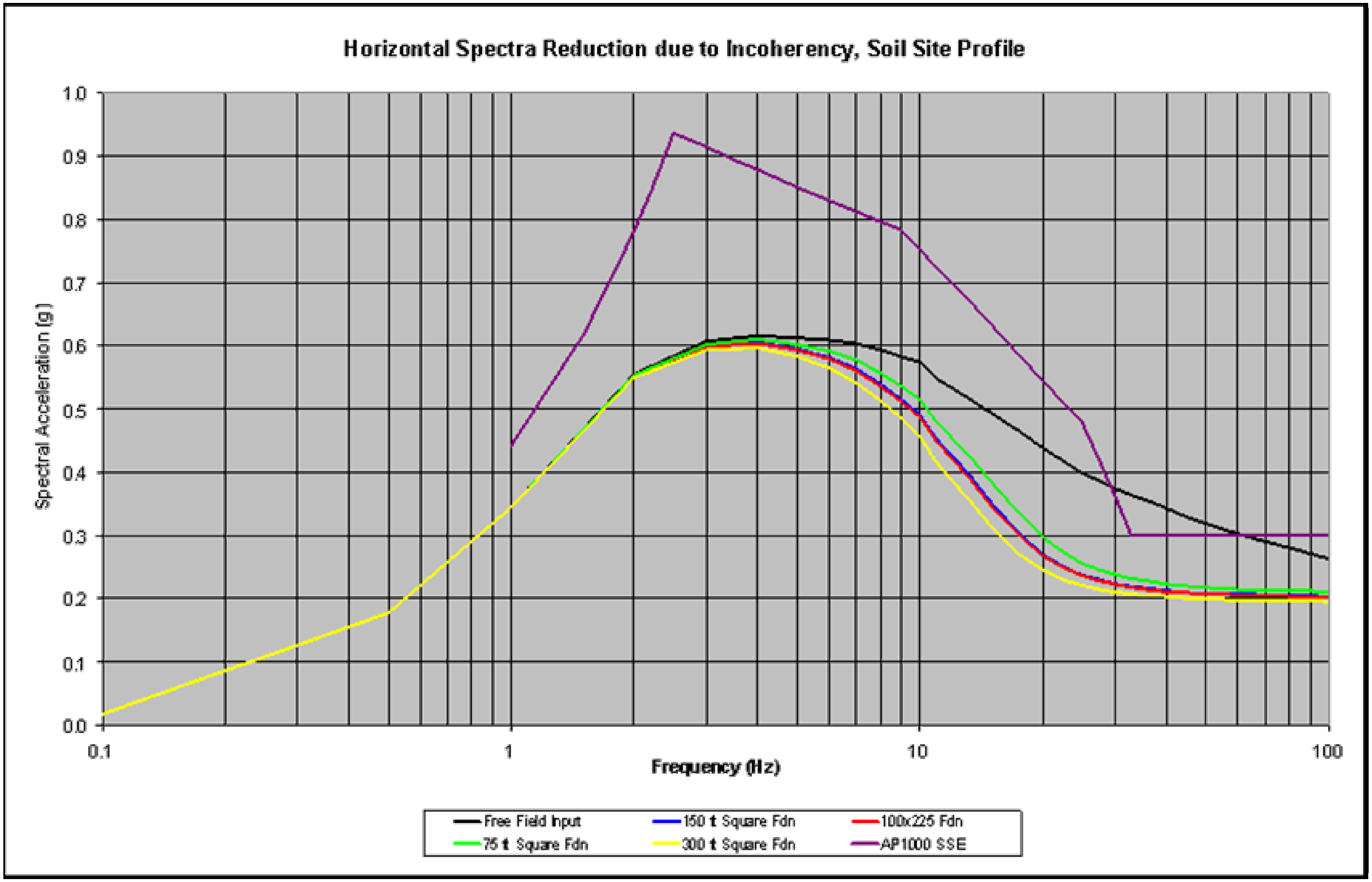
S2.1 Effect of Site Conditions (Soil/Rock): Horizontal Motion



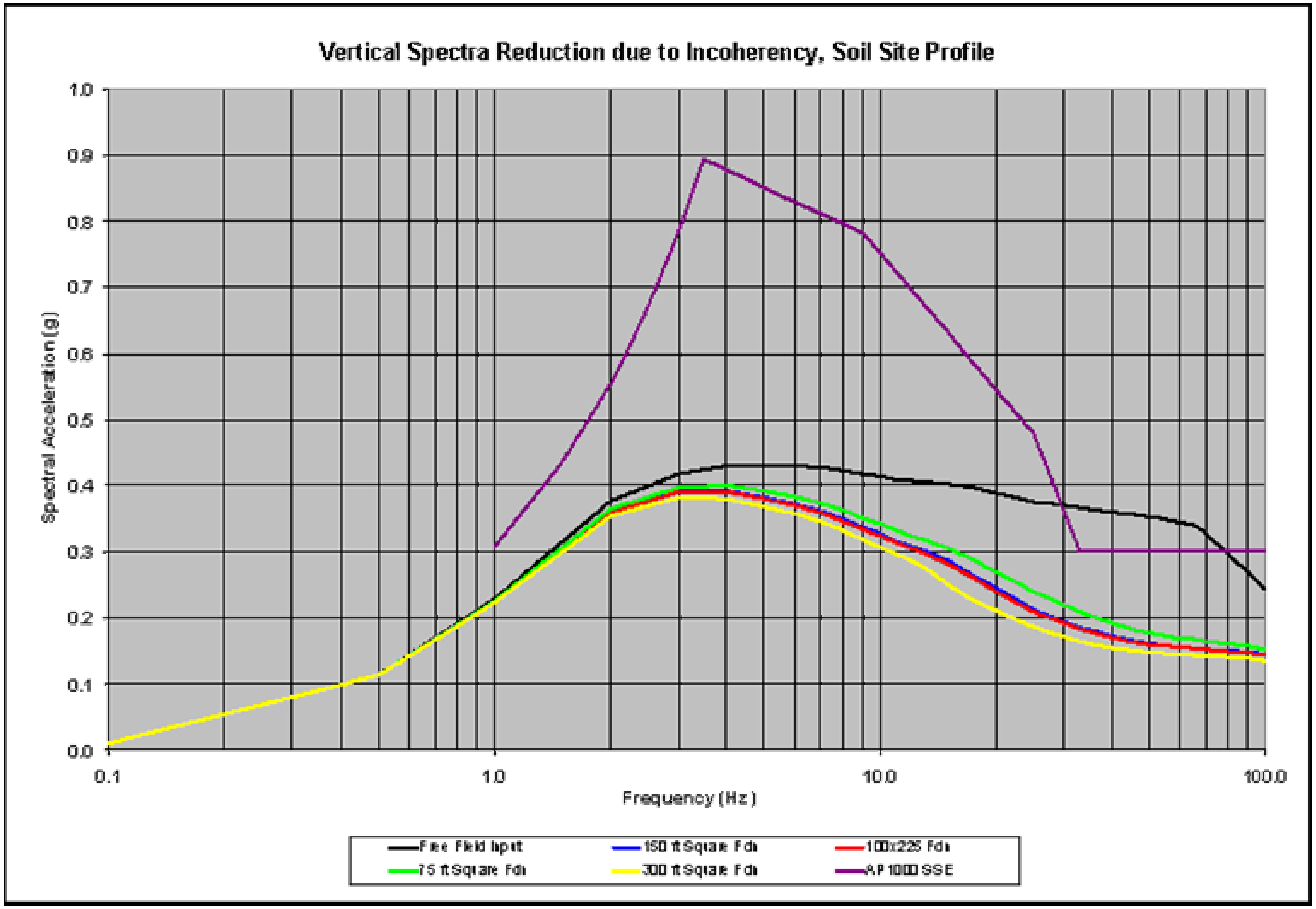
S2.1 Effect of Site Conditions (Soil/Rock): Vertical Motion



S2.1 Effect of Foundation Area & Shape: Soil Site/Horizontal Motion



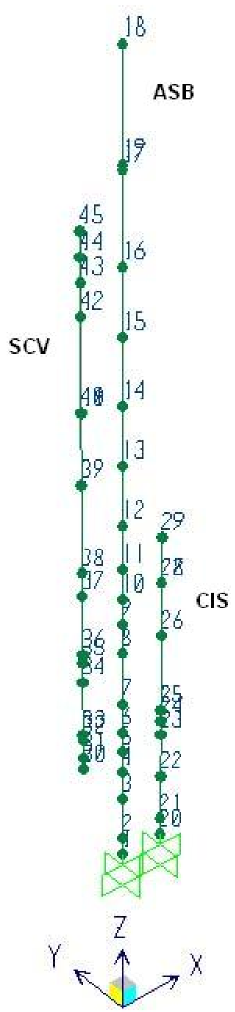
S2.1 Effect of Foundation Area & Shape: Rock Site/Vertical Motion



S2.1 SSI and Structure Response

- SSI inertial interaction foundation & structure response – 6 cases
  - 1 site condition/ground motion defined as site specific ground response spectra/ground motion time histories to be used in the analyses
  - 1 foundation footprint
  - 1 structural model
  - 3 directions - H1; H2; V
  - Coherent ground motions (Dr. Abrahamson)
  - Ground motion time histories modified by CTFs to account for incoherence
    - Exact treatment through scattering functions
    - Derived CTF to be applied to the Fourier amplitude spectra

Very Simplified Three Stick Model of NPP Configuration for Illustration Purposes

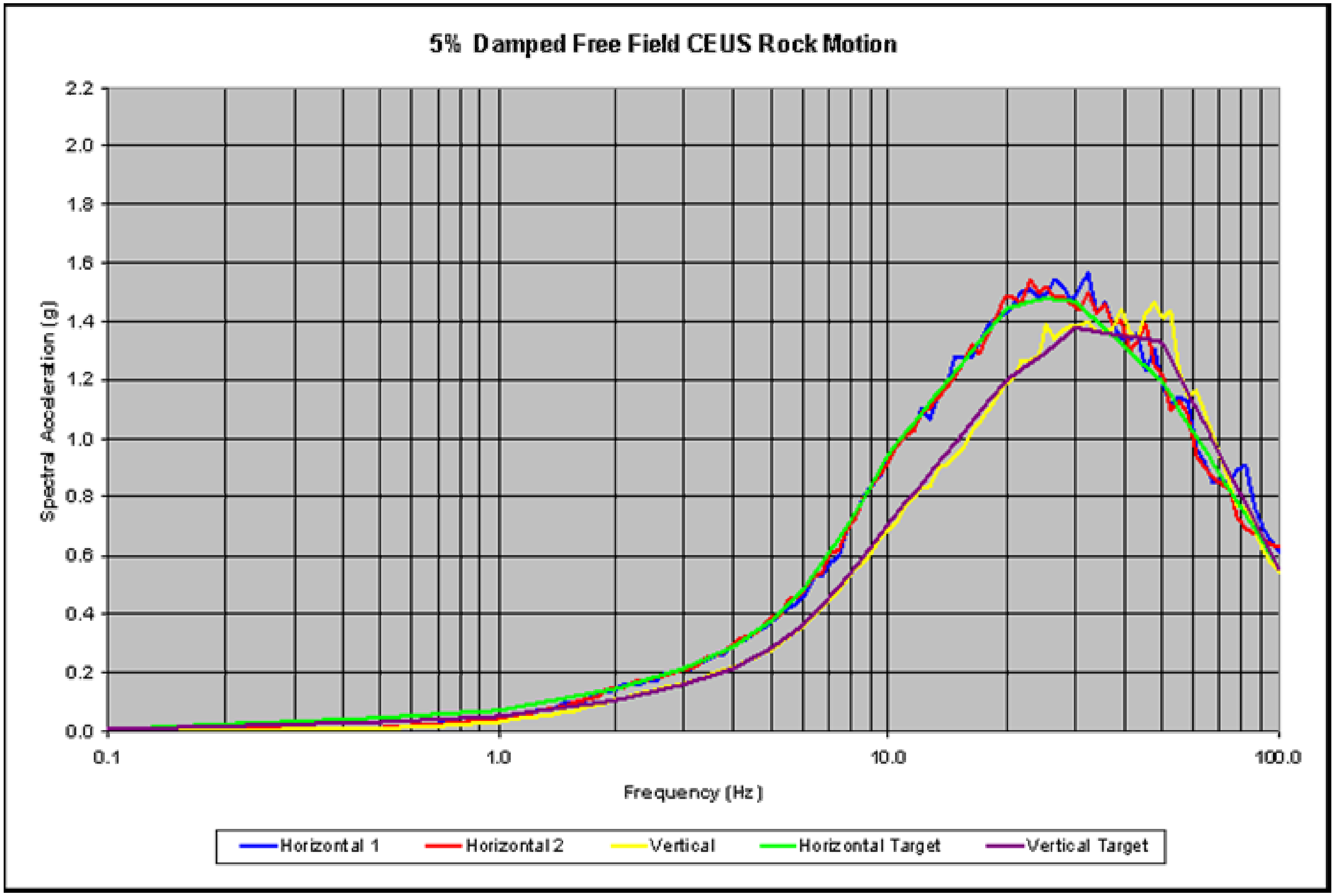


ASB: Auxiliary/Shield Building

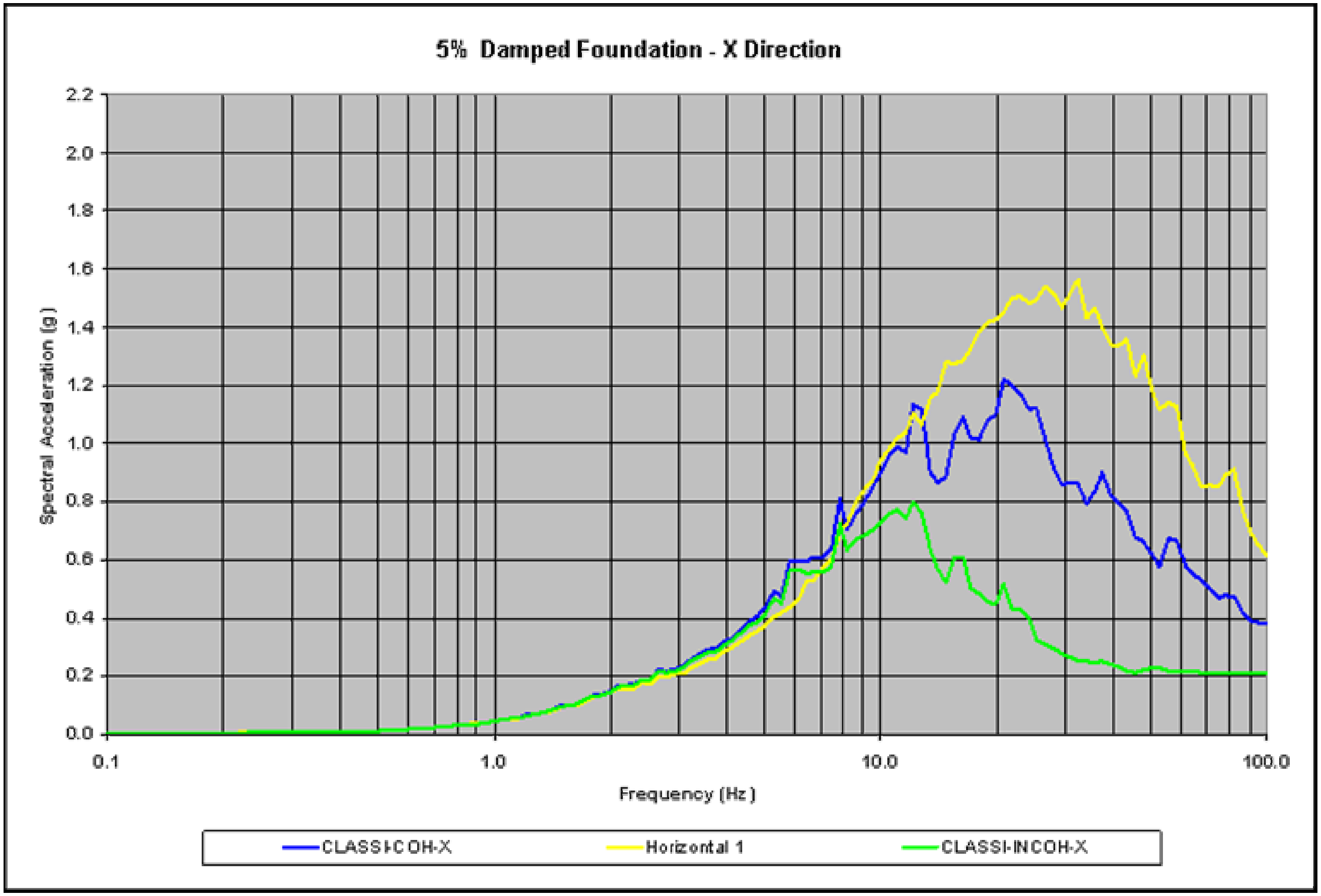
CIS: Containment Internal Structure

SCV: Steel Containment Vessel

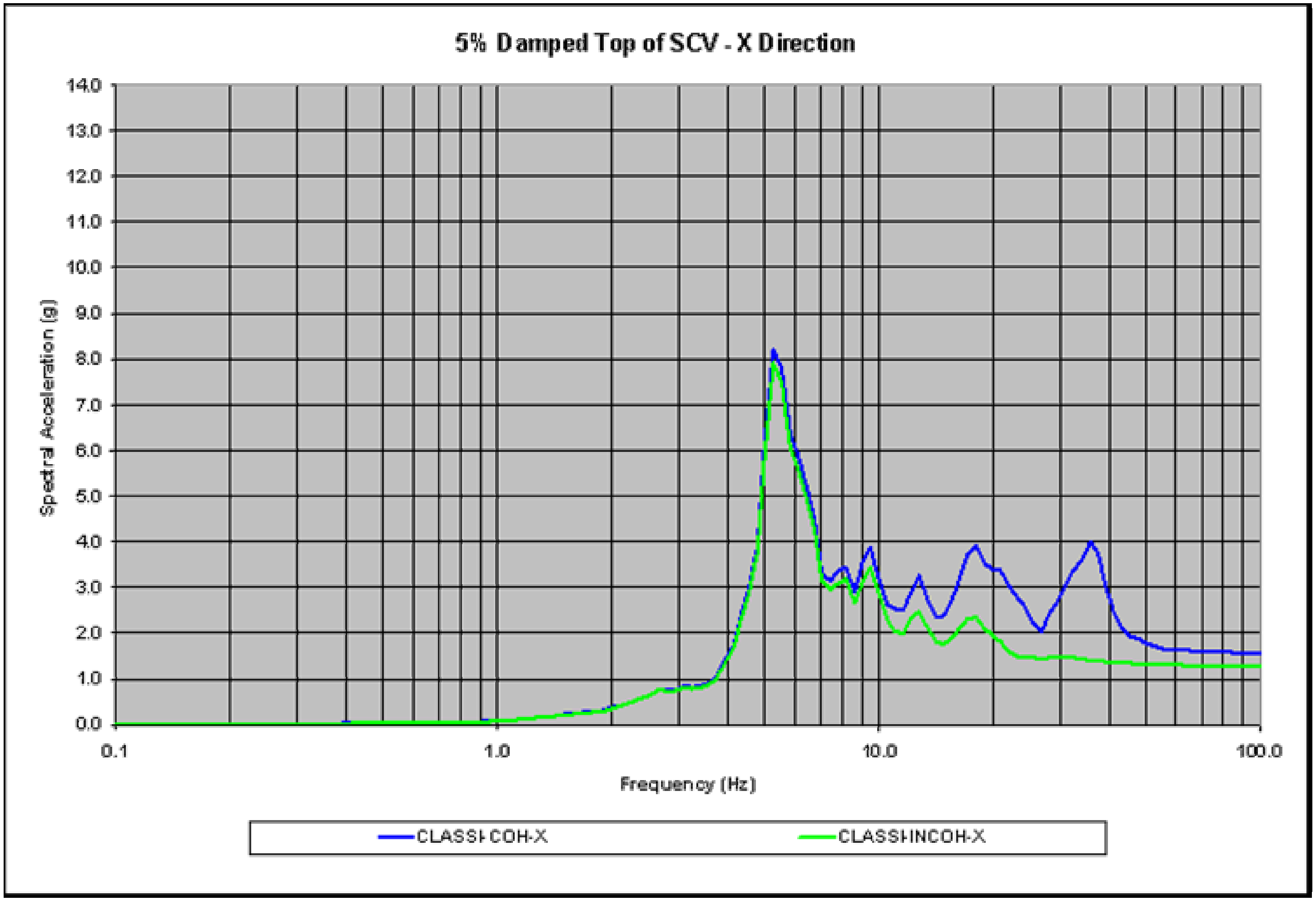
S2.1 Input Motion: Rock Ground Response Spectra and Time History Match



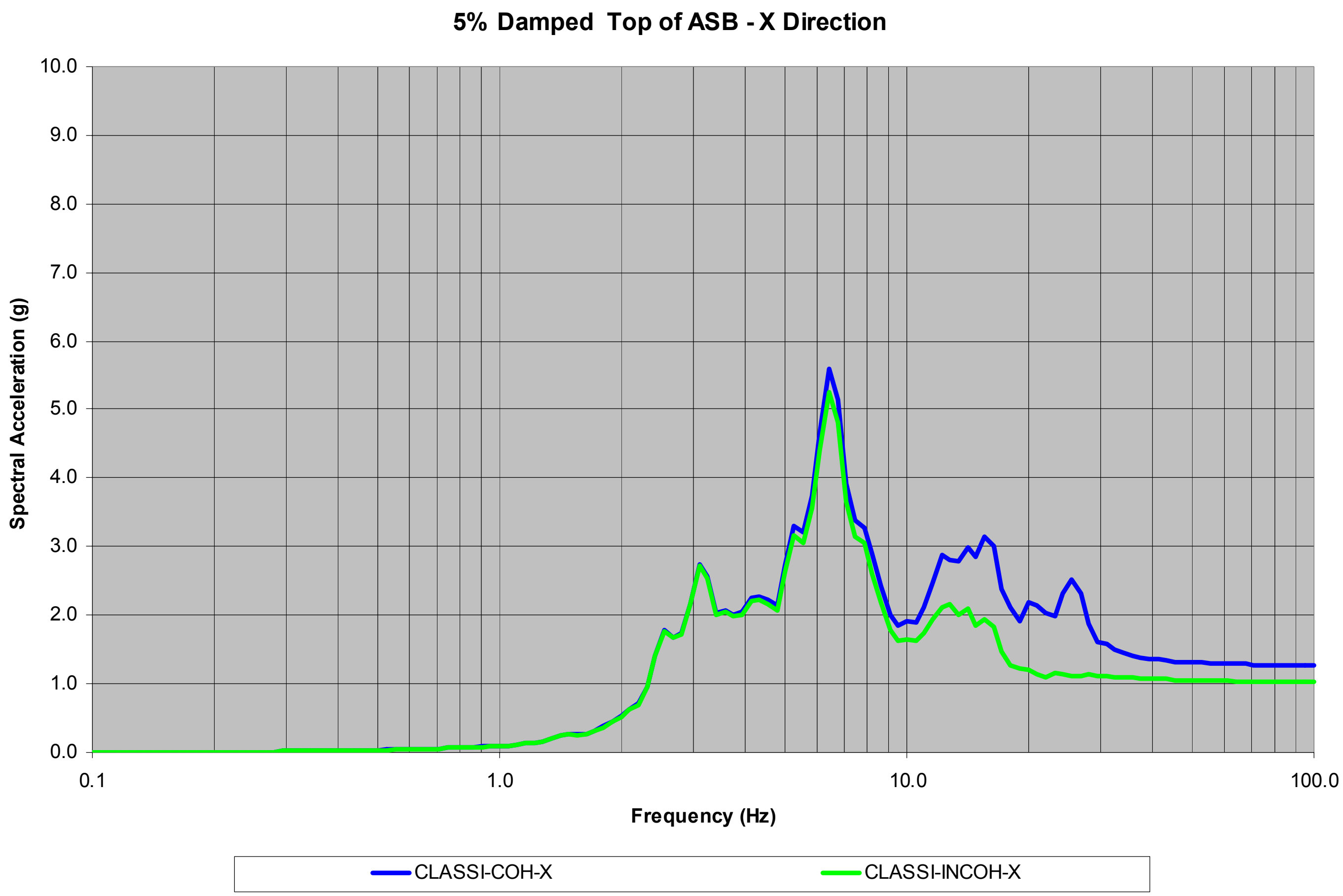
S2.1 Foundation Response: Horizontal Direction



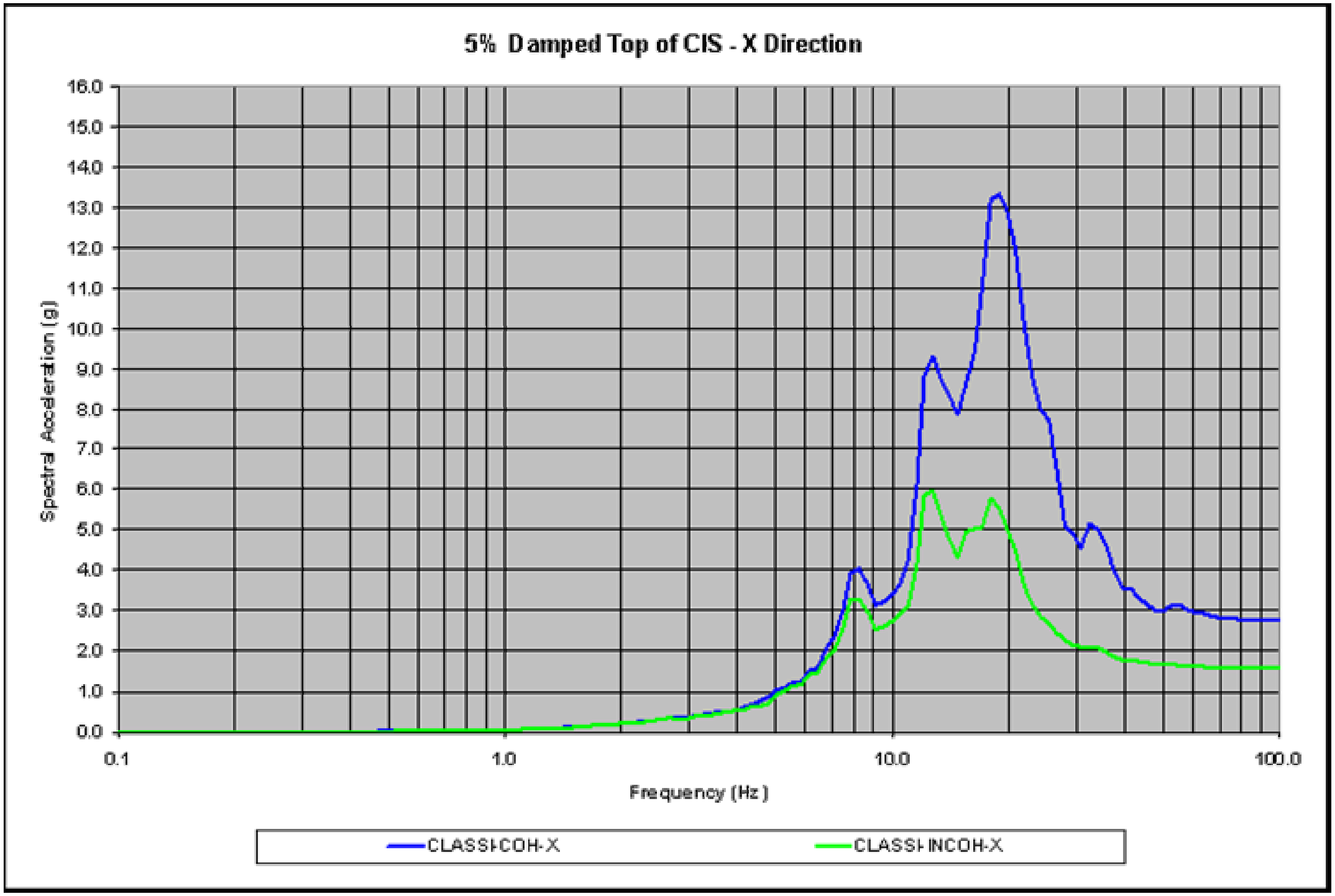
S2.1 Top of SCV Response: Horizontal Direction



S2.1 Top of ASB Response: Horizontal Direction



S2.1 Top of CIS Response: Horizontal Direction

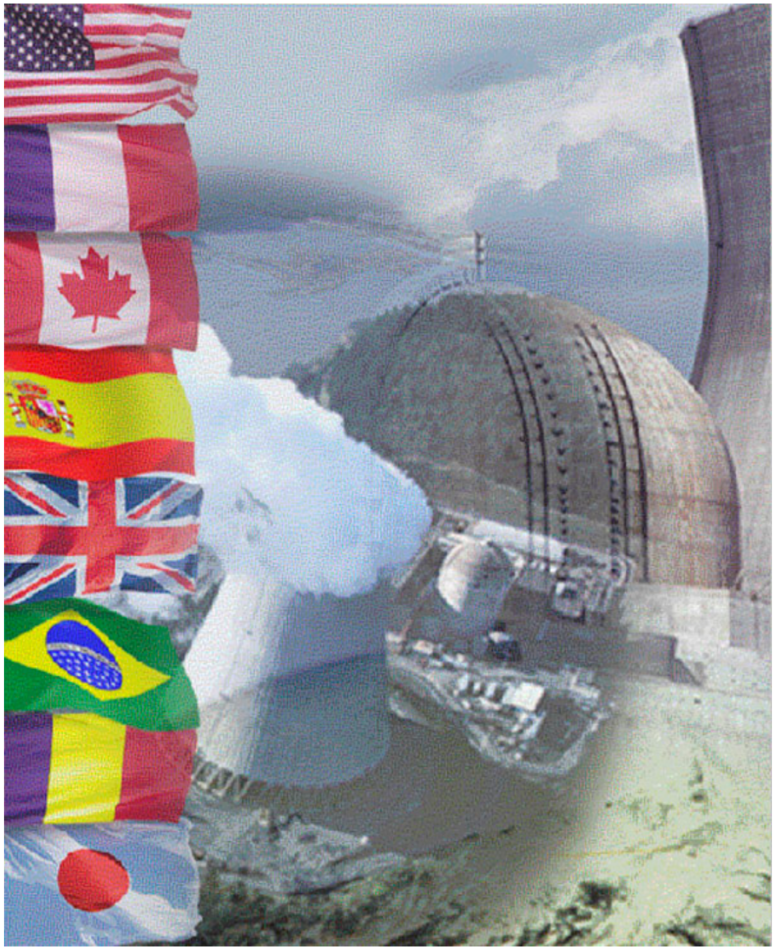


Status/Schedule of S2.1 Tasks

- Define cases to be analyzed (4/2005)
  - Site conditions
  - Foundation characteristics
  - Structural characteristics
- Ground motion input
  - Response spectra
  - Coherency functions
    - Horizontal and vertical
    - Uncertainty bands
  - PSD by random vibration theory
- Coherency Transfer Function
  - Rigid-Massless Foundation Rock
  - Rigid Massless Foundation Soil
  - Validation with SASSI (Bechtel)
  - Coherency Transfer Function SSI Validation (In progress)

Status/Schedule of S2.1 Tasks (cont.)

- Sensitivity studies
  - 4 & 2 km/s apparent wave velocity
  - Foundation shape
  - Foundation size
  - Embedment (Bechtel/SASSI)
- Evaluation of spectra reductions on foundation
  - Rock and soil sites
- Evaluation of spectra reductions in structure (In progress)
  - Rock site
  - Comparison with SASSI (Bechtel)
- Development and validation of functional fit of CTFs (In progress)
- Final Report to NRC (1/06)



S2.1 Backup

Horizontal Spatial Variation of Ground Motion - Incoherence

- Wave passage effects
  - Systematic spatial variation due to difference in arrival times of seismic waves across a foundation
- Random spatial variation
  - Scattering of waves due to heterogeneous nature of the soil or rock at the locations of interest and along the propagation paths of the incident wave fields
- Horizontal spatial variation of both horizontal and vertical ground motion are considered

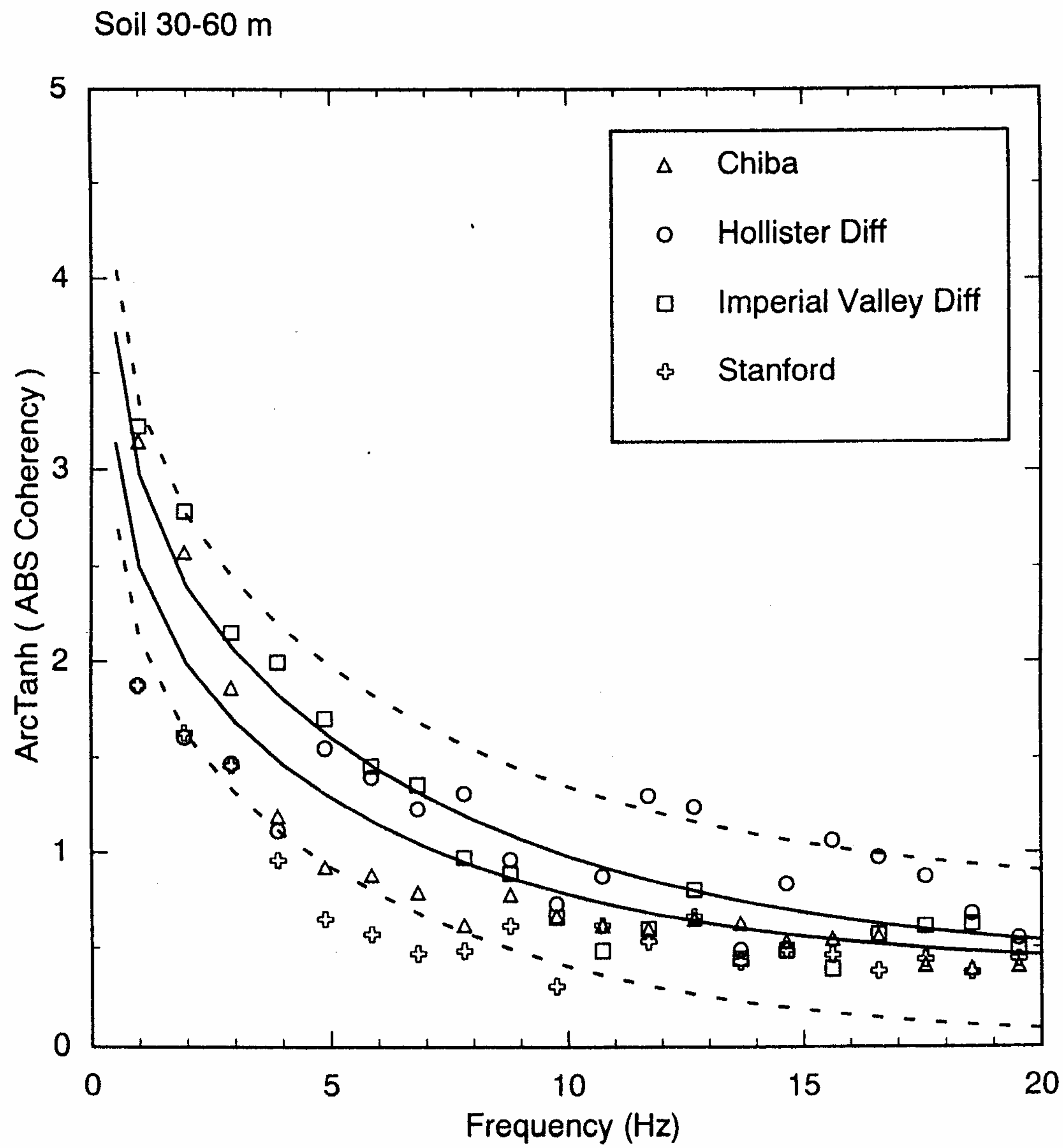
Response Spectra & Power Spectral Density by Random Vibration Theory

- Standard relationships of stationary random vibration theory are used to convert response spectra (RS) into power spectral density (PSD) functions and vice versa
- To calculate a PSD from a RS, an iterative process is used. A starting PSD uniform function (white noise) is used and iterations performed until the RS calculated from the new PSD matches the target RS
- To calculate a RS from a PSD, a direct integral relationship exists. Numerical integration is performed to calculate the moments of the PSD and the peak factors relating the standard deviation of the maximum response to the mean of the maximum peak response (RS)
- Der Kiureghian, A., "Structural Response to Stationary Excitation," Journal of the Engineering Mechanics Division, American Society of Civil Engineers, December 1980 is the basic reference followed

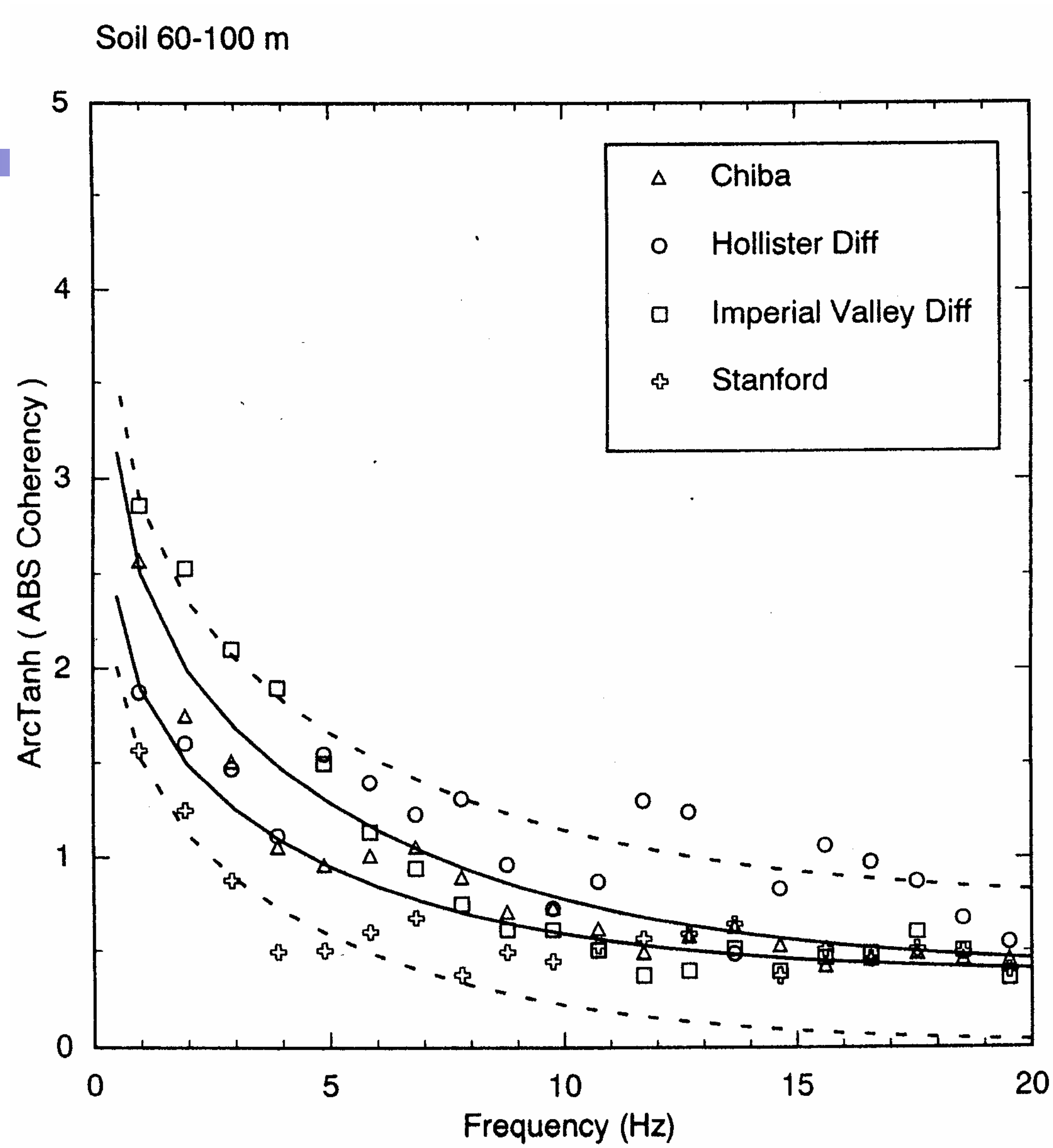
Wave Passage Effects

- The 150 foot square foundation on a rock halfspace was also evaluated including wave passage
  - Apparent wave velocity of 2000 m/s
    Slowness of 0.00050 s/m
  - Apparent wave velocity of 4000 m/s
    Slowness of 0.00025 s/m
  - No wave passage effects
    - Apparent wave velocity = infinity
      Slowness of 0 s/m

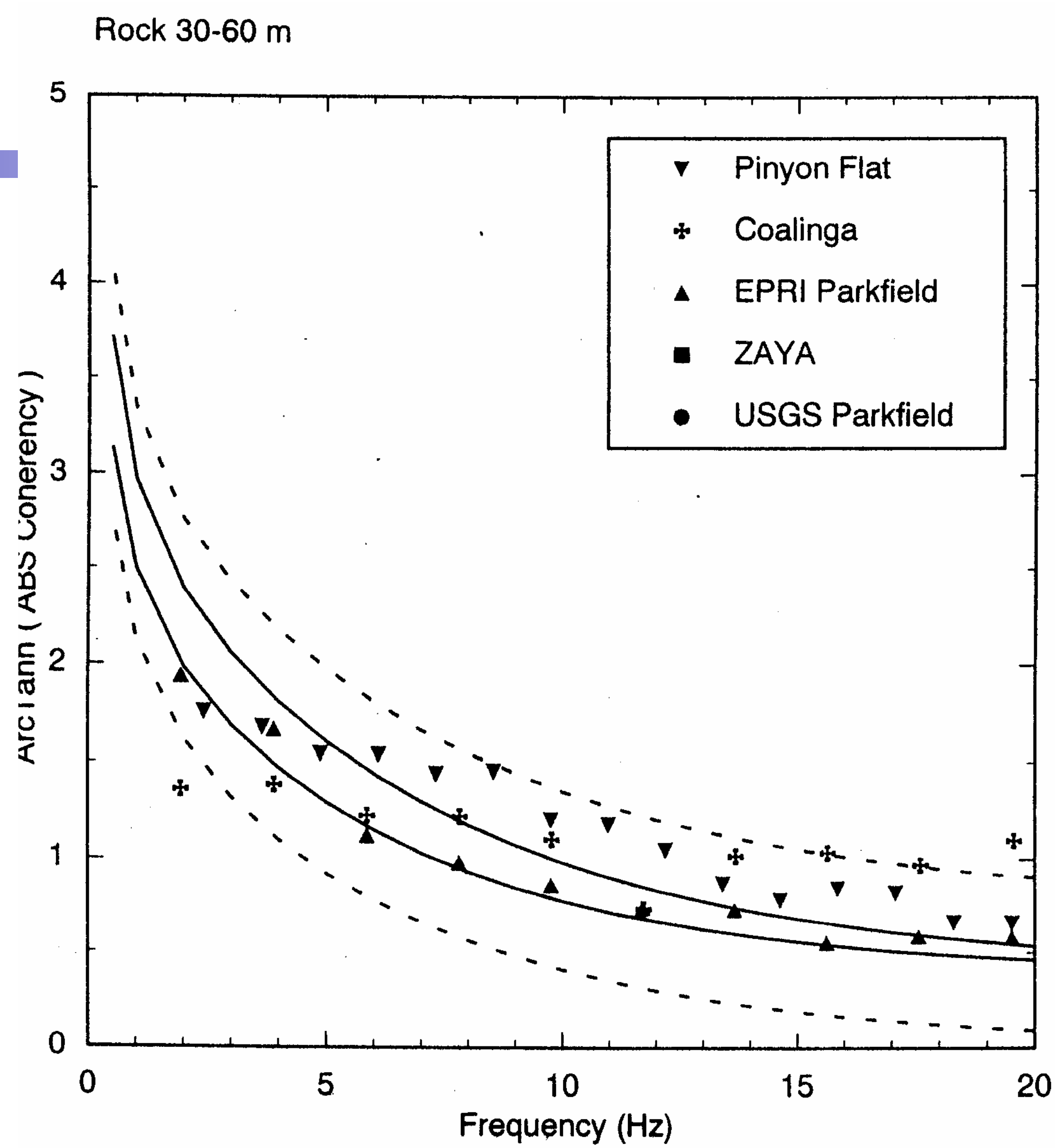
Comparison with Other Soil Sites 30-60m



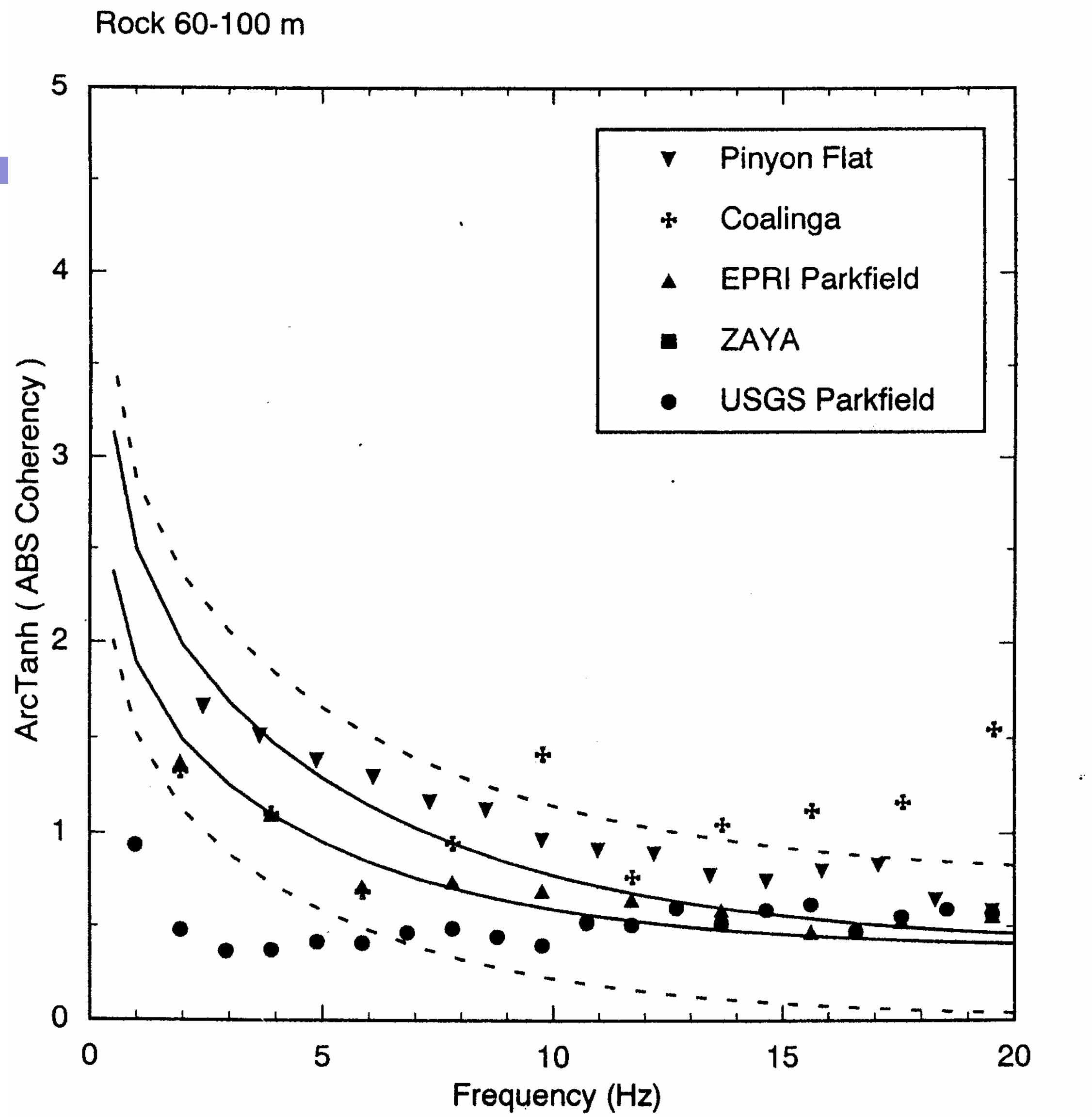
Comparison with Other Soil Sites 60-100m



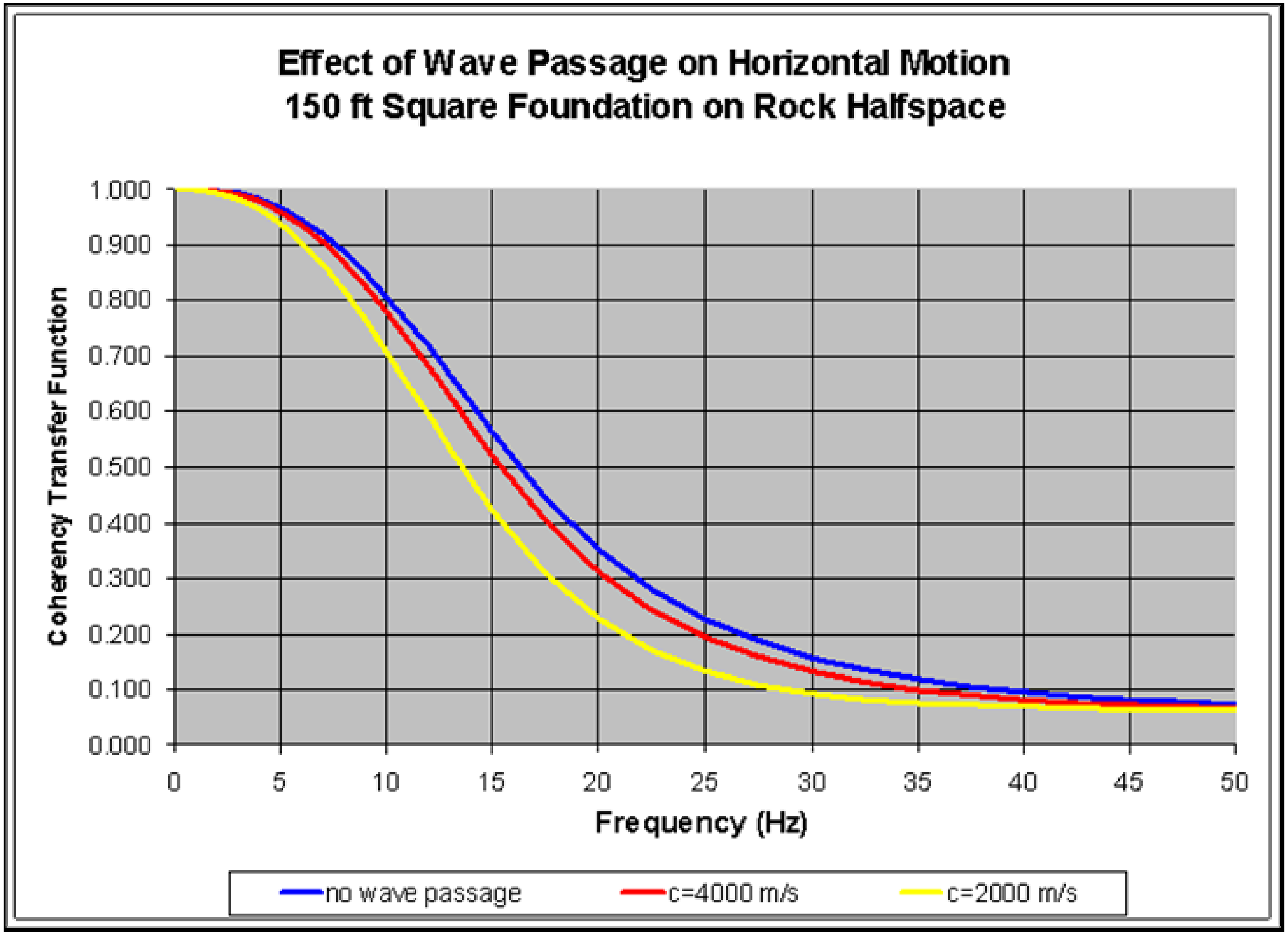
Comparison with Rock Sites 30-60m



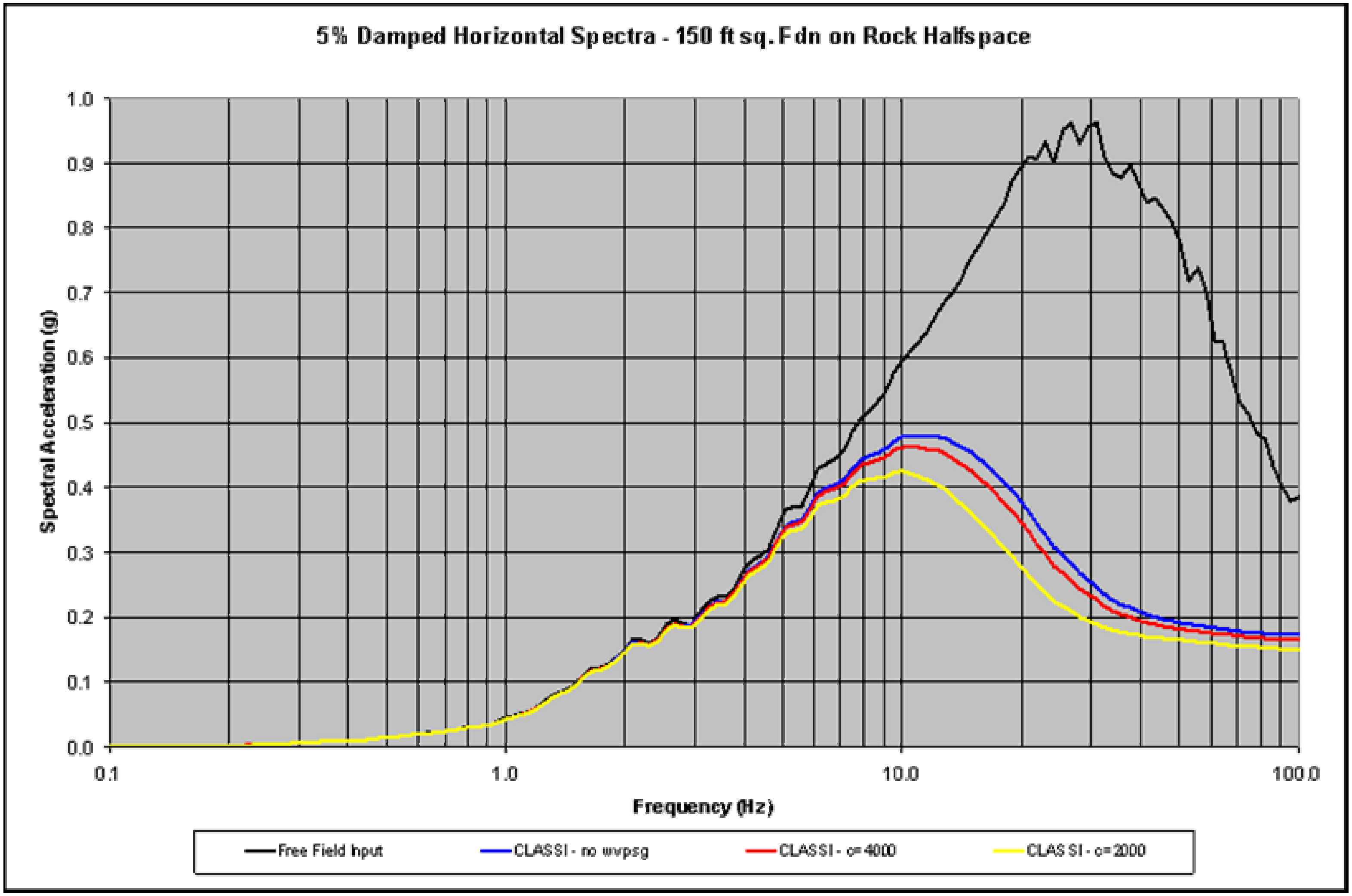
Comparison with Rock Sites 60-100m



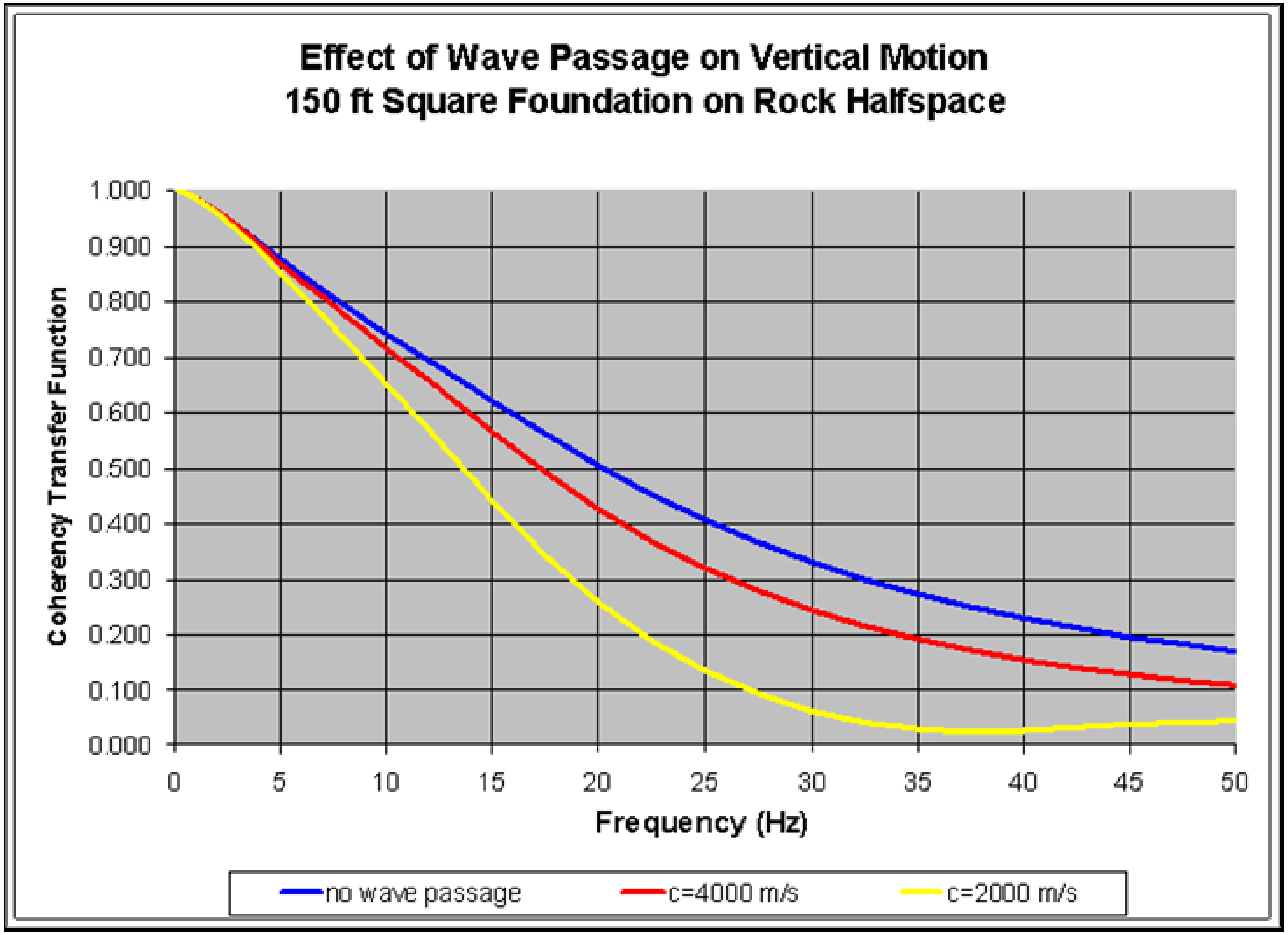
Wave Passage Effects – Horizontal Motion



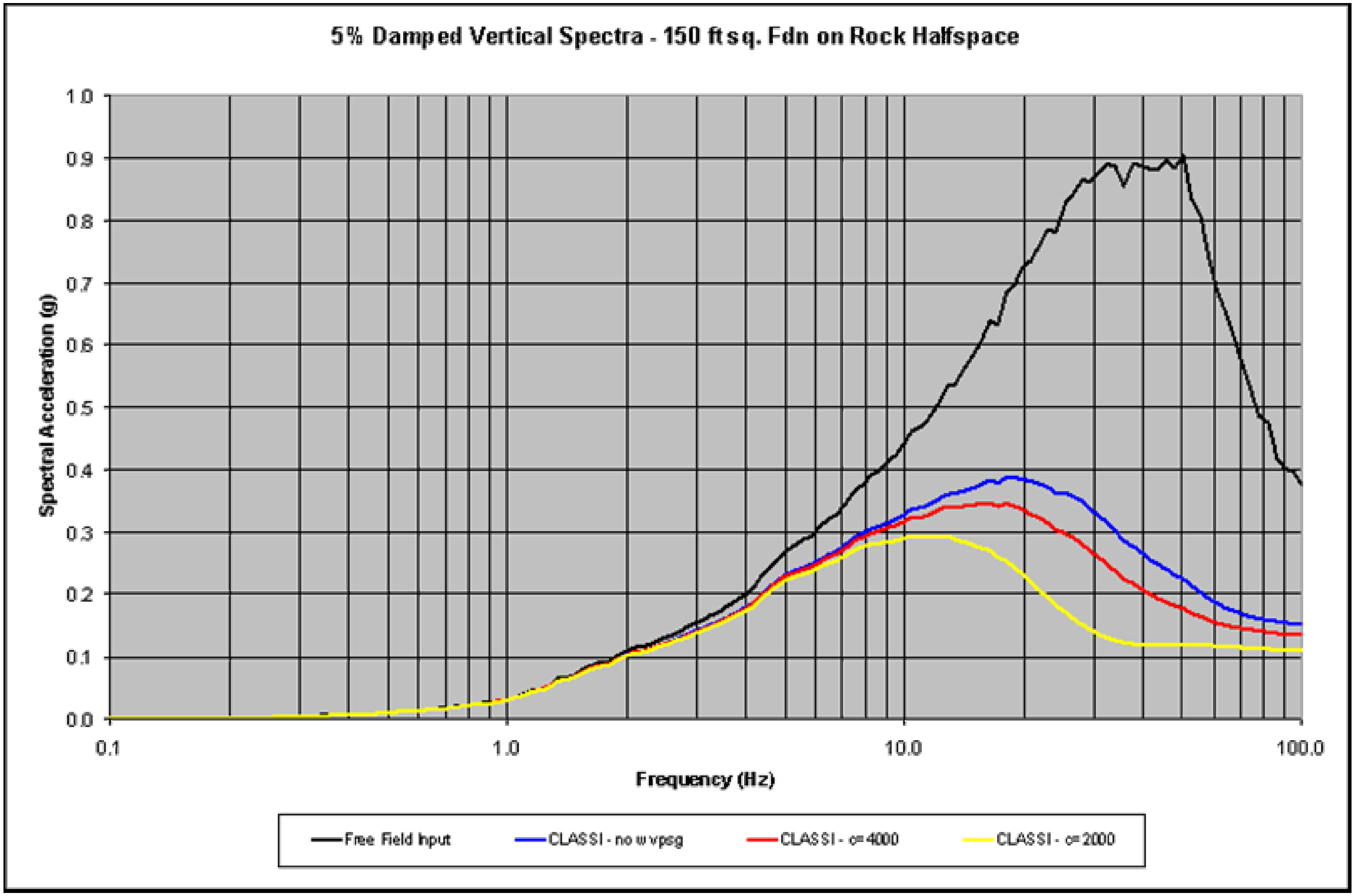
Wave Passage Effects – Horizontal Motion



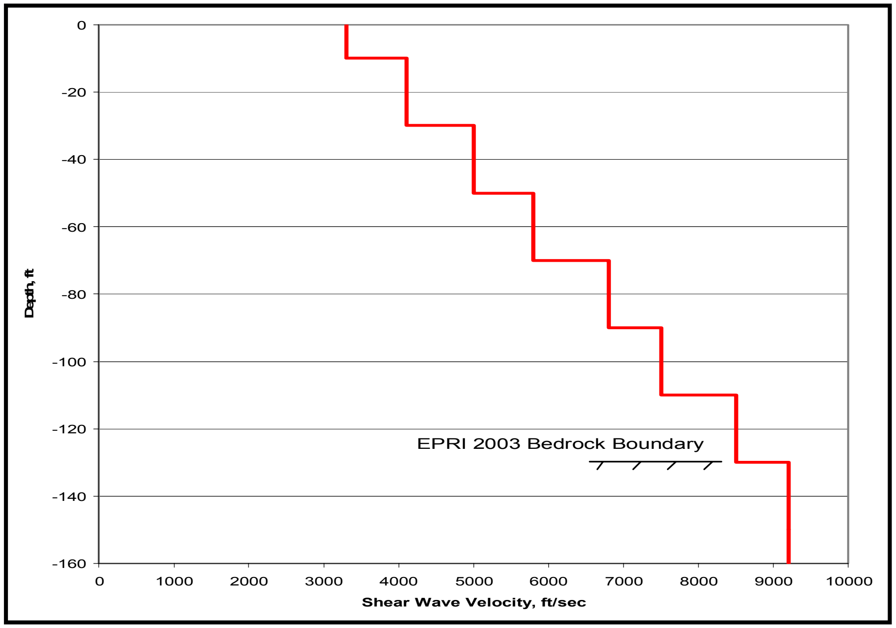
Wave Passage Effects – Vertical Motion



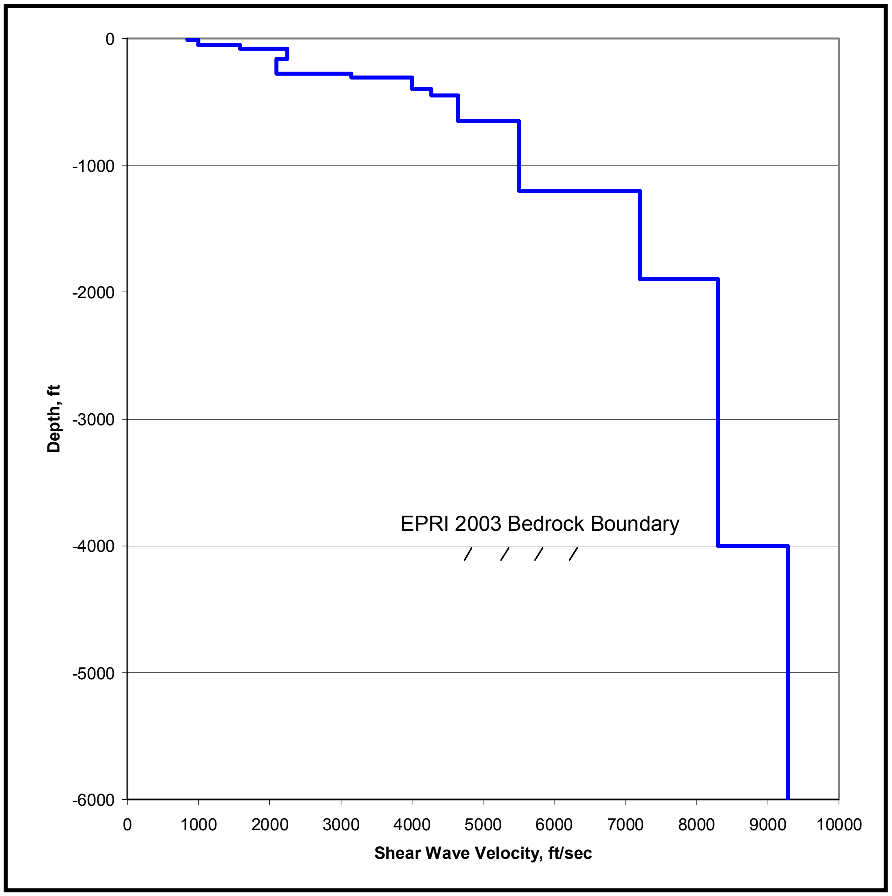
Wave Passage Effects – Vertical Motion



S2.1 Soil Profiles



High Frequency Rock Site



Lower Frequency Soil Site

Spectra Reductions for Horizontal Motion

	ASCE 4		Rock-H			Soil-H		
Frequency	150	300	75	150	300	75	150	300
5.00	1.00	1.00	0.95	0.93	0.89	0.98	0.97	0.95
10.00	0.90	0.80	0.84	0.78	0.71	0.90	0.85	0.79
15.00	0.86	0.71	0.68	0.59	0.49	0.78	0.71	0.63
20.00	0.82	0.65	0.50	0.41	0.33	0.68	0.62	0.56
25.00	0.80	0.60	0.38	0.30	0.24	0.64	0.60	0.55
30.00	0.80	0.60	0.32	0.25	0.20	0.64	0.60	0.56
40.00	0.80	0.60	0.27	0.22	0.19	0.65	0.62	0.59
50.00	0.80	0.60	0.26	0.22	0.19	0.68	0.66	0.63

Spectra Reductions for Vertical Motion

	ASCE 4		Rock-V			Soil-V		
Frequency	150	300	75	150	300	75	150	300
5.00	1.00	1.00	0.88	0.85	0.80	0.91	0.89	0.86
10.00	0.90	0.80	0.78	0.73	0.66	0.83	0.79	0.74
15.00	0.86	0.71	0.69	0.62	0.54	0.76	0.71	0.62
20.00	0.82	0.65	0.61	0.52	0.43	0.69	0.63	0.54
25.00	0.80	0.60	0.53	0.44	0.36	0.64	0.57	0.50
30.00	0.80	0.60	0.46	0.38	0.30	0.59	0.52	0.46
40.00	0.80	0.60	0.36	0.29	0.23	0.53	0.48	0.43
50.00	0.80	0.60	0.31	0.25	0.20	0.50	0.46	0.42

Significant Modes – Mass Participation

		Mass Participation Ratio			
Mode	Freq (Hz)	X	Y	Z	Description
1	3.00	0.000	0.215	0.000	ASB Y-direction mode
2	3.21	0.199	0.000	0.000	ASB X-direction mode
5	5.46	0.031	0.000	0.000	SCV X-direction mode
6	6.14	0.000	0.053	0.000	SCV Y-direction mode
11	9.47	0.000	0.216	0.000	ASB Y-direction mode, CIS Y-direction mode
13	9.85	0.000	0.000	0.253	ASB Z-direction mode
14	9.89	0.163	0.000	0.000	ASB X-direction mode, CIS X-direction mode, SCV X-direction mode
16	12.04	0.000	0.041	0.000	CIS Y-direction mode
17	13.29	0.068	0.000	0.000	CIS X-direction mode

S2.1 SSI and Structure Response

- SSI inertial interaction foundation & structure response – 6 cases
  - 1 site condition/ground motion defined as site specific ground response spectra/convert to PSD
  - 1 foundation footprint
  - 1 structural model
  - 3 directions - H1; H2; V
  - 2 coherency functions; NAA, coherent

- **SSI inertial interaction foundation & structure response – 6 cases**
  - **1 site condition/ground motion defined as site specific ground response spectra/ground motion time histories to be used in the analyses**
  - **1 foundation footprint**
  - **1 structural model**
  - **3 directions - H1; H2; V**
  - **Coherent ground motions**
  - **Ground motion time histories modified by CTFs to account for incoherence**