Application of Random Vibration Theory Methodology for Seismic Soil-Structure Interaction Analysis

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Background

- Current practice for SSI analysis utilizes time histories matched to design response spectra
  - Structural responses may vary significantly depending on the time history seed selection
- Recently, the number of time histories required to obtain a stable mean response has been challenged
  - Forthcoming version of ASCE 4 recommends a minimum of 5 sets of time histories to capture variability of ground motion on structural response
  - SRP 3.7.1 requests closer inspection of Power Spectral Density before a time history is selected

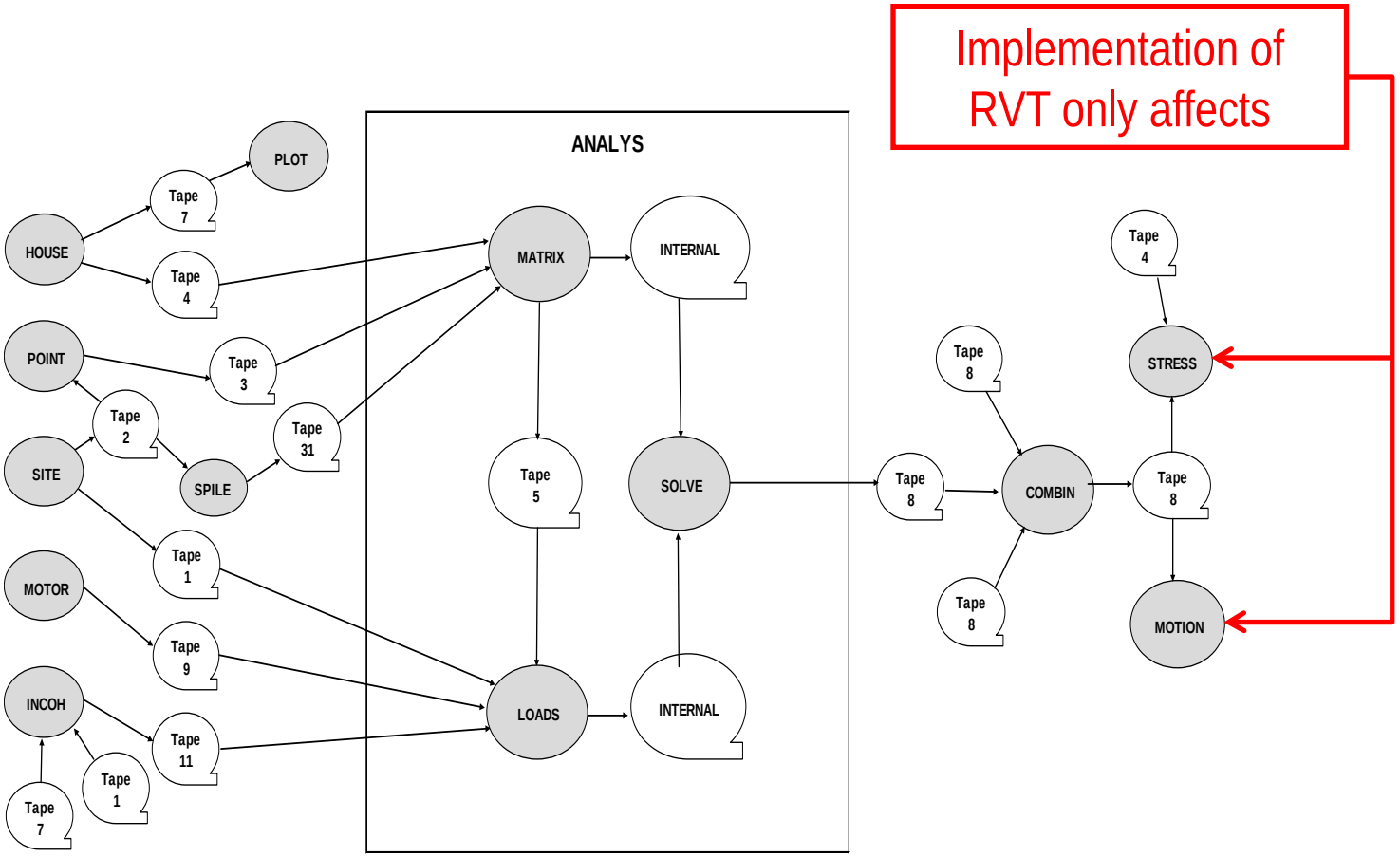
Background

- In RVT analysis, the structural response is directly calculated from a design response spectrum, eliminating the need to work with time histories
- RVT has been used in recent years for seismic site response and development of ground motions
- Using the same methodology RVT has been applied to SSI analysis
  - Reviewed in technical publications and regulatory reviews
  - Is permitted in the forthcoming version of ASCE 4

RVT Formulation in SASSI2010

- RVT Formulation for SASSI2010
  - Published by Farhang Ostadan and Nan Deng
  - Proceedings of the 15th World Conference on Earthquake Engineering
  - "Random Vibration Theory-Based-Soil-Structure Interaction Analysis"

RVT Implementation in SASSI2010



Objective

- Demonstrate use of RVT analysis to produce a stable mean response in one step through comparison with multiple time history analyses
- Four Demonstration Cases:
  - Diesel Generator Type Structure on Hard Rock
  - Lumped Mass Stick Model of Reactor Type Structure on Hard Rock
  - Deeply Embedded Structure on Rock Site
  - Deeply Embedded Structure on Soil Site

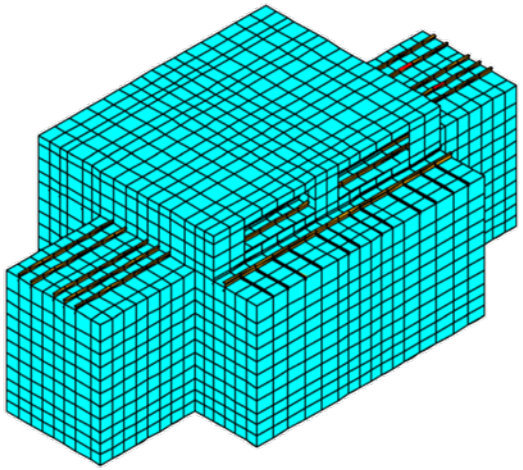
Diesel Generator – Inputs and Parameters

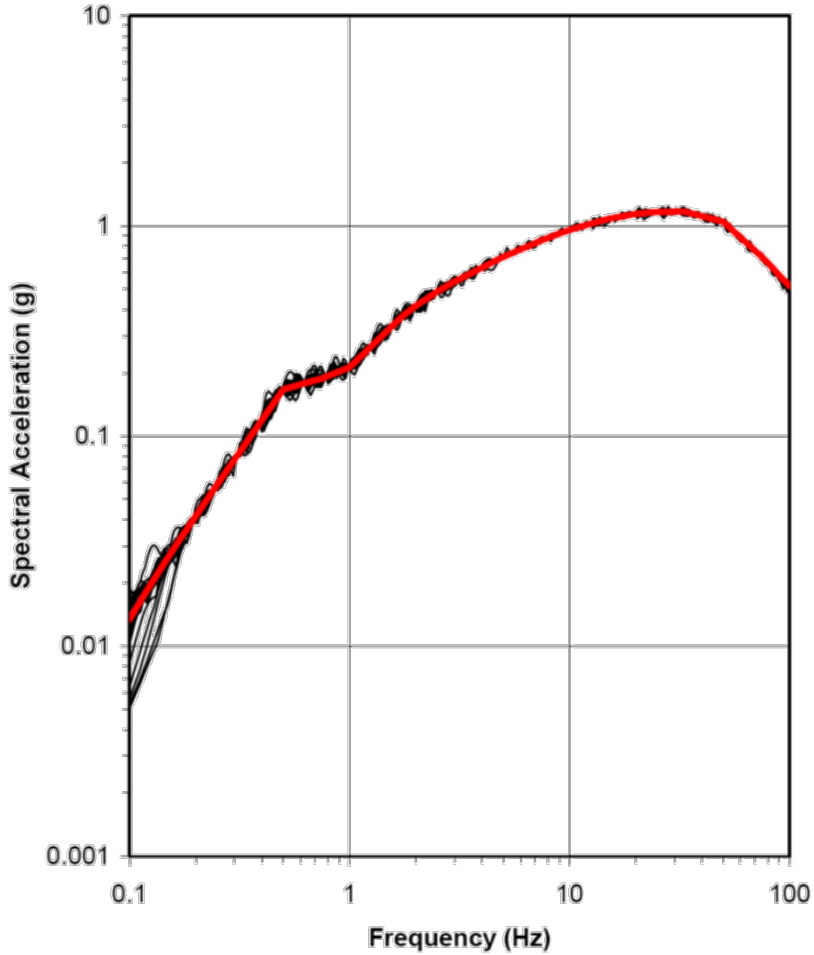
SASSI2010 Verification for RVT DG Building

Surface-Founded, Finite Element Model

Hard Rock

30 Time Histories Matched to One Target Spectrum

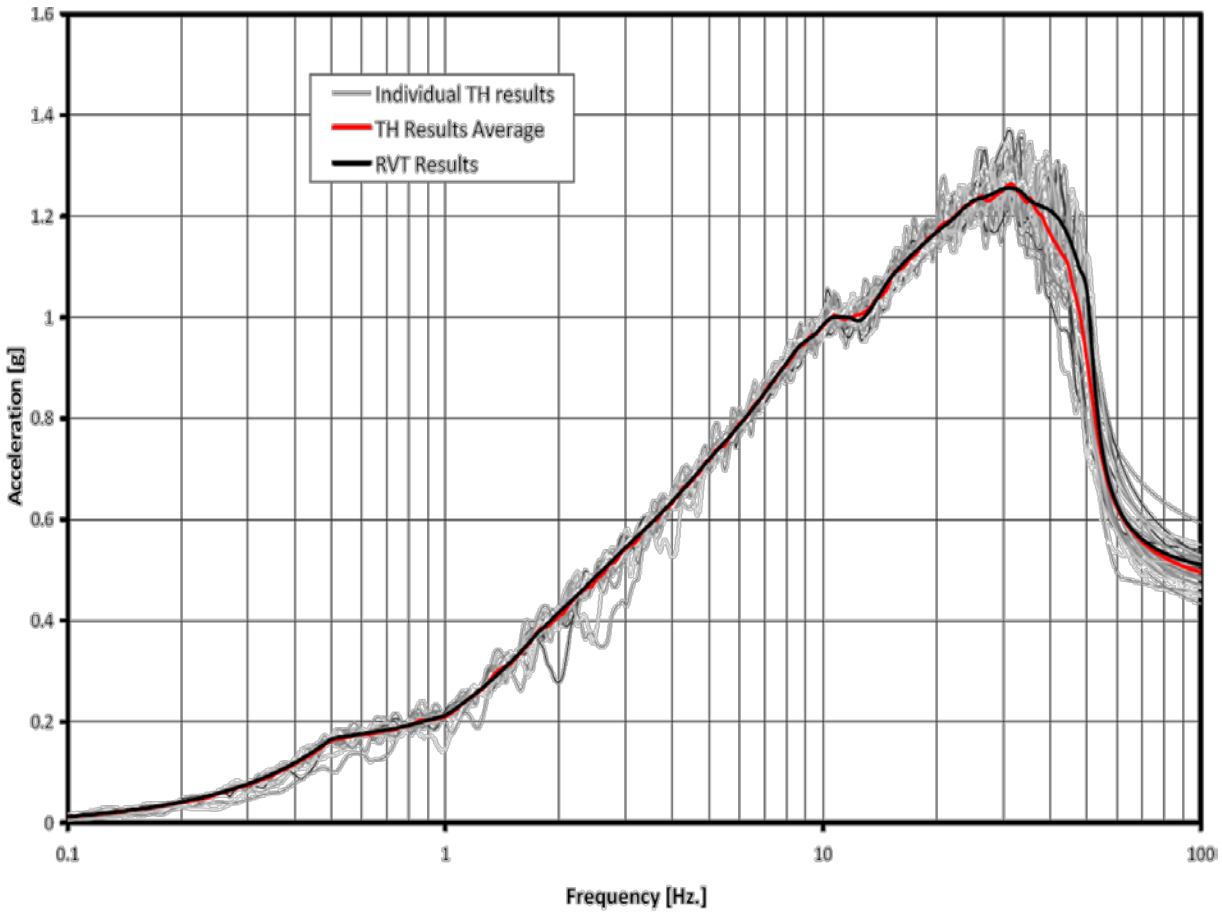




Note: Thin black lines show ARS calculated from each time history, red line is the target spectrum

Diesel Generator – Comparisons

5% Damped Horizontal ARS at Basemat Level, DG



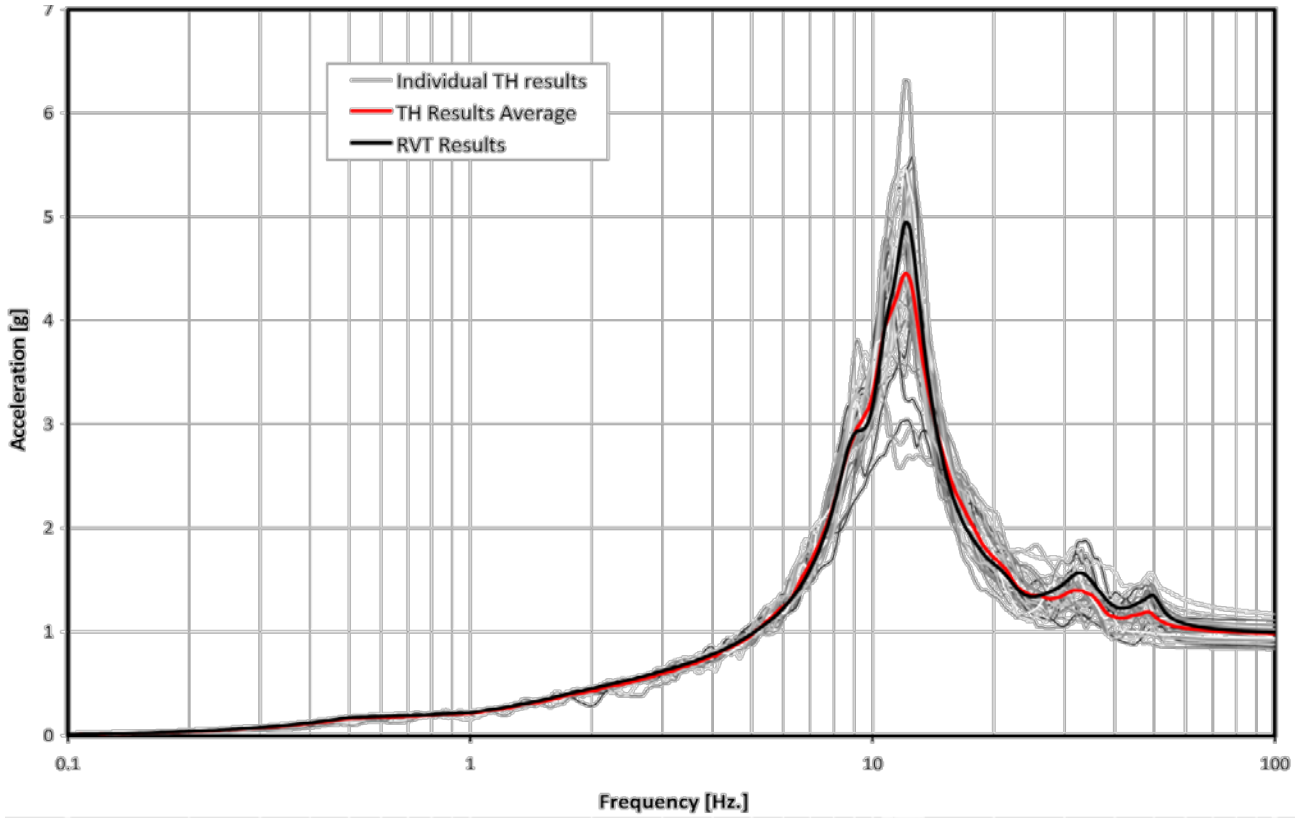
Diesel Generator – Comparisons

Results from time history analyses are sensitive to time history input

The variation in the response is large

Obtaining mean stable responses requires several sets of time histories

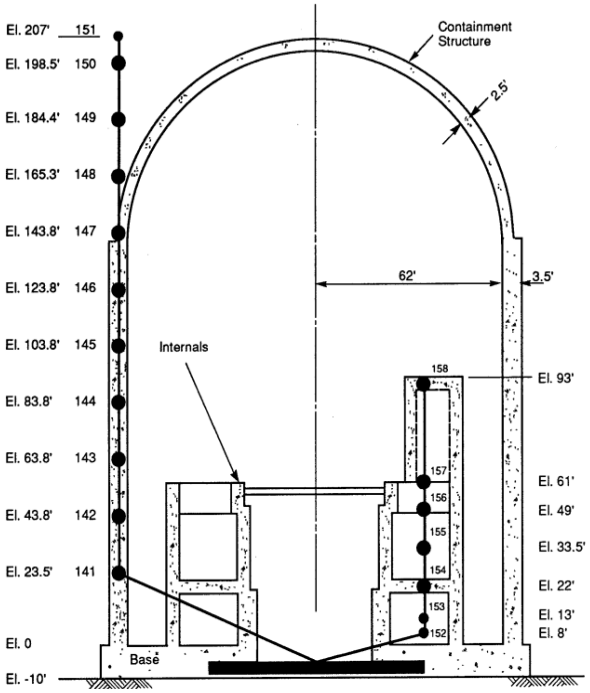
5% Damped Horizontal ARS at Roof Level, DG



Lumped Mass Stick – Input and Parameters

SASSI2010 Verification for RVT using Reactor Stick Models on Hard Rock

30 Time Histories Matched to One Target Spectrum



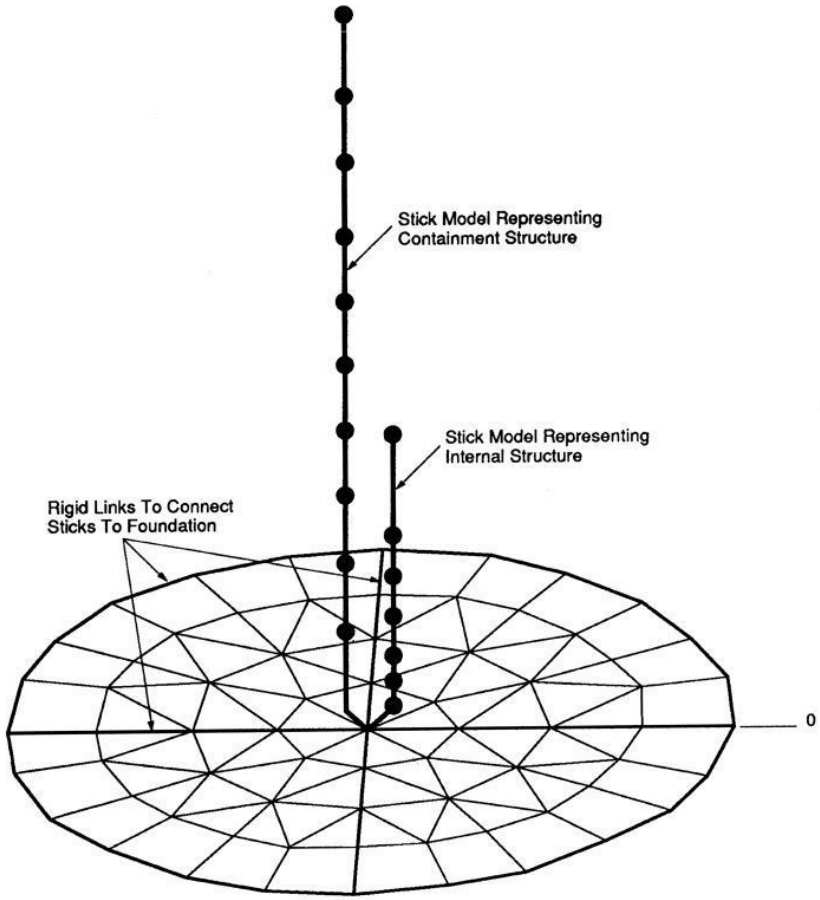
Soil Properties

V_s = 12,000 ft/s

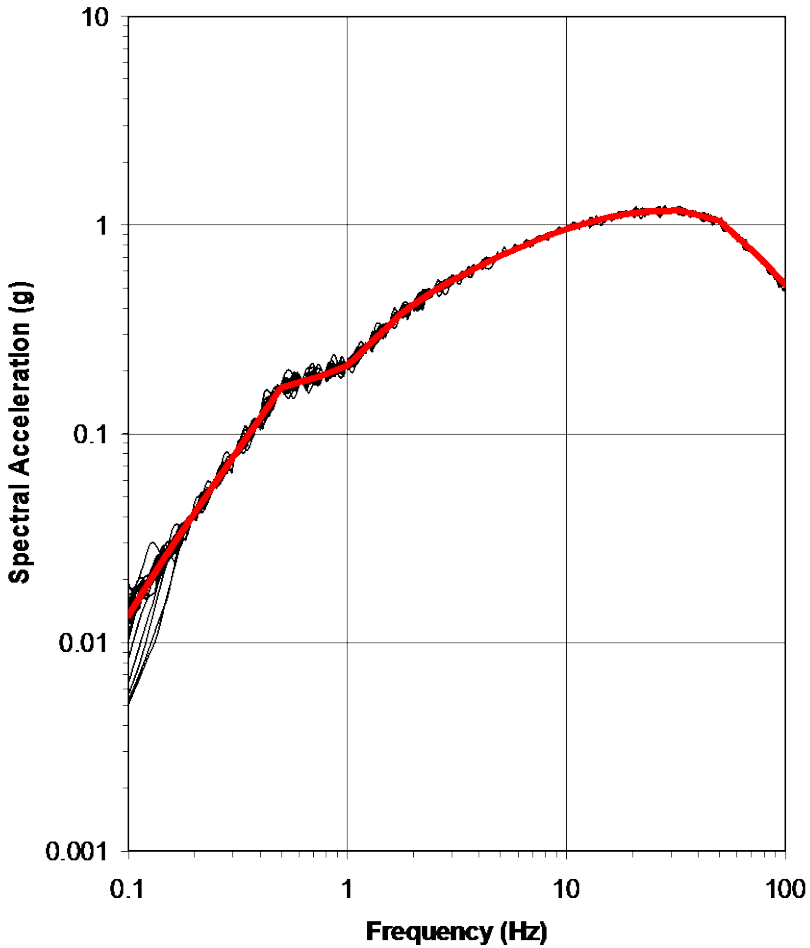
V_p = 24000 ft/s

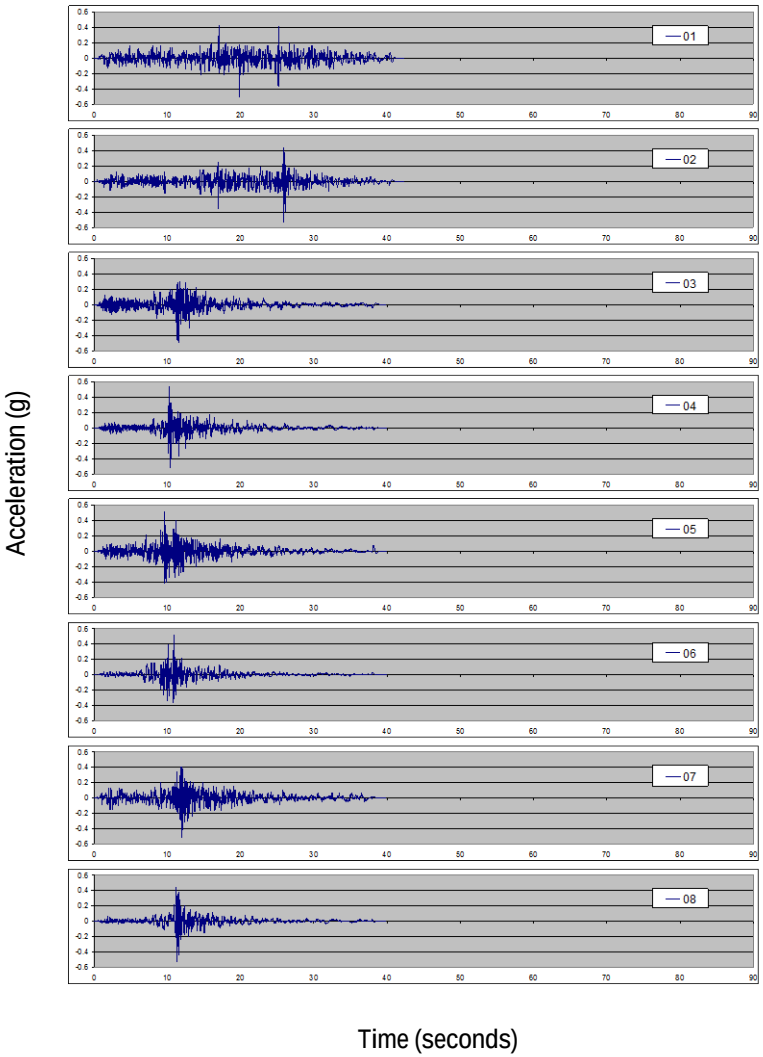
γ = 0.130 kcf

β = 0.05

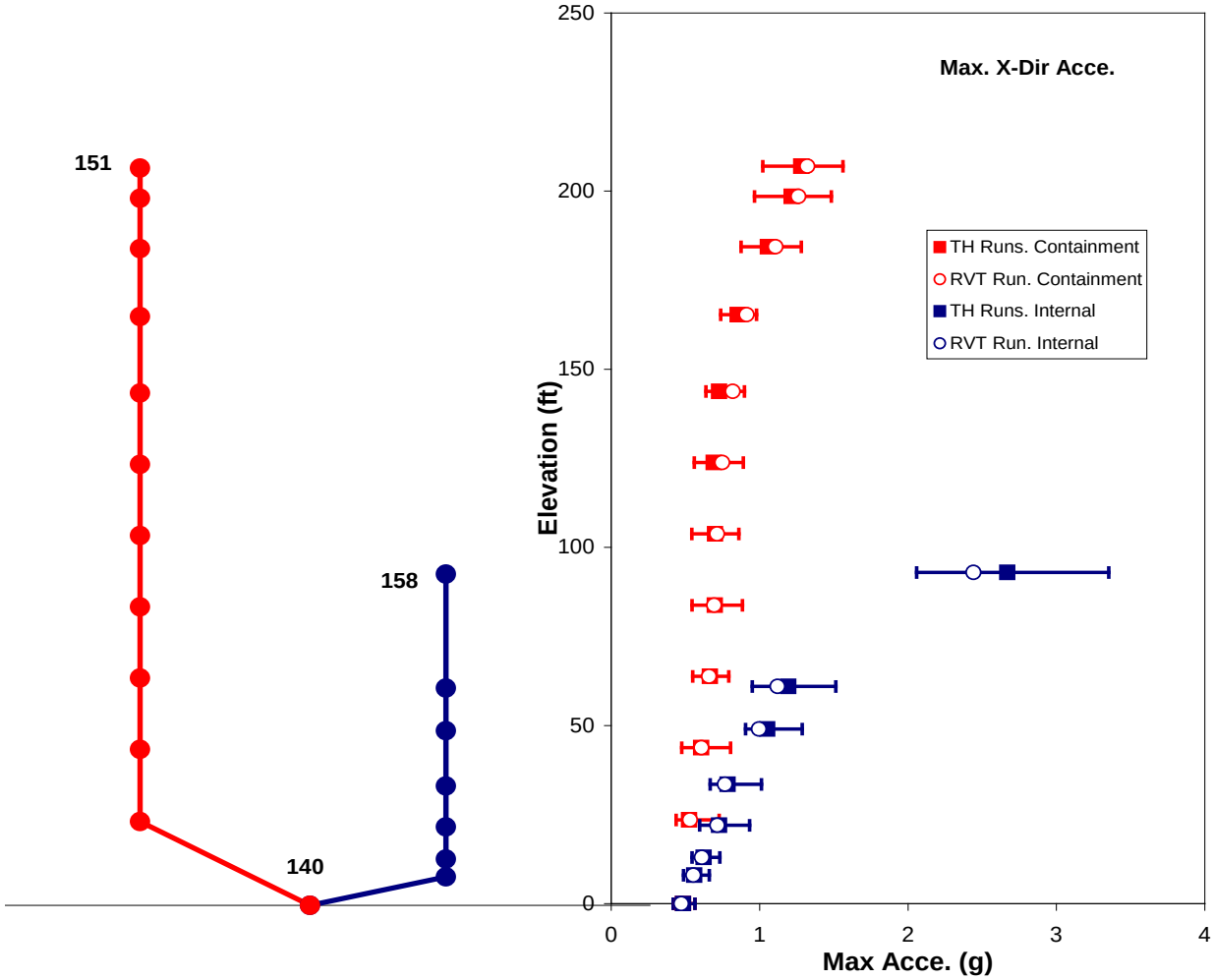


Lumped Mass Stick – Input and Parameters





Lumped Mass Stick – Comparisons



Comparison of Calculated Maximum Accelerations at Lumped Mass Nodes

Lumped Mass Stick – Comparisons

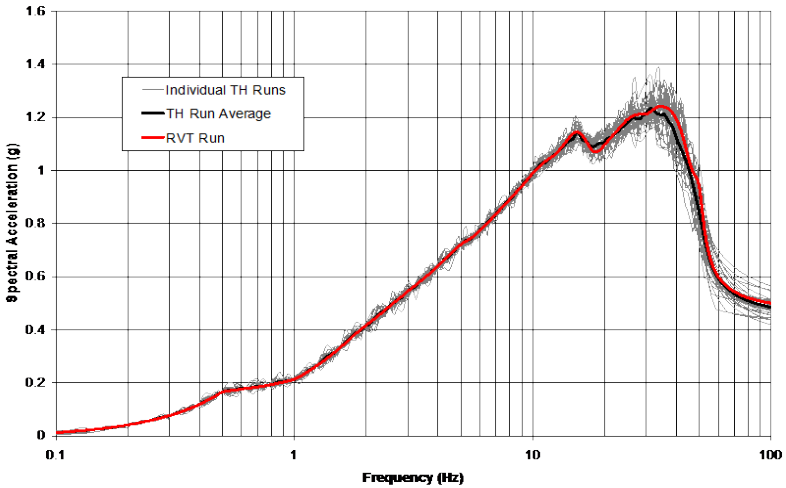


Figure 5.1-4 Comparison of 5% Damped ISRS at the Basemat

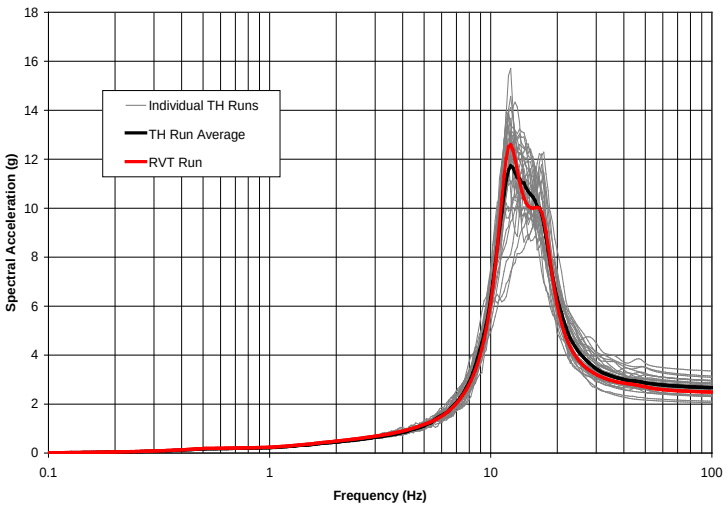


Figure 5.1-6 Comparison of 5% Damped ISRS at Top of Internal Structure

- Results from time history analysis are sensitive to time history input
- Variation in the response is large
- Obtaining mean stable response requires several sets of time histories

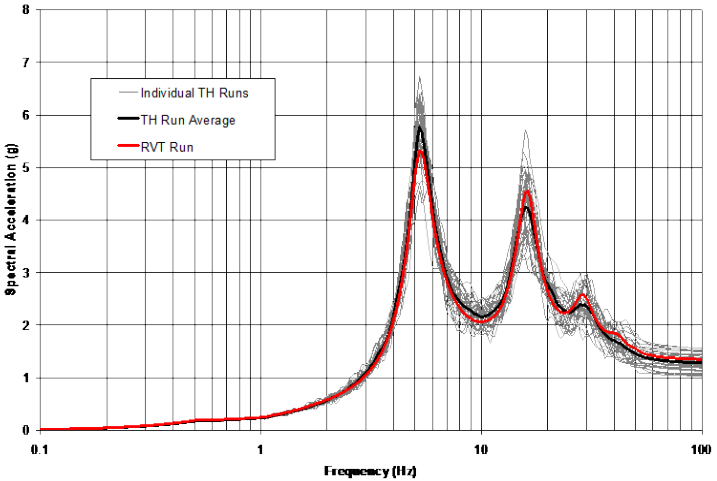


Figure 5.1-5 Comparison of 5% Damped ISRS at Top of Containment Structure

Lumped Mass Stick – Comparisons

Base Shear and Moments in the Containment Model

Analysis Case		Base Shear X-Dir (kips)	Base Moment YY-Dir (kip-ft)
30 TH	Min	17790	2.283E+06
	Mean	19764	2.446E+06
	Max	23130	2.670E+06
RVT	Single analysis	20980	2.449E+06
RVT Diff from TH Mean		6.2%	< 1%

Base Shear and Moments in the Internal Structural Model

Analysis Case		Base Shear X-Dir (kips)	Base Moment YY-Dir (kip-ft)
30 TH	Min	13870	4.866E+05
	Mean	17350	6.438E+05
	Max	21130	7.771E+05
RVT Run	Single Analysis	16690	6.196E+05
RVT Diff from TH Mean		3.8%	3.8%

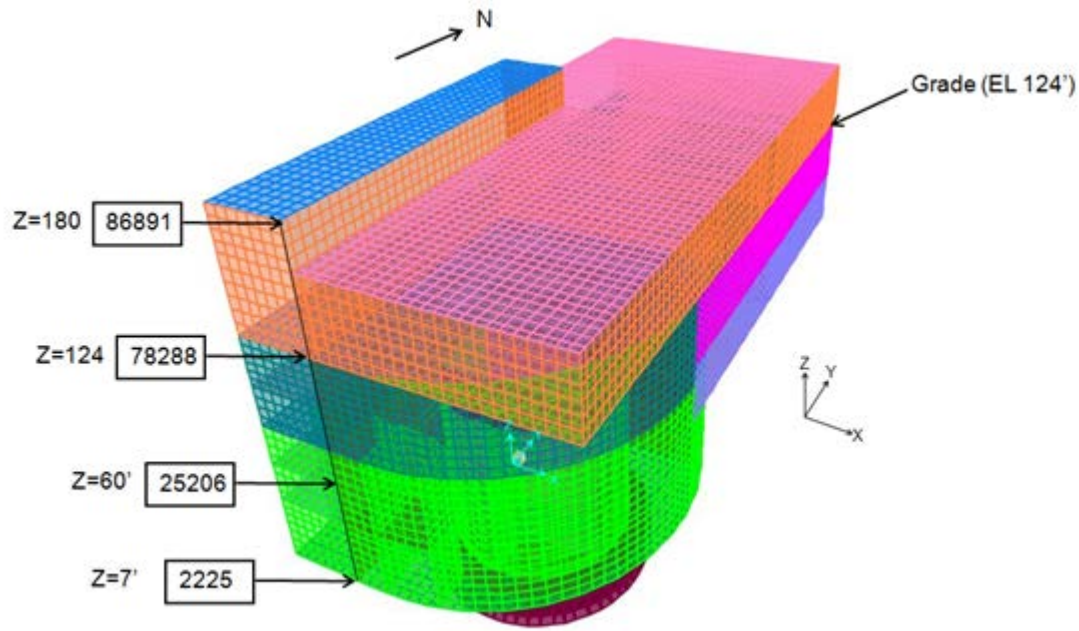
Deeply Embedded Rock – Input and Parameters

SASSI2010 Verification and Validation Analysis using Deeply Embedded Model

Total Nodes:	**90,376**
Total Interaction Nodes:	**9,752**
Total Shell Elements:	**19,931**
Total Brick Elements:	**69,865**
Total Beam Elements:	**1,045**
Total Lumped Masses:	**32,985**

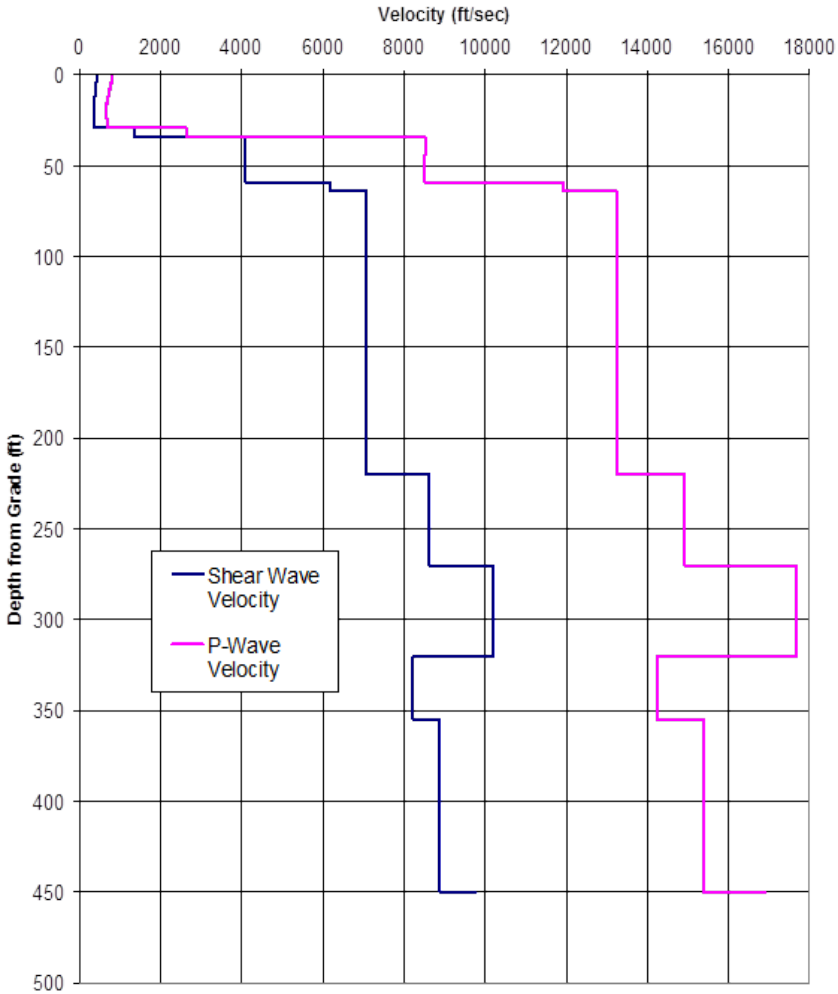
CEUS and WUS Input Spectra

30 Time Histories Matching Each Input Spectrum

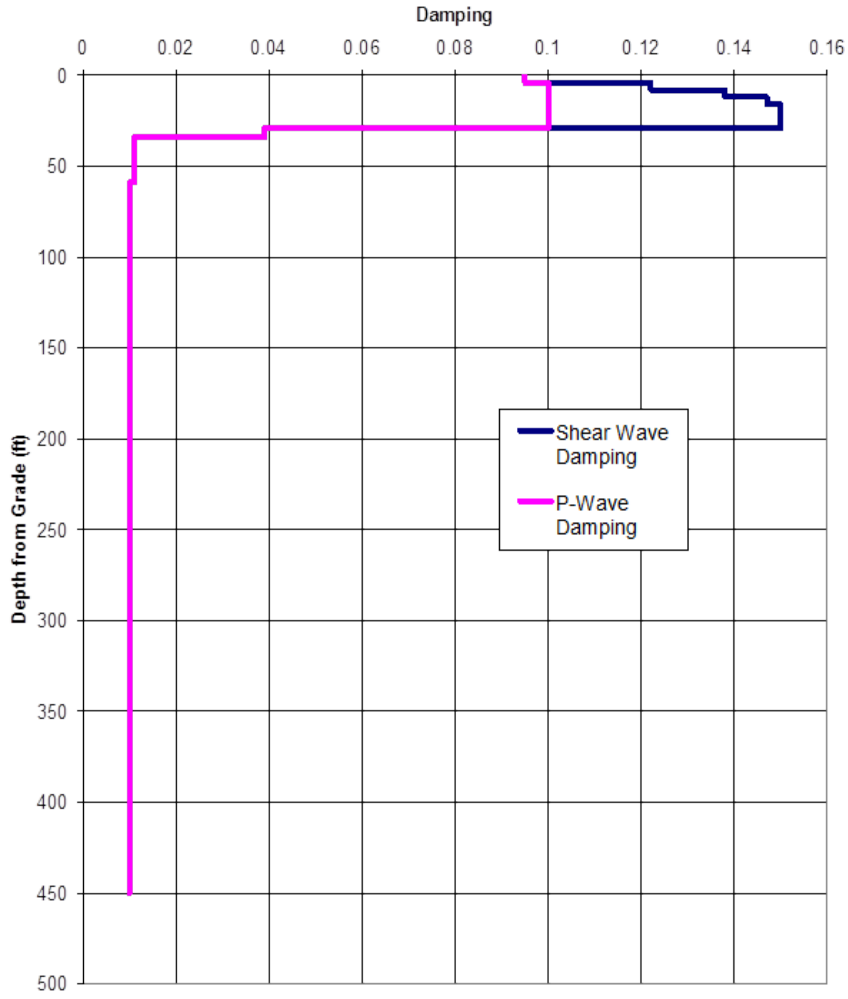


Finite Element Half Model Showing Nodes Where ISRS are Computed

Deeply Embedded Rock – Input and Parameters

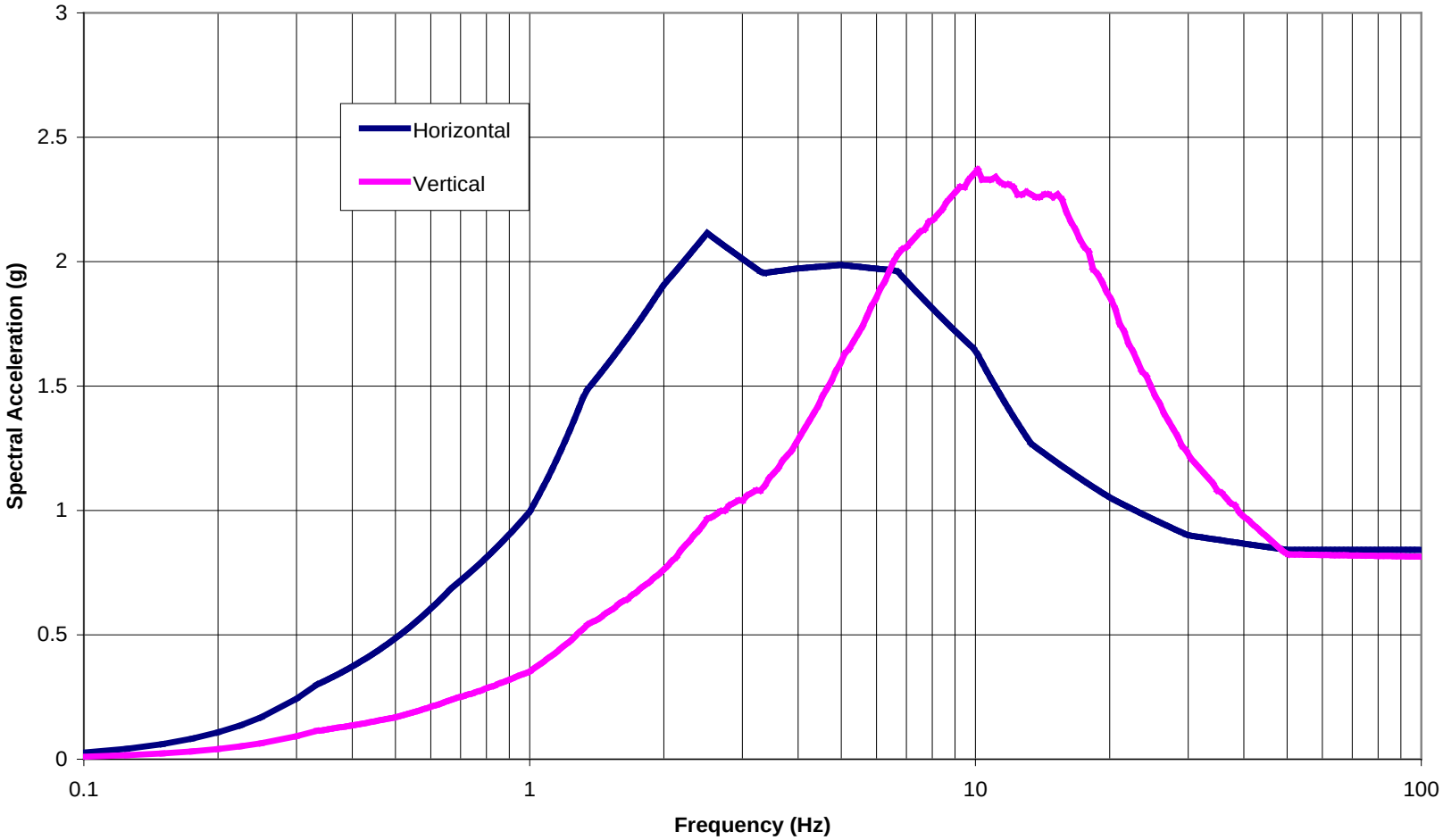


Soil Velocity Profiles



Rock Site (with 30 ft of Fill on Top) Damping Ratio Profiles

Deeply Embedded Rock – Input and Parameters



5% Damped WUS Design Response Spectra

Deeply Embedded Rock – Comparisons

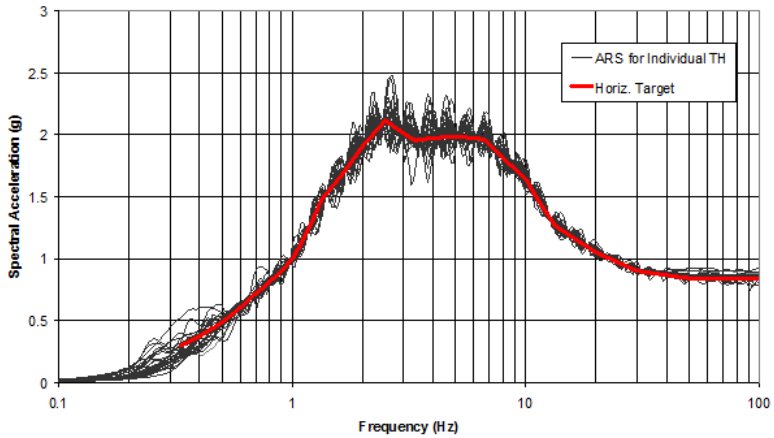


Figure 5.2-6(a) 5% Damped ARS for 30 Time Histories Matched to WUS Target Spectrum - H1 Component

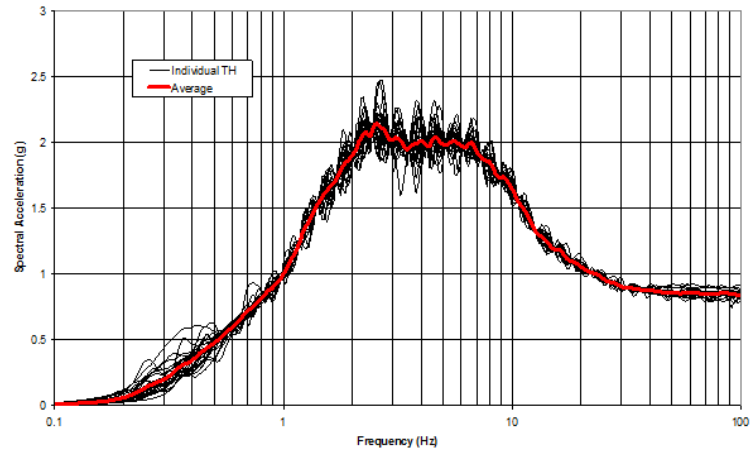


Figure 5.2-6(c) Comparison of ARS for 30 Time Histories at 5% Damping to Mean - WUS H1 Component

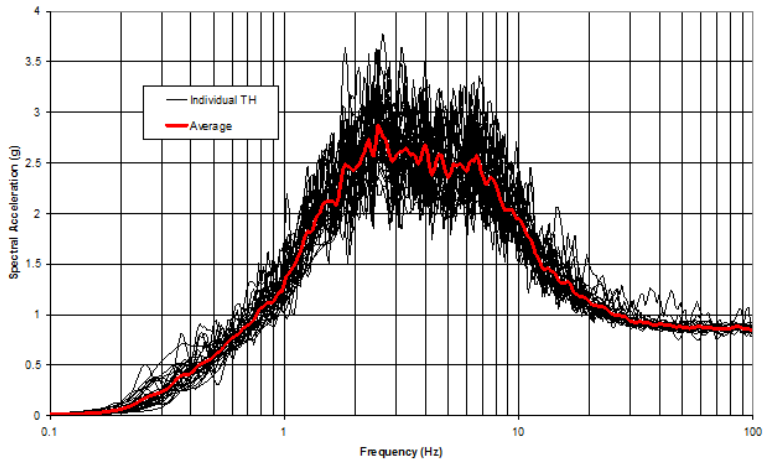


Figure 5.2-6(b) Comparison of ARS for 30 Time Histories at 2% Damping to Mean - WUS H1 Component

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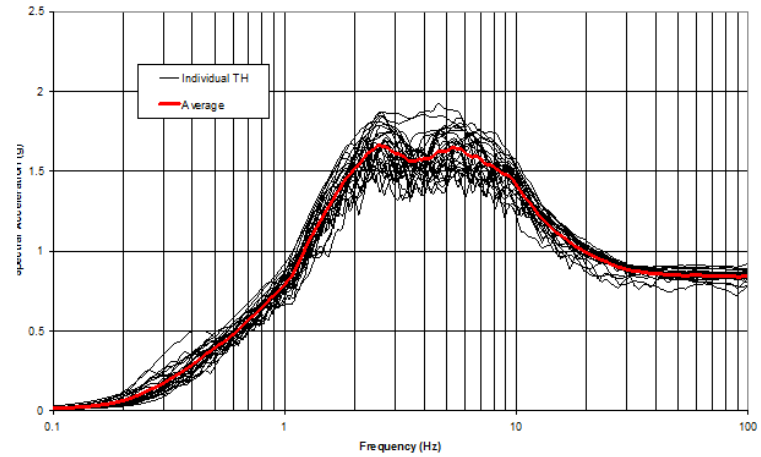

Figure 5.2-6(d) Comparison of ARS for 30 Time Histories at 10% Damping to Mean - WUS H1 Component

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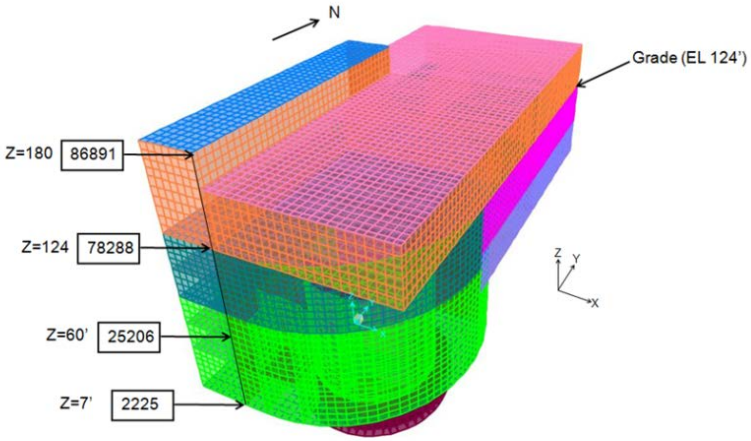
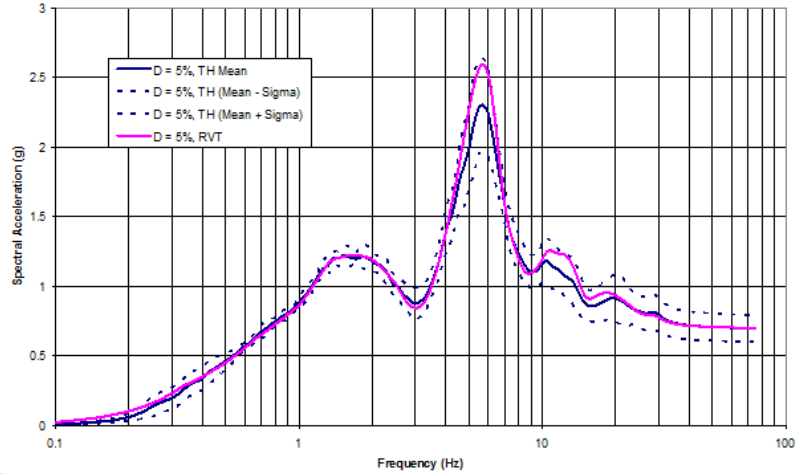
Deeply Embedded Rock – Comparisons



Finite Element Half Model Showing Nodes Where ISRS are Computed



5.2-10(b) Comparison of XX, 5% Damped ISRS at Node 25206, Elevation 60', Rock Profile, WUS X-Direction Motions

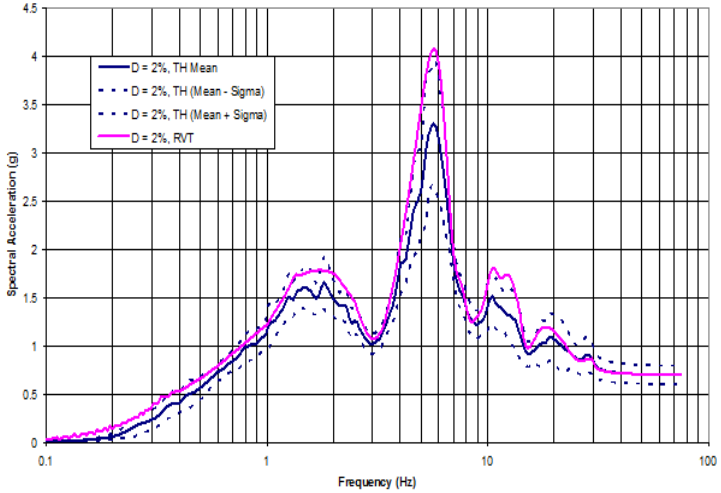


Figure 5.2-10(a) Comparison of XX, 2% Damped ISRS at Node 25206, Elevation 60', Rock Profile, WUS X-Direction Motions

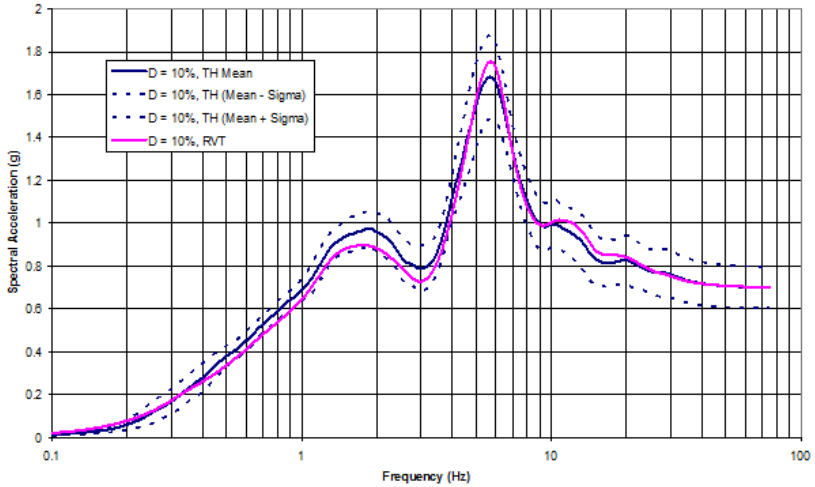


Figure 5.2-10(c) Comparison of XX, 10% Damped ISRS at Node 25206, Elevation 60', Rock Profile, WUS X-Direction Motions

Deeply Embedded Rock – Comparisons

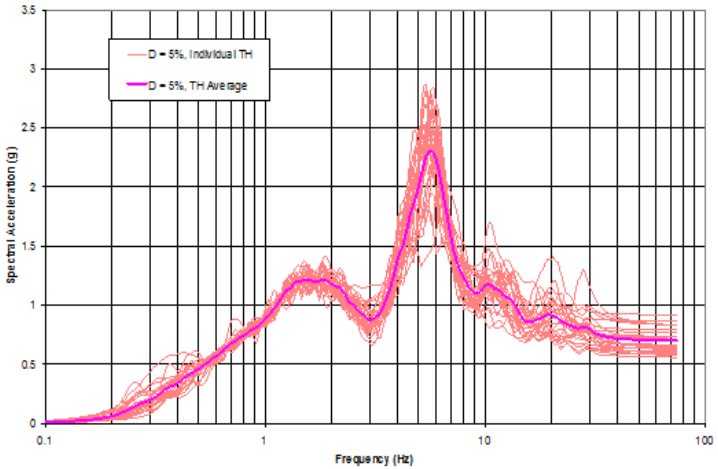


Figure 5.2-13(b) Range of XX-Responses (5% damping) from Time History Analysis, Node 25206, Elevation 60', Rock Profile, WUS X-Direction Motions

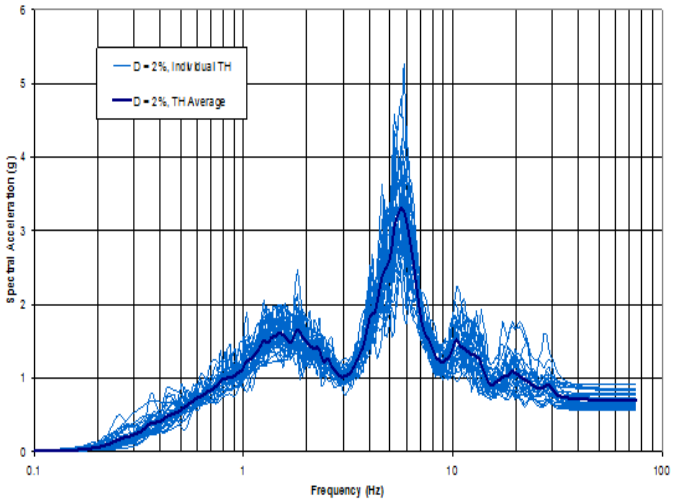


Figure 5.2-13(a) Range of XX-Responses (2% damping) from Time History Analysis, Node 25206, Elevation 60', Rock Profile, WUS X-Direction Motions

Results from time history analysis are sensitive to time history input

Variation in the response is large

Obtaining mean stable responses requires several sets of time histories

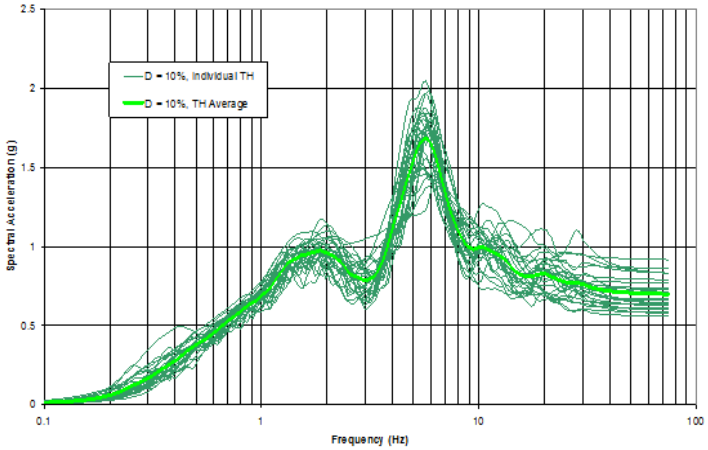
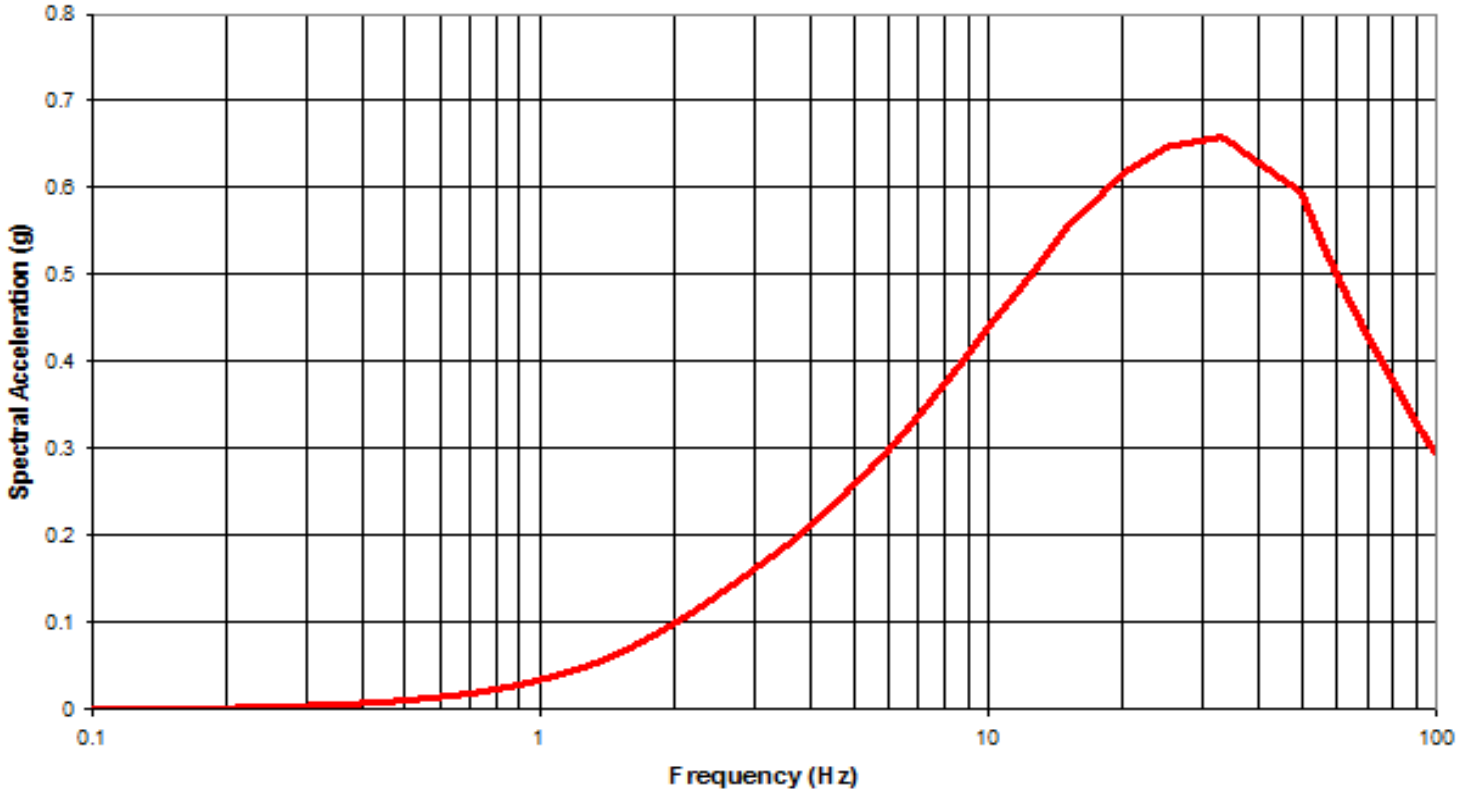


Figure 5.2-13(c) Range of XX-Responses (10% damping) from Time History Analysis, Node 25206, Elevation 60, Rock Profile, WUS X-Direction Motions

Deeply Embedded Rock – Input and Parameters



5% Damped Rock Target Spectrum, CEUS Input Motion

Deeply Embedded Rock – Comparisons

5%

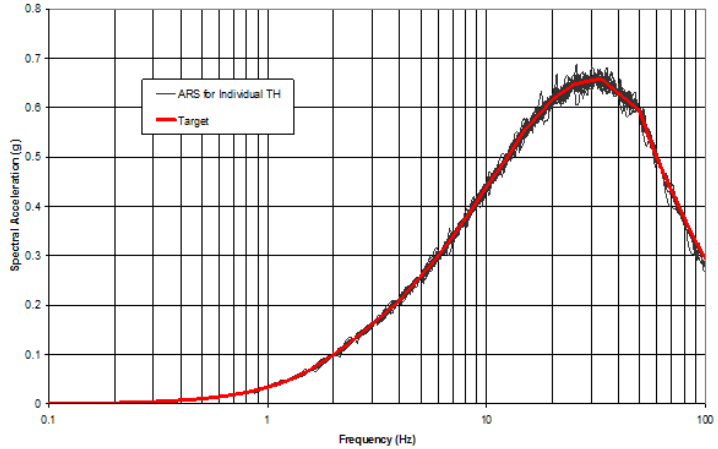


Figure 5.2-31(a) 5% Damped ARS for 30 Time Histories Matched to CEUS High Frequency Horizontal Rock Spectrum

2%

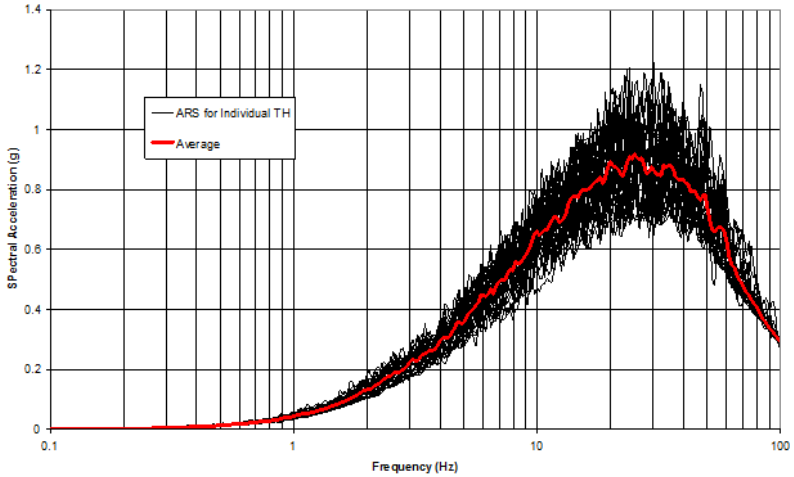


Figure 5.2-31(b) Comparison of ARS for 30 Time Histories at 2% Damping to Mean - CEUS High Frequency Horizontal Component

10%

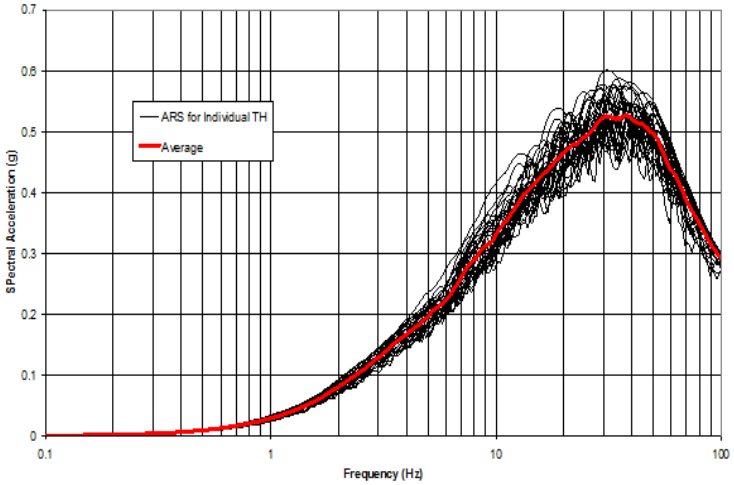
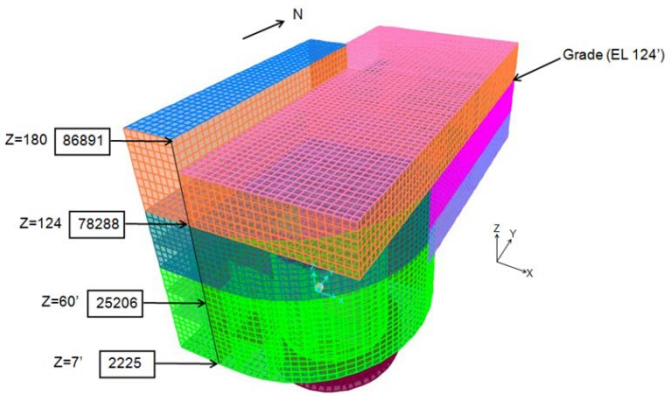


Figure 5.2-31(d) Comparison of ARS for 30 Time Histories at 10% Damping to Mean - Rock Profile, CEUS High Frequency Horizontal Component

Deeply Embedded Rock – Comparisons



Finite Element Half Model Showing Nodes Where ISRS are Computed

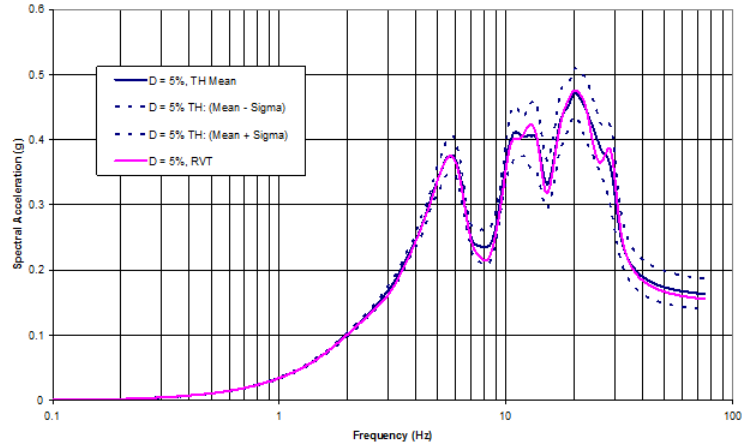


Figure 5.2-33(b) Comparison of XX, 5% Damped ISRS at Node 25206, Elevation 60', Rock Profile, CEUS High Frequency X-Direction Motions at Z = 7' Outcrop, Propagated to Grade

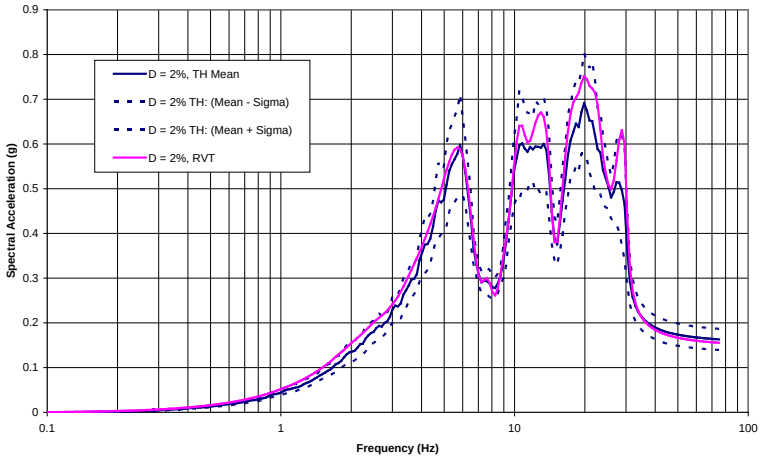


Figure 5.2-33(a) Comparison of XX, 2% Damped ISRS at Node 25206, Elevation 60', Rock Profile, CEUS High Frequency X-Direction Motions at Z = 7' Outcrop, Propagated to Grade

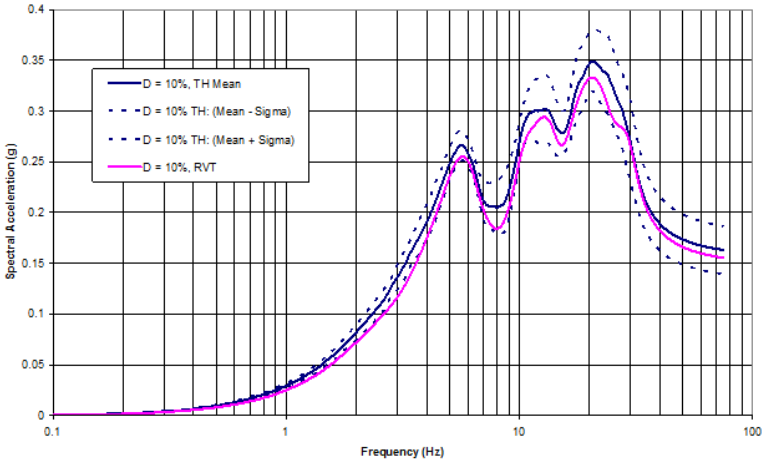


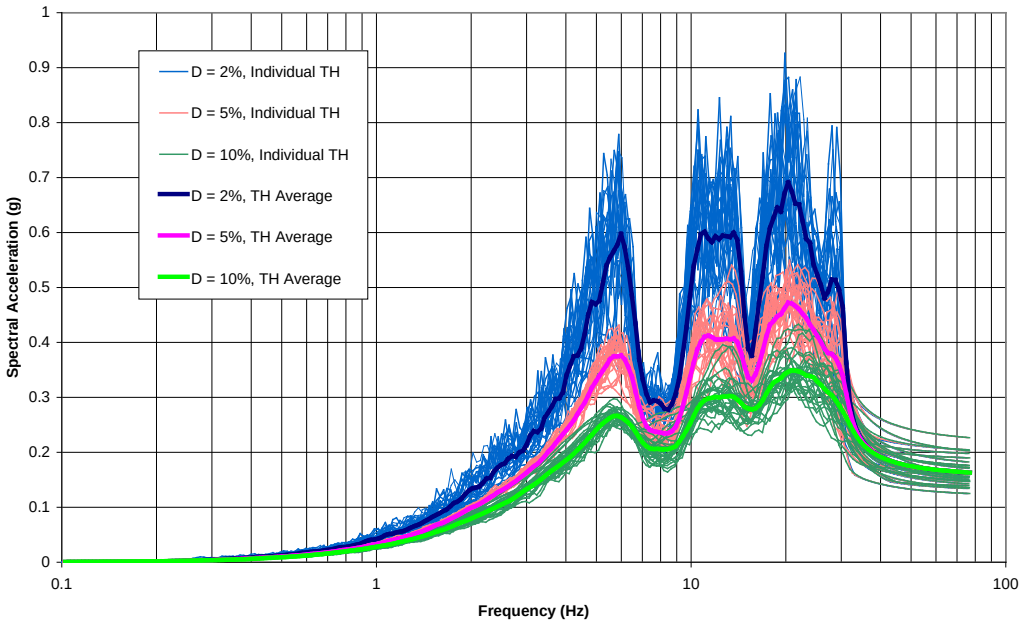
Figure 5.2-33(c) Comparison of XX, 10% Damped ISRS at Node 25206, Elevation 60', Rock Profile, CEUS High Frequency X-Direction Motions at Z = 7' Outcrop, Propagated to Grade

Deeply Embedded Rock – Comparisons

Results from time history analysis are sensitive to time history input

The variation in the response is large

Obtaining mean stable responses requires several sets of time histories



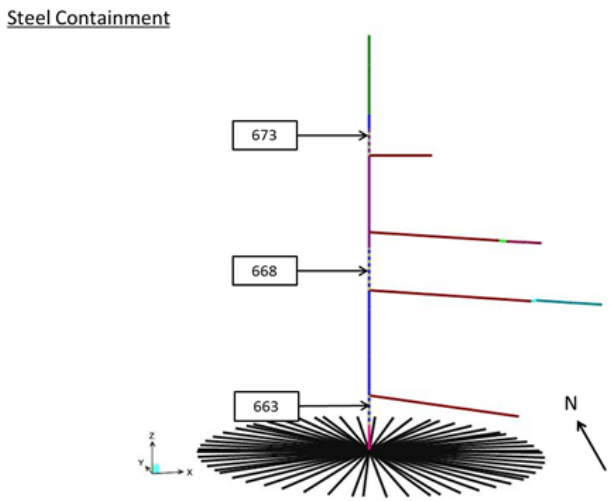
Range of XX-Responses from Time History analysis, Node 25206, Elevation 60', Rock Profile, CEUS High Frequency X-Direction Motions at Z = 7' Outcrop, Propagated to Grade

Deeply Embedded Rock – Comparisons

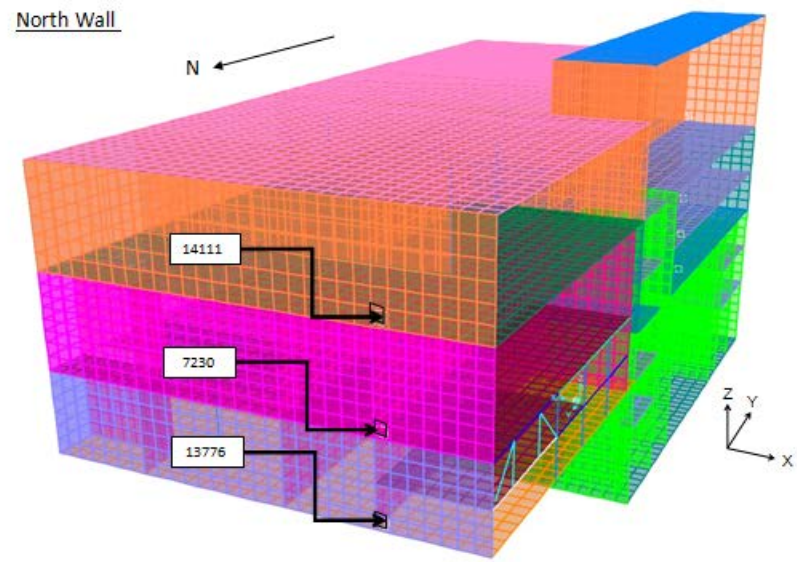
Member forces

Plate Element

Beam Element



Steel Containment Model Beam Elements
Selected for Member Force Comparisons



Locations of Plate Elements to Compare
Maximum Seismic Member Forces

Deeply Embedded Rock – Comparisons

Maximum Forces for Plate Element No. 7230, WUS X-Input Motion

Element 7230: @CG, x = -19, y = 230.25, z = 92.5, WUS Motion, X-Shaking								
T.H. No.	Sxx (kips/ft)	Syy (kips/ft)	Sxy (kips/ft)	Mxx (kips*ft/ft)	Myy (kips*ft/ft)	Mxy (kips*ft/ft)	Vxz (kips/ft)	Vyz (kips/ft)
1	4.873	3.590	165.625	3.364	0.769	1.742	1.113	0.950
2	6.493	4.451	216.359	4.448	1.326	2.444	1.261	1.131
3	6.309	4.408	195.187	3.812	0.742	1.657	1.201	1.140
4	5.828	4.759	223.468	4.056	0.773	1.766	1.454	1.120
5	5.937	4.372	190.824	5.639	0.858	1.543	1.899	0.979
6	5.321	4.854	207.389	4.067	0.986	1.550	1.471	0.927
8	5.928	4.325	211.420	3.589	0.736	1.698	1.370	0.984
9	5.801	4.668	157.467	5.362	0.947	1.612	1.729	1.020
10	6.376	4.613	208.618	4.853	1.041	1.737	1.798	0.951
11	5.850	4.381	191.928	4.241	0.777	2.000	1.267	1.103
12	5.947	4.368	179.108	3.775	1.105	1.939	1.241	0.923
14	4.826	4.217	193.065	3.412	0.663	1.764	1.204	1.034
15	5.355	4.342	192.937	3.651	0.851	1.561	1.375	1.005
17	5.588	5.295	170.457	4.461	1.175	1.606	1.397	0.971
18	5.380	4.299	187.855	3.365	1.094	1.885	1.038	0.940
19	5.532	4.439	205.052	3.094	0.624	1.427	1.115	1.083
20	5.840	4.877	243.732	4.355	0.855	2.070	1.420	1.322
21	5.630	3.703	186.463	4.268	1.171	1.868	1.473	0.900
22	4.666	4.127	185.228	3.346	0.839	1.594	1.064	0.866
23	5.886	4.610	203.852	3.923	1.265	1.999	1.307	1.102
24	6.656	4.869	234.921	4.443	0.891	1.355	1.490	1.046
25	4.626	4.165	170.726	4.118	1.016	1.369	1.469	0.802
26	6.375	4.466	193.262	4.187	1.583	2.302	1.503	1.126
27	4.963	3.546	172.903	3.529	0.867	1.601	1.231	0.819
28	4.836	4.488	193.278	4.285	0.933	1.521	1.530	0.935
29	4.990	4.598	180.373	3.392	1.216	1.575	1.115	0.976
30	6.085	4.419	180.194	4.311	1.472	1.789	1.330	0.973
min	4.626	3.546	157.467	3.094	0.624	1.355	1.038	0.802
($\mu-\sigma$)	5.038	4.032	173.661	3.440	0.741	1.478	1.150	0.892
mean (μ)	**5.626**	**4.417**	**194.137**	**4.050**	**0.984**	**1.740**	**1.365**	**1.005**
($\mu+\sigma$)	6.213	4.801	214.612	4.660	1.227	2.002	1.581	1.117
max	6.656	5.295	243.732	5.639	1.583	2.444	1.899	1.322
stdev (σ)	0.587	0.385	20.476	0.610	0.243	0.262	0.216	0.112
RVT	**5.346**	**4.425**	**194.008**	**4.098**	**0.953**	**1.805**	**1.401**	**1.014**

Deeply Embedded Rock – Comparisons

Maximum Forces at Steel Containment Beam Element 663 (Node 6661), WUS X-Input Motion

Beam Element No. 663 (Node 6661) - WUS Motion, X-Shaking						
T.H. No.	P1 (kips)	P2 (kips)	P3 (kips)	M1 (kips-ft.)	M2 (kips-ft.)	M3 (kips-ft.)
1	120.0	1134.0	56.2	8.0E-06	3315.0	62920.0
2	353.8	2614.0	134.2	1.0E-05	8186.0	151000.0
3	112.5	1268.0	44.5	7.3E-06	2654.0	69170.0
4	141.0	1971.0	83.2	1.1E-05	4941.0	106100.0
5	149.7	1963.0	82.5	1.2E-05	4822.0	110000.0
6	125.7	1461.0	79.8	9.8E-06	4900.0	75300.0
8	143.4	2028.0	84.8	1.3E-05	5002.0	112200.0
9	113.0	1187.0	41.6	2.2E-05	2452.0	66510.0
10	233.8	2065.0	133.4	1.4E-05	7777.0	116900.0
11	152.2	1633.0	95.3	1.0E-05	5650.0	91190.0
12	229.0	1935.0	112.9	1.2E-05	6603.0	110900.0
14	86.2	1189.0	57.3	8.7E-06	3390.0	63840.0
15	106.0	1263.0	48.6	9.4E-06	2896.0	69090.0
17	169.2	2099.0	143.4	1.0E-05	8491.0	120000.0
18	155.4	1442.0	78.0	1.4E-05	4506.0	81810.0
19	130.1	1800.0	50.9	1.2E-05	3013.0	98980.0
20	164.0	1761.0	83.0	1.2E-05	4919.0	98070.0
21	163.2	1827.0	123.3	1.9E-05	7201.0	102900.0
22	148.6	2012.0	117.1	1.3E-05	6755.0	114100.0
23	314.8	2914.0	251.5	1.6E-05	14890.0	171500.0
24	201.9	1900.0	110.2	2.0E-05	6394.0	108300.0
25	155.9	2190.0	120.5	1.0E-05	7212.0	125700.0
26	250.7	2380.0	168.6	1.2E-05	10140.0	144200.0
27	159.2	1401.0	93.8	1.2E-05	5614.0	81270.0
28	135.1	1500.0	74.1	1.3E-05	4304.0	78650.0
29	267.6	2489.0	118.6	1.3E-05	7091.0	142600.0
30	284.1	2234.0	120.4	1.9E-05	7311.0	128000.0
min	86.2	1134.0	41.6	0.00	2452.0	62920.0
($\mu-\sigma$)	108.7	1373.5	55.5	0.00	3276.1	75023.1
mean (μ)	**176.5**	**1839.3**	**100.3**	**0.00**	**5941.8**	**103748.1**
($\mu+\sigma$)	244.3	2305.0	145.1	0.00	8607.5	132473.2
max	353.8	2914.0	251.5	0.00	14890.0	171500.0
stdev (σ)	67.8	465.8	44.8	0.00	2665.7	28725.1
RVT	**161.5**	**1943.0**	**114.7**	**0.00**	**6790**	**109600.0**

Deeply Embedded Soil – Input and Parameters

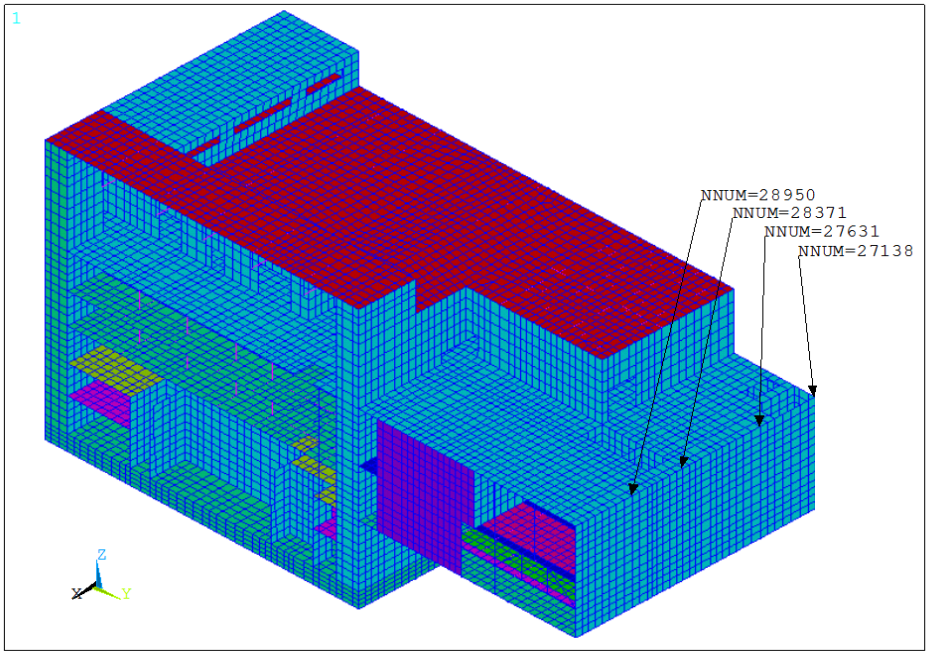
SASSI2010 Verification and Validation Analysis using Deeply Embedded Model

Total Nodes:	**87,325**
Total Interaction Nodes:	**9,477**
Total Shell Elements:	**27,277**
Total Brick Elements:	**58,932**
Total Beam Elements:	**1,498**
Total Lumped Masses:	**21,044**

WUS Input Spectra

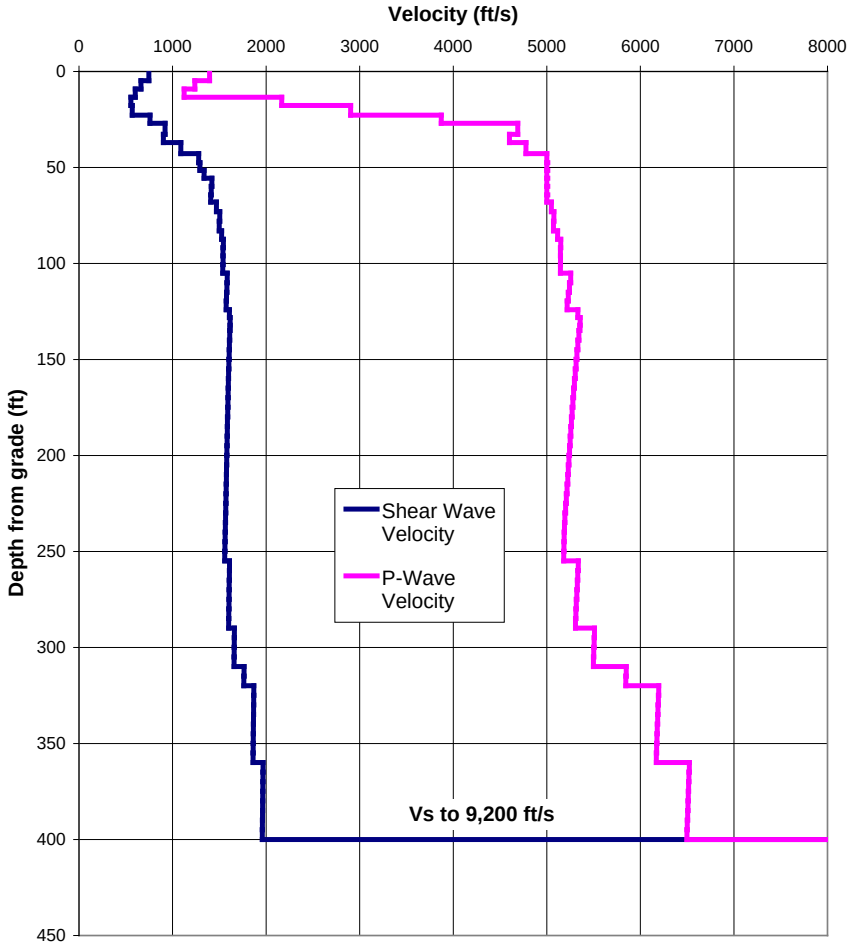
30 Time Histories Matching Input Spectrum

Deep Soil Profile

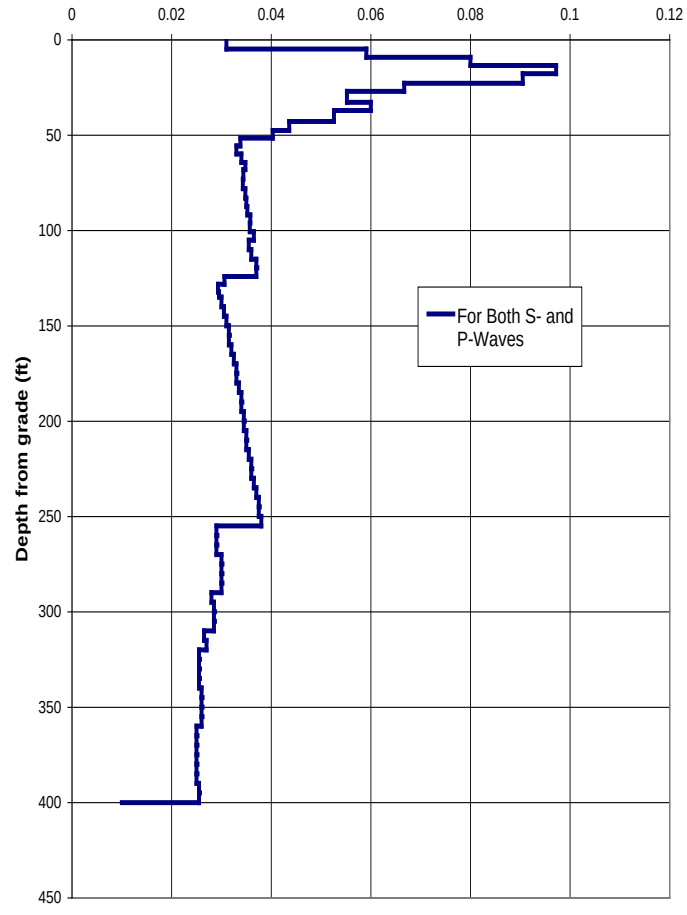


Finite Element Half Model Showing Nodes Where ISRS are Computed

Deeply Embedded Soil – Input and Parameters

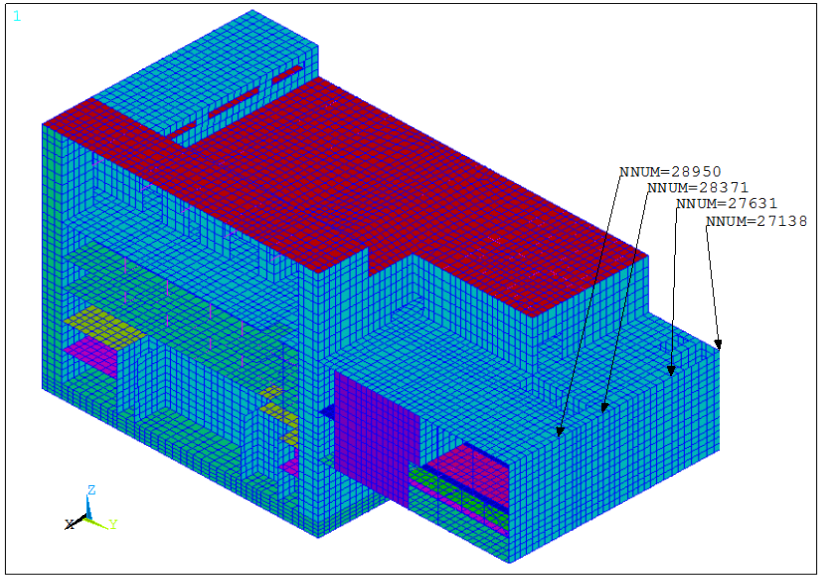


Soil Site Velocity Profiles



Soil Site Damping Ratio Profiles

Deeply Embedded Soil – Comparisons



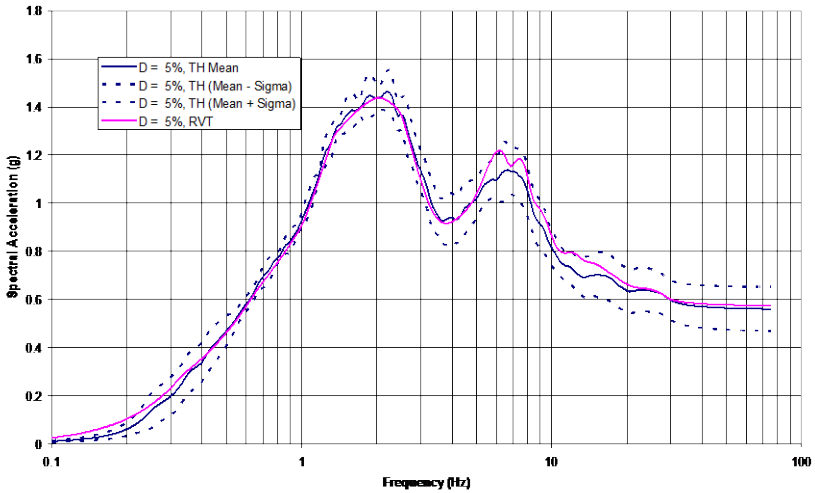


Figure 5.3-7(b) Comparison of XX, 5% Damped ISRS at Node 27138, Soil Profile, WUS X-Direction Input Motions

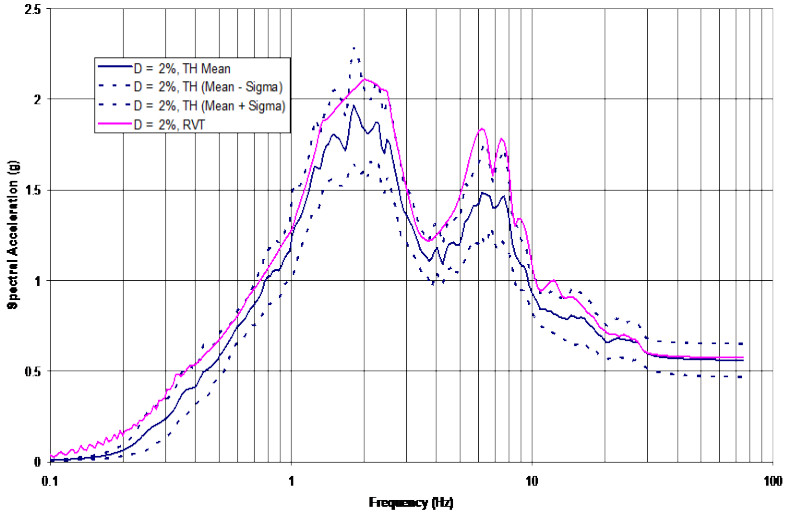


Figure 5.3-7(a) Comparison of XX, 2% Damped ISRS at Node 27138, Soil Profile, WUS X-Direction Input Motions

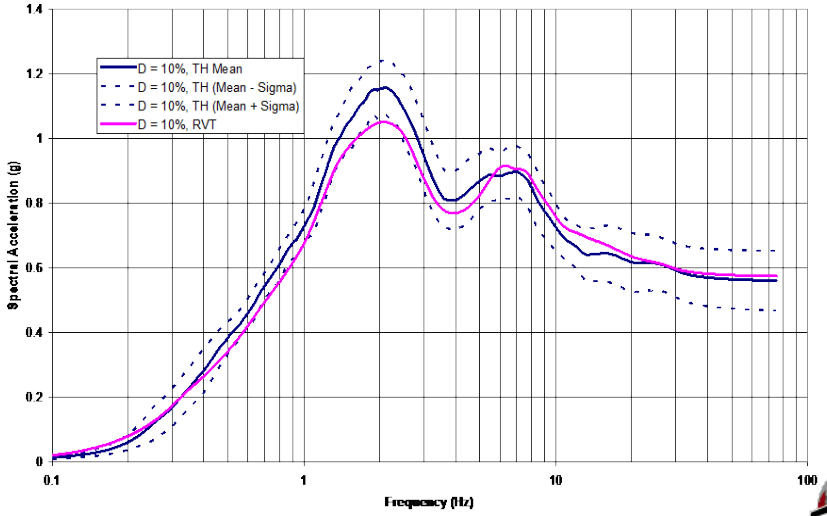


Figure 5.3-7(c) Comparison of XX, 10% Damped ISRS at Node 27138, Soil Profile, WUS X-Direction Input Motions

Deeply Embedded Soil – Comparisons

5%

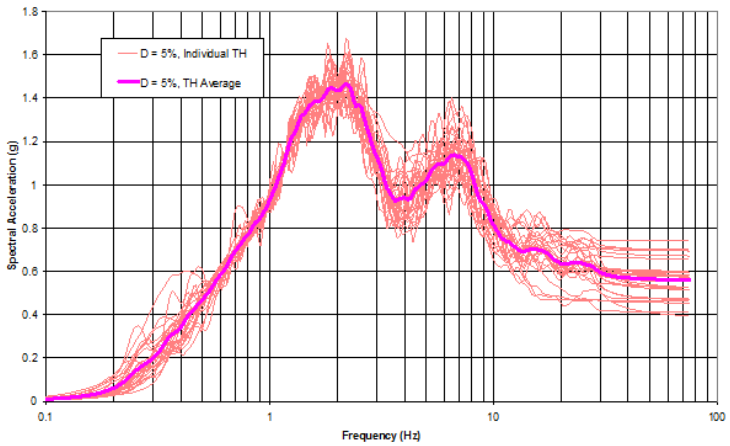


Figure 5.3-8(b) Range of XX-Responses (5% damping) from Time History Analysis, Node 27138, Soil Profile, WUS X-Direction Motions

2%

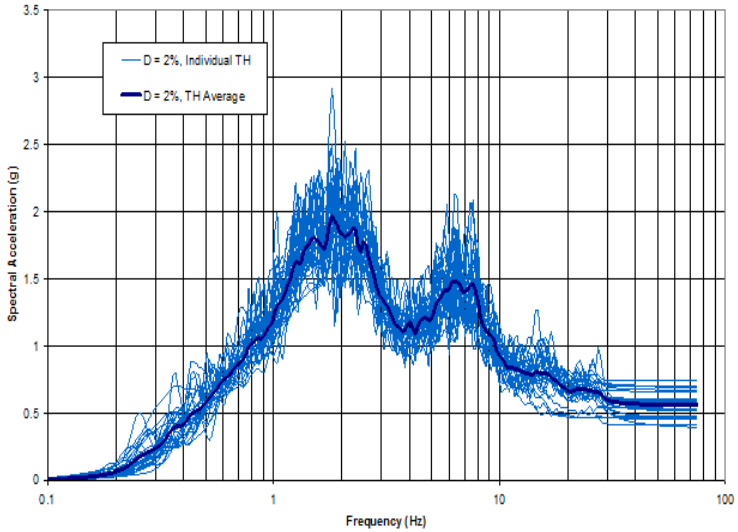


Figure 5.3-8(a) Range of XX-Responses (2% damping) from Time History Analysis, Node 27138, Soil Profile, WUS X-Direction Motions

10%

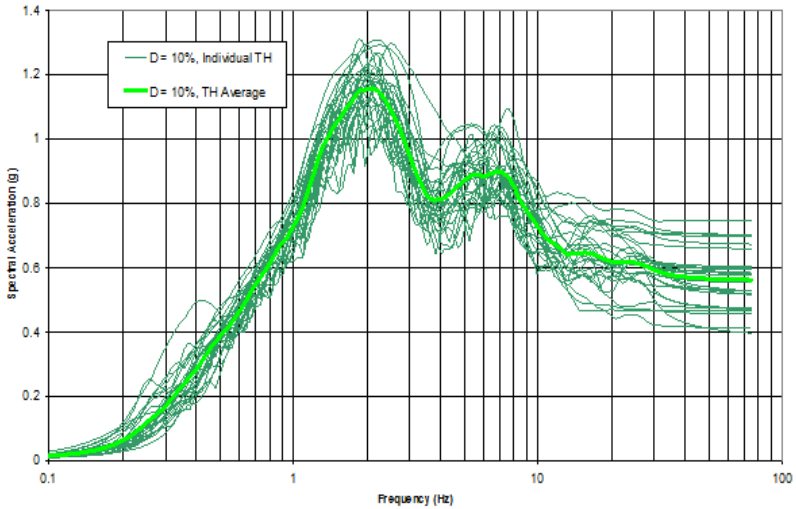


Figure 5.3-8(c) Range of XX-Responses (10% damping) from Time History Analysis, Node 27138, Soil Profile, WUS X-Direction Motions

Conclusions

- Developing a stable mean solution using time history methods may require up to 30 seed time histories
  - Developing a stable standard deviation of the response may require even more time histories
- Using RVT methodology, as implemented in SASSI2010, produces a stable mean response more efficiently
  - Responses at other confidence levels can be determined as needed