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New Plant Seismic Issues Resolution Program – S2.1 Incoherence Project – SASSI-CLASSI Validation

July 23-24, 2007

EPRI Palo Alto, CA

Bob Kennedy
Jim Johnson
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Farhang Ostadan
Dan Ghiocel
Greg Hardy

Topics for Discussion

- Past NRC Interactions
  - Meetings
  - Effect of Rock Coherency Function
- "Validation of CLASSI and SASSI to Treat Seismic Wave Incoherence in SSI Analysis of Nuclear Power Plant Structures," Draft Issued July 7, 2007
- Guidelines for application of CLASSI and SASSI to seismic wave incoherence analysis of nuclear power plant structures
- Conclusions and Next Steps
- NRC Comments

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Past NRC Interaction on Seismic Wave Incoherence

- EPRI Report 1013504
- Dec. 20-21, 2006 NRC Meeting @ EPRI
  - CLASSIinco was validated for use in analysis of incoherent ground motion by comparison to analytical solutions from published literature
    - Luco & Mita, 1987; Veletsos & Prasad, 1989; Luco & Wong, 1986
- March 1, 2007 NRC Meeting
  - SASSI results for rigid massless foundations agreed closely with CLASSIinco and analytical solutions from published literature (Luco & Mita, 1987)
  - Preliminary SASSI and CLASSI comparisons presented for representative NPP stick model with SSI

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Conclusions from March 2007 NRC Meeting

- Response spectra and transfer functions for CLASSIinco, SASSI-SRSS, & SASSI-AS were presented
- Very close agreement for coherent ground motion as would be expected.
- All methods agreed closely for incoherent response spectra & transfer function amplitudes at the foundation
- There was generally good agreement at structure locations, but there are some exceptions requiring more investigation
- Overall, good agreement between CLASSIinco and either SASSI method was demonstrated
- Recommended action - Examine outrigger response not in agreement

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Past NRC Interaction on Seismic Wave Incoherence (cont)

- May 31, 2007 NRC Meeting
  - Five CLASSI-SASSI methodologies identified (CLASSIinco, CLASSIinco-SRSS, SASSI-Simulation, SASSI-SRSS, SASSI-Algebraic Sum)
  - Representative, limited response spectra comparisons presented
  - Preliminary conclusions subject to completion of validation analyses
    - CLASSI and SASSI incoherency approaches that incorporate random phasing are in close agreement for all cases considered to date
    - CLASSIinco-SRSS, SASSI-Simulation, and SASSI-SRSS are validated for evaluation of seismic response to incoherent ground motion
    - CLASSIinco and SASSI-AS are good approximations

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Past NRC Interaction on Seismic Wave Incoherence (cont)

- May 31, 2007 NRC Meeting
  - Next steps
    - Industry Actions
      - Document CLASSI-SASSI comparisons (July 7)
      - Develop user guide for running incoherent SSI analysis (Target July 27)
    - NRC Action
      - Reach closure
      - Concurrence that CLASSI and SASSI can be used to evaluate seismic response to incoherent ground motion

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Effect of Rock Coherency Function

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Abrahamson Coherency Functions

- Ground motion coherency functions
  - Soil – Surface foundations (NAA 2005-2006)
  - Soil – Embedded foundations (NAA Dec 2006)
  - Rock – Surface and embedded foundations (NAA April 2007)
- Effect of rock ground motion coherency functions
  - CLASSIinco seismic analyses performed
  - Rock site profile & high frequency input motion
  - Three free-field components applied simultaneously
  - Comparison of structure response due to coherent motion, incoherent motion (soil), and incoherent motion (rock)

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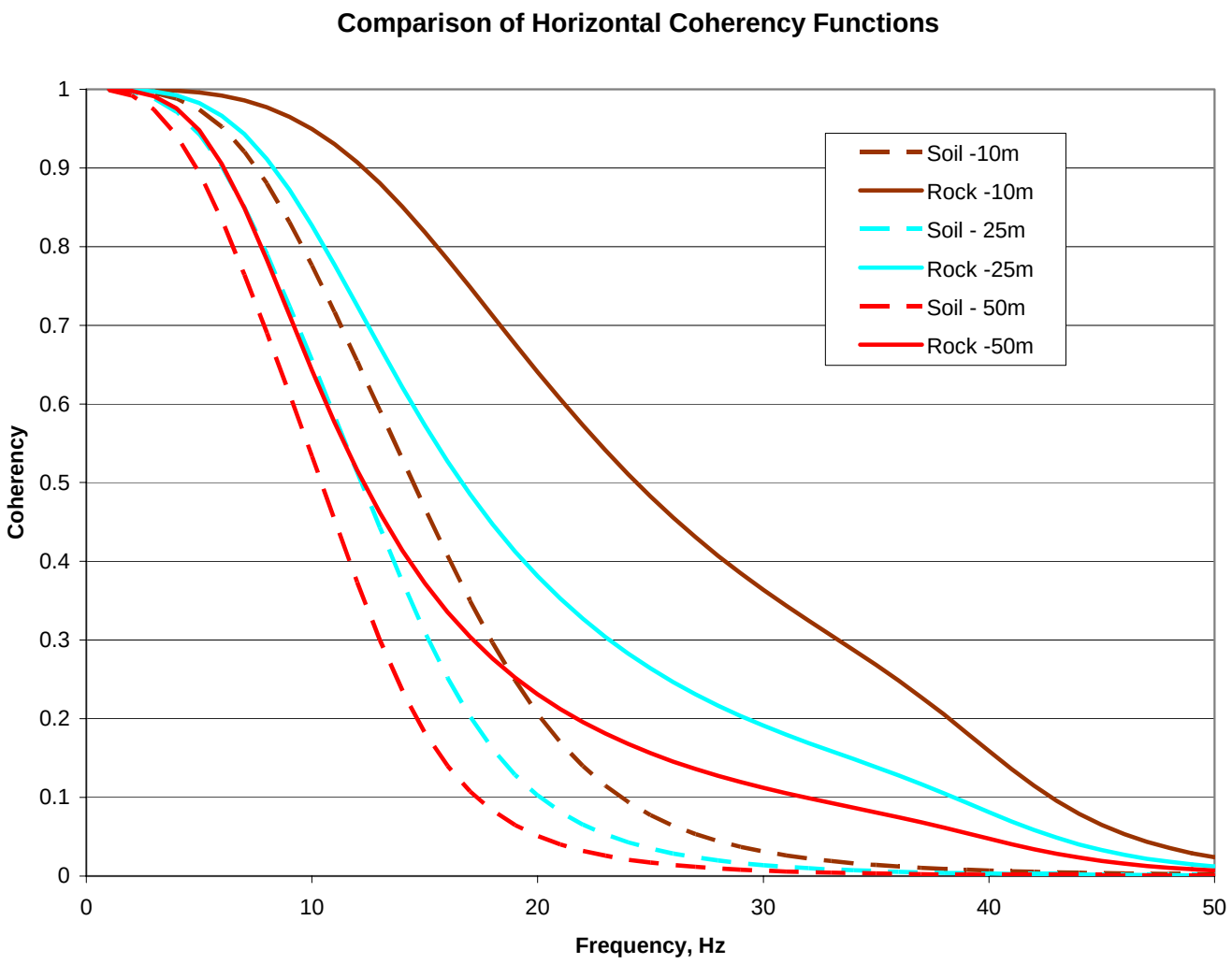
Comparison of Rock and Soil Coherency Functions



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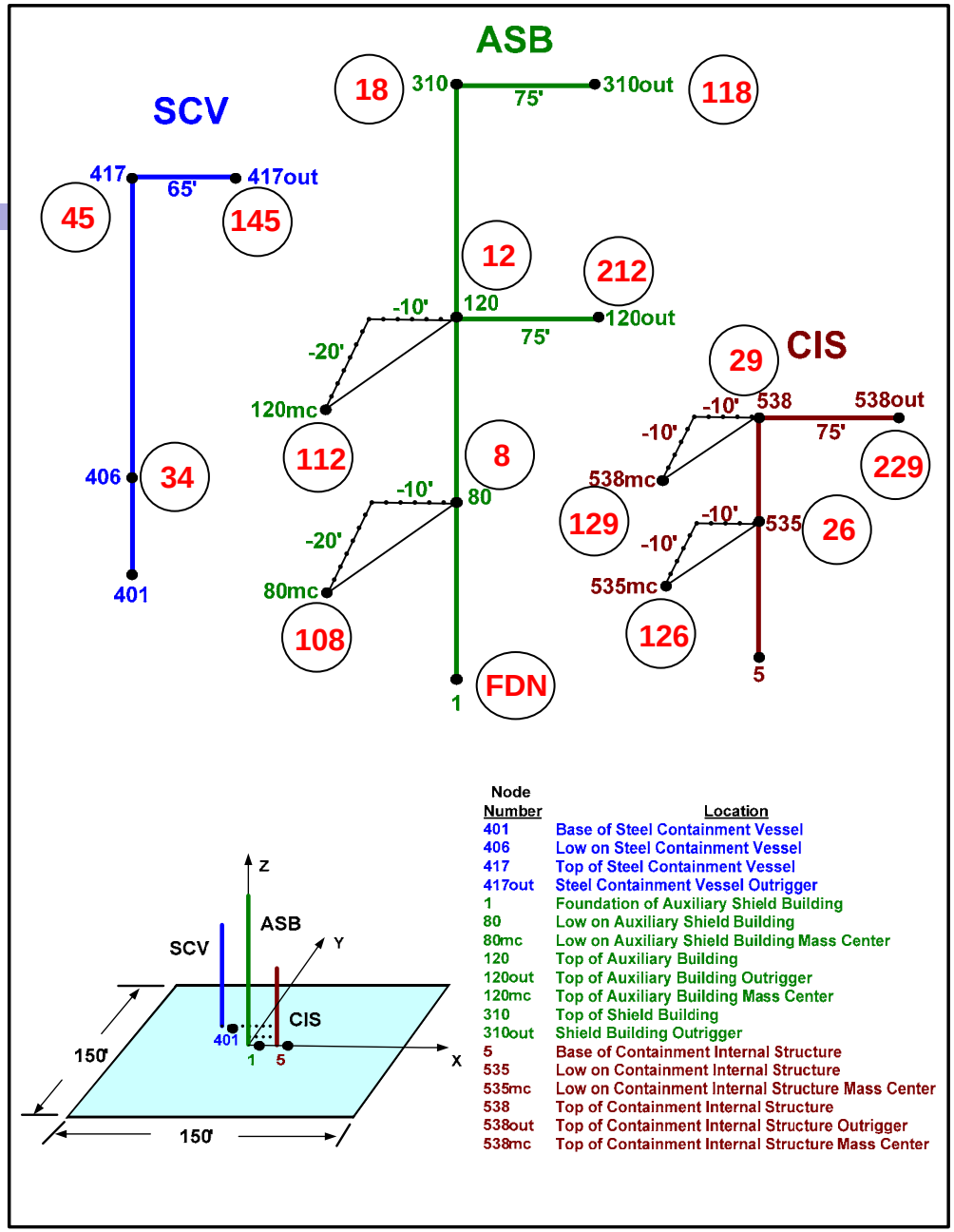
Representative NPP Structure Stick Model with Outriggers and Offset Mass Centers



Node Number	Location
401	Base of Steel Containment Vessel
406	Low on Steel Containment Vessel
417	Top of Steel Containment Vessel
417out	Steel Containment Vessel Outrigger
1	Foundation of Auxiliary Shield Building
80	Low on Auxiliary Shield Building
80mc	Low on Auxiliary Shield Building Mass Center
120	Top of Auxiliary Building
120out	Top of Auxiliary Building Outrigger
120mc	Top of Auxiliary Building Mass Center
310	Top of Shield Building
310out	Shield Building Outrigger
5	Base of Containment Internal Structure
535	Low on Containment Internal Structure
535mc	Low on Containment Internal Structure Mass Center
538	Top of Containment Internal Structure
538out	Top of Containment Internal Structure Outrigger
538mc	Top of Containment Internal Structure Mass Center

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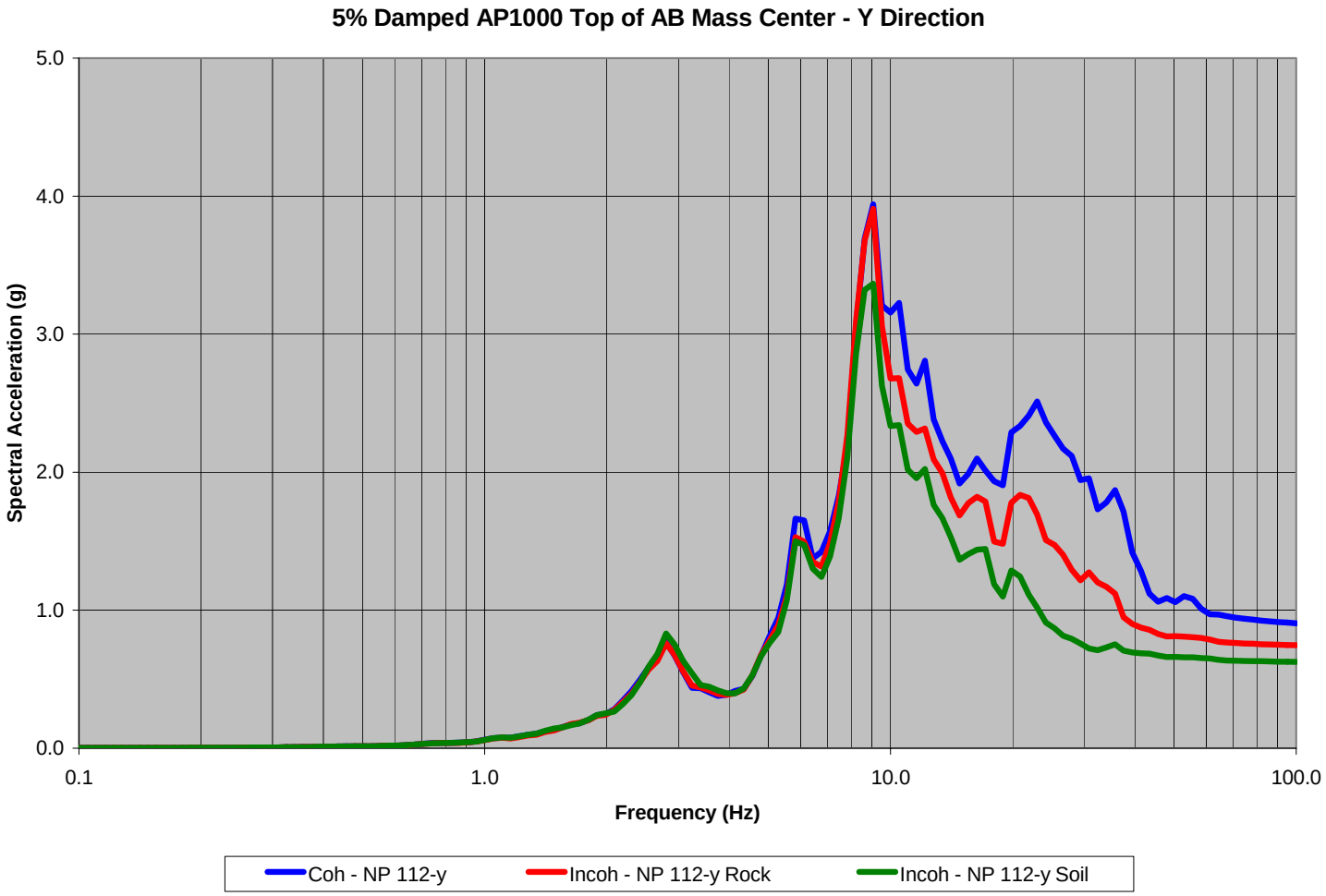
Comparison of In-Structure Response Spectra Horiz. Y – Top of Auxiliary Building Node 112



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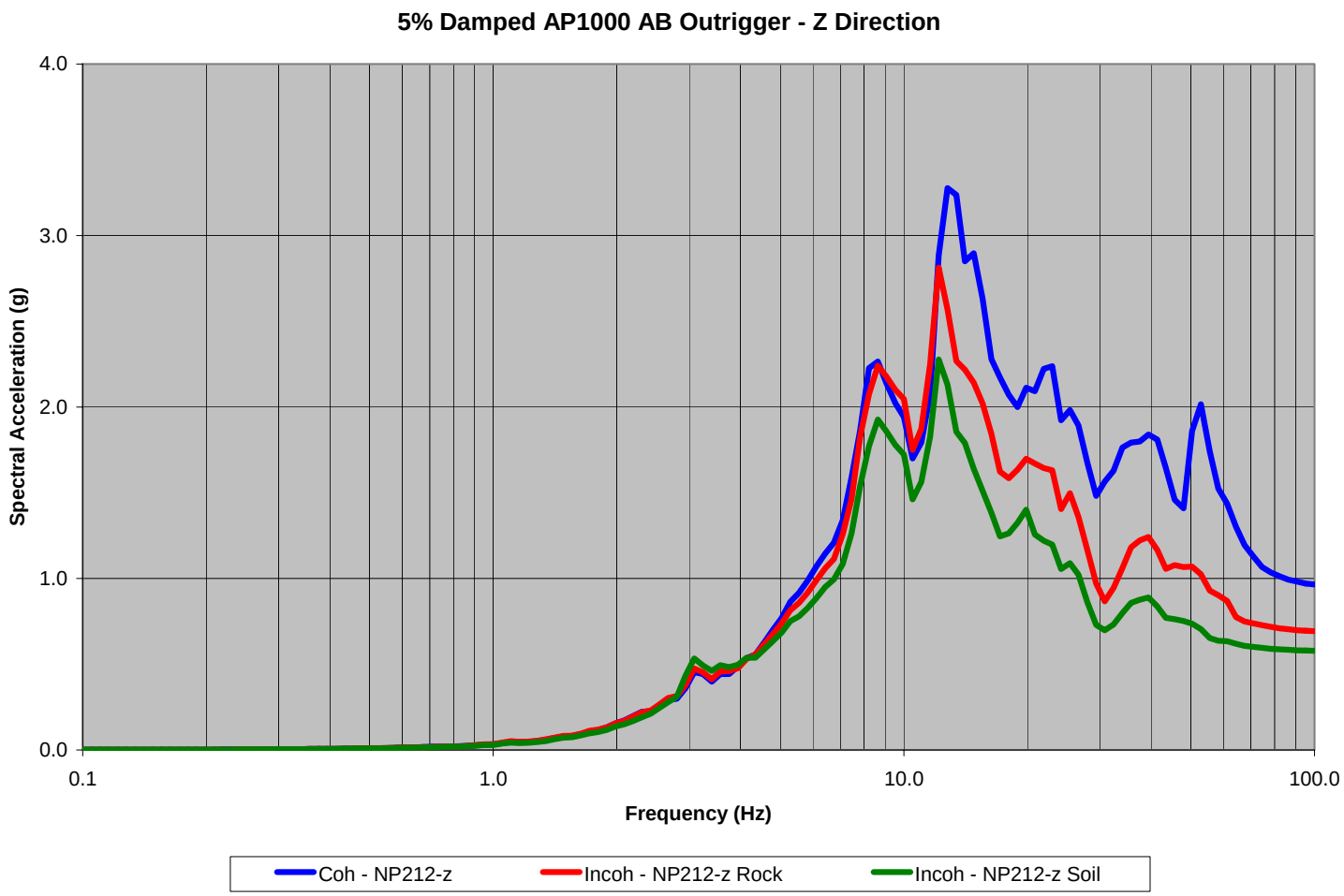
Comparison of In-Structure Response Spectra Vert. Z – Outrigger Top of Auxiliary Building Node 212



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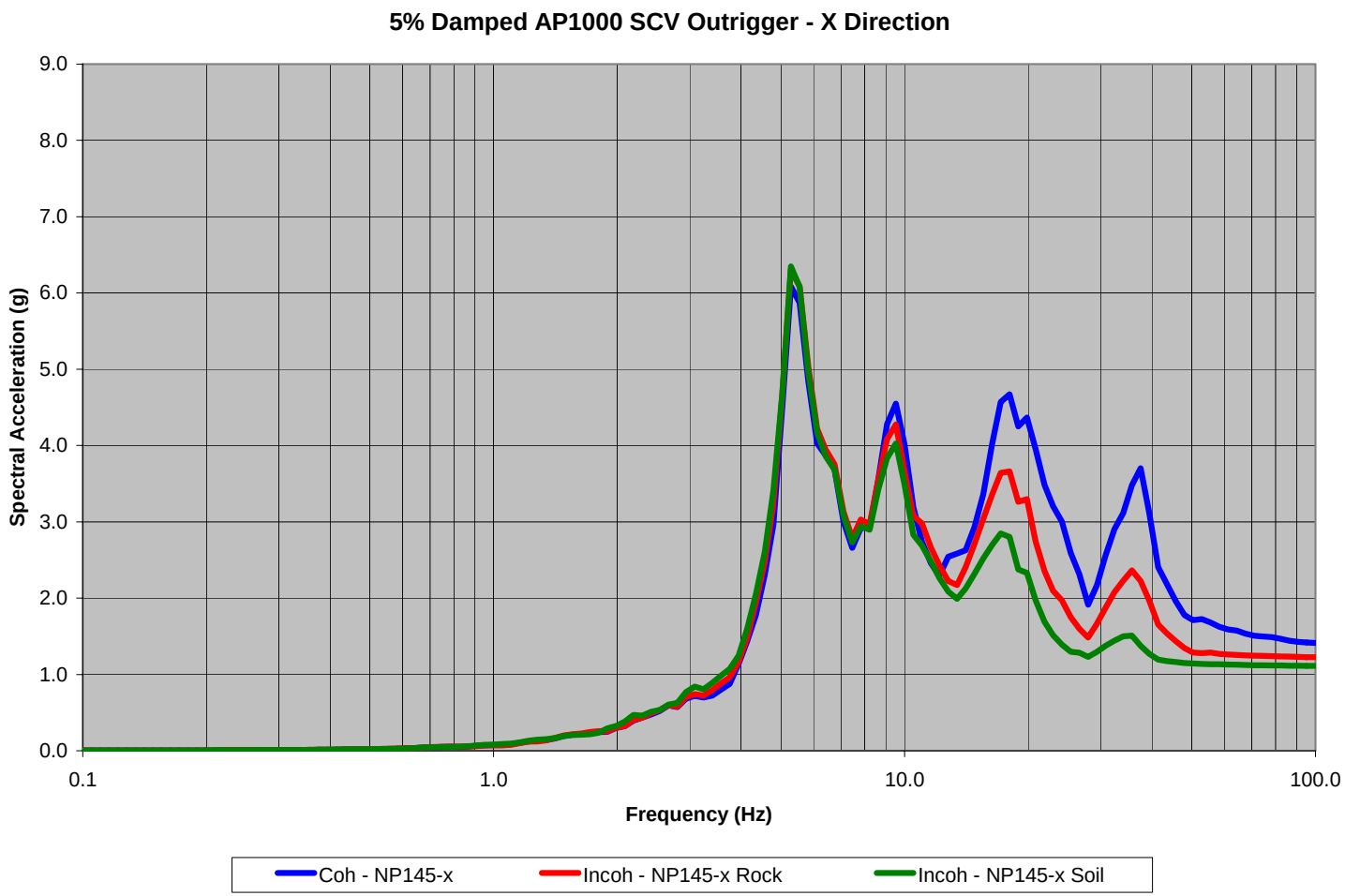
Comparison of In-Structure Response Spectra Horiz. X – Outrigger Top of Steel Containment Vessel Node 145



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Task S2.1b Project Team Activities – May 31 through July 23

- Complete and document CLASSI-SASSI comparisons
  - "Validation of CLASSI and SASSI to Treat Seismic Wave Incoherence in SSI Analysis of Nuclear Power Plant Structures," Draft Issued July 7, 2007.
- Developed draft guidelines for application of CLASSI and SASSI to seismic wave incoherence analysis of nuclear power plant structures (to be discussed July 23-24)

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"Validation of CLASSI and SASSI to Treat Seismic Wave Incoherence in SSI Analysis of Nuclear Power Plant Structures"

- Parameters of the Validation Problem
- CLASSI-SASSI Methodologies
- In-Structure Response Spectra (ISRS) Comparisons
- Conclusions

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Parameters of the Validation Problem

- Coherency functions – NAA (2005, 2006) – Soil
- Free-field ground motion defined by acceleration time histories matching site specific spectra for rock site (horizontal and vertical)
- Rock site profile
- Foundation is square - 150 ft on a side – 15 ft thick with mass properties
- Structure model based, in part, on an advanced reactor structure stick model with eccentricities (160 modes)
- In-Structure Response Spectra (ISRS) (5% damped)

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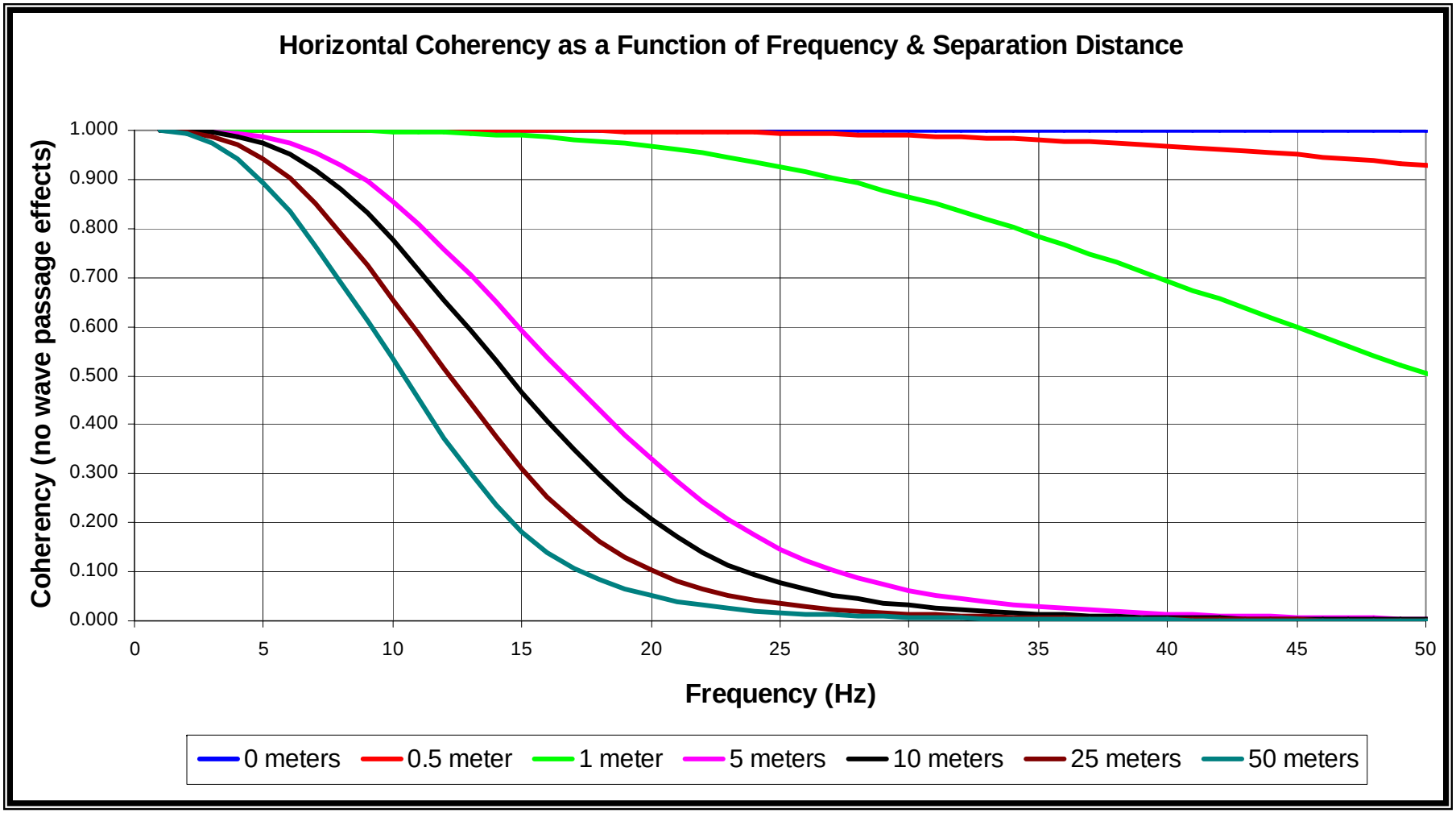
Coherency Function for Horizontal Ground Motion (Soil)



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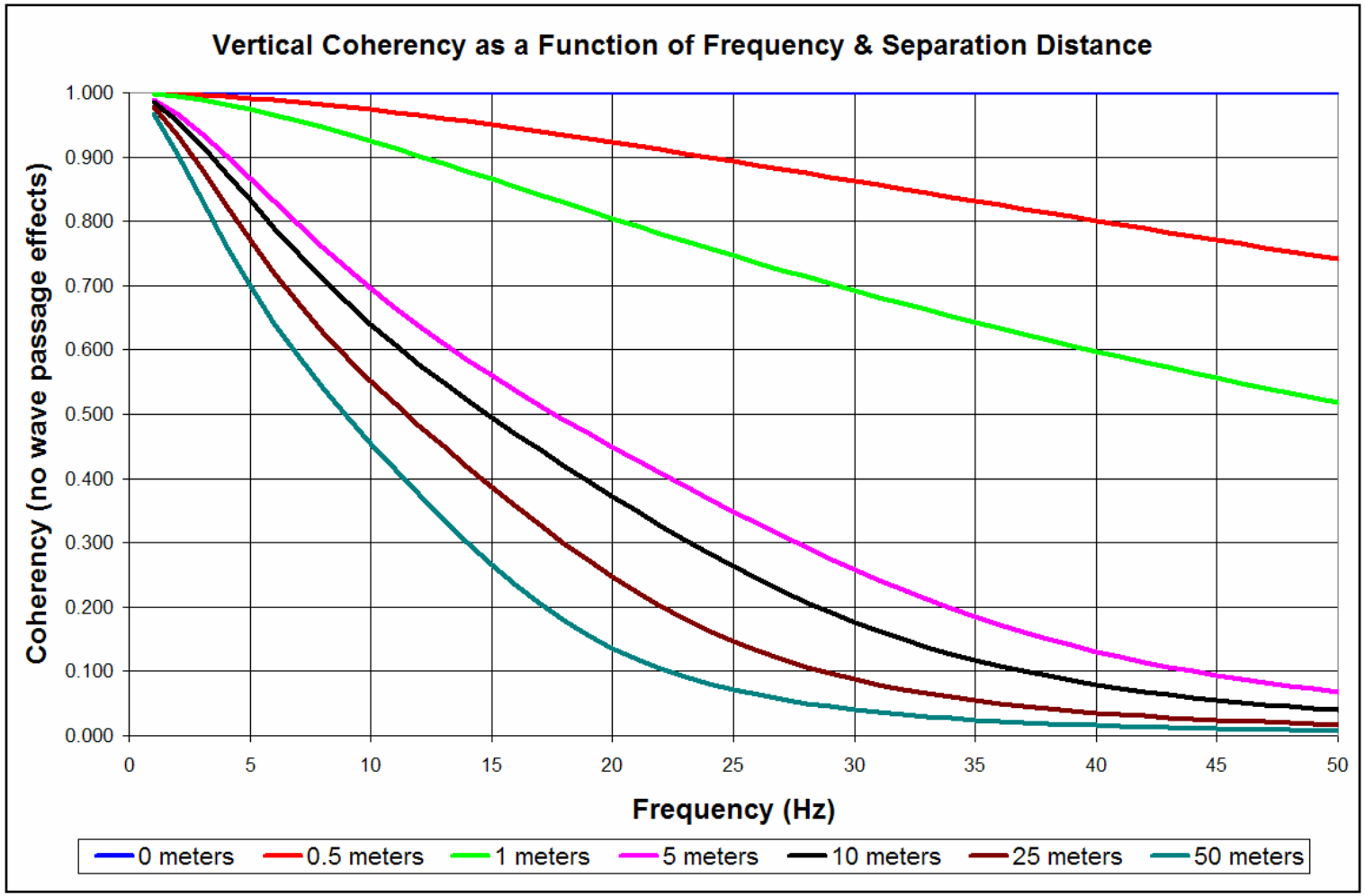
Coherency Function for Vertical Ground Motion (Soil)



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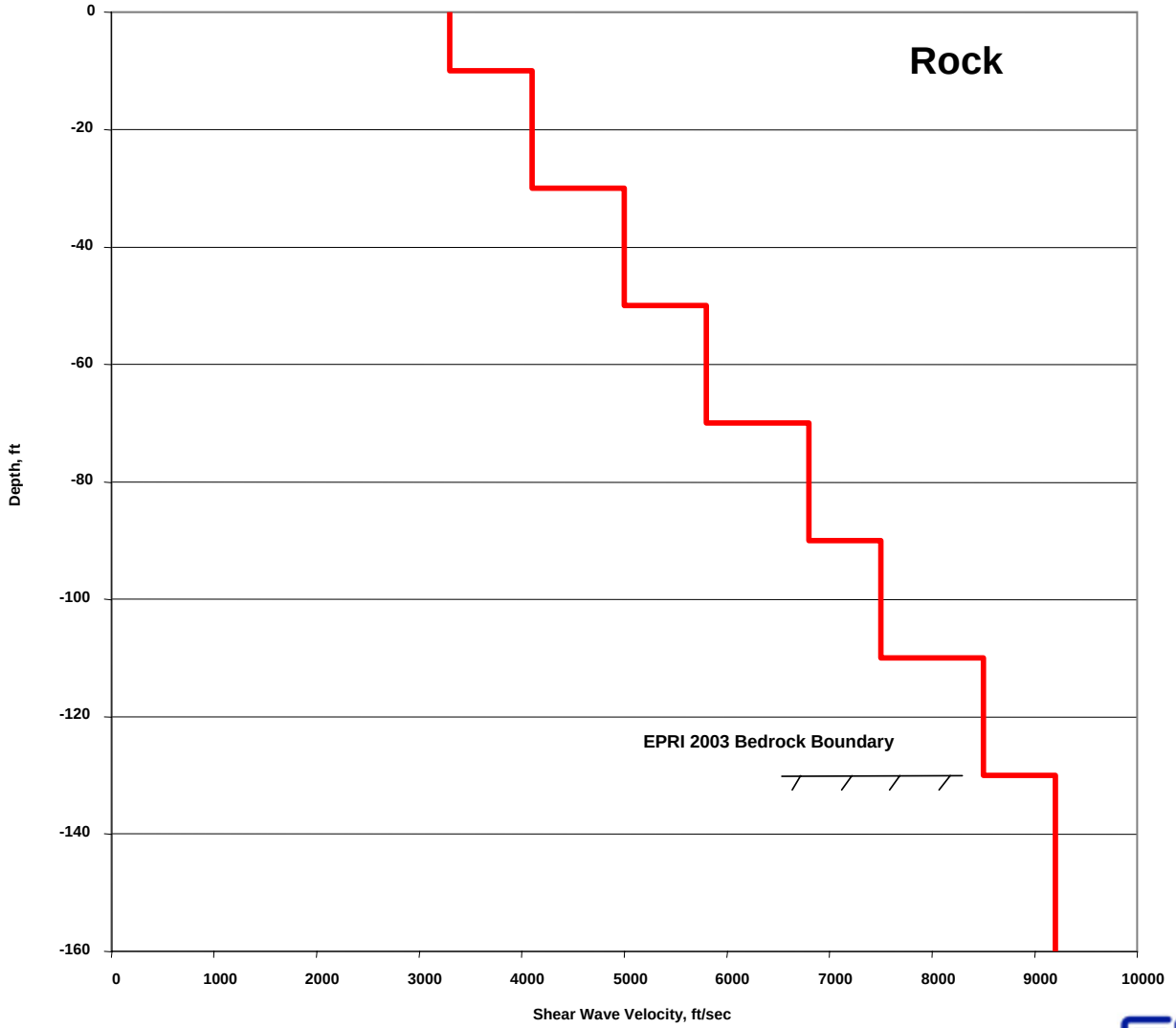
Rock Site Profile
Shear Wave Velocities vs. Depth



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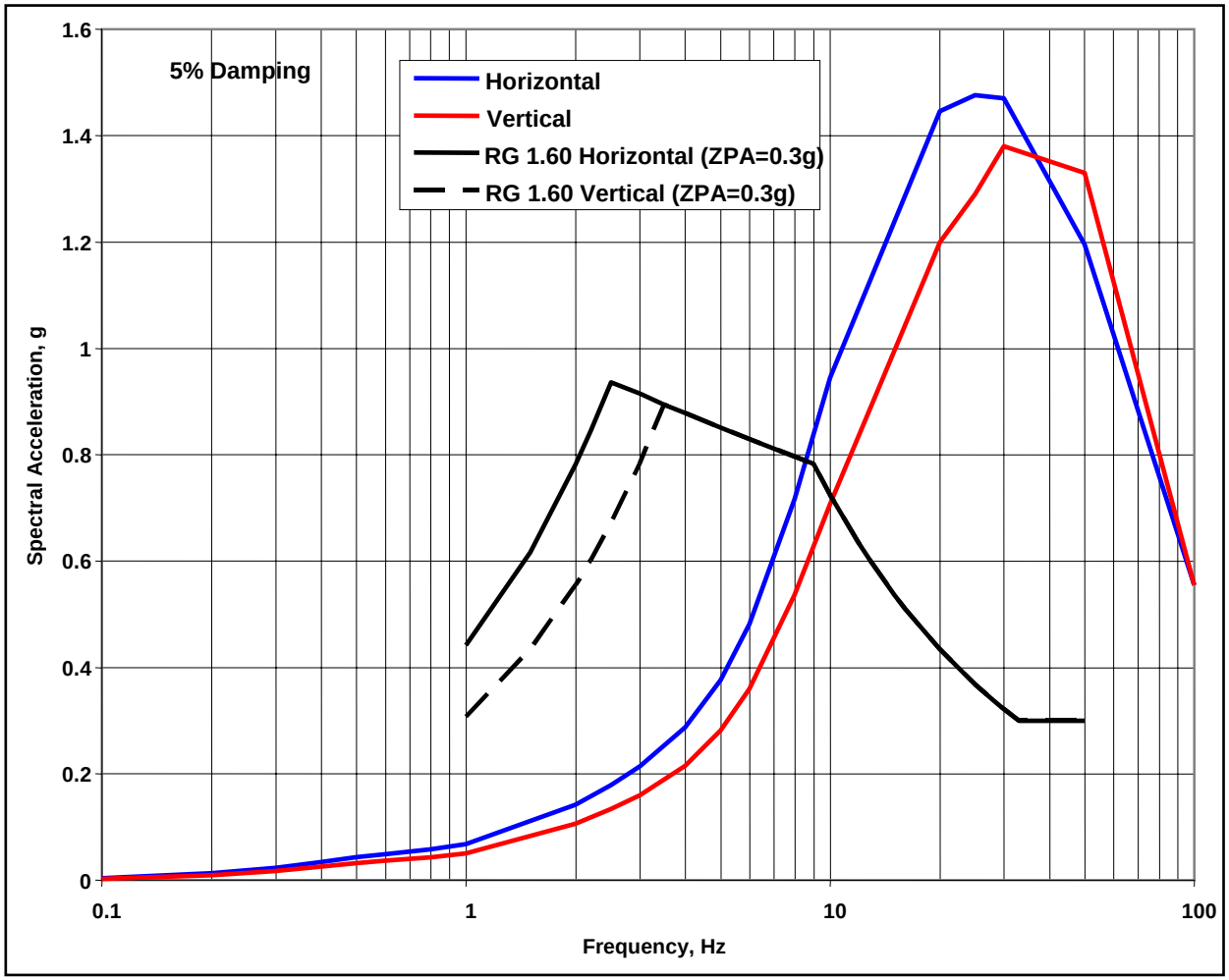
Site-Specific Response Spectra for Rock Site at Ground Surface (Depth 0-ft)



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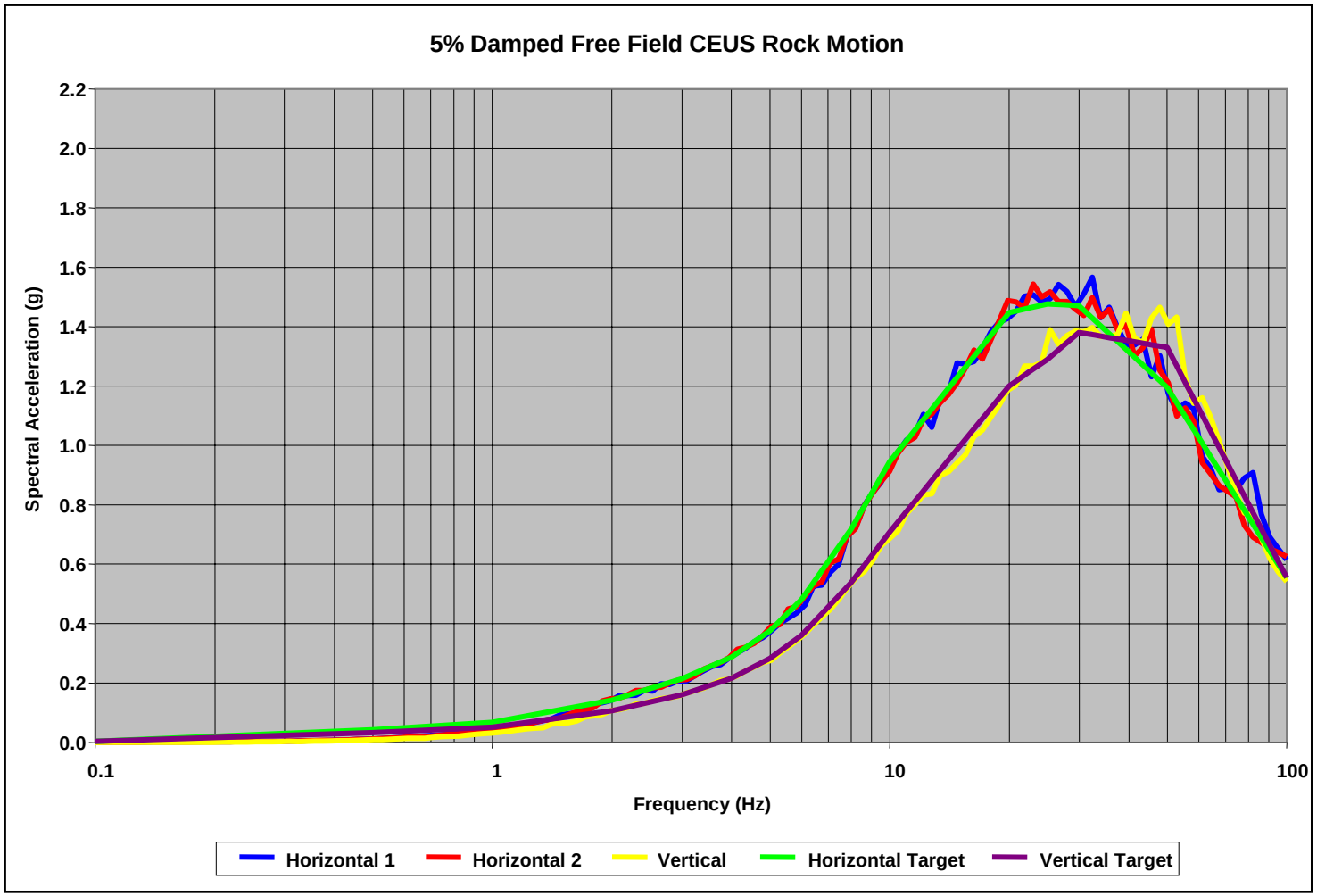
Computed and Target Response Spectra for Rock Site



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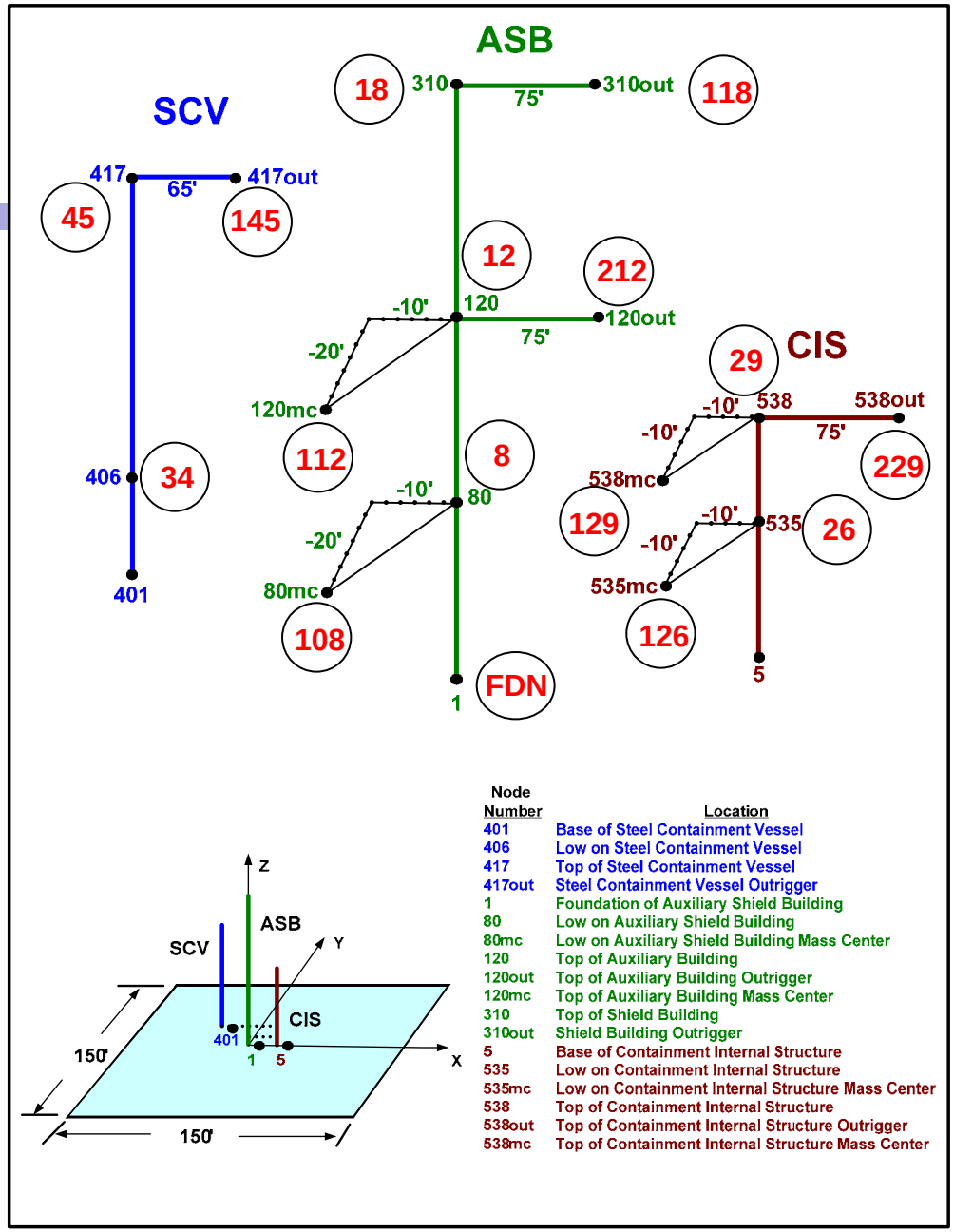
Representative NPP Structure Stick Model with Outriggers and Offset Mass Centers



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Structural Model Characteristics

- Advanced reactor structure stick model with eccentricities
  - 160 fixed-base modes model the dynamic characteristics of the structure
  - Frequencies 3.0 Hz – 141 Hz
  - Total mass (x = 92.7%, y = 92.5%, z = 93.1%)
- Three sticks are coupled at various locations – modes are coupled
  - ASB-3.2 Hz; SCV-5.5 Hz;CIS-13.3 Hz fixed base
- Relative mass distribution
  - ASB – 86%
  - CIS – 11%
  - SCV – 3%

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CLASSI-SASSI Methodologies

- CLASSIinco
  - Deterministic phasing
- CLASSIinco-SRSS
  - Structure response to each foundation input motion combined by SRSS
- SASSI-Simulation
  - Spatial modes assigned random phasing
  - Mean of structural response to spatial modes computed
- SASSI-SRSS
  - Structural responses to each spatial mode are combined by SRSS
- SASSI-AS
  - Linear combination (algebraic sum) of spatial modes used to compute structural response

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Application of CLASSI-SASSI Methodologies

- Calculate three directions of seismic input and combine the results as in the seismic design/qualification process
- Compare response spectra as calculated
  - Coherent (light blue)
  - CLASSIinco (dark blue)
  - CLASSIinco-SRSS (green)
  - SASSI-SRSS (yellow)
  - SASSI-Simulation mean (black)
  - SASSI-AS (red)
- Response comparisons for each direction of seismic input separately (Appendix A)

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Foundation Response Comparisons

- Translations at the center of the foundation
  - Incoherent response significantly less than coherent response
  - Responses calculated by all methods are in very good agreement
- Rotations as measured by translations on the periphery of the foundation
  - Little or no reduction due to incoherency compared to coherent response
  - Responses calculated by all methods are in good agreement

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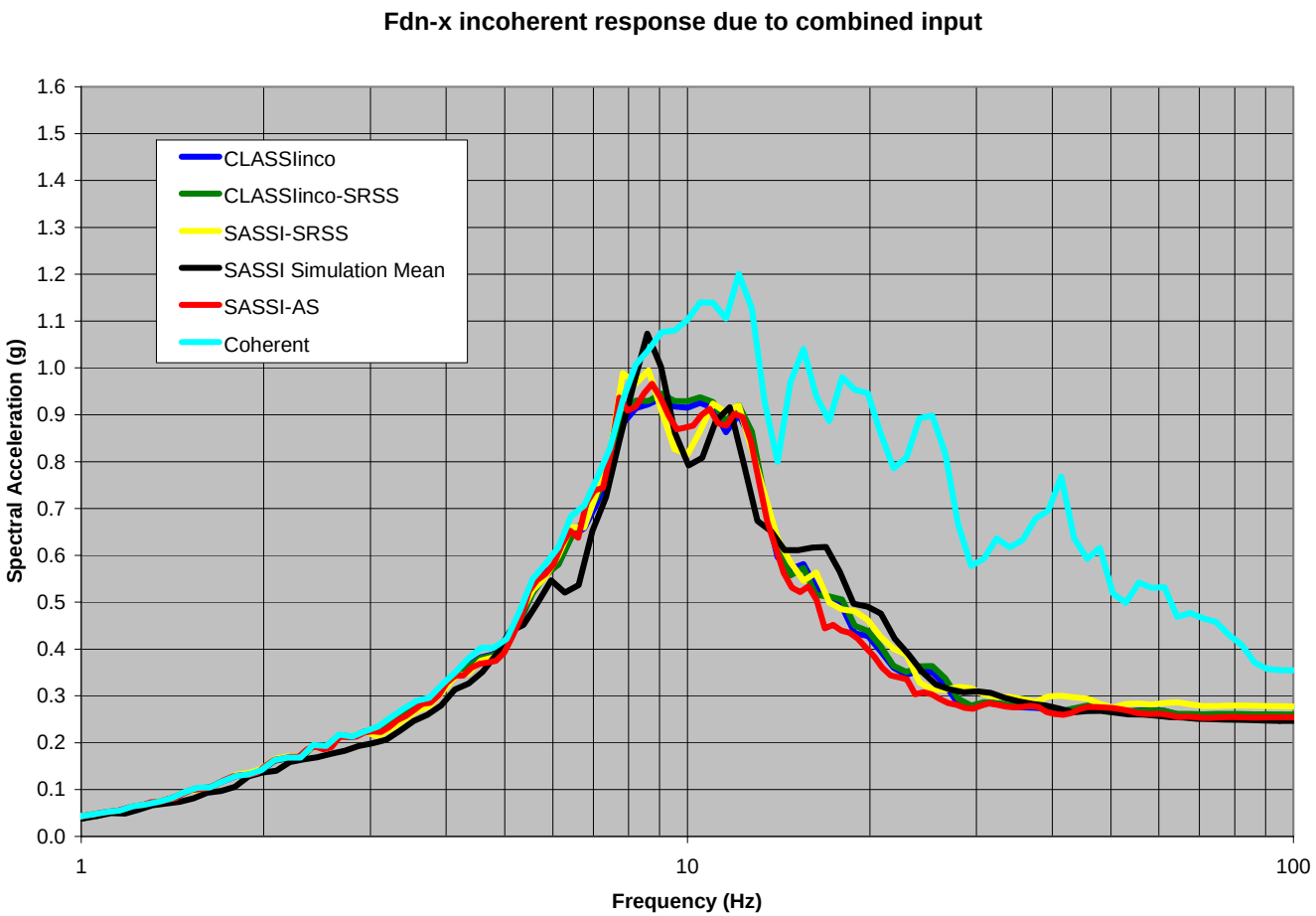
Center of Foundation Response – X- Direction Coherent and Incoherent All Input Directions Combined



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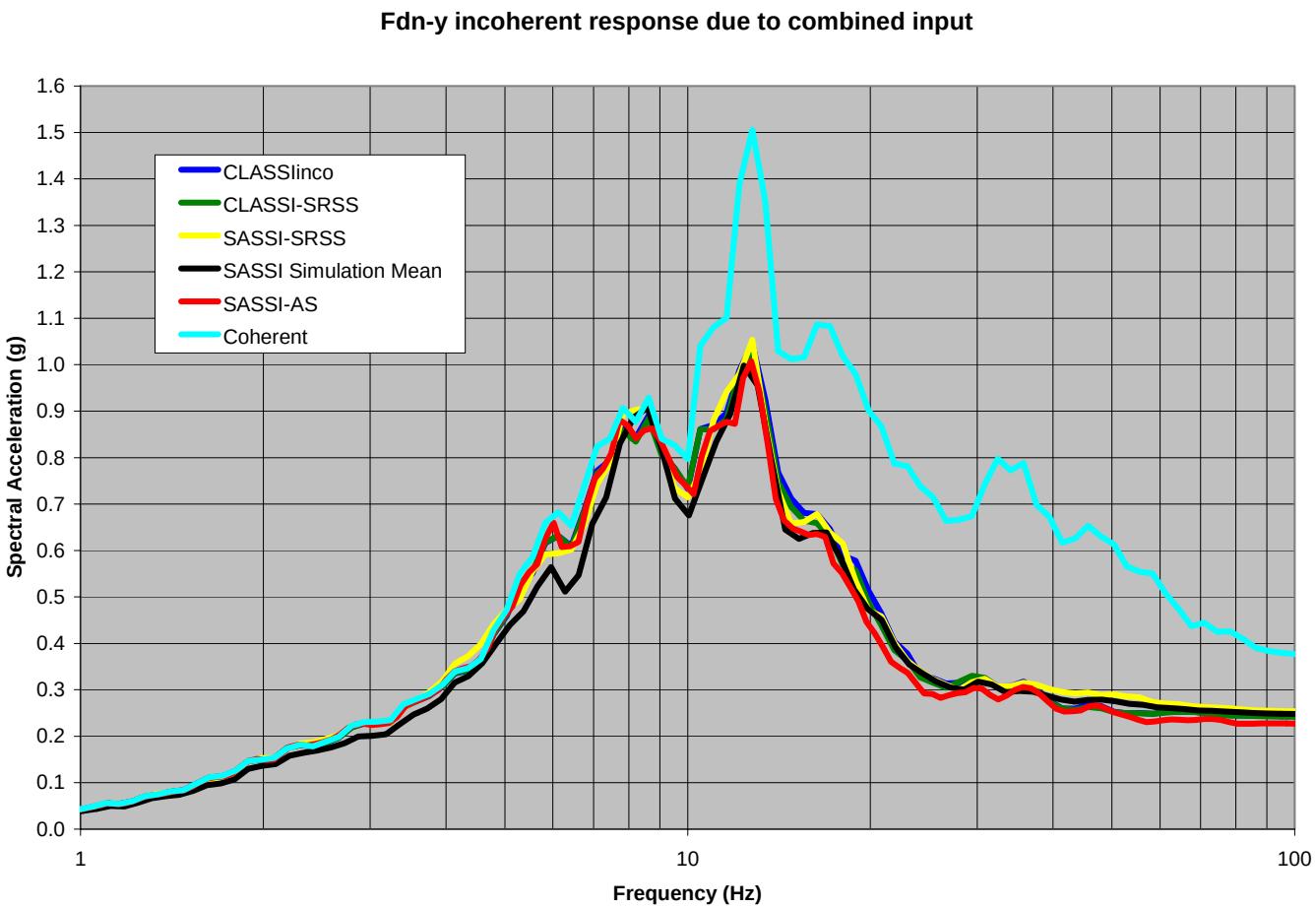
Center of Foundation Response – Y- Direction Coherent and Incoherent All Input Directions Combined



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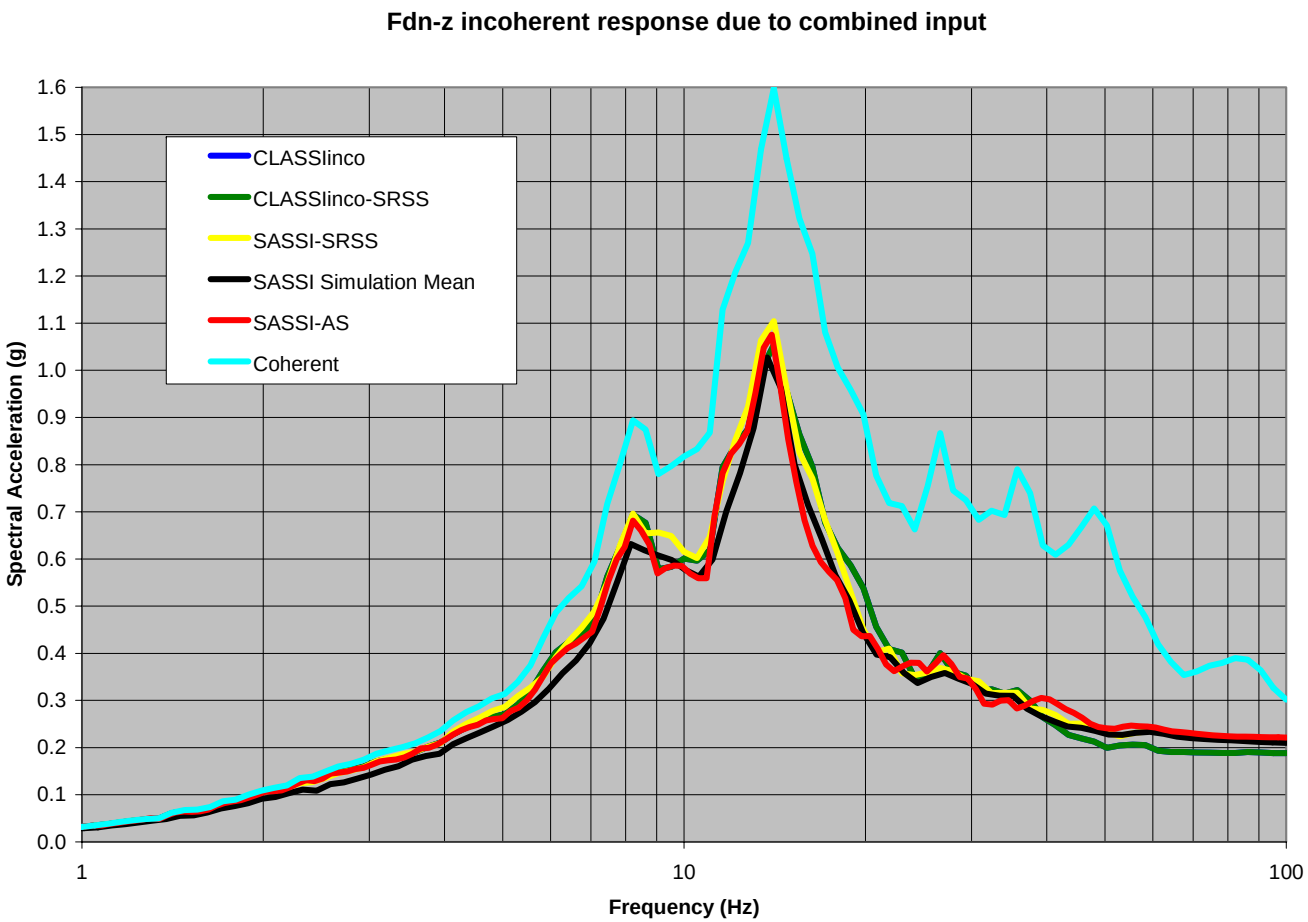
Center of Foundation Response – Z- Direction Coherent and Incoherent All Input Directions Combined



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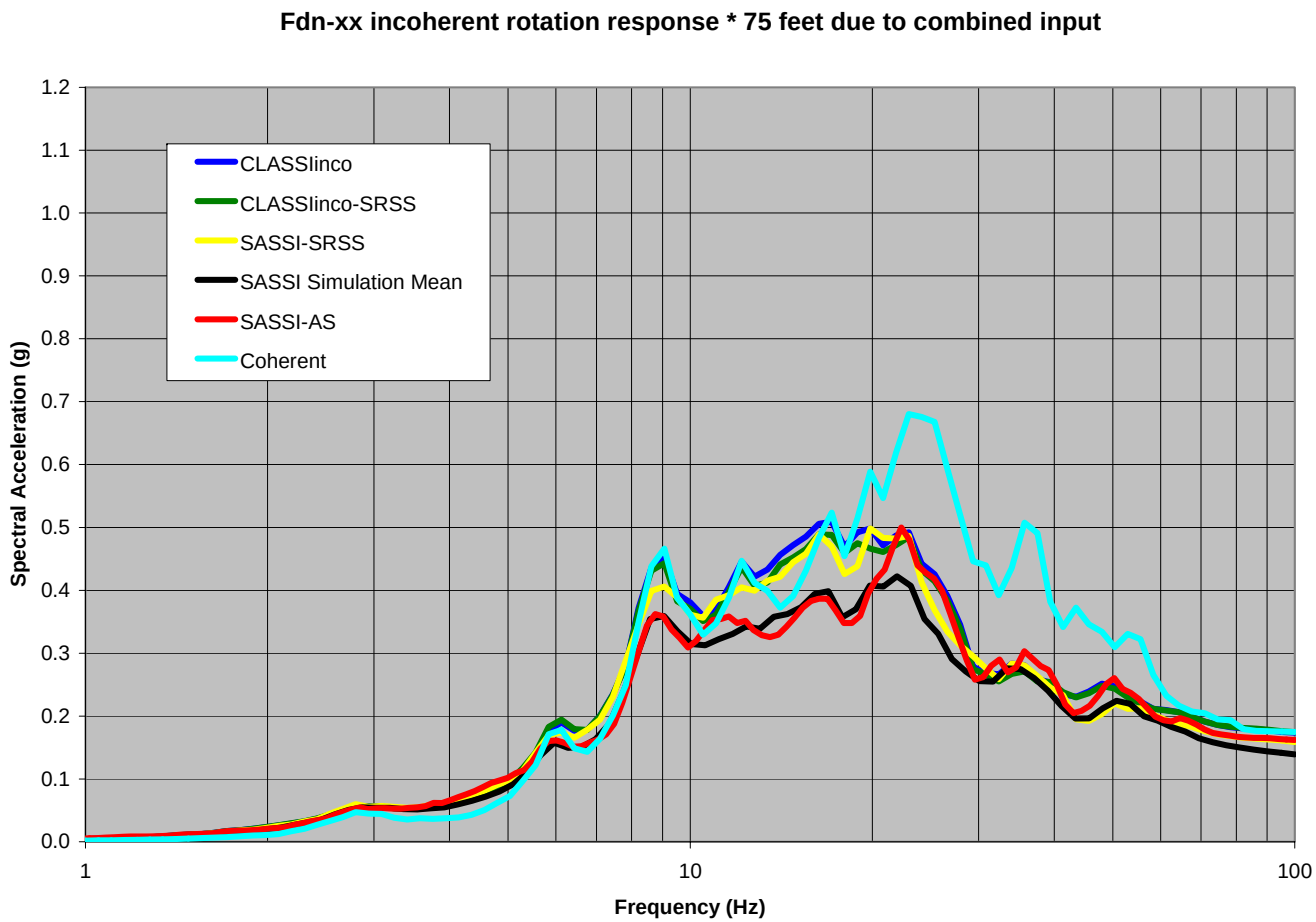
Edge of Foundation Response XX - Rotation Coherent and Incoherent All Input Directions Combined



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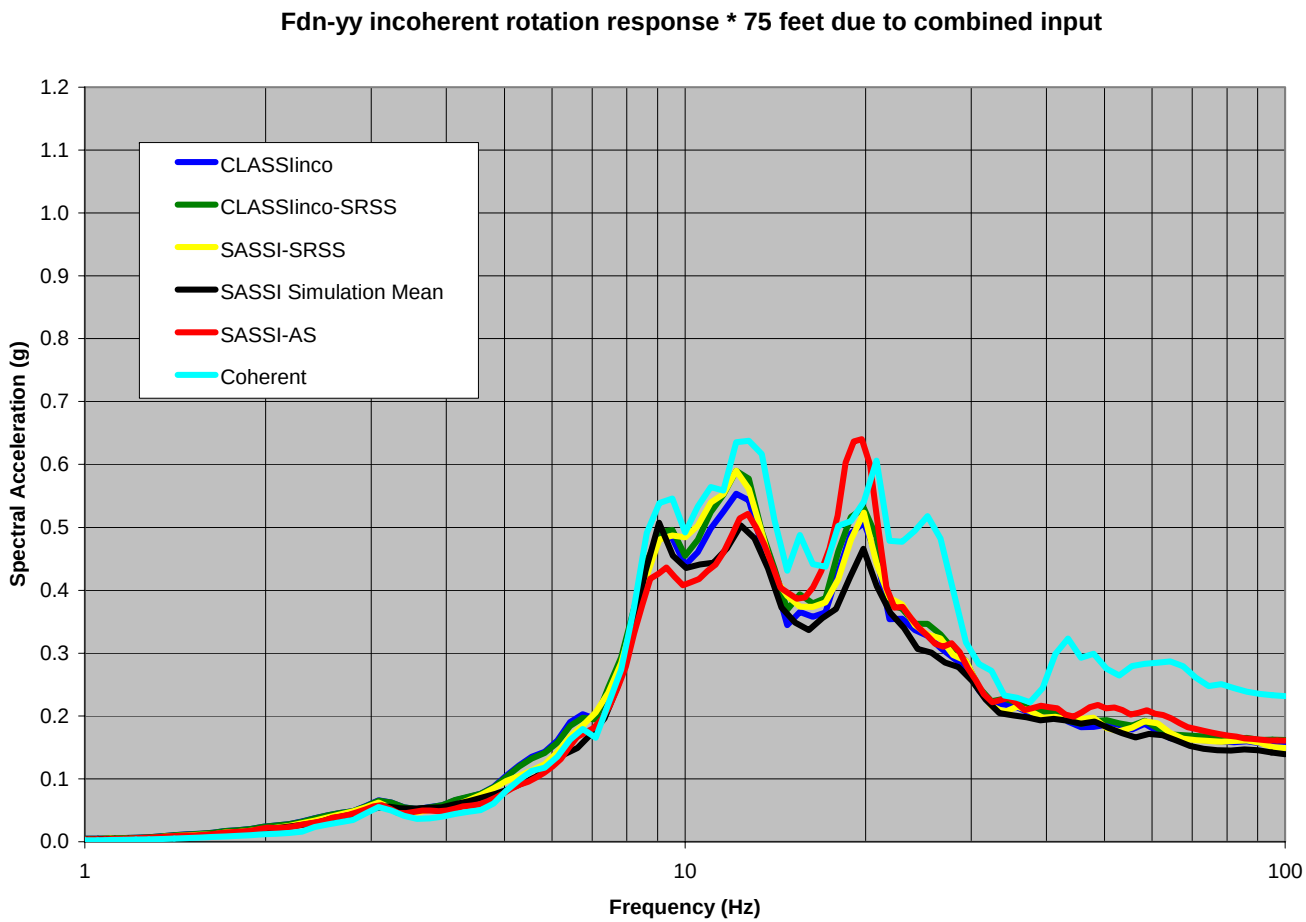
Edge of Foundation Response YY - Rotation Coherent and Incoherent All Input Directions Combined



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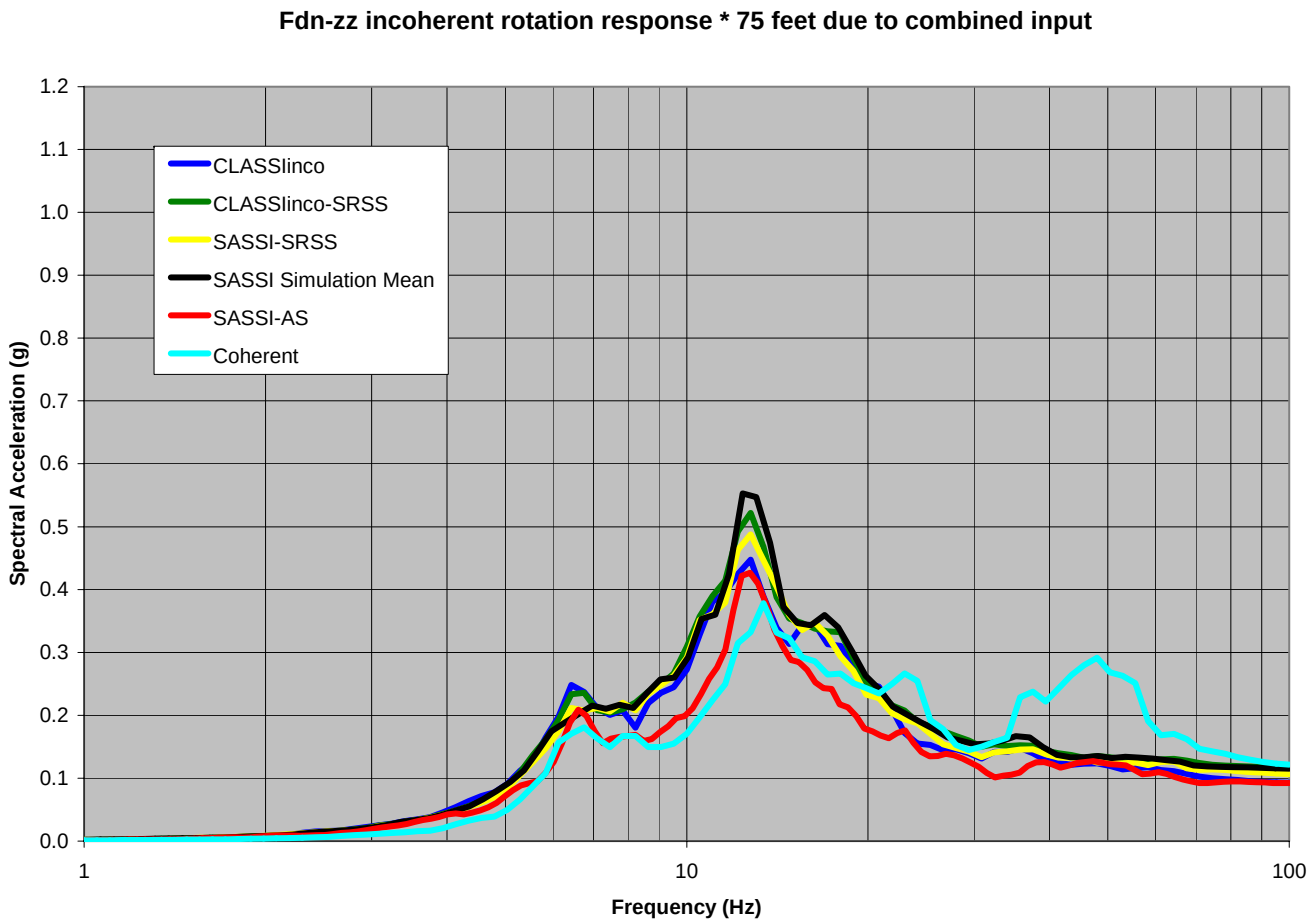
Edge of Foundation Response ZZ - Rotation Coherent and Incoherent All Input Directions Combined



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Top of Shield Building – Centerline (Node 18) and Outrigger (Node 118 – 75 ft.)

- Incoherent response significantly less than coherent response
  - Horizontal - frequencies greater than 12 Hz up to 30 Hz (less reductions at ZPA)
  - Vertical – greater than 10 Hz
  - Outrigger reductions somewhat less than on centerline
- Responses calculated by all methods are in good agreement – generally within 10% except Z-direction at Node 18 for CLASSIinco-SRSS
- Small increases in incoherent response over coherent response at peak spectral frequencies less than 10 Hz are observed – induced rotations effects

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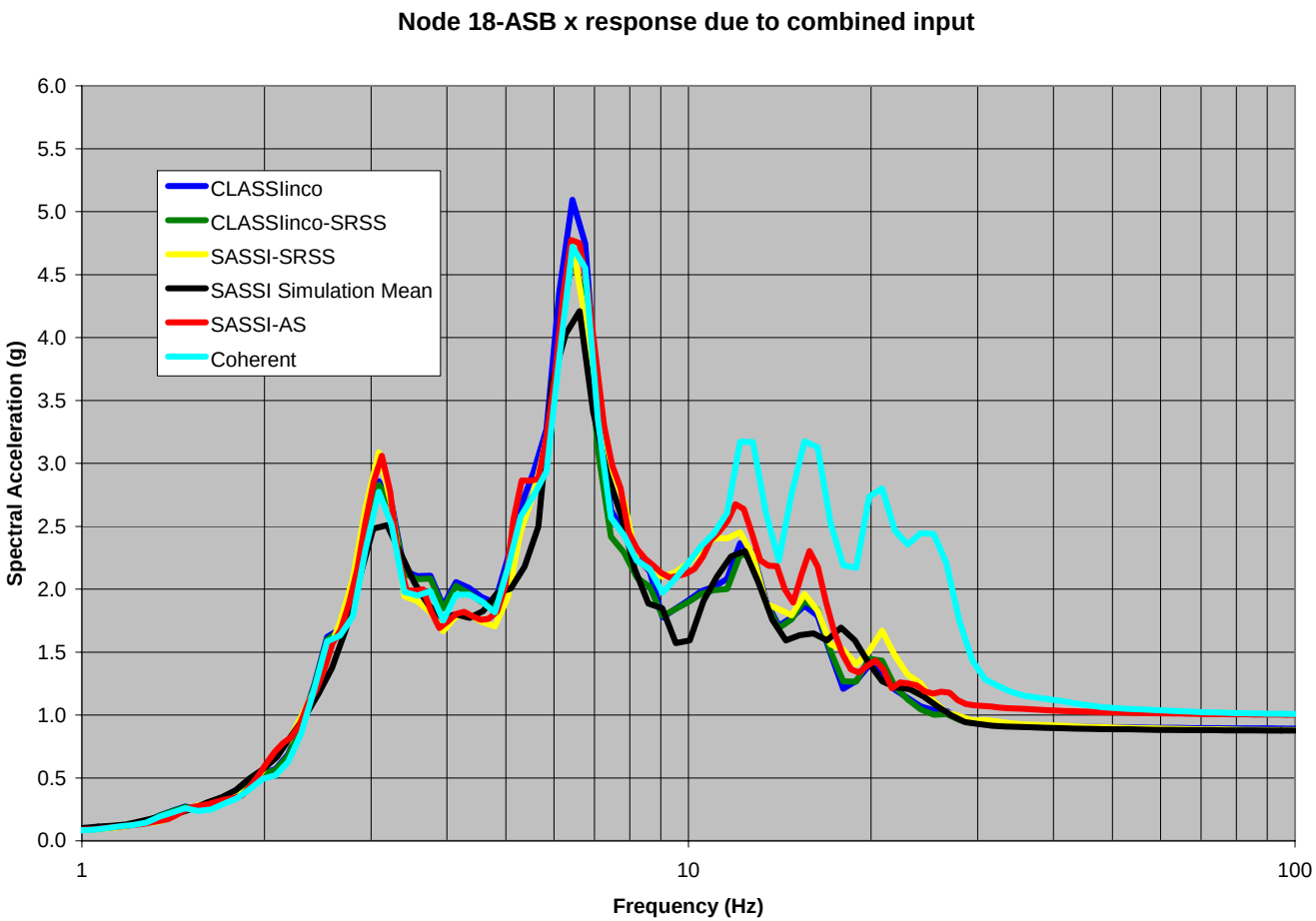
Top of Shield Building Centerline (Node 18) - X- Direction Coherent and Incoherent All Input Directions Combined



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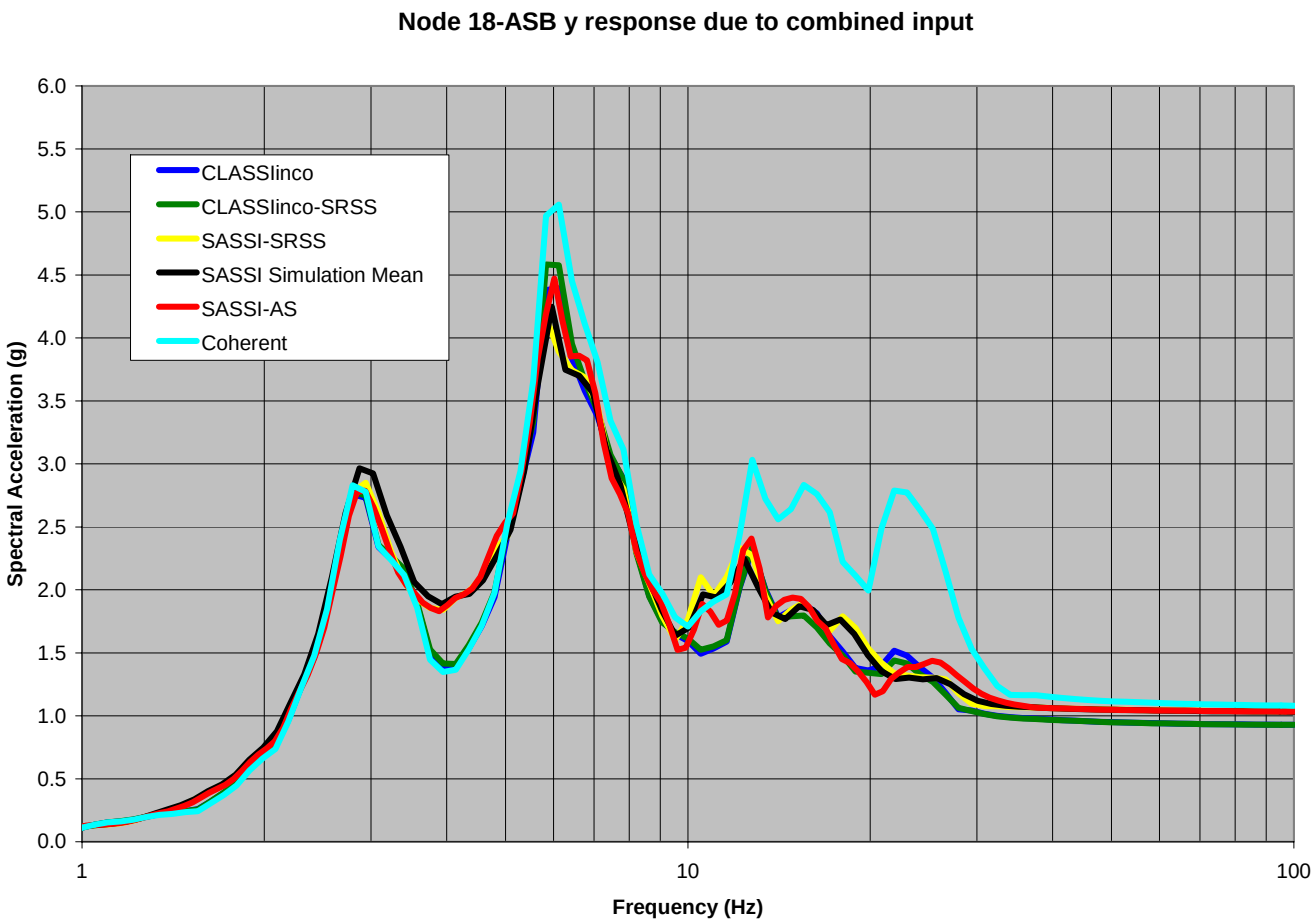
Top of Shield Building Centerline (Node 18) - Y- Direction Coherent and Incoherent All Input Directions Combined



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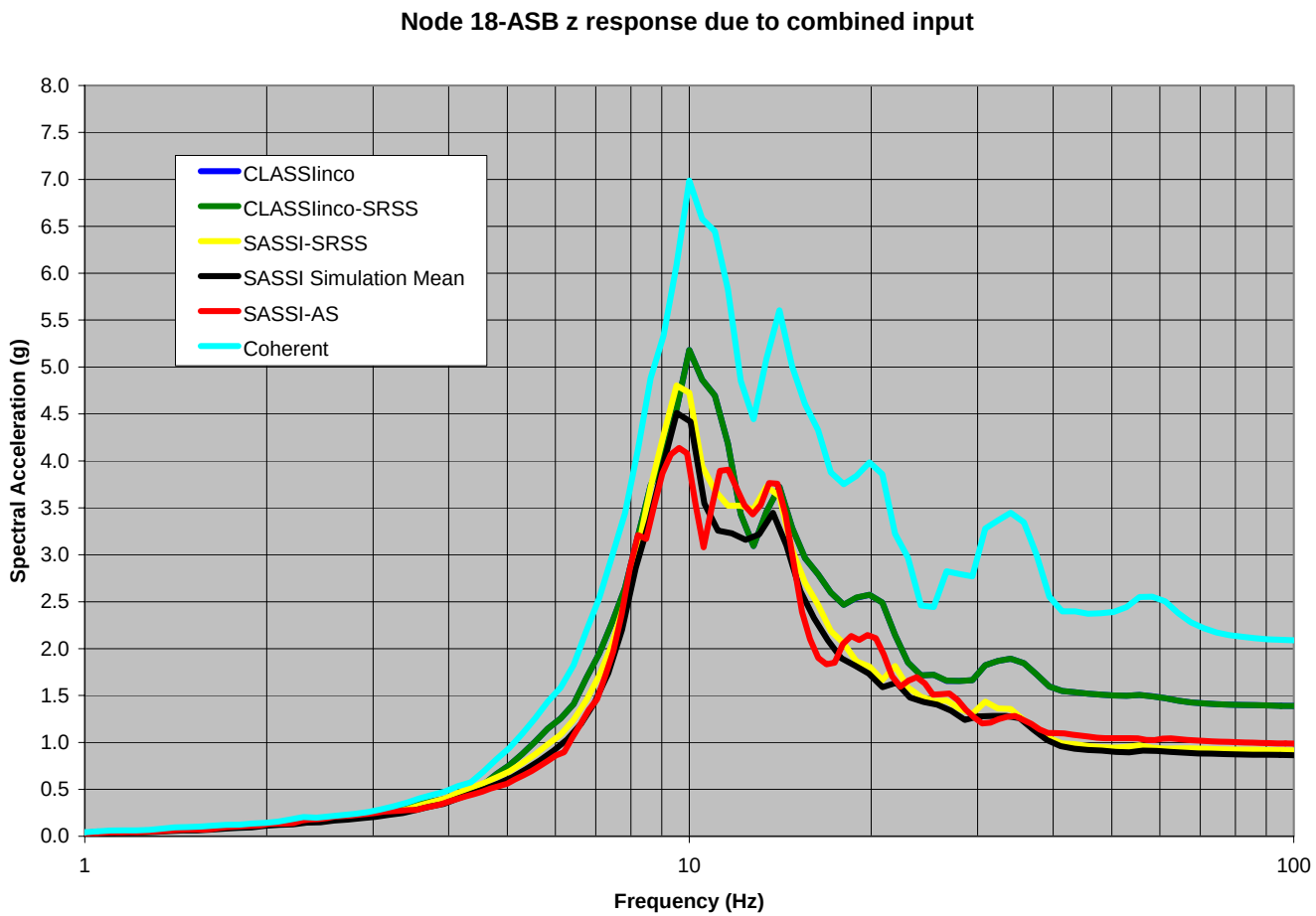
Top of Shield Building Centerline (Node 18) - Z- Direction Coherent and Incoherent All Input Directions Combined



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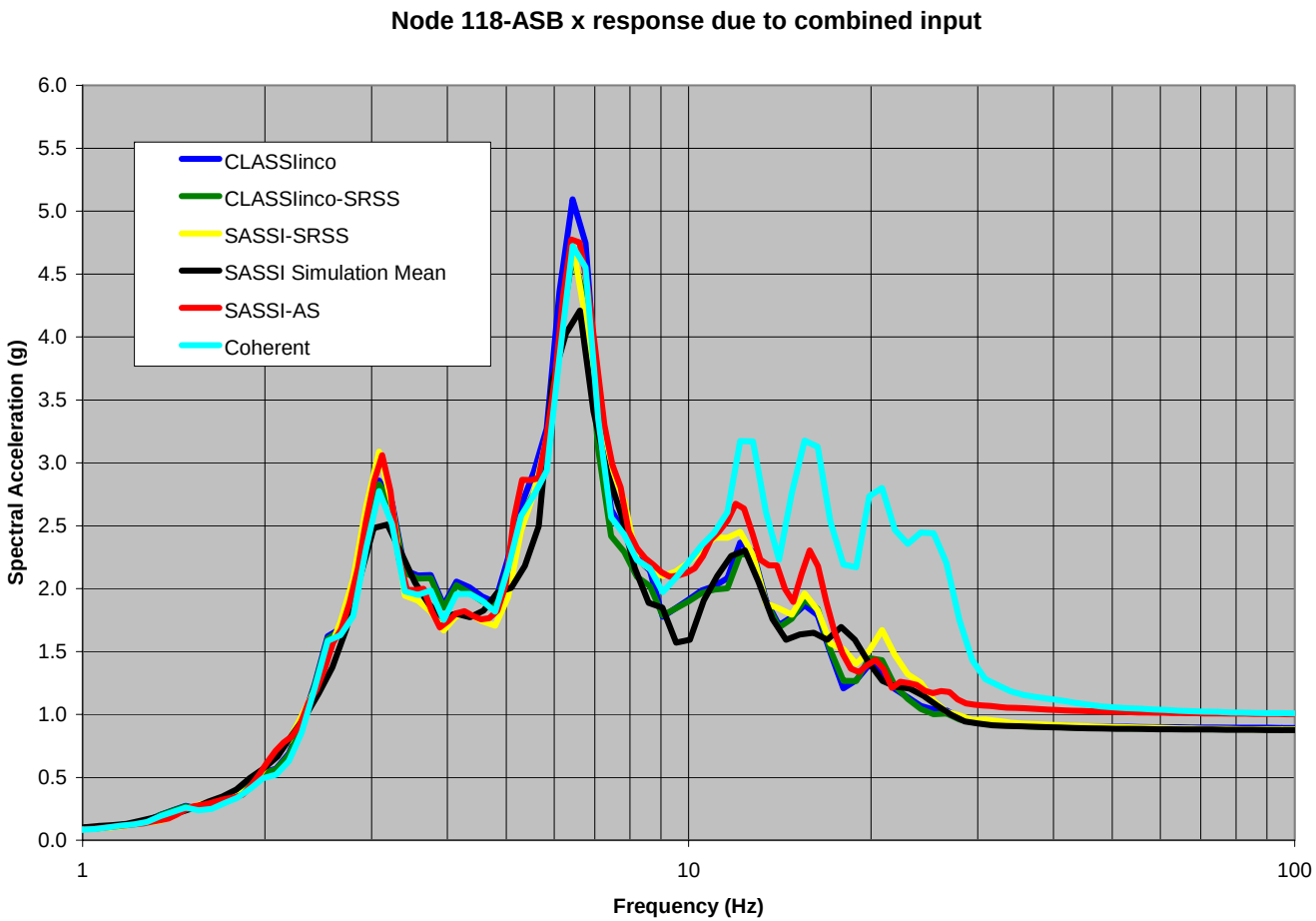
Top of Shield Building Outrigger (Node 118) - X- Direction Coherent and Incoherent All Input Directions Combined



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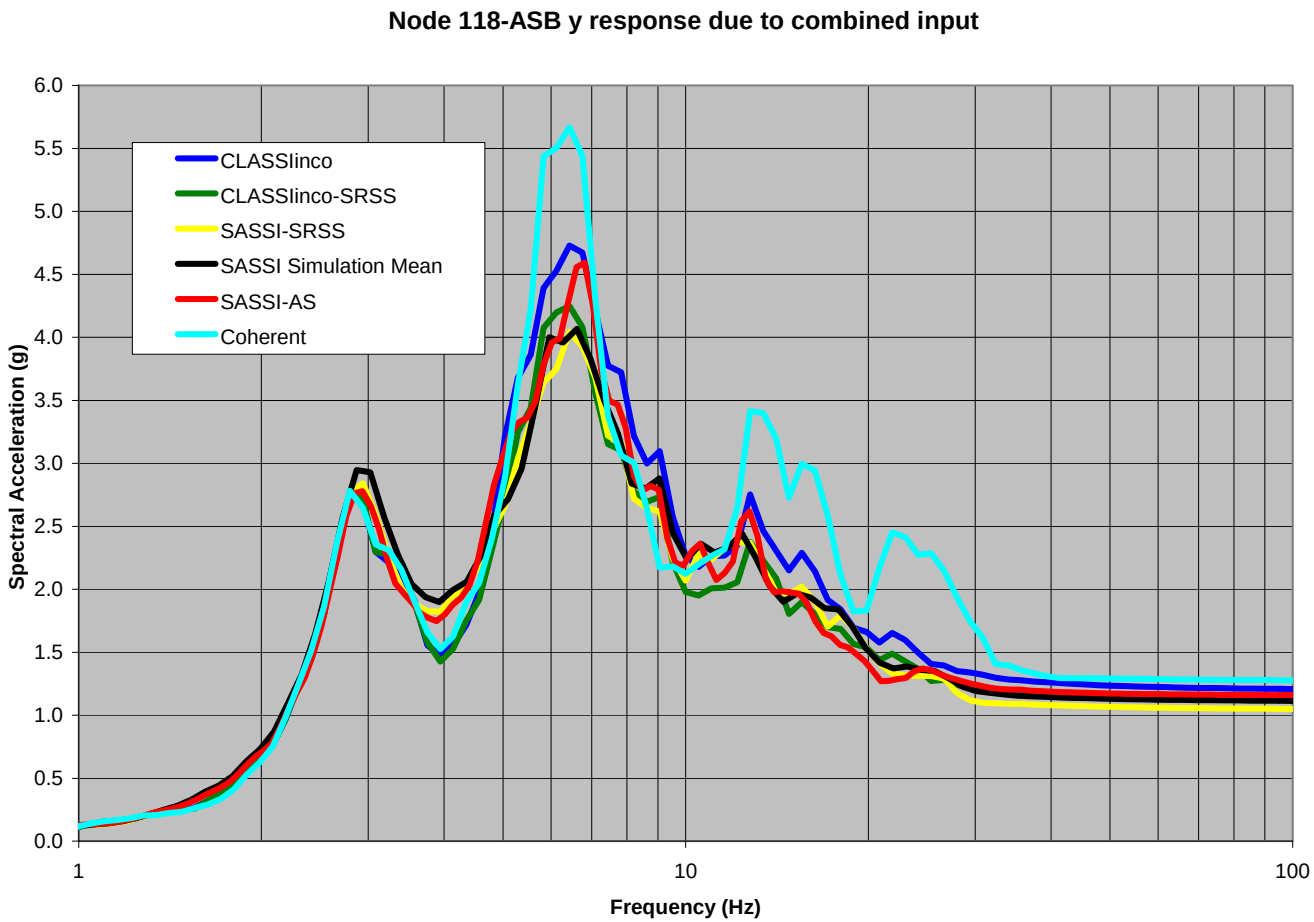
Top of Shield Building Outrigger (Node 118) - Y- Direction Coherent and Incoherent All Input Directions Combined



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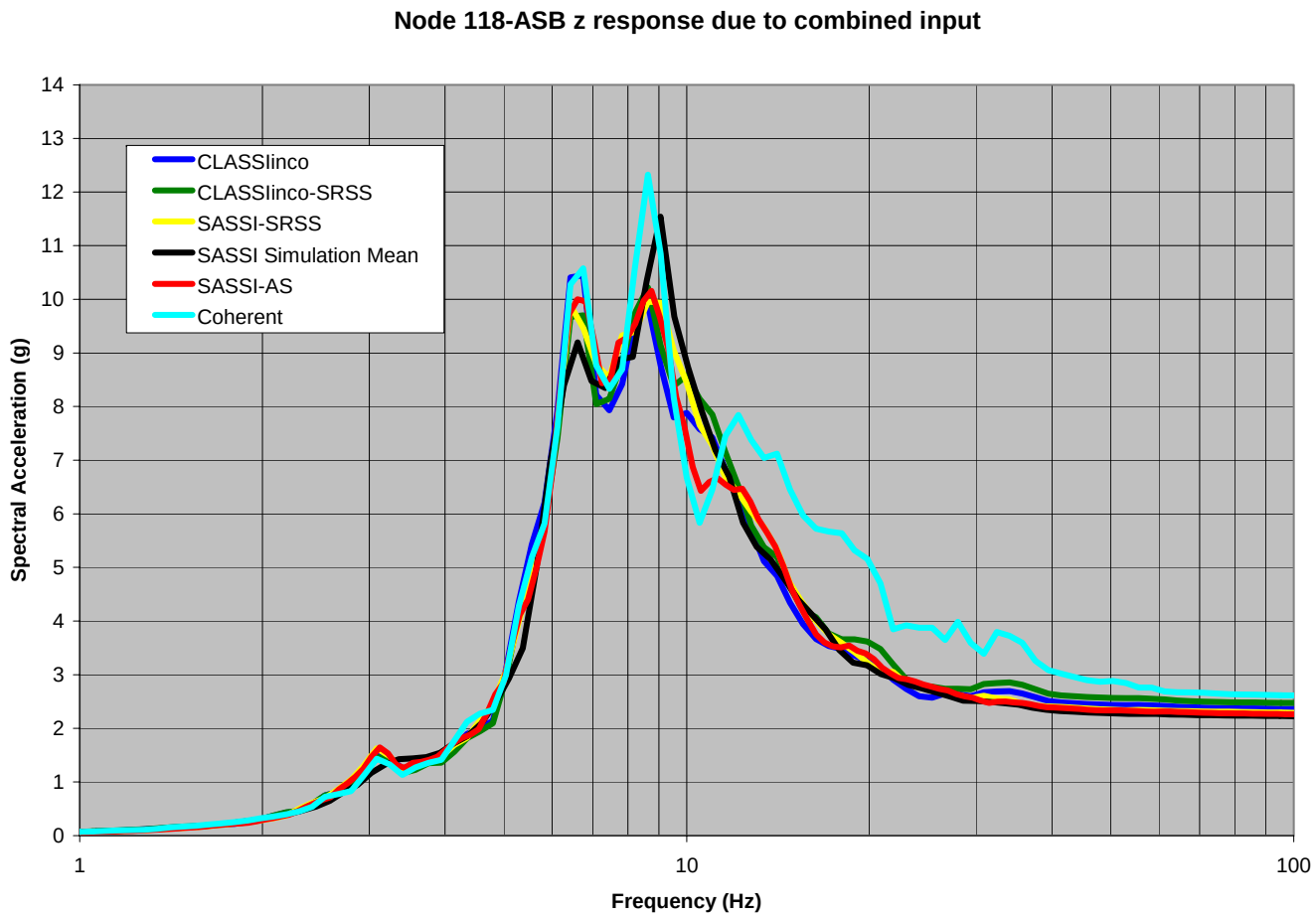

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Top of Containment Internal Structure (CIS) – Centerline (Node 29) Offset Mass (Node 129) Outrigger (Node 229 – 75 ft.)

- Incoherent response significantly less than coherent response for frequencies greater than about 12 Hz – some reductions greater than 50%
- For this high frequency structure, responses calculated by all methods are in very good agreement – generally within 10%

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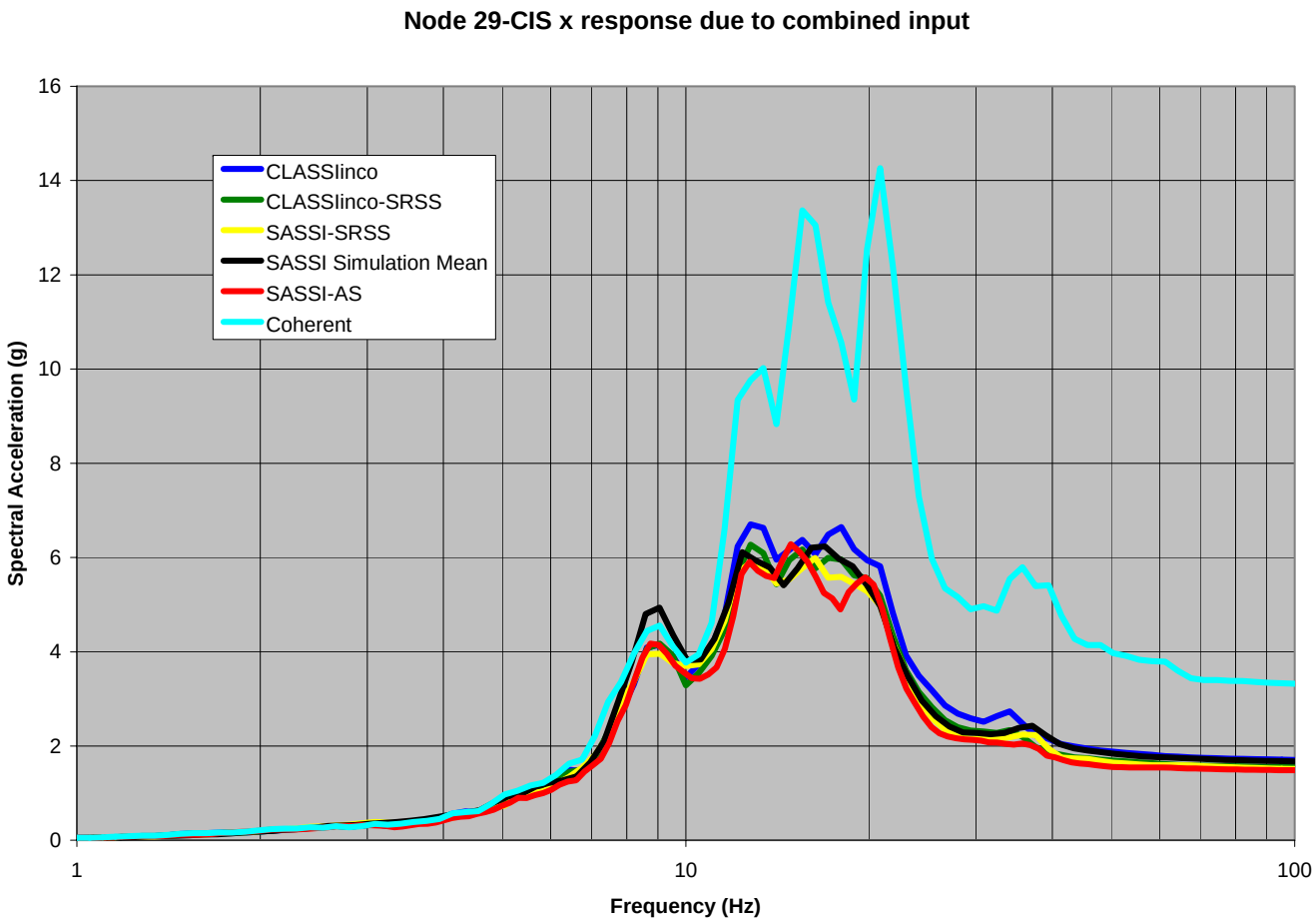
Top of CIS Centerline (Node 29) - X- Direction Coherent and Incoherent All Input Directions Combined



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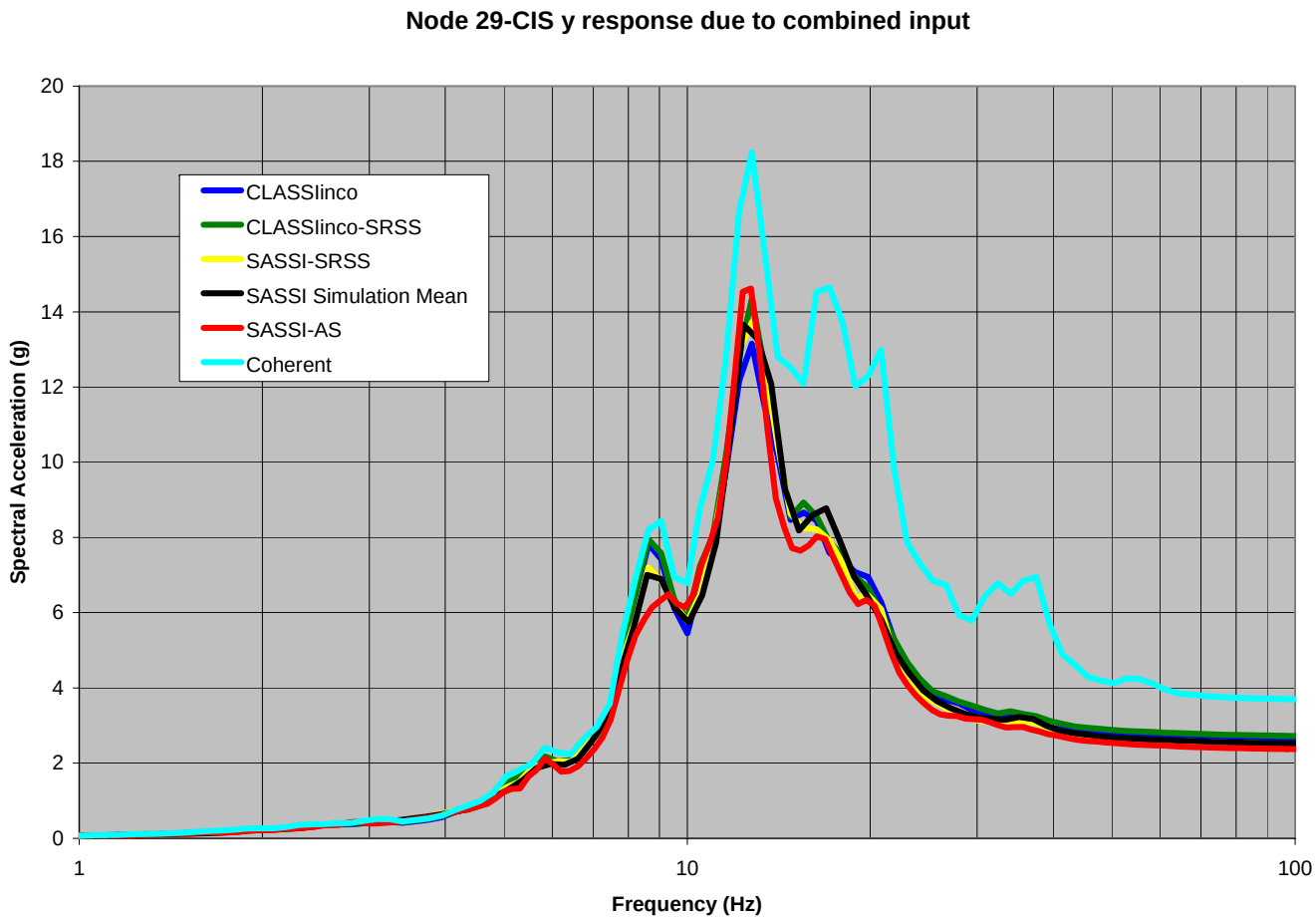
Top of CIS Centerline (Node 29) - Y- Direction Coherent and Incoherent All Input Directions Combined



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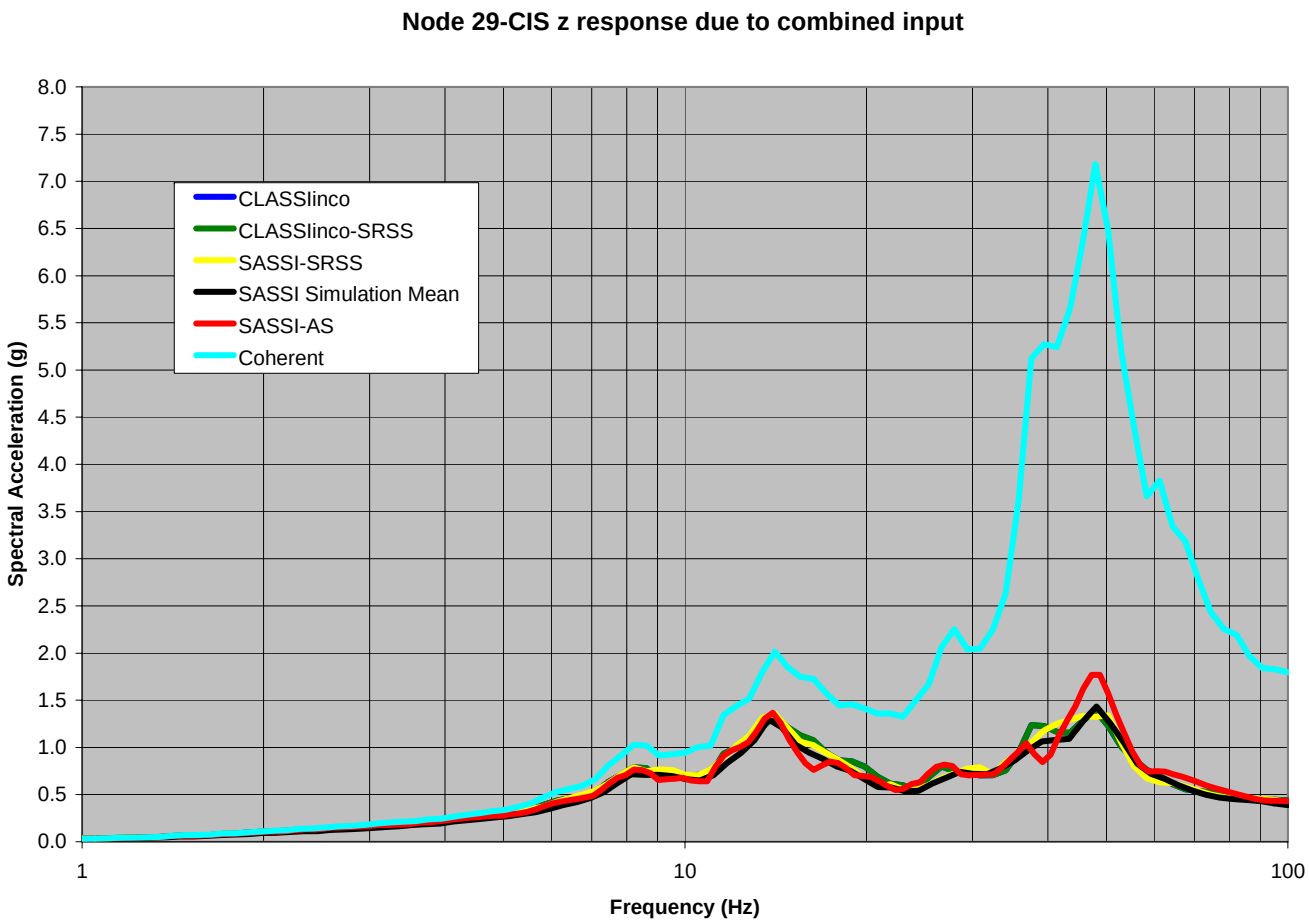
Top of CIS Centerline (Node 29) – Z - Direction Coherent and Incoherent All Input Directions Combined



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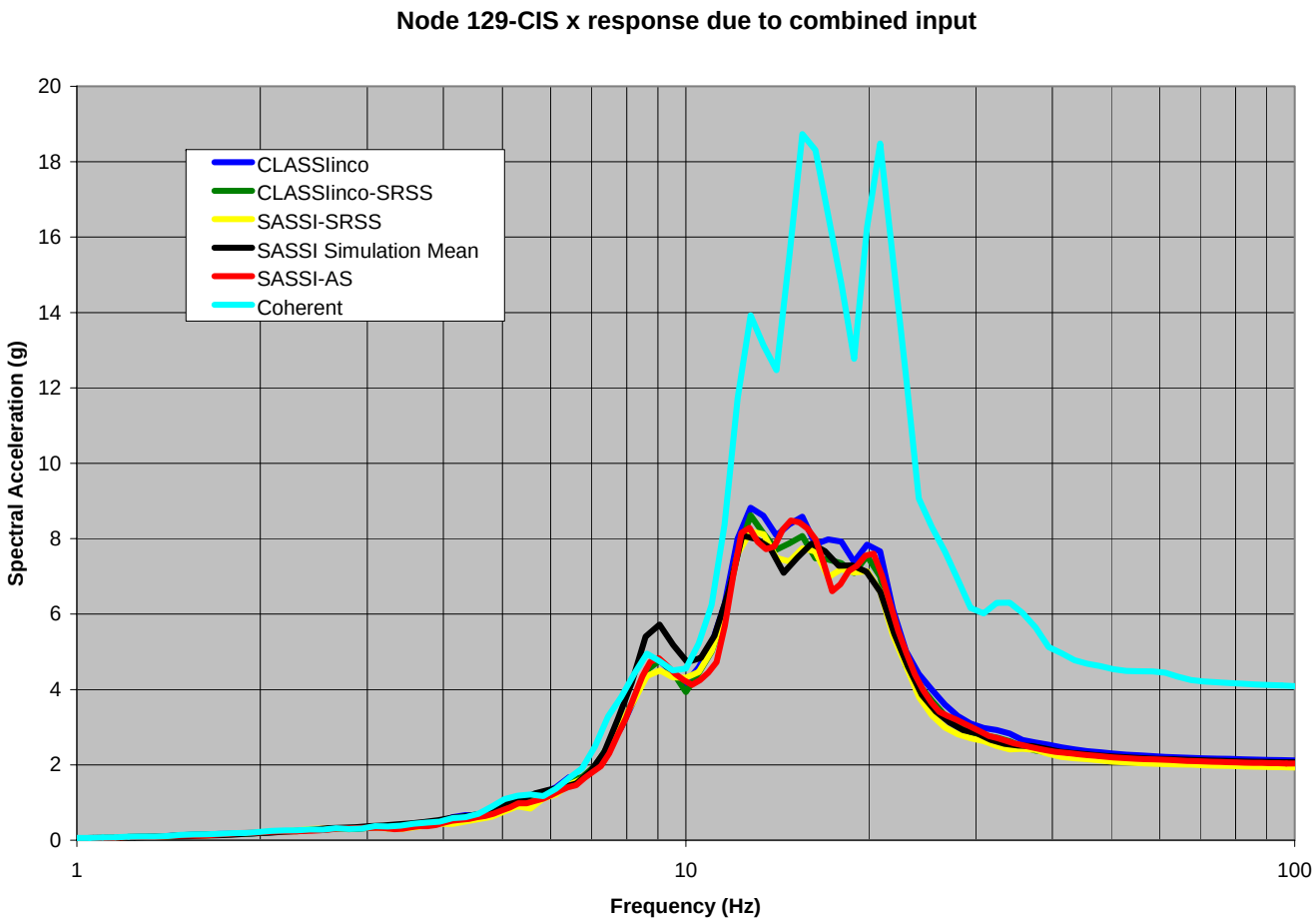
Top of CIS Offset Mass (Node 129) - X- Direction Coherent and Incoherent All Input Directions Combined



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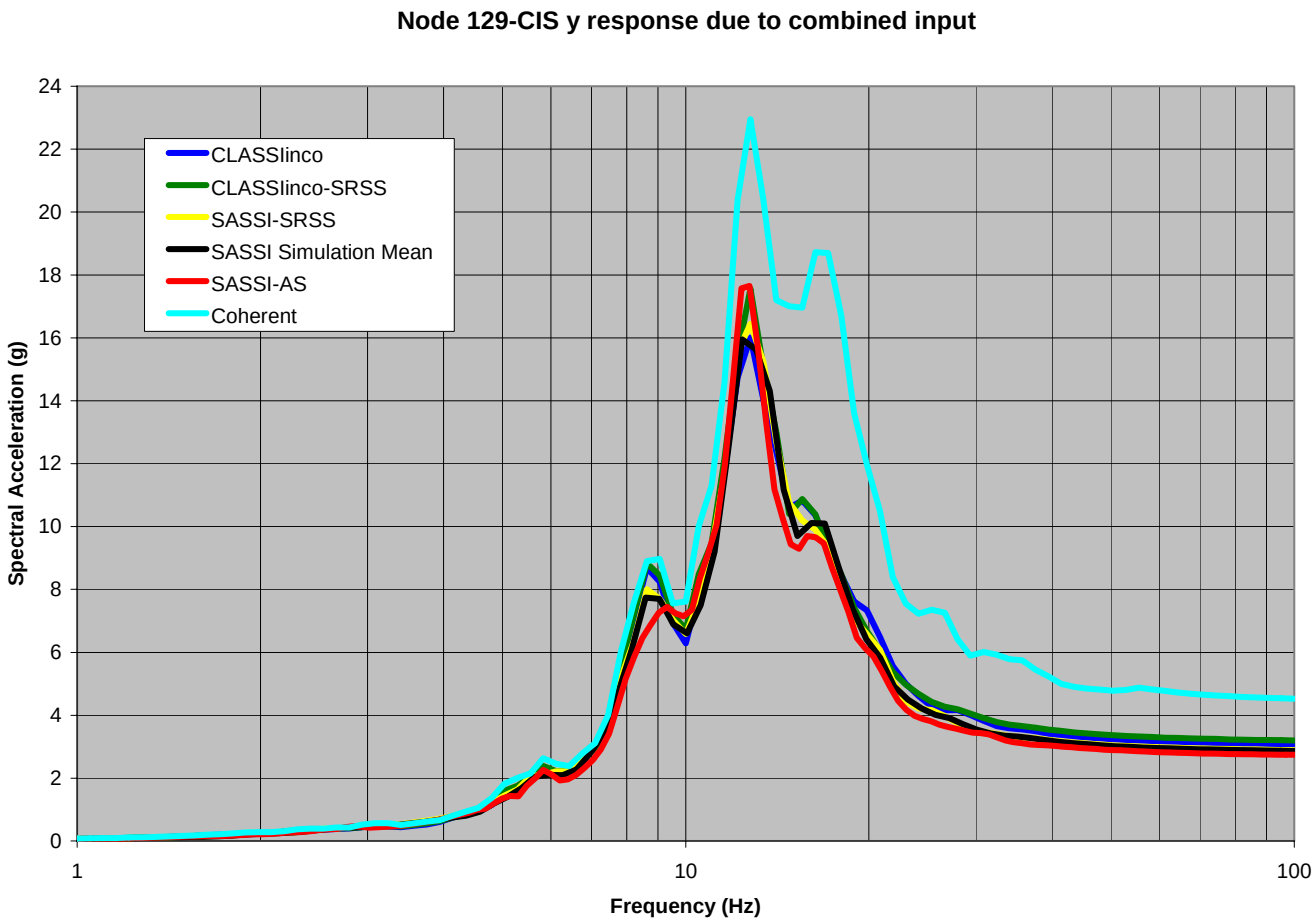
Top of CIS Offset Mass (Node 129) - Y- Direction Coherent and Incoherent All Input Directions Combined



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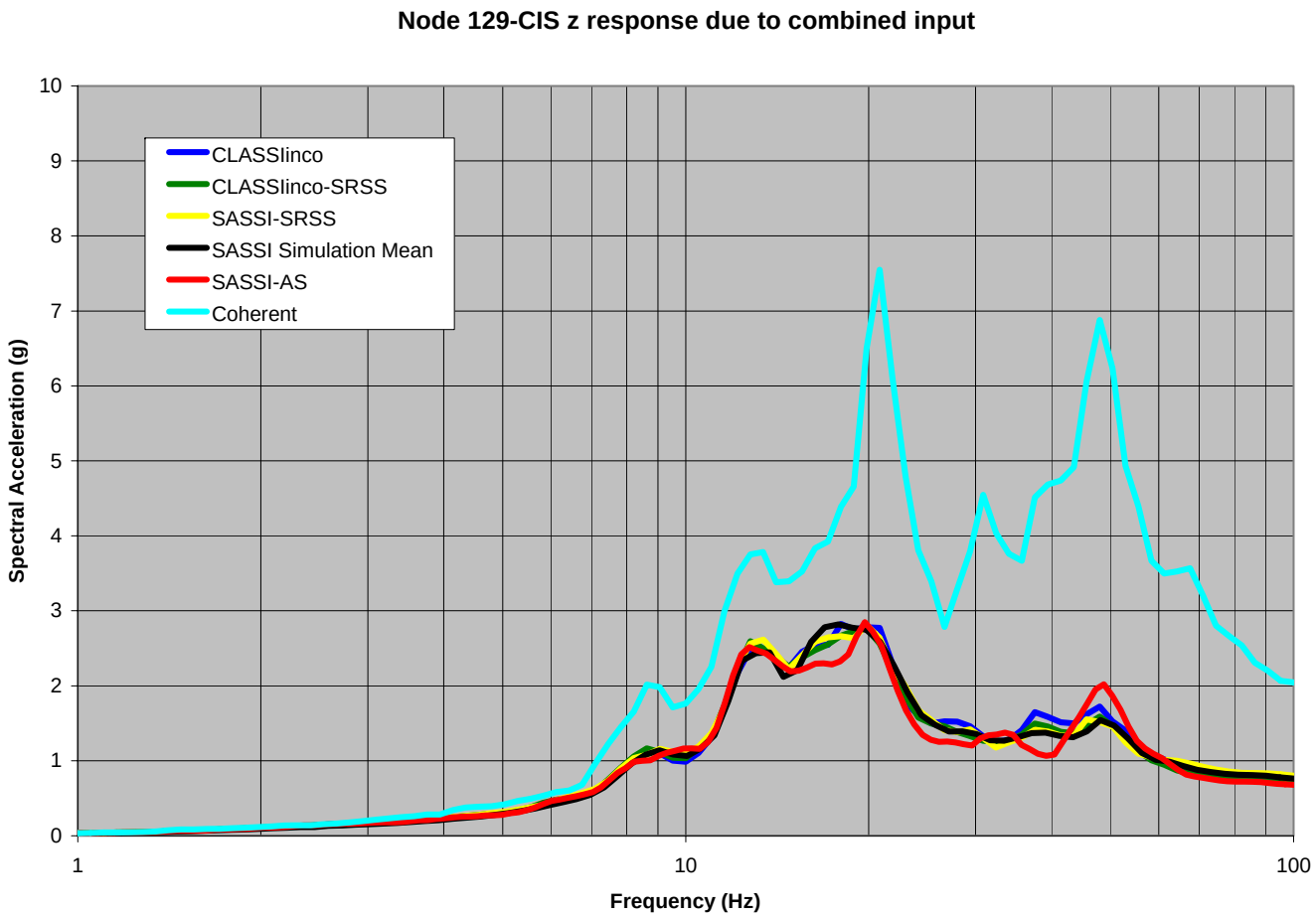
Top of CIS Offset Mass (Node 129) - Z- Direction Coherent and Incoherent All Input Directions Combined



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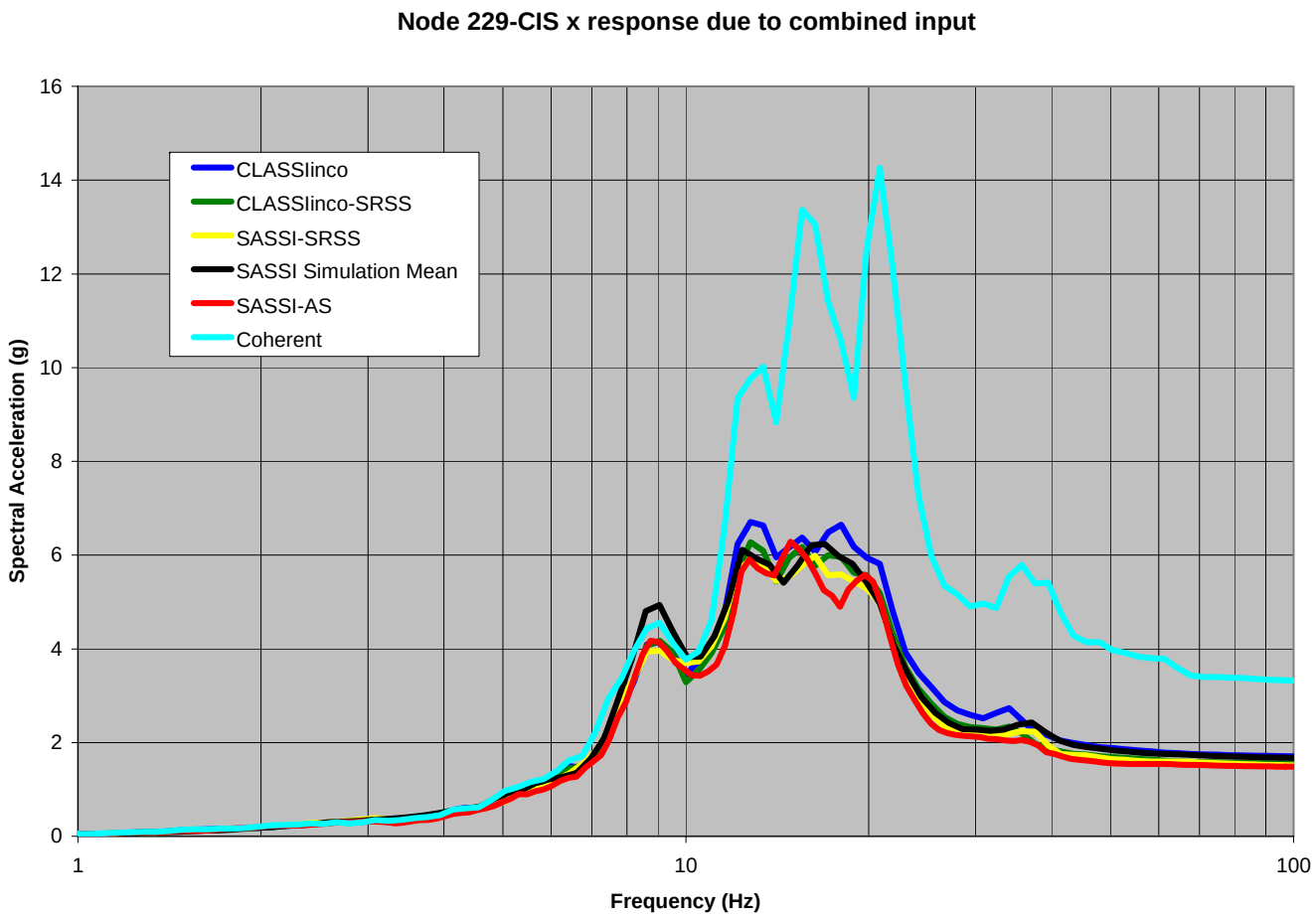
Top of CIS Outrigger (Node 229) - X- Direction Coherent and Incoherent All Input Directions Combined



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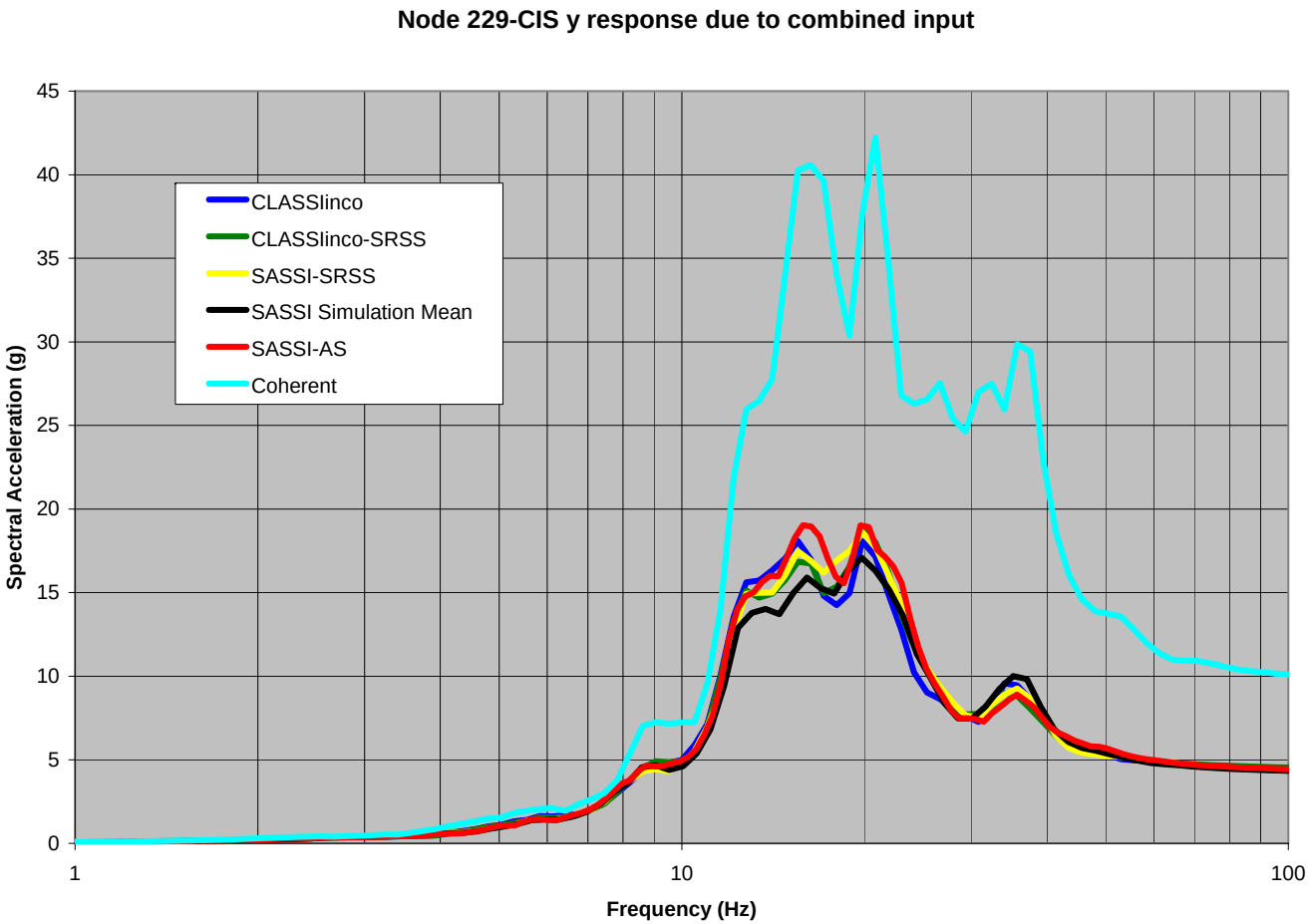
Top of CIS Outrigger (Node 229) - Y- Direction Coherent and Incoherent All Input Directions Combined



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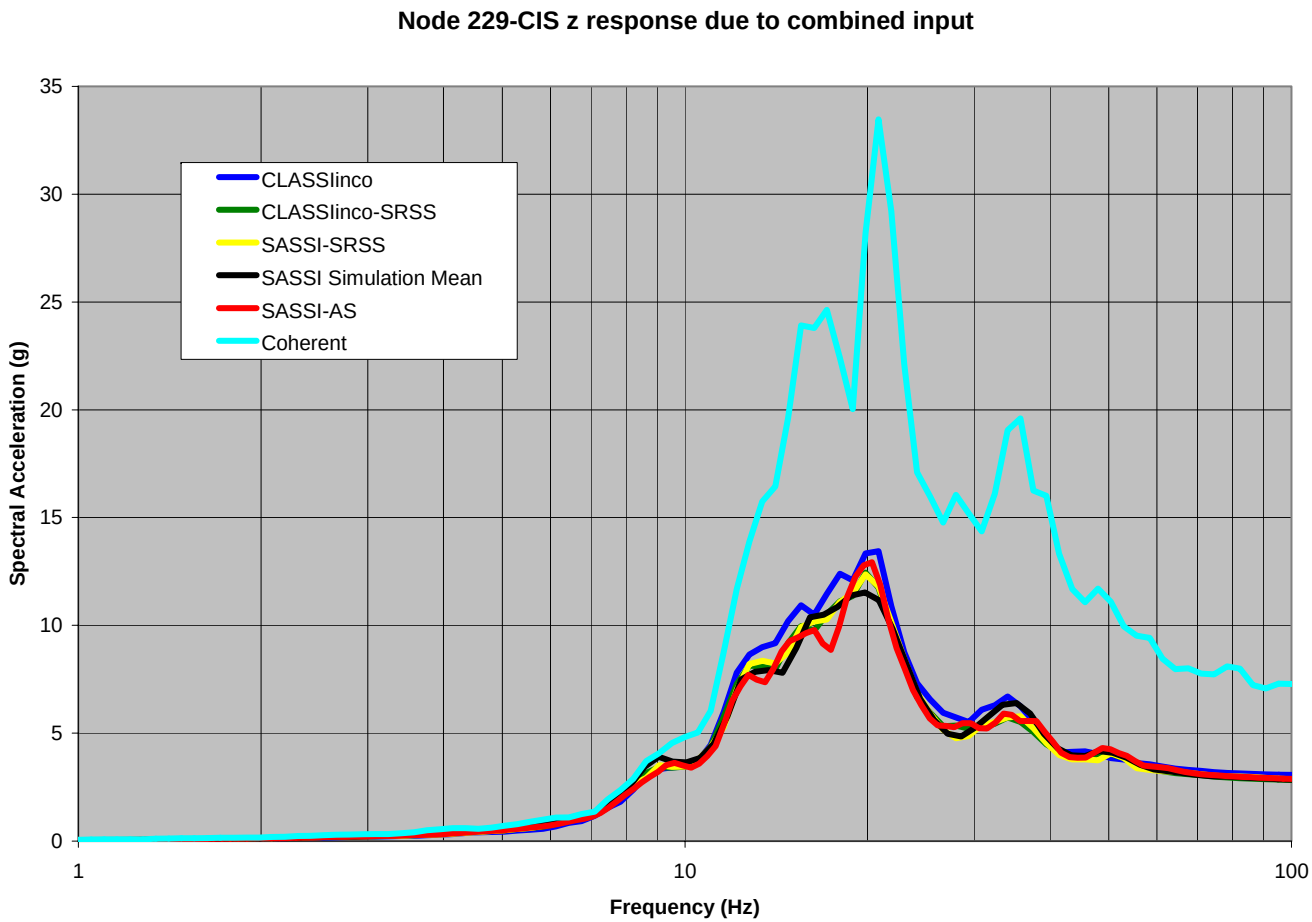
Top of CIS Outrigger (Node 229) - Z- Direction Coherent and Incoherent All Input Directions Combined



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Top of Steel Containment Vessel (SCV) – Centerline (Node 45) Outrigger (Node 145 – 65 ft.)

- Incoherent response significantly less than coherent response
  - Horizontal - frequencies greater than 12 Hz (less reductions at ZPA)
  - Vertical – very significant reductions for frequencies greater than 10 Hz
  - Outrigger reductions somewhat less than on centerline
- Responses calculated by all methods are in very good agreement – generally within 10%

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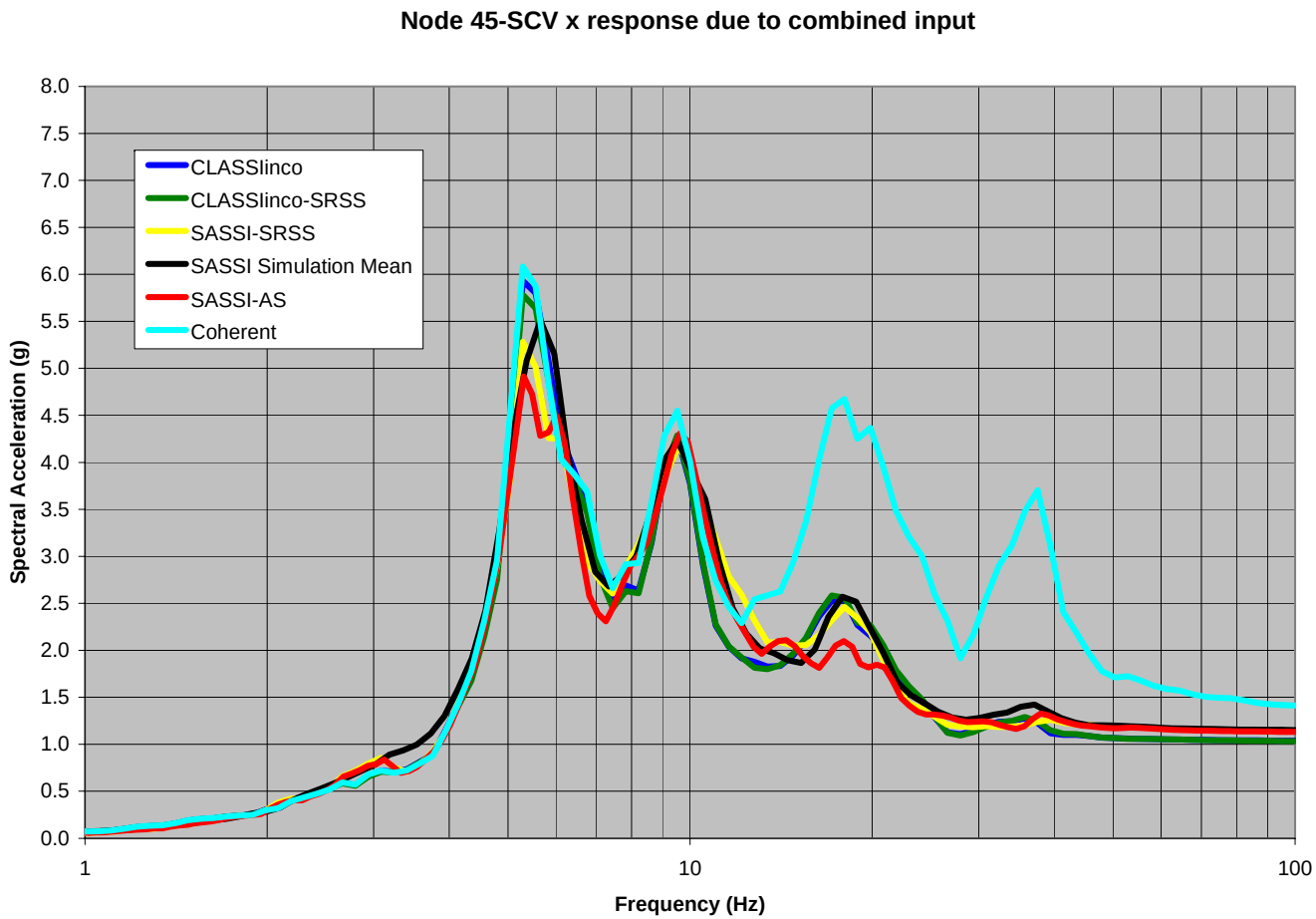
Top of SCV Centerline (Node 45) - X- Direction Coherent and Incoherent All Input Directions Combined



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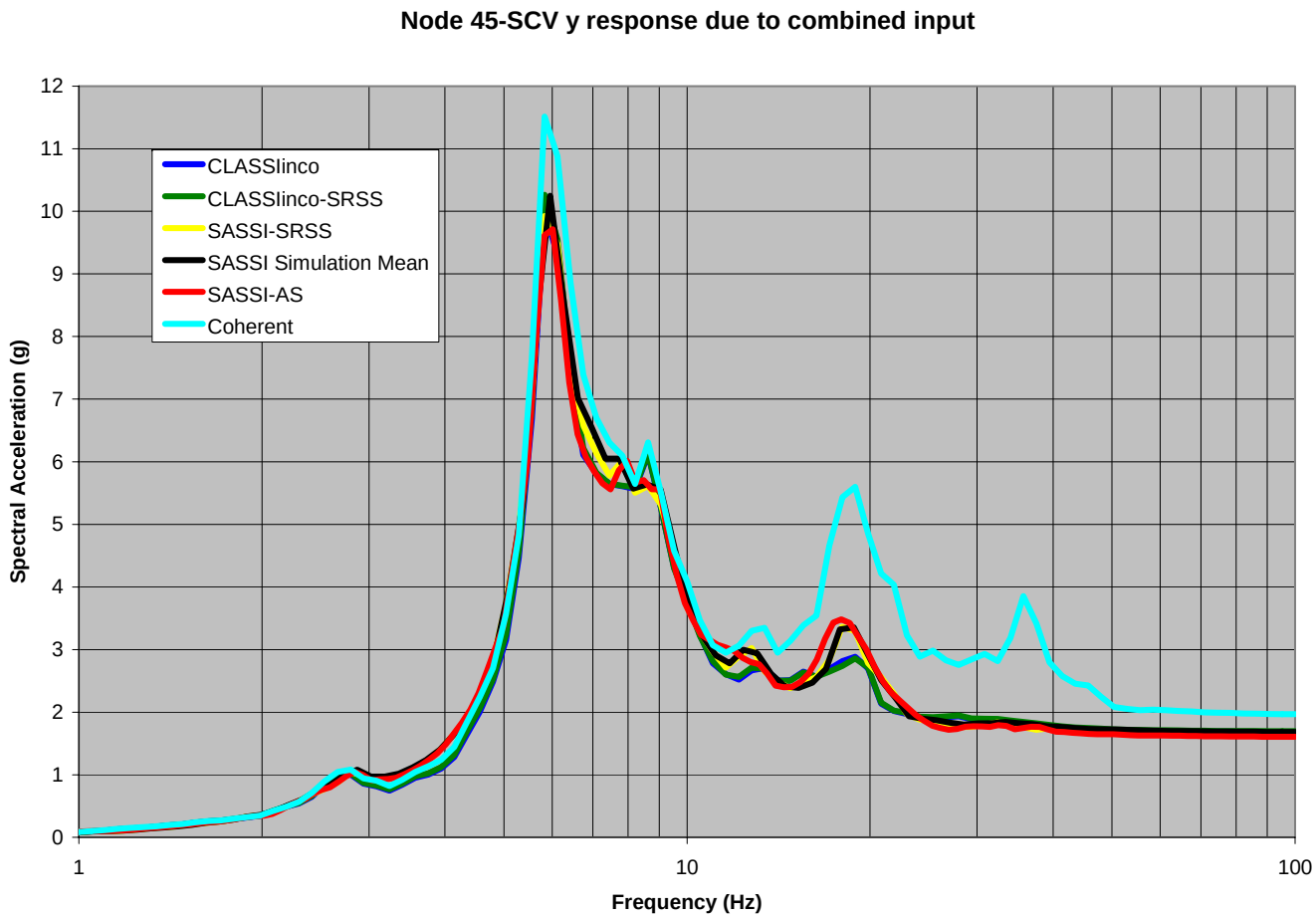
Top of SCV Centerline (Node 45) - Y- Direction Coherent and Incoherent All Input Directions Combined



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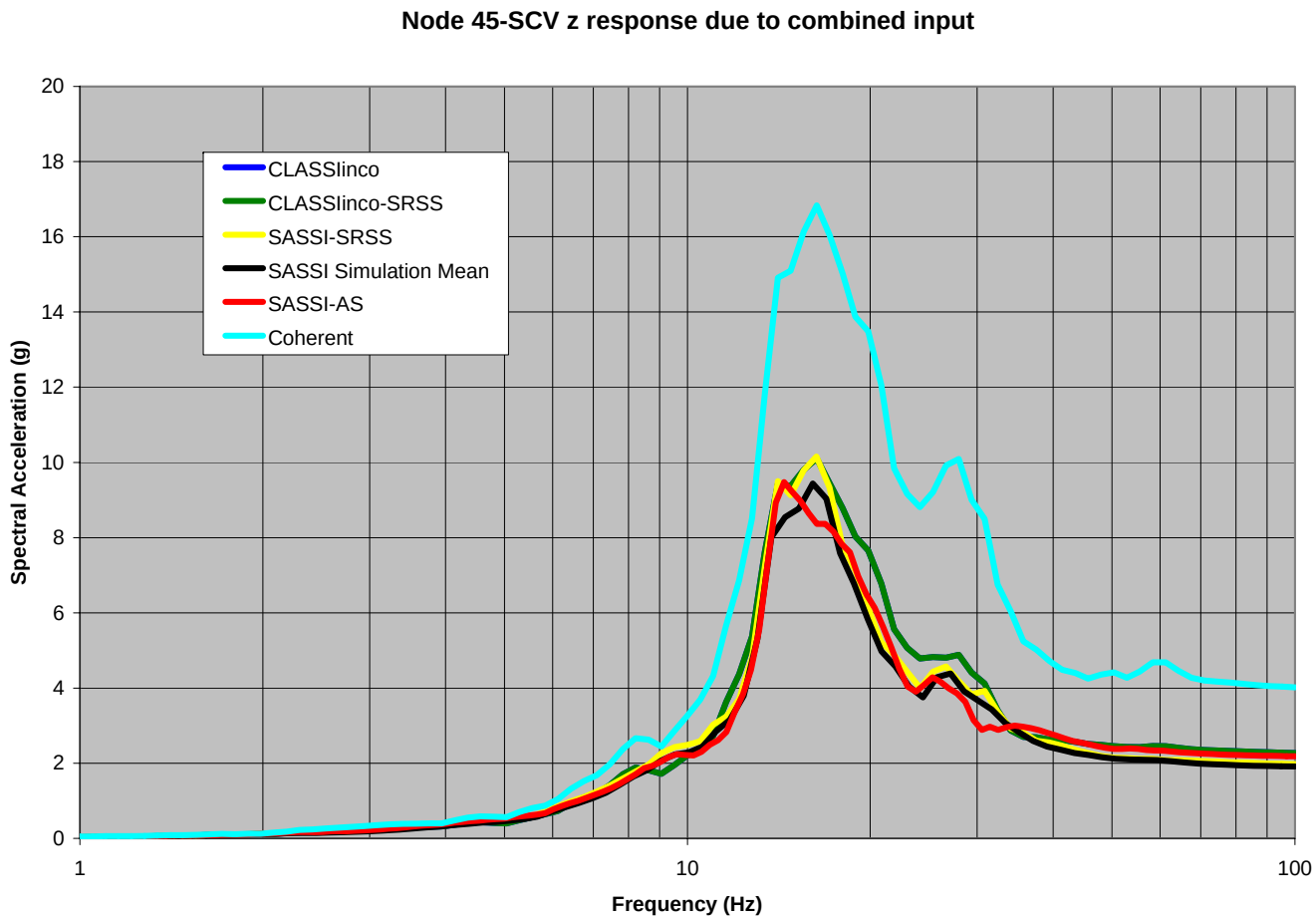
Top of SCV Centerline (Node 45) - Z- Direction Coherent and Incoherent All Input Directions Combined



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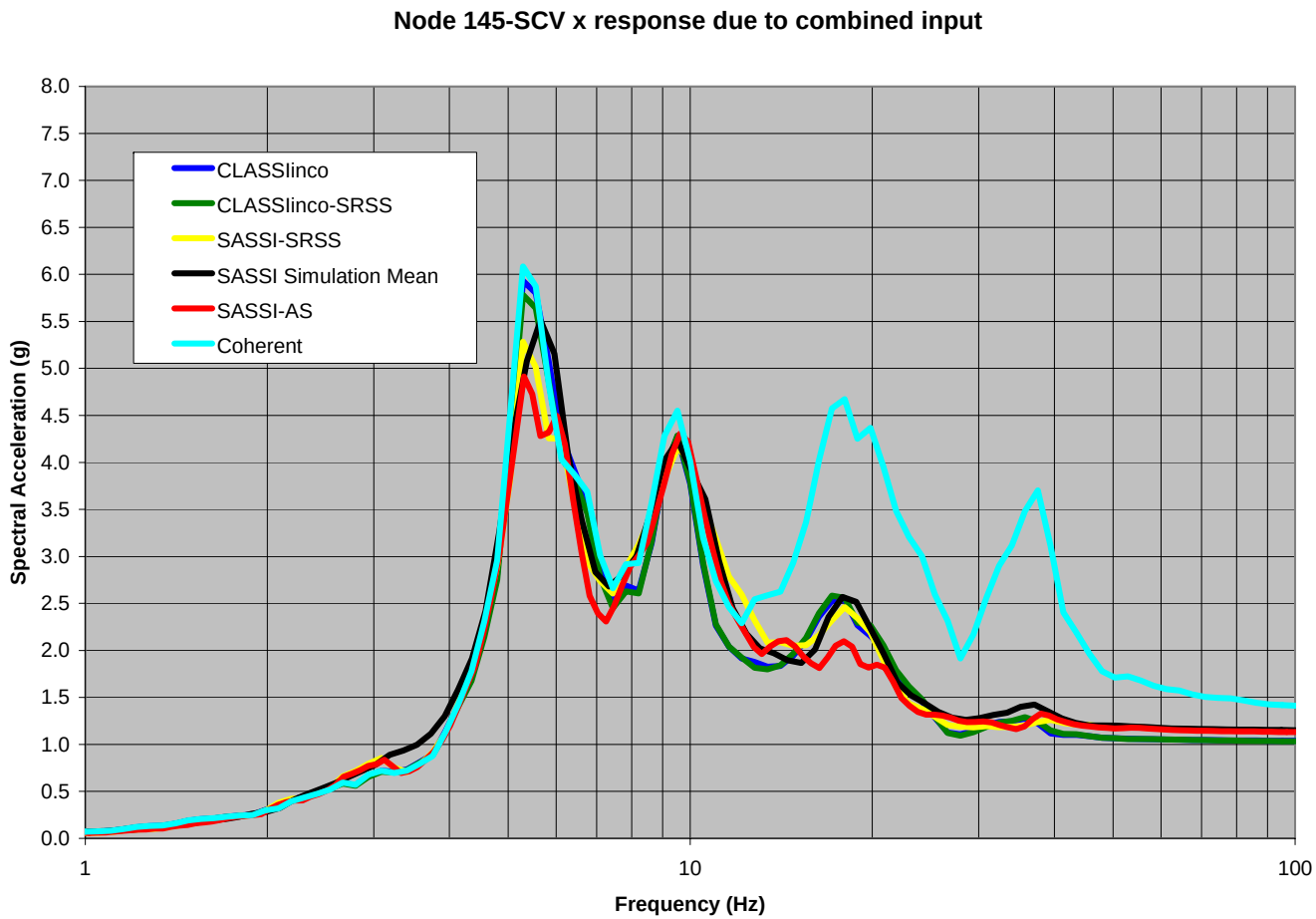
Top of SCV Centerline (Node 145) - X- Direction Coherent and Incoherent All Input Directions Combined



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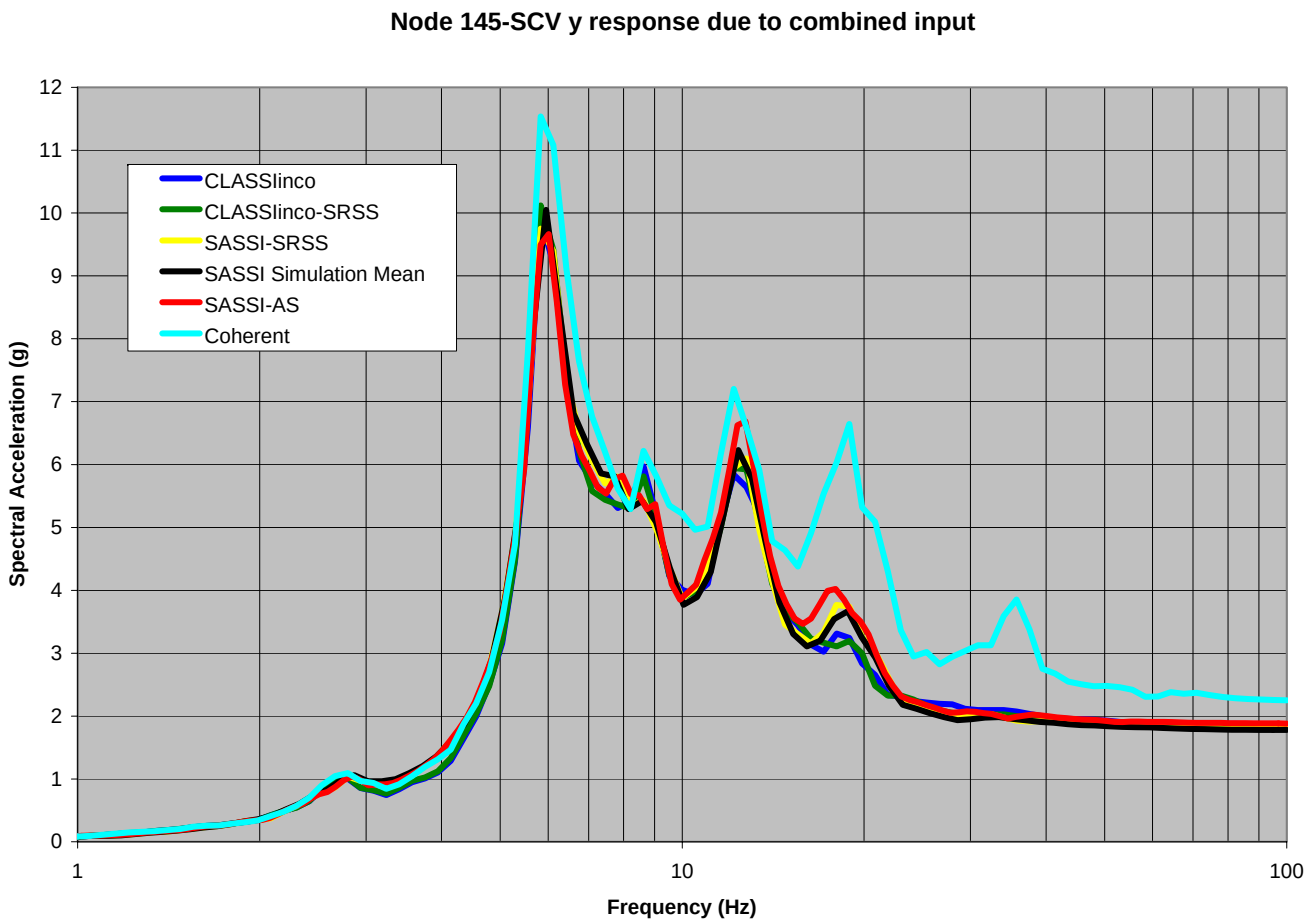
Top of SCV Centerline (Node 145) - Y- Direction Coherent and Incoherent All Input Directions Combined



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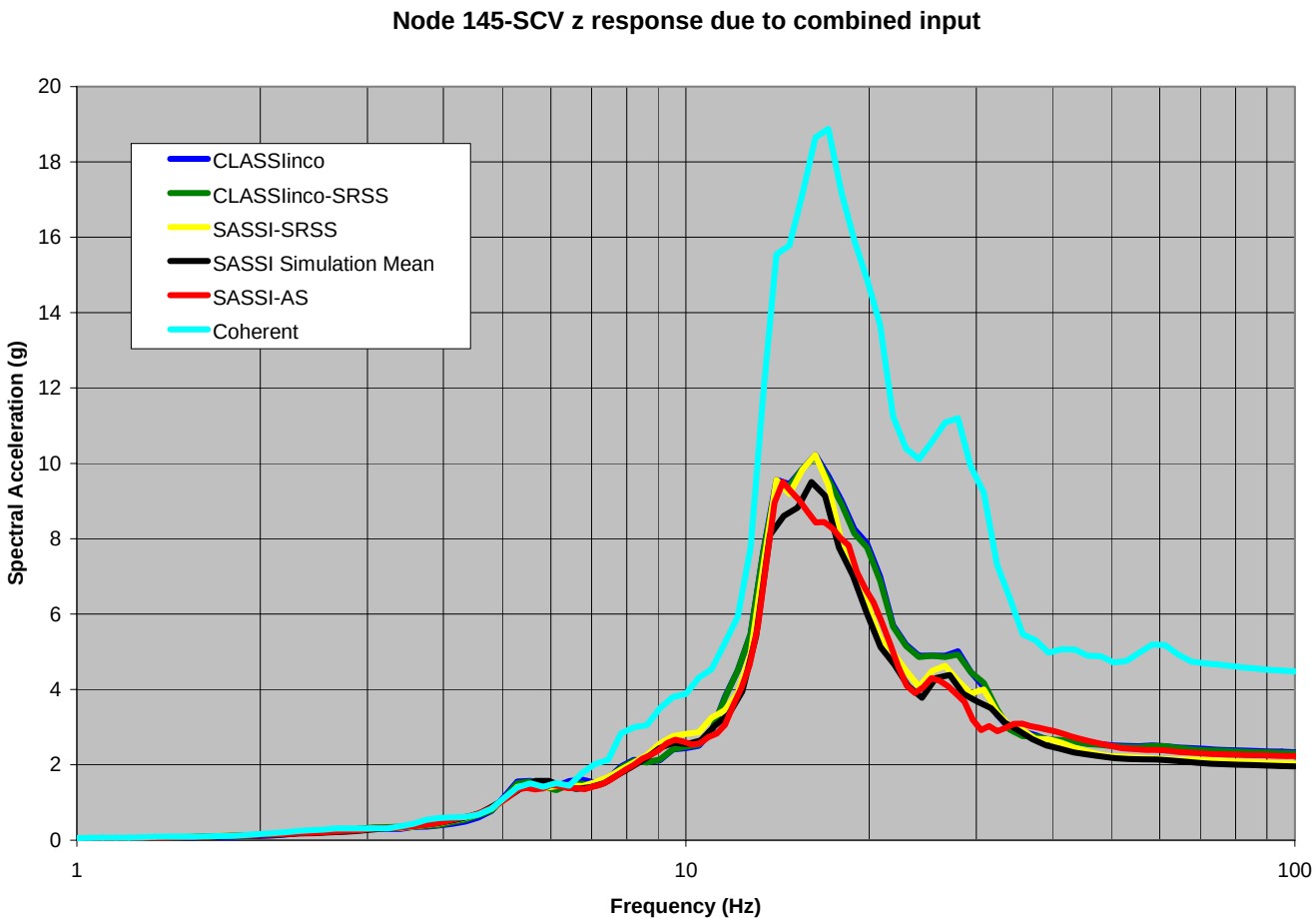
Top of SCV Centerline (Node 145) - Z - Direction Coherent and Incoherent All Input Directions Combined



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Considering individual excitation directions independently may show differences for CLASSIinco, SASSI-AS, and others in some cases (Appendix A)

- One example case is where phase relationships of induced rotations on the foundation are important
  - CIS Node 229Z due to Z

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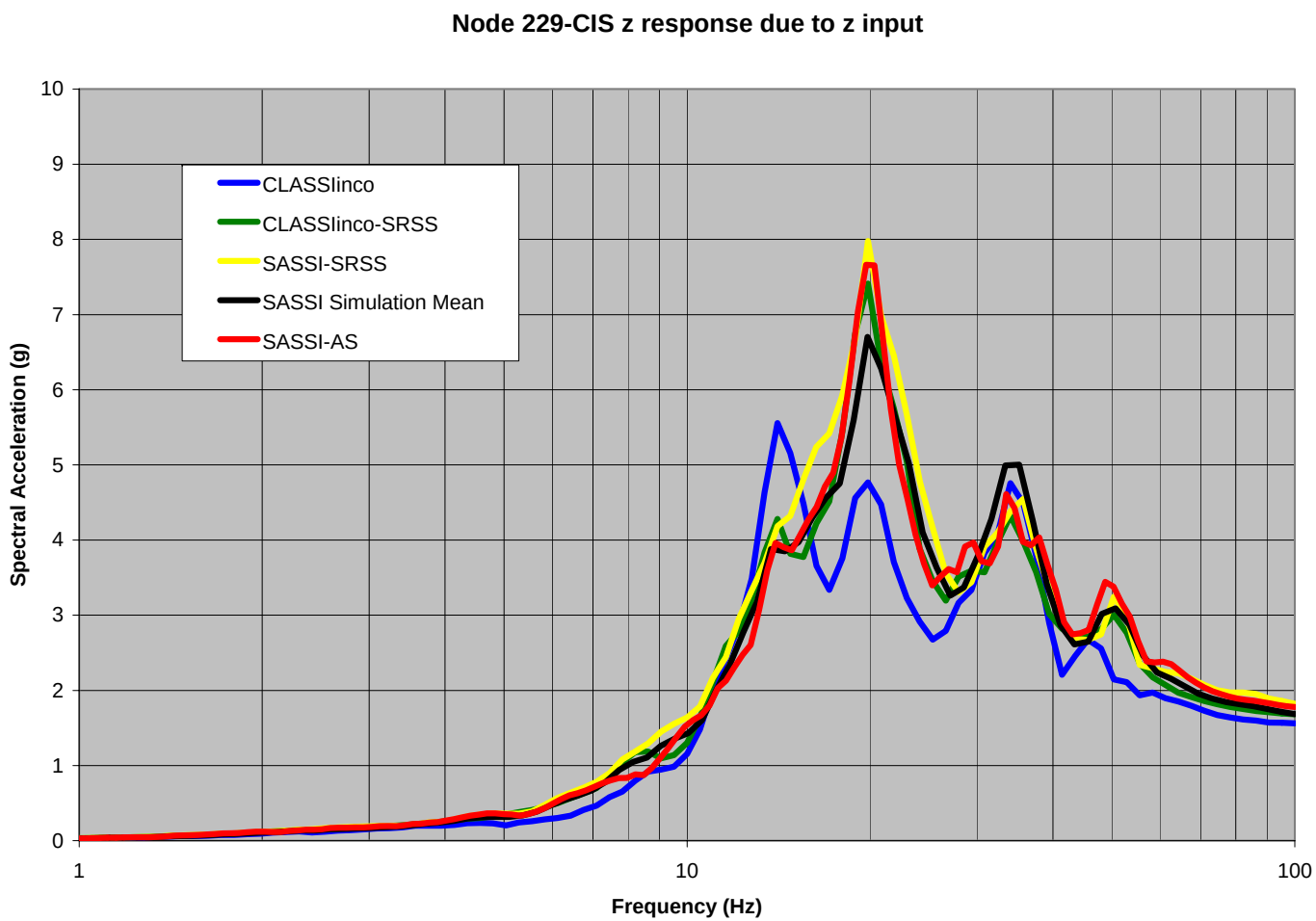
CLASSIinco differs from other Methods for CIS Outrigger (Node 229) Z response due to Z input (March and May meetings)



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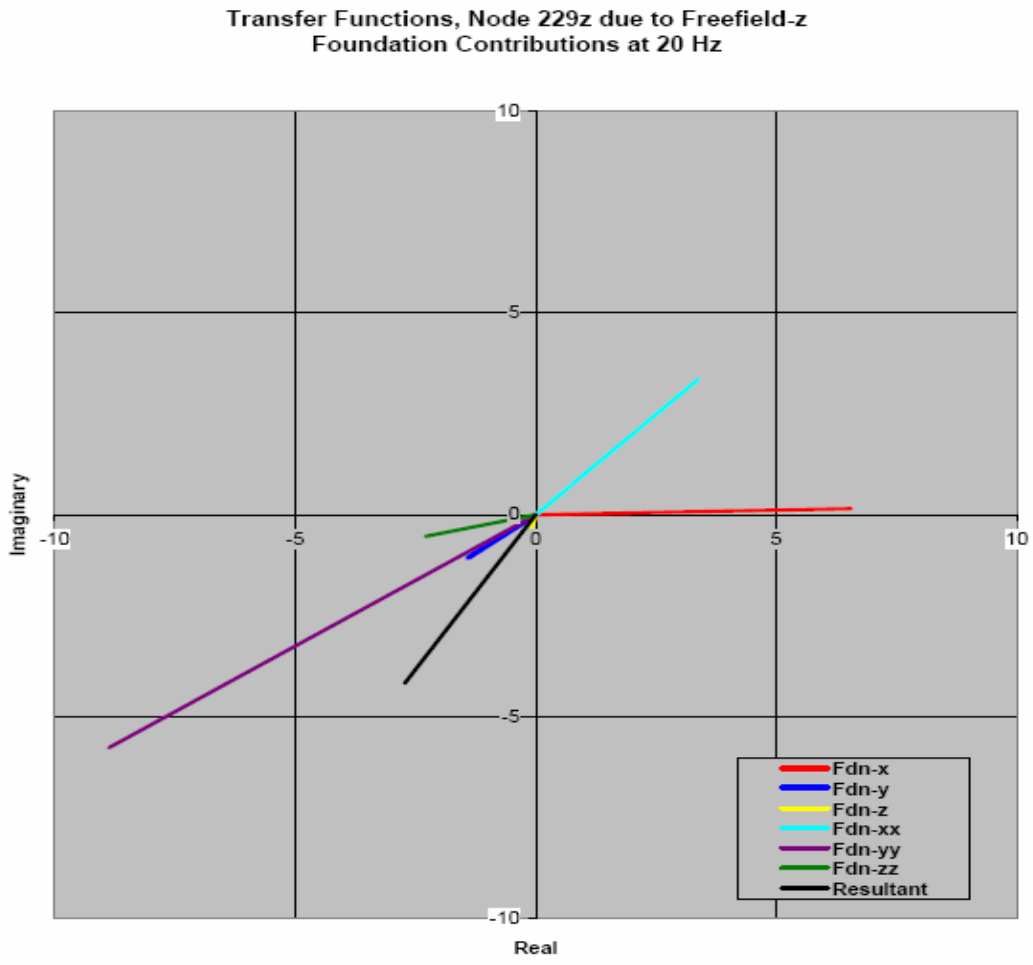
CIS Outrigger (Node 229Z due to Z) Transfer Function @ 20 Hz

- Structure transfer function (CLASSI) is composed of many foundation components of varying amplitude and phase
- The resultant transfer function @ 20 Hz includes significant addition and subtraction of 5 foundation components and the 6th component has a 10% effect



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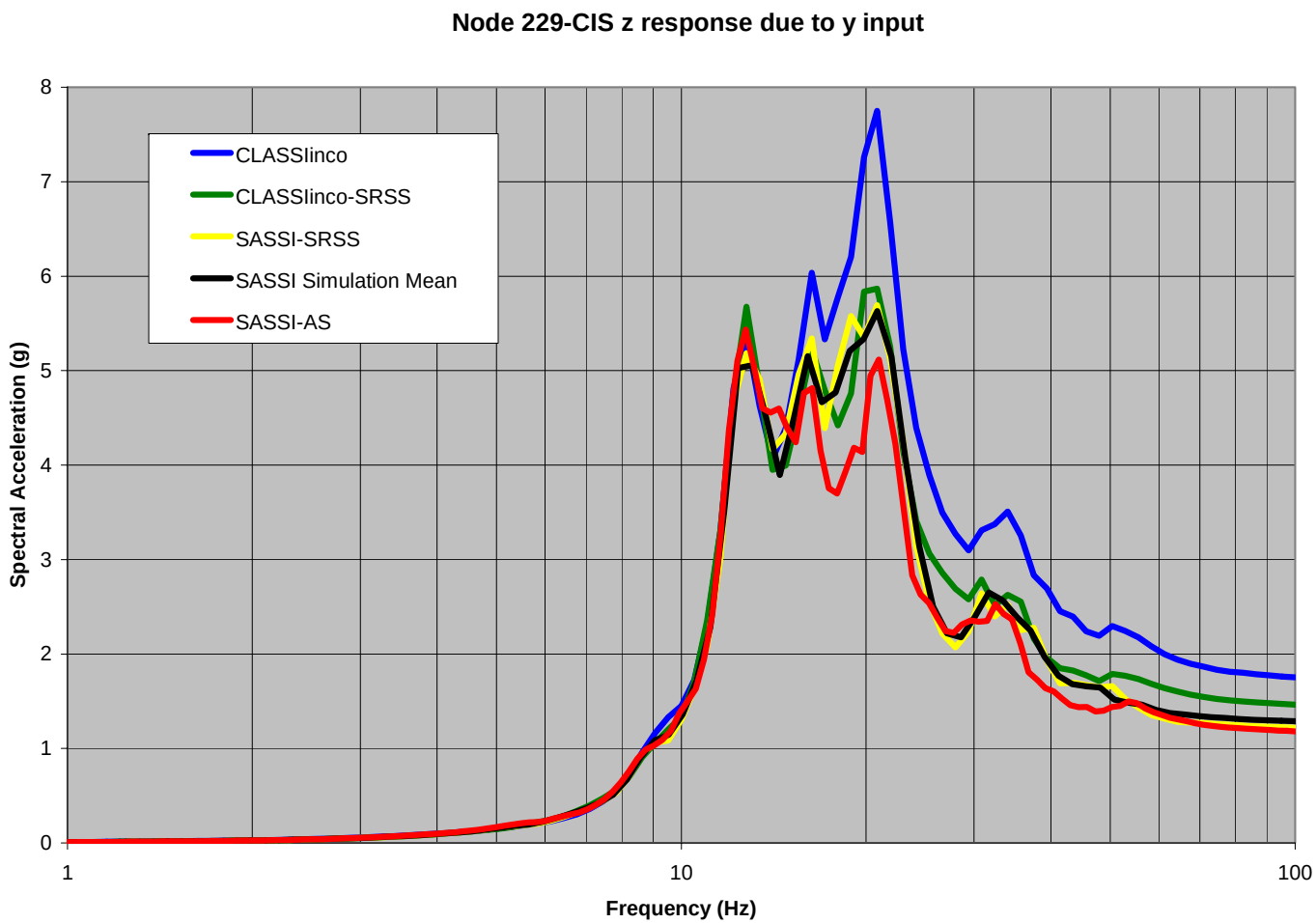
CLASSIinco differs from other Methods for CIS Outrigger (Node 229) Z response due to Y input



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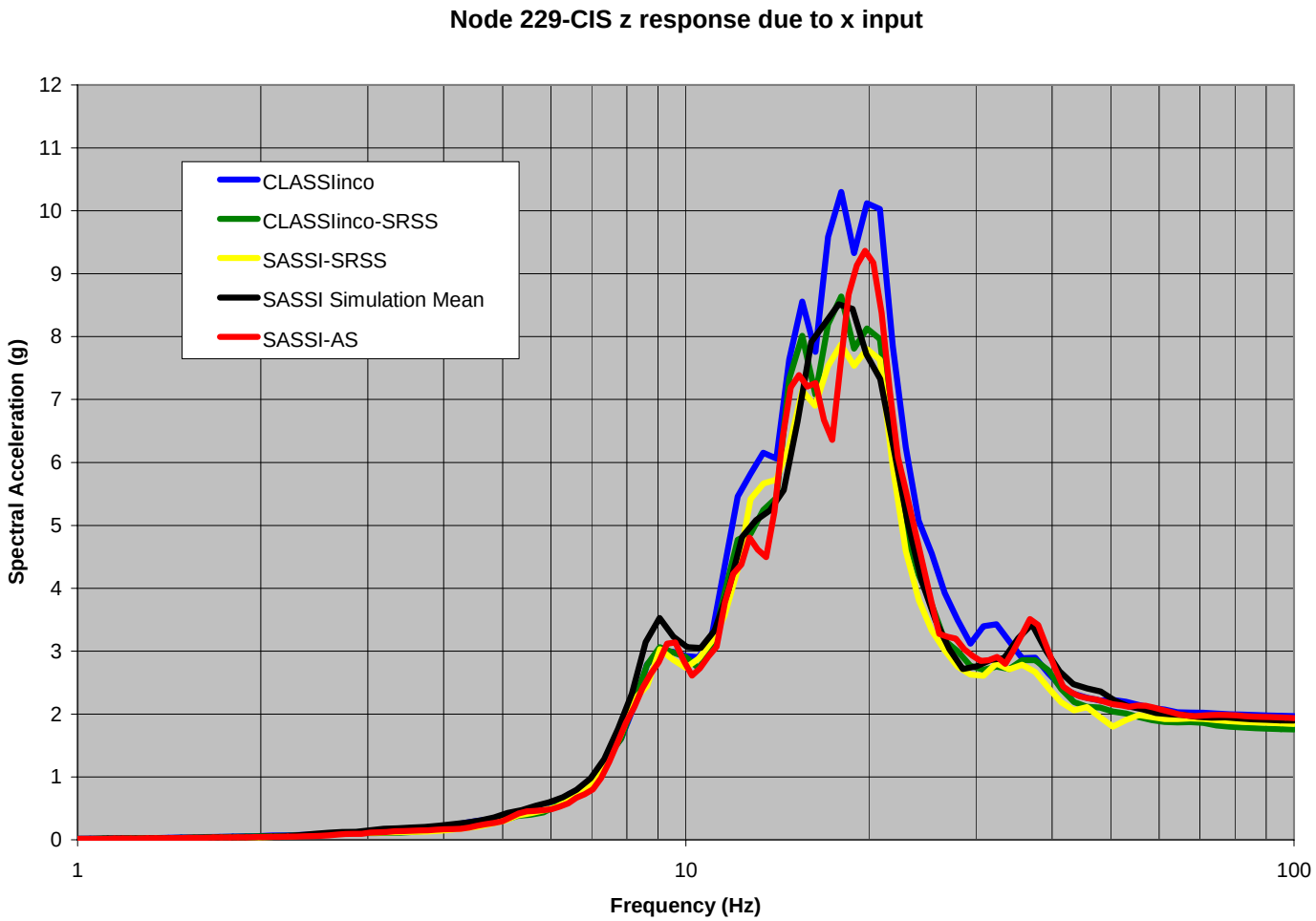
CLASSIinco differs from other Methods for CIS Outrigger (Node 229) Z response due to X input



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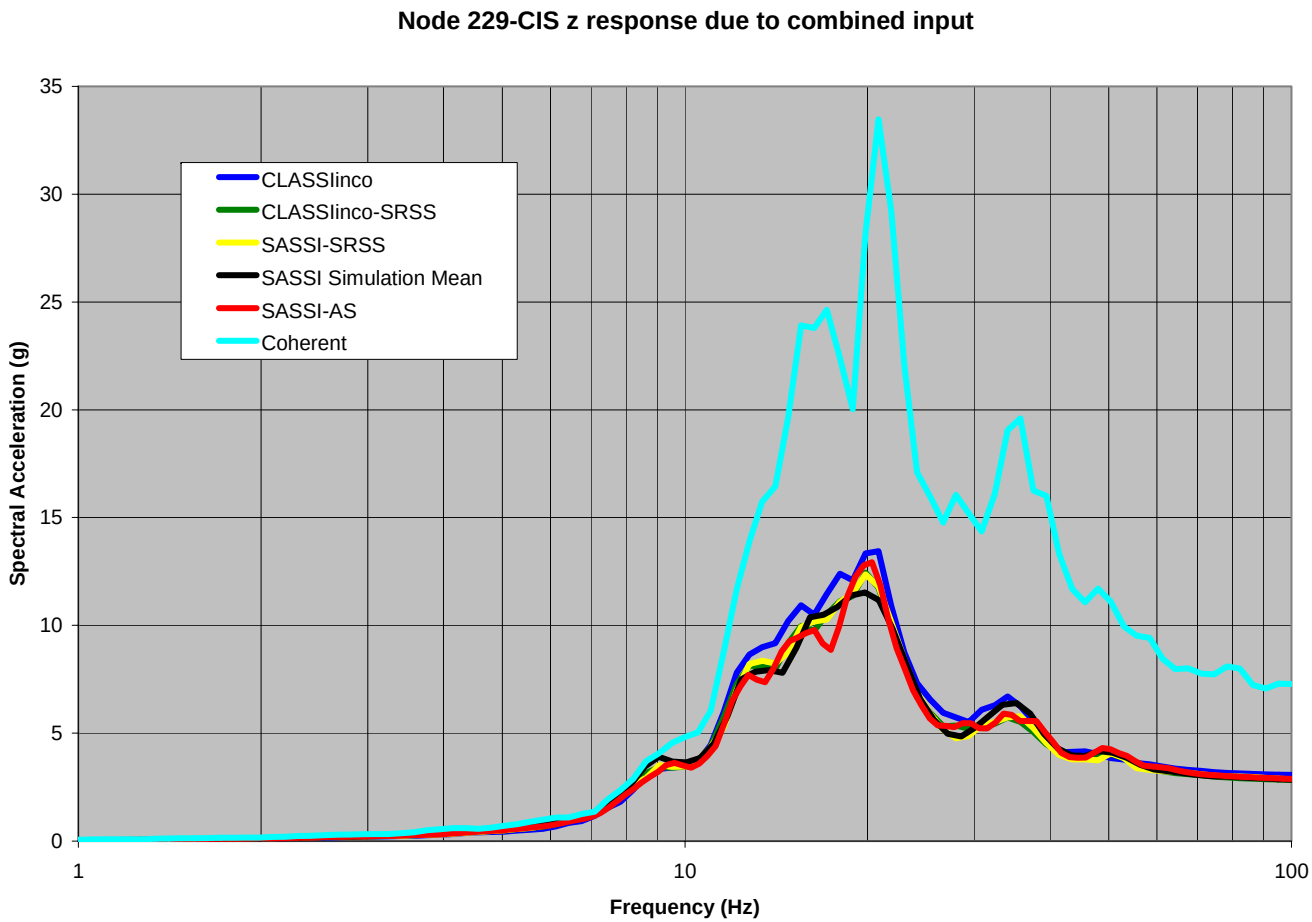
Top of CIS Outrigger (Node 229) - Z- Direction Coherent and Incoherent All Input Directions Combined



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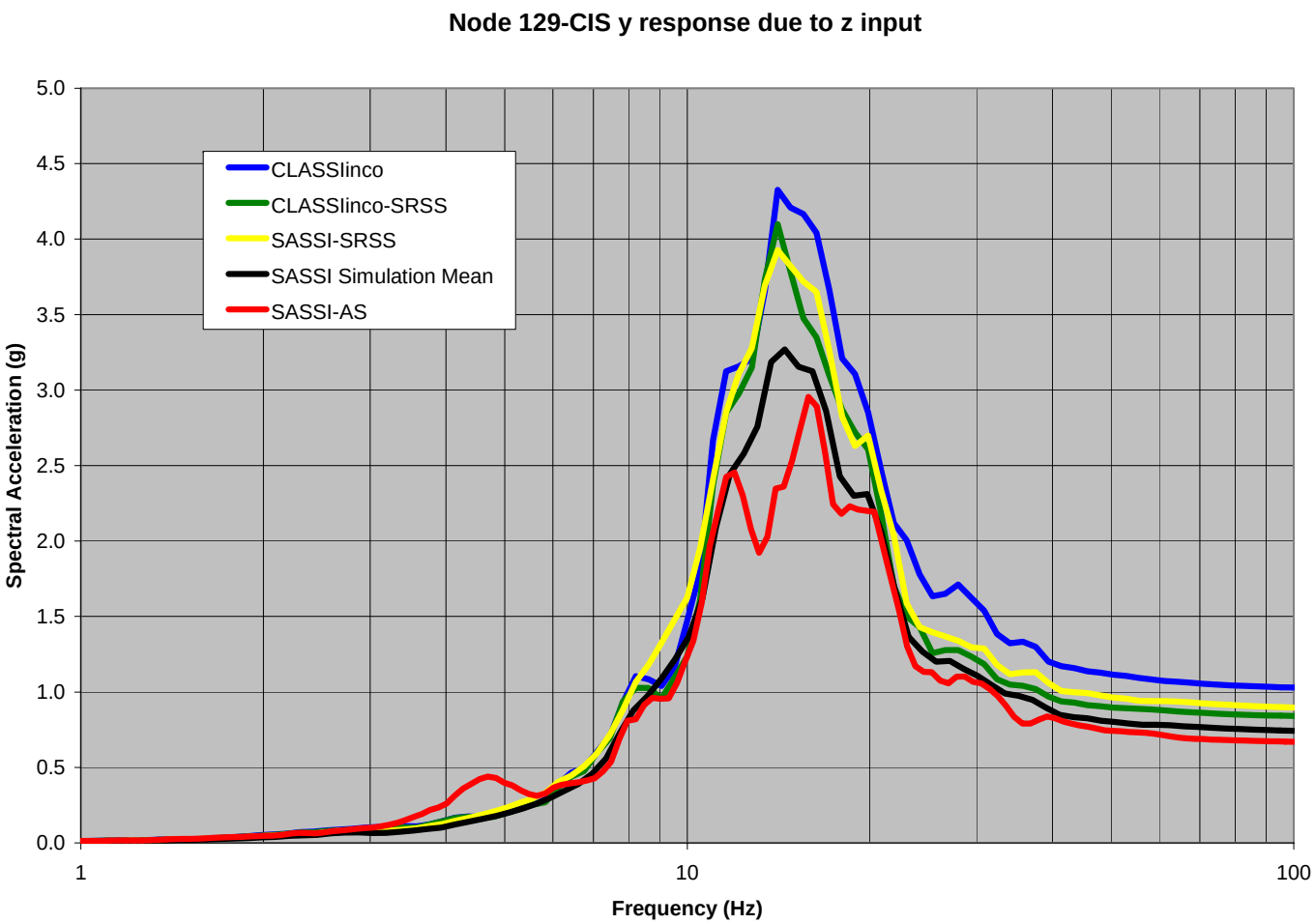
CLASSI-SRSS and SASSI-SRSS agree closely – others differ for Top of CIS Mass Center (Node 129) Y response due to Z input



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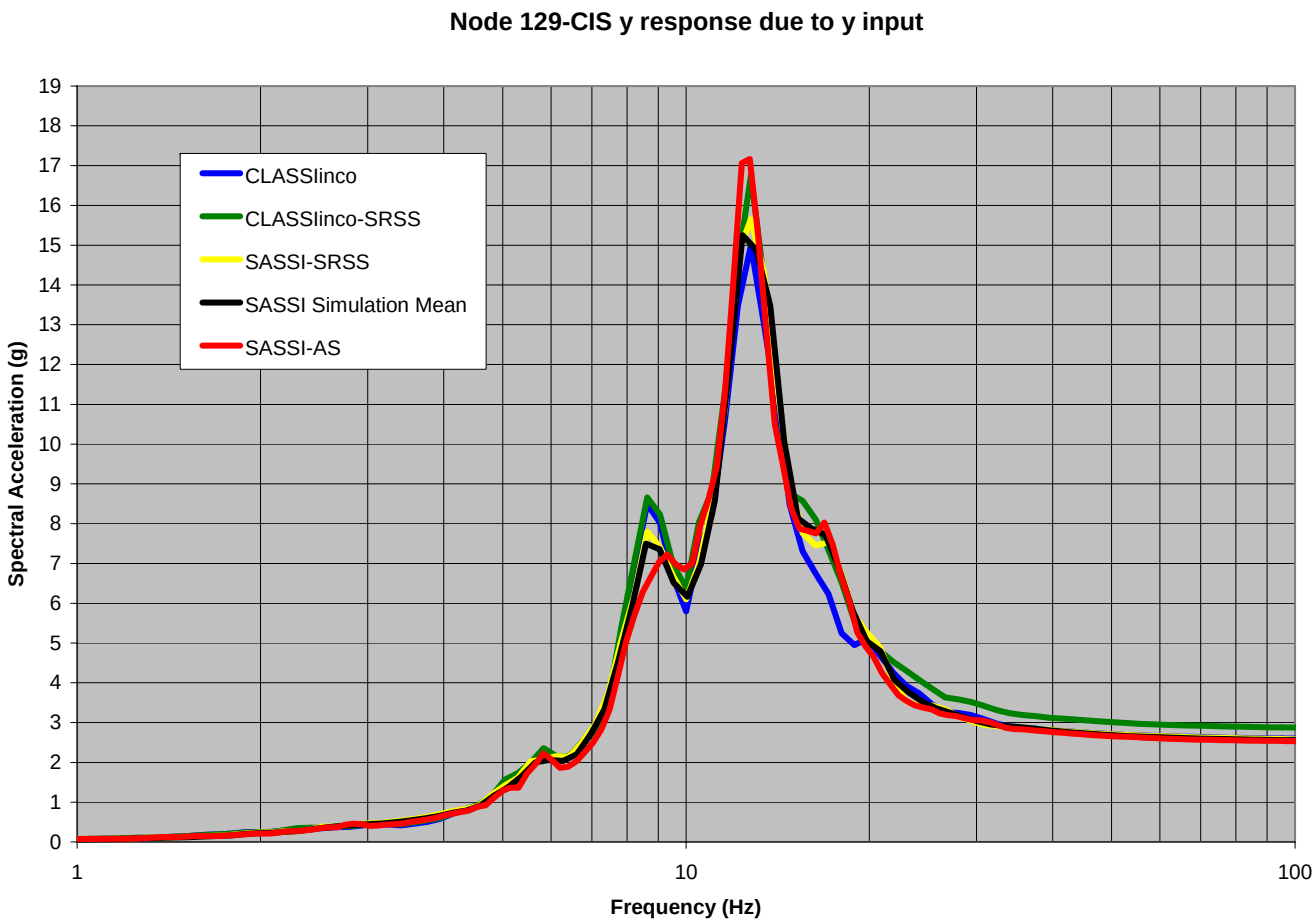
All Methods Compare Well for Top of CIS Mass Center (Node 129) Y response due to Y input



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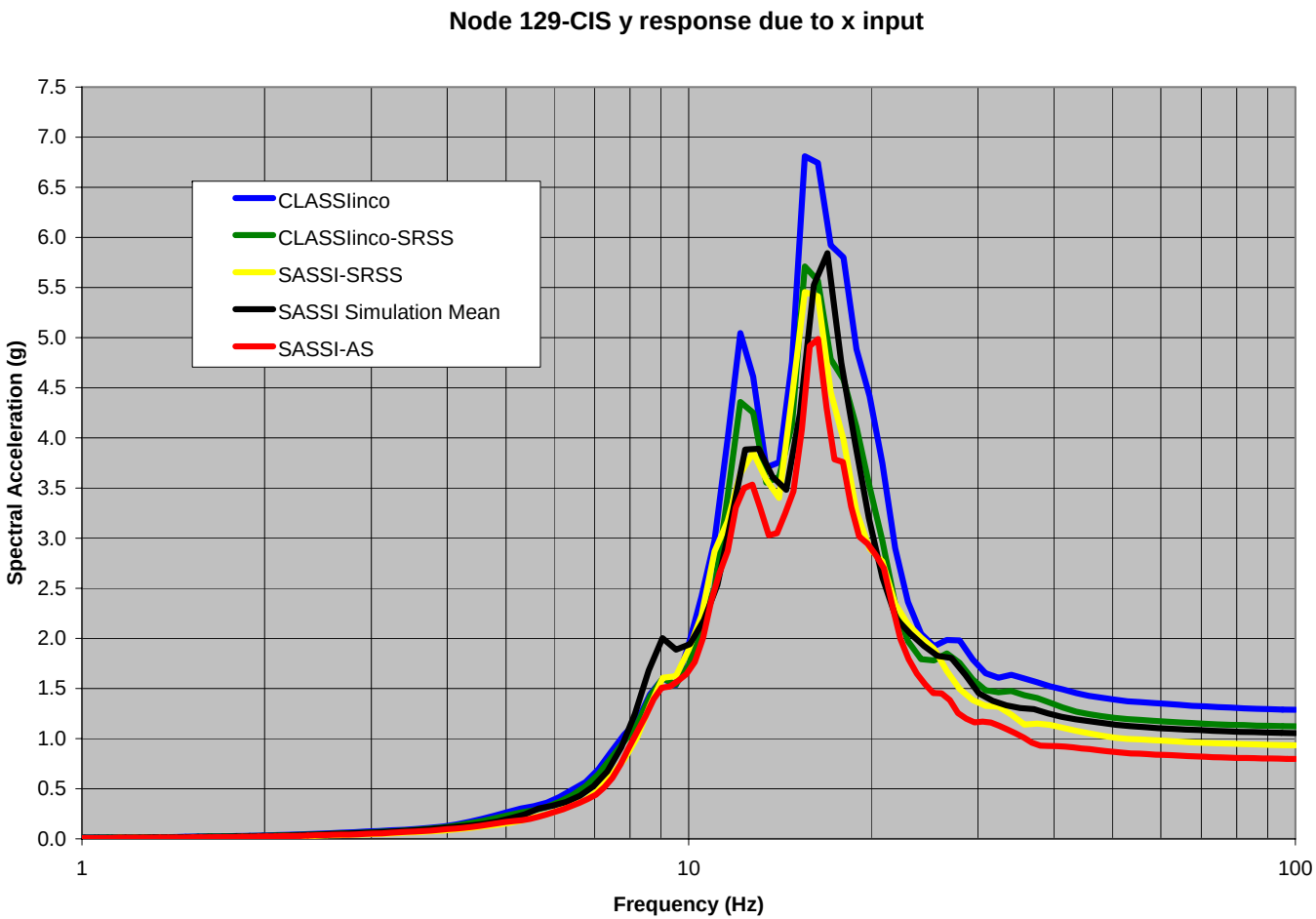
All Methods differ somewhat for Top of CIS Mass Center (Node 129) Y response due to X input



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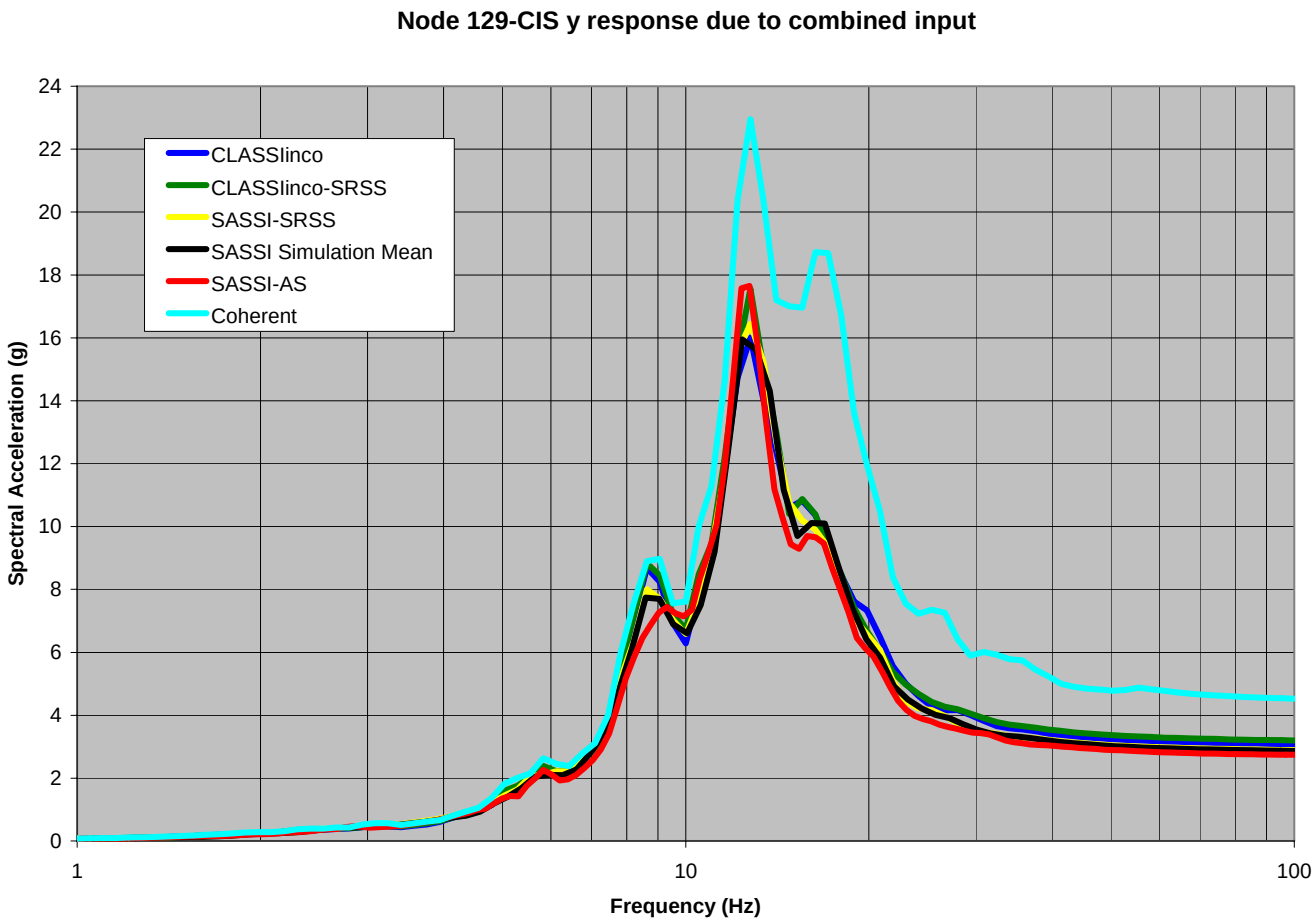
Top of CIS Offset Mass (Node 129) - Y- Direction Coherent and Incoherent All Input Directions Combined



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Guidelines for application of CLASSI and SASSI to seismic wave incoherence analysis of nuclear power plant structures

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CLASSIinco Analysis Steps

- GLAY (same as for coherent analysis)
- CLANINCO (creates input file for CLAN6; otherwise same as for coherent analysis)
- CLAN6 (new module for incoherence)
- Replace IMPFN with an incoherent IMPFN created by CLAN6 as input to SSIN
- SAP (same as for coherent analysis)
- INSSIN (same as for coherent analysis)
- SSIN (same as for coherent analysis)

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CLASSIinco-SRSS Analysis Steps

- GLAY (same as for coherent analysis)
- CLANINCO (creates input file for CLAN6; otherwise same as for coherent analysis)
- CLAN6-SRSS (new module for incoherence)
- Replace IMPFN with incoherent IMPFNs created by CLAN6 as input to SSIN. Six IMPFN files are created for each foundation degree of freedom, 3 translations and 3 rotations.
- SAP (same as for coherent analysis)
- INSSIN (same as for coherent analysis)
- SSIN (same as for coherent analysis, except that six SSIN runs are performed for each of the six IMPFN files)
- Generate six response spectra for each of the foundation degrees of freedom and combine by SRSS to obtain the in-structure response spectra for incoherent motion.

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SASSI-Simulation Analysis Considerations

- Selection of coherency function (1 through 5)
- Specification of the number of spatial modes
- Specification of random seeds and range for spatial mode phasing
- Selection of transfer function smoothing parameter
- Decide on number of simulations
- Compute the mean of the response quantities of interest

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SASSI-AS Analysis Considerations

- Selection of coherency function (1 through 5)
- Specification of the number of spatial modes
- Choice of deterministic spatial mode phasing
- Selection of transfer function smoothing parameter

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SASSI-SRSS Analysis

Addressed by Ostadan & Deng, 2007

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Conclusions: Importance of SSI

- SSI analysis important for structures on rock sites subjected to high frequency ground motion
- There is as much reduction in high frequency response from SSI on a rock site with high frequency input motion as there is from incoherence

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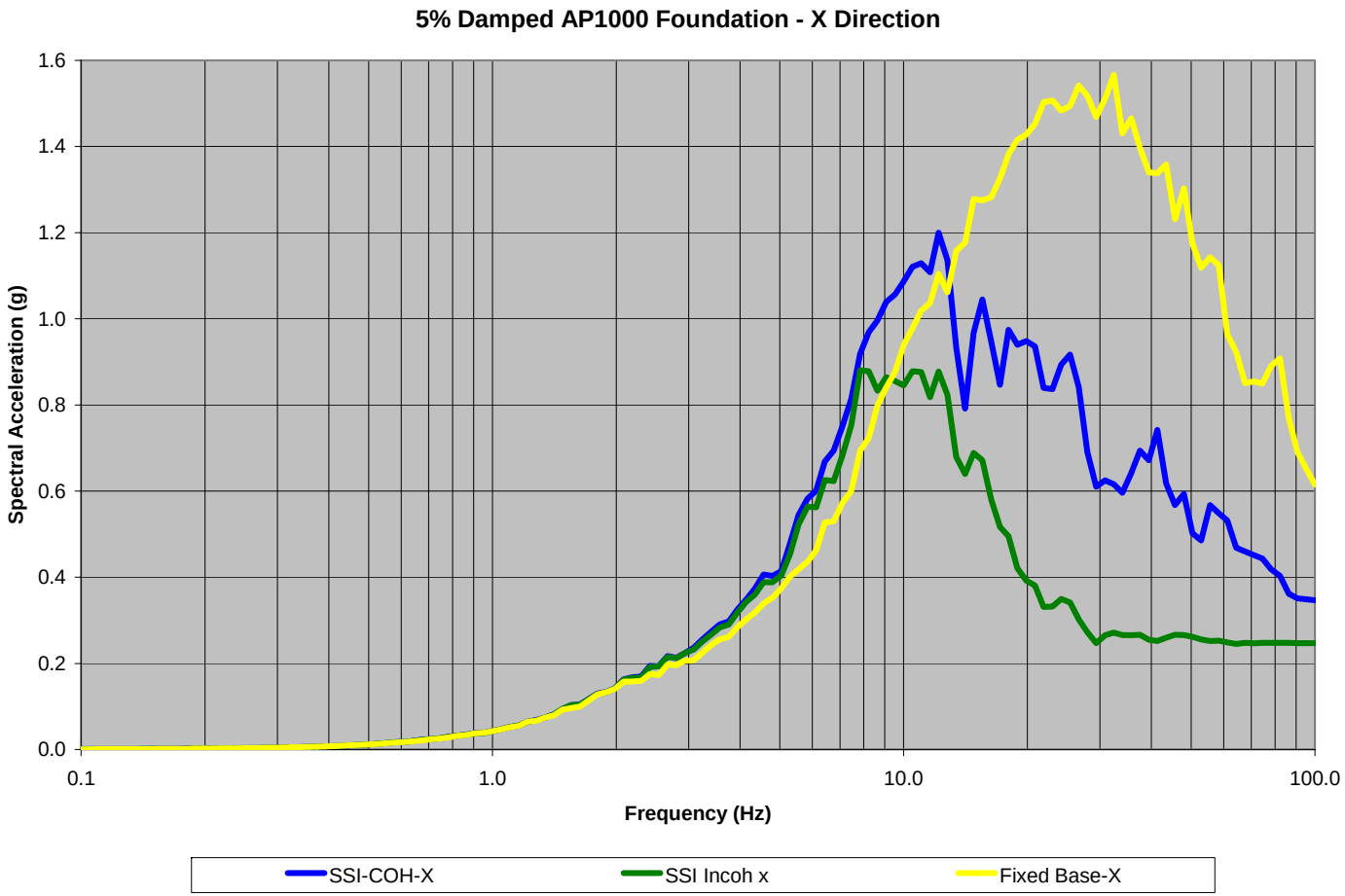
Importance of SSI – Foundation Response



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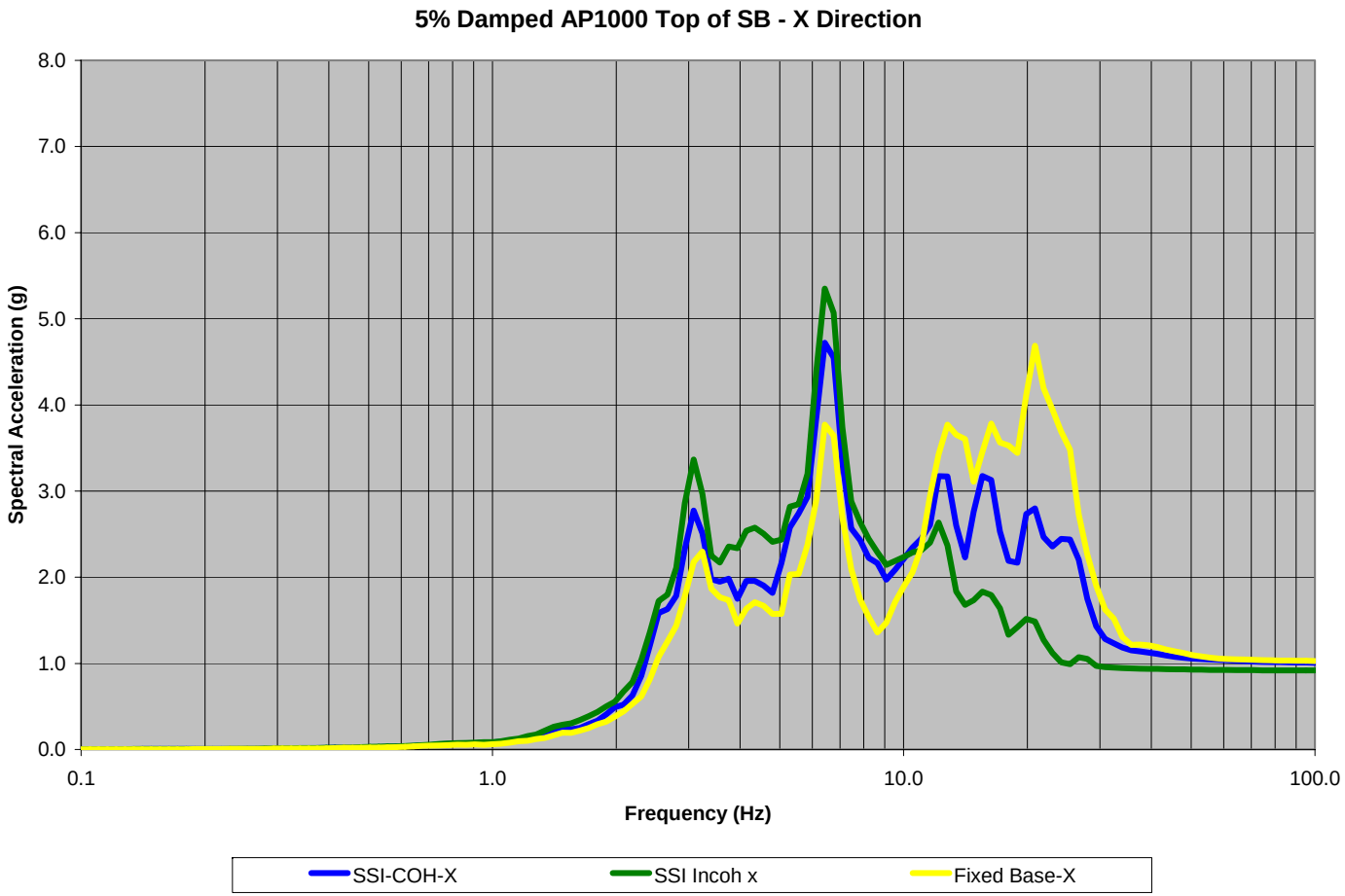
Importance of SSI – Shield Building Response



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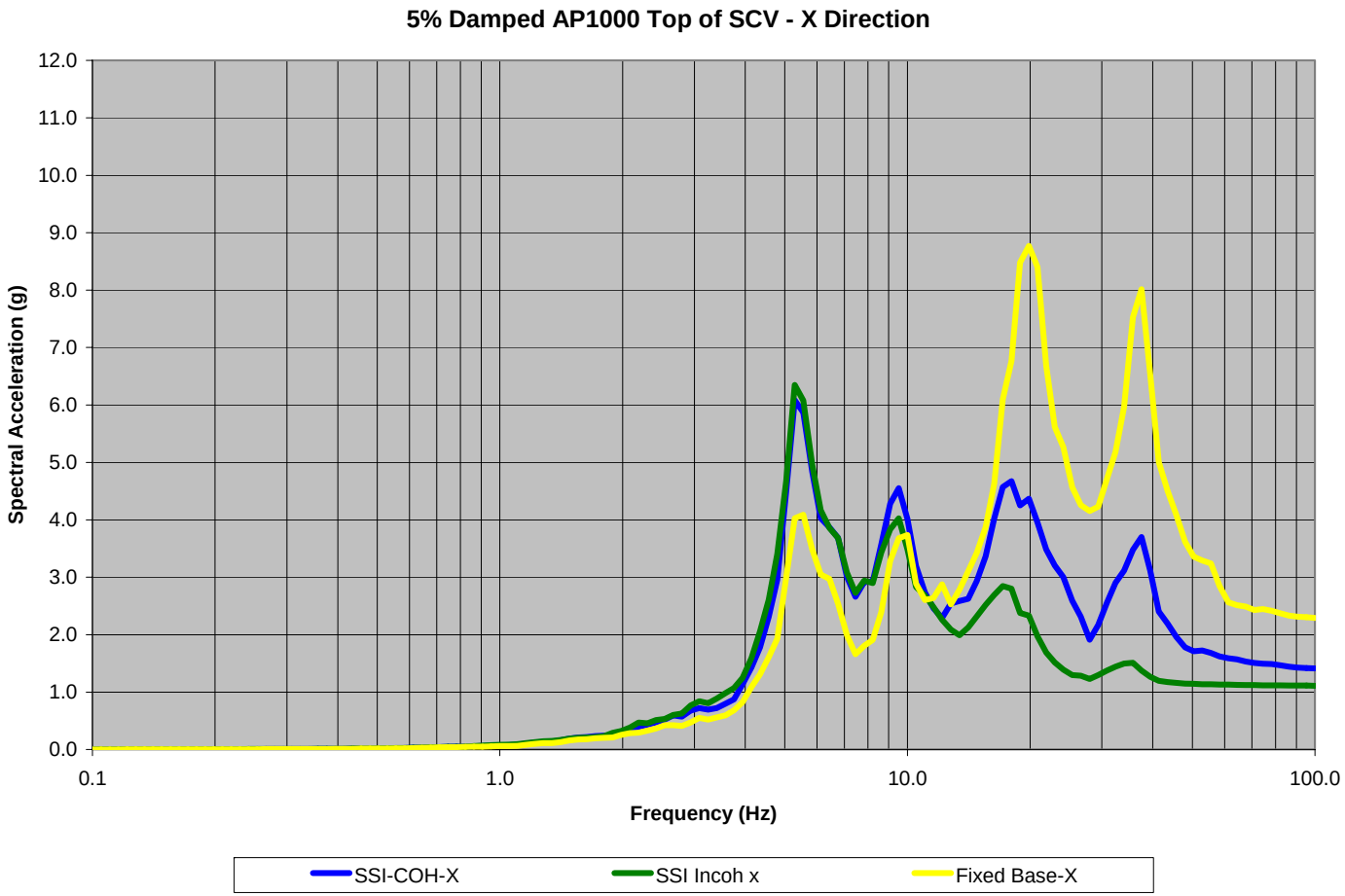
Importance of SSI – Steel Containment Vessel Response



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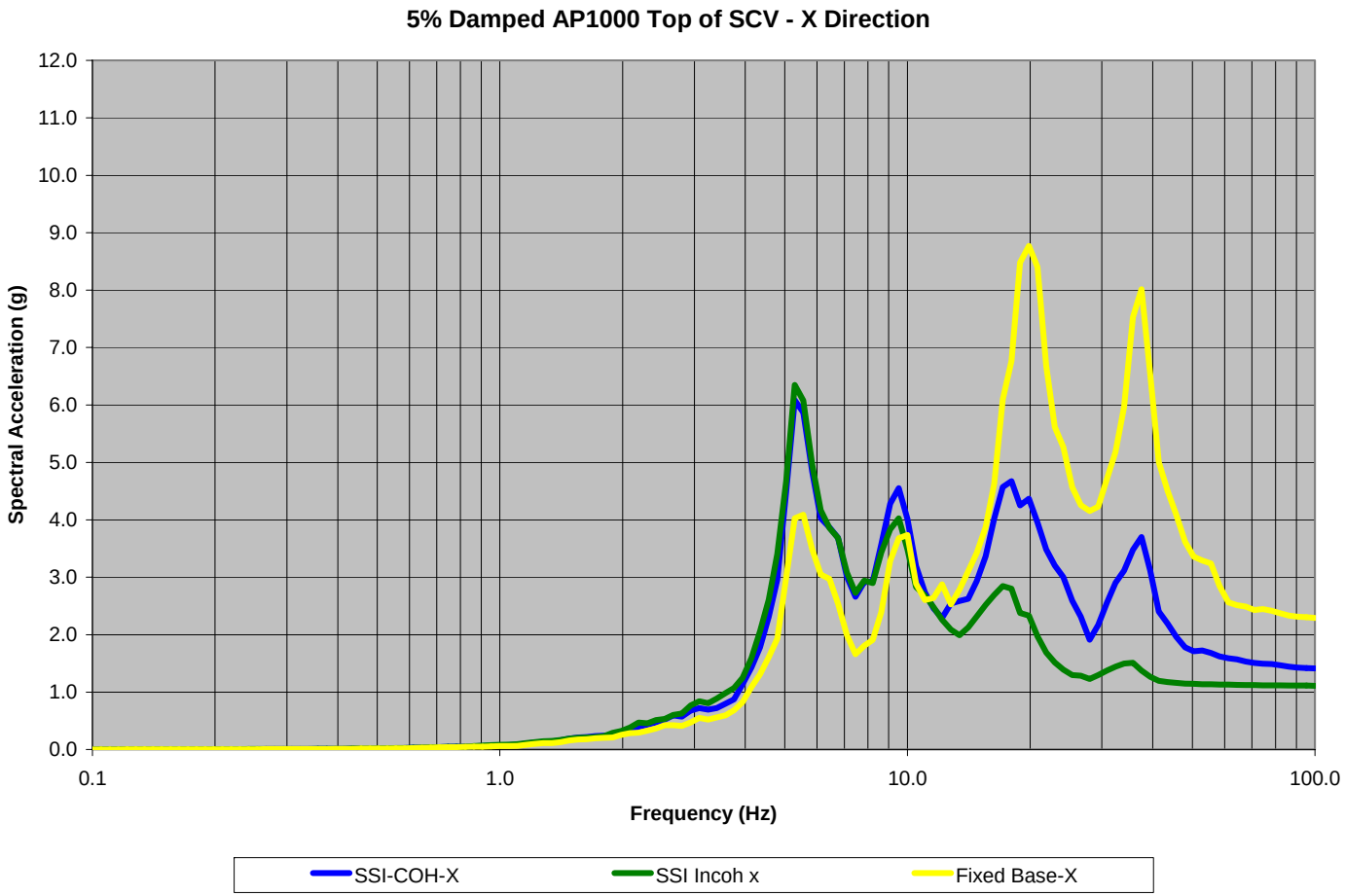
Importance of SSI –Containment Internal Structure Response



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Conclusions: Application of SSI Programs

- CLASSIinco and CLASSIinco-SRSS
  - Computationally efficient
  - Currently limited to rigid surface foundations
- SASSI is required for structures
  - Foundation, including the stiffening effects of the foundation/structure system, deemed to behave flexibly
  - Embedded foundation/partial structure
- SASSI-AS requires computational effort comparable to standard SASSI analyses
- SASSI-Simulation and SASSI-SRSS require significantly greater computational effort to standard SASSI analyses for incoherent analysis of complex structure models

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Conclusions: Validation

- CLASSIinco-SRSS, SASSI-SRSS, and SASSI-Simulation, have been fully validated to treat the phenomena of incoherency for nuclear power plant structures applied in the design/qualification process
  - Published literature
  - Seismic response comparisons for example rock/structure model
- CLASSIinco-SRSS, SASSI-SRSS, and SASSI-Simulation most theoretically correct due to treatment of random nature of the phase of the incoherent SSI response

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Conclusions: Validation (cont.)

- CLASSIinco and SASSI-AS have been shown to be acceptable based on comparisons to other methods for response to combined excitations (i.e., Chapter 5)
- CLASSIinco and SASSI-AS deviate from other methods for some instances where single excitation direction was considered (i.e., Appendix A)
- CLASSIinco and SASSI-AS are acceptable for foundation/structure systems demonstrated to have minimal induced rotation effects
- CLASSIinco and SASSI-AS may be used if their applicability can be demonstrated by sensitivity studies

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Next Steps

- Industry Actions
  - Complete and issue report on validation and guidelines (27 July to NEI)
- NRC Action
  - Reach closure
  - Concurrence that CLASSI and SASSI can be used to evaluate seismic response to incoherent ground motion

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Discussion

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Back-Up

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CLASSI-SASSI Methodologies

- CLASSIinco
  - Deterministic phasing
- CLASSIinco-SRSS
  - Structure response to each foundation input motion combined by SRSS
- SASSI-Simulation (Randomization)
  - Spatial modes assigned random phasing
  - Mean of structural response to spatial modes computed
- SASSI-SRSS
  - Structural responses to each spatial mode are combined by SRSS
- SASSI-AS
  - Linear combination (algebraic sum) of spatial modes used to compute structural response

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Coherency Matrix Gamma [$\gamma(\omega)$]

- CLASSI and SASSI – foundation footprint divided into sub-regions
  - CLASSI – centroids of the sub-regions
  - SASSI – interaction nodes
- Gamma [$\gamma(\omega)$]
  - 3N x 3N where N is the number of sub-regions or interaction nodes (3 is three directions of free-field motion)
  - If centroids of sub-regions (C) coincide with locations of interaction nodes (S) - [$\gamma(\omega)$] is identical

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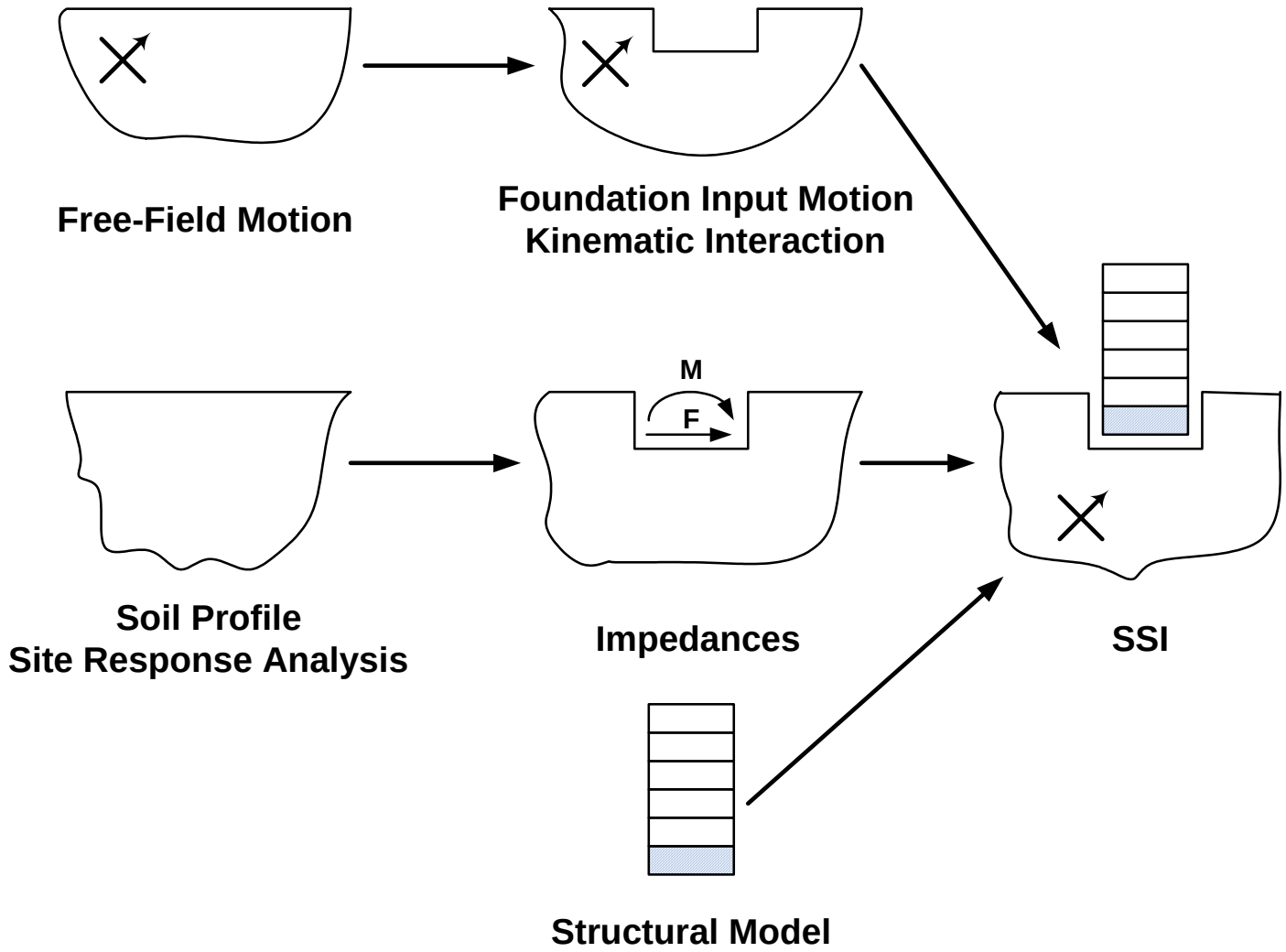
Elements of the Substructure SSI Analysis as Implemented in CLASSI Programs



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Coherency Matrix Gamma [$\gamma(\omega)$]

- CLASSI
  - Applies the constraint of rigid massless foundation behavior to determine the amplitude of the multipliers to be applied to the sub-region tractions
  - Rigid body motion
  - CPSD matrix - square root of the diagonal terms = incoherency transfer functions (scattering functions)
  - FIM = IFFT[(FFT - free-field ground motion) * Incoherency Transfer Functions (ITFs)]

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Kinematic Interaction is the Key Element of the Incoherence Problem for CLASSI

- Each component of free-field motion (x, y, z) could produce six components of foundation input motion (FIM)
  - Square foundation – three important components of FIM per direction of excitation
    - X (free-field) → X, Y, Z, XX, YY, ZZ
    - Y (free field) → X, Y, Z, XX, YY, ZZ
    - Z (free-field) → X, Y, Z, XX, YY, ZZ
- For a given direction of input (X, Y, or Z), what is the phase relationship between the three FIM components?
  - Deterministic
  - Random

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Phase Relationship of the FIM Components

- Deterministic (CLASSIinco)
  - Most applicable to cases where the phase relationship is known (e.g., wave passage)
- Random (CLASSIinco-SRSS)
  - Assume each component of FIM has random phase vs. the other components
  - E.G., X-input → (X, Y, Z, XX, YY, ZZ) FIM randomly phased
- CLASSIinco-SRSS
  - Perform six analyses with input for each defined by the individual FIM components
  - SSI analysis
  - Repeat process until all FIM analyzed
  - Repeat for all directions
  - SRSS responses for each direction ground motion input and all combined

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Coherency Matrix Gamma [$\gamma(\omega)$]

- SASSI
  - Decomposes [$\gamma(\omega)$] into spatial modes

    $([\gamma(\omega)] - \lambda_i^2[I])\ \{\phi(\omega)\}_i\ ) = \{0\},\ \ i = 1,2,\ldots N$
  - Generalized solution denoted Karhunen-Loeve (KL) based on the spectral factorization of the coherency kernel
  - $\{U_g^I\} = [\phi(\omega)]\ [\lambda(\omega)]\ \{\eta_\theta(\omega)\}\ U_0(\omega)$

    $\{U_g^I\}$ = interaction node motion

    $\{\eta_\theta(\omega)\}$ = random phase vector of form exp $[i\theta(\omega)]$

    where $-\pi \leq \theta \leq \pi$

    $U_0(\omega)$ is the free-field ground motion component

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SASSI – General considerations

- For each SASSI frequency of solution, the spatial modes are derived
  - Total number of spatial modes equals the number of interaction node points (N) for each direction of excitation
  - Complete set of spatial modes may be used (SASSI-Simulation and SASSI-AS) or a subset (SASSI-SRSS)
- Treatment of the spatial modes distinguishes the three methods

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SASSI – Simulation (Randomization)

- Perform Monte Carlo simulations varying the random phase θ for each spatial mode
- Loop on number of simulations (5, 10, 15, 20)
  - Loop on no. of SASSI solution frequencies (10s to 100s)
  - Randomly sample θ for each spatial mode (for example = 169)
    - At each SASSI solution frequency, form $\{U_g^l\}$
    - Numerical techniques for smoothing & phase adjustment
    - Calculate SSI response for the simulation (ISRS)
- Calculate the mean of the responses

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SASSI – SRSS

- Applied in two contexts
  - SRSS of transfer functions (validated here)
  - SRSS of end response of interest (Tseng and Lilhanand)
- SRSS of transfer functions
  - Loop on no. of SASSI solution frequencies (100 plus)
  - For each frequency -
    - Loop on spatial modes (generally subset of N)
      - $\theta = 0$
      - Calculate TF for response quantities of interest
    - Calculate SRSS of TF (ω)
- Calculate response (ISRS) from SRSS of TFs at all ω

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SASSI – AS (Algebraic Sum)

- Equivalent to one simulation of SASSI – Simulation with:
  - Phase angle $\theta = 0$ for each spatial mode
  - Numerical techniques to assure the proper relationship of transfer function frequency to frequency
    - Smoothing and interpolation – using the Parzen windowing technique
    - Response phasing adjusted by limiting to range of $-\pi/2$ to $+\pi/2$ to produce higher energy response time histories
- All spatial modes included
- SSI response calculated directly

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