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New Plant Seismic Issues Resolution Program

Structural Tasks Working Meetings Task S2.1 – Effect of Seismic Wave Incoherence on Foundation and Building Response

Presentation to USNRC

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Jim Johnson

May 12, 2006

B-2C

Outline of Presentation

- Background and Summary of Key Points
- Status
  - Phase 2 Work Scope
  - Responses to RAIs
- Overview of S2.1 Implementation Approaches
- S2.1 Phase 2 Activities
  - Re-evaluate induced rotations from Phase 1 analyses
  - Sensitivity study on coherency function uncertainty
  - Compute incoherence at Diablo Canyon and compare to data from recent small earthquakes
  - Review Perry Nuclear Power Plant recordings due to Leroy Earthquake
  - Additional foundation analysis
- NRC RAI Discussion

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NRC Request for Information (4/24/06)

- Results from Phase 2 tasks will address many NRC comments/questions, others potentially beyond the scope of current program
- Key NRC Issues
  - Verification from real earthquake data
  - Rocking and torsion induced by incoherence
  - Effects of embedment on incoherence
  - Effects of basemat flexibility on incoherence
  - Effects of other foundation shapes
  - Peer review of coherency functions
  - Phase 1 report comments
- Presentation will address these issues

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Background and Summary
Phase 1 Activities

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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
- 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
  - Based on recorded data, apparent wave velocities are typically on the order of 4 km/sec or greater. Structure response is minimally affected by wave passage for these large apparent wave speeds

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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
  - Systematically study the ground motion incoherency effects on structures/foundations similar to those being considered for Advanced Reactor designs

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Motivation for S2.1 Task (Cont)

- Significant New Data Exists:
  - EPRI TR-100463, "Spatial Variation of Earthquake Ground Motion for Application to Soil-Structure Interaction", 1992, presented coherency functions based on LLST array (Taiwan) data for fifteen earthquake events
  - Arrays used for coherency model also include all available and appropriate data, e.g., :
    - EPRI Parkfield
    - Chiba, Japan
    - Coalinga
    - UCSC ZIYA
    - Pinyon Flat

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Coherency Observations/Conclusions

- Spatial Coherency Models for Soil-Structure Interaction
  - EPRI #1012968
- Coherency functions are appropriate for all frequencies (including above 20 Hz)
- For the purposes of this Task S2.1 study:
  - Coherency does not vary as a function of site conditions
  - 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
- Mean input ground motion is the goal. Mean and median coherency functions are approximately the same. Median values are used.

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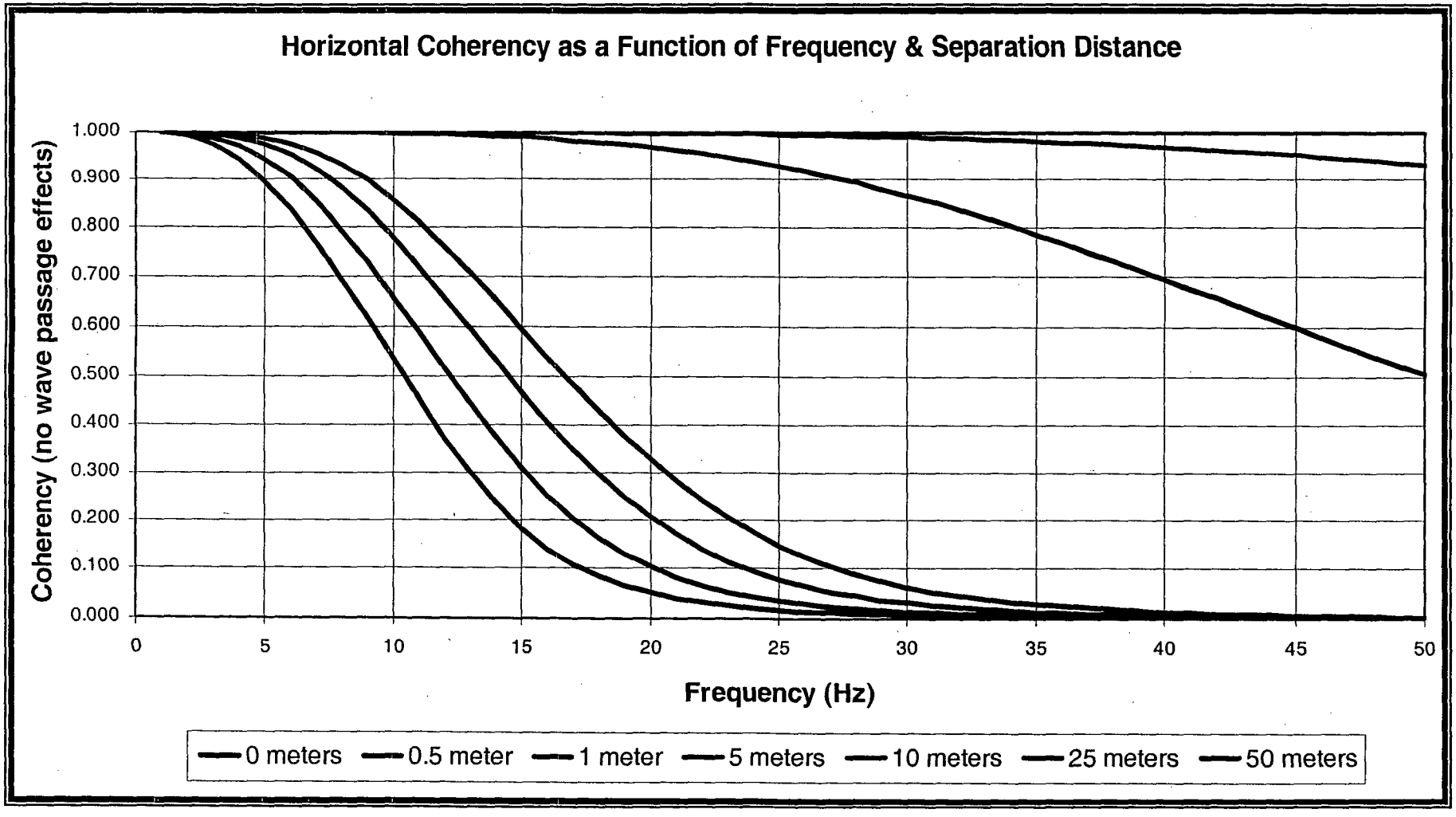
Coherency for Horizontal Motion



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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 Incoherency Transfer Functions (ITFs) to be applied to the Risk Informed Site Specific SSE Ground Motion (RISS-SSE) to account for the effects of incoherence on NPP structures/foundations as a function of foundation size, site conditions, and other relevant parameters (ARES Team)
  - Apply to the Fourier amplitude spectra of the free field ground motion
  - Input to SSI analysis (CLASSI or SASSI)
- Validate Incoherency Transfer Functions (ITFs) and their implementation:
  - CLASSI
  - SASSI

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S2.1 Phase 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; eigen function decomposition by SASSI
- Excellent agreement is obtained for Incoherency Transfer Functions and response spectra reductions
  - Verification completed for application methodology given coherence function
  - NRC and TRAG Agree
- Reductions for Foundations Significant and Expected to be Prime Tool to Alleviate High Frequency Issue

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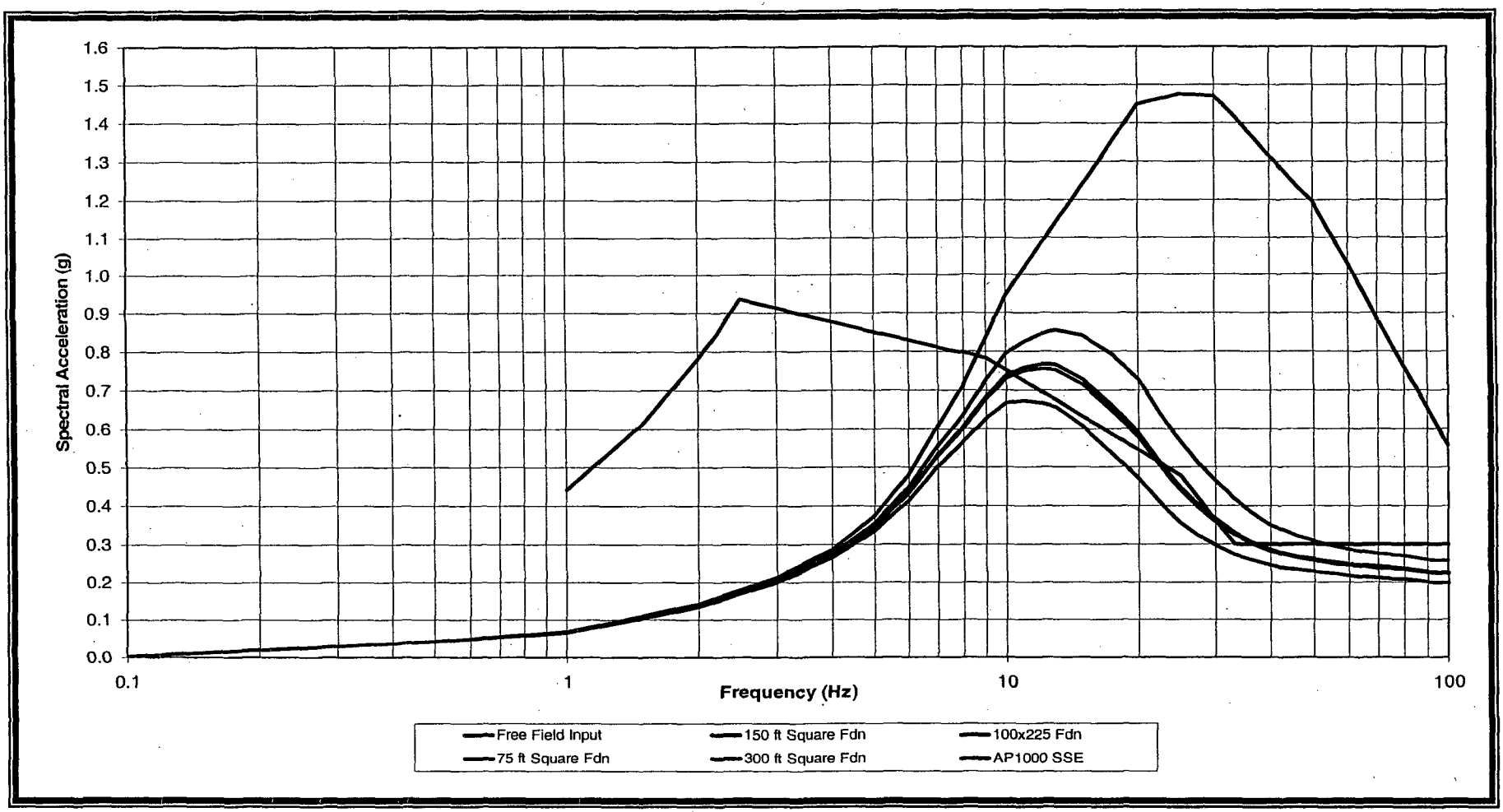
Horizontal Spectra Reduction Due to Incoherency, Rock Site Profile



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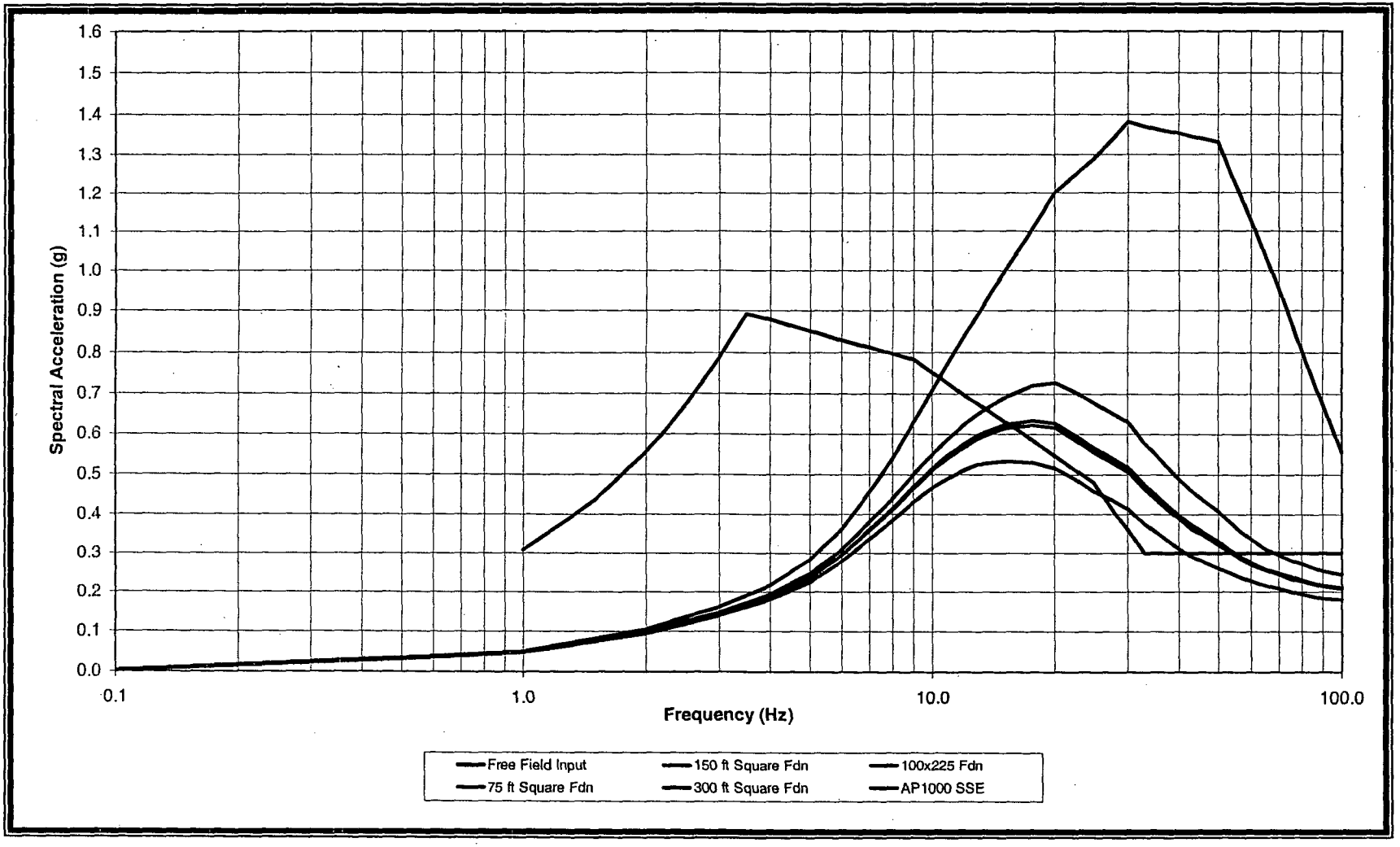
Vertical Spectra Reduction Due to Incoherency, Rock Site Profile



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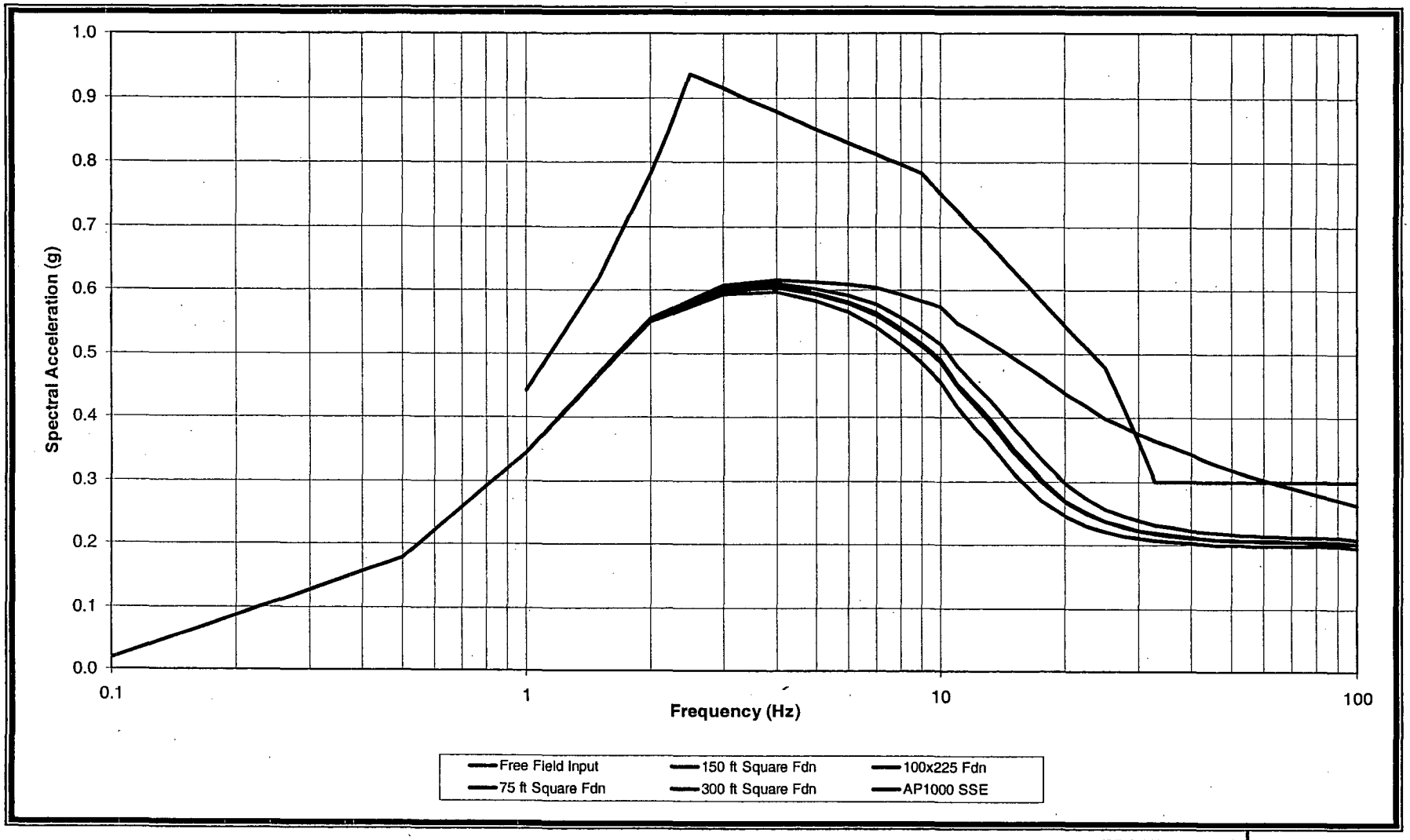
Horizontal Spectra Reduction Due to Incoherency, Soil Site Profile



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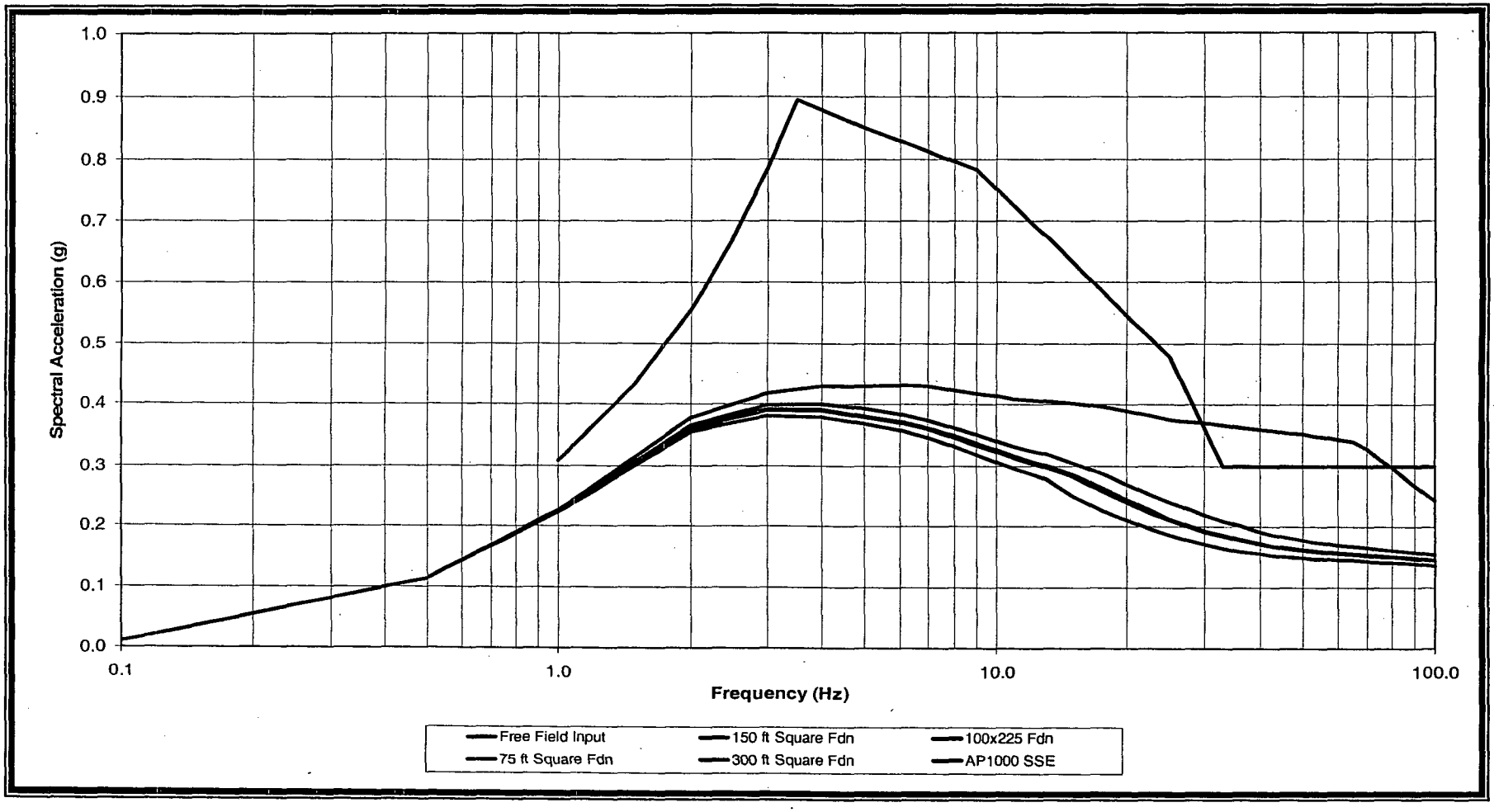
Vertical Spectra Reduction Due to Incoherency, Soil Site Profile



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Task S2.1 Ground Motion Incoherence : Phase 2 Tasks

- Benchmark study comparing CLASSI and SASSI SSI response of representative NPP structure
  - **Completed (Report to be updated to include SASSI results)**
- Coherency Function
  - Sensitivity Study for Coherency Uncertainty **(Ongoing)**
  - Peer Review of Coherency Data **(Completed)**
- Further Case Analyses for Foundation Shape **(Ongoing)**
- Address the Data from Recent Earthquake Response Measurements
  - Deer Canyon at Diablo **(Ongoing)**
  - Perry Plant **(Ongoing)**
  - Kim and Stewart Paper **(Ongoing)**

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NRC Request for Information (4/24/06)

- Key NRC Issues
  - Verification from real earthquake data
  - Rocking and torsion induced by incoherence
  - ***Effects of embedment on incoherence***
  - ***Effects of basemat flexibility on incoherence***
  - Effects of other foundation shapes
  - Peer review
  - Phase 1 report comments
- Current activities
  - Phase 2 ongoing tasks
  - Examine rocking and torsion more closely from Phase 1 runs
  - Incorporation of approach into overall integration document

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Overview of Implementation Approaches

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Incorporation of Incoherency Effects into Risk Informed Site-Specific SSE Ground

Risk Informed Site-Specific SSE Ground Motion (RISS-SSE)

Incorporate the Effects of Incoherence of Ground Motion

NAA = Norm A. Abrahamson

Direct Incorporation of NAA Coherency Functions into SSI Analysis Procedures e.g., CLASSI, SASSI

- CLASSI-TYPE
- SASSI-TYPE

Incoherency Transfer Functions (ITFs)

- Applied to Fourier Amplitude Spectra-RISS-SSE
- Function of
  - Foundation Size, Shape
  - Site Conditions
- Existing SSI/ Dynamic Analysis Computer Programs Used Without Modification

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Direct Incorporation of NAA Coherency Functions into SSI Analysis Programs

- Phase 1 effort evaluated implementations of NAA coherency functions into two substructure approaches to the SSI analysis of soil-structure systems
  - CLASSI – type
  - SASSI – type
  - Characteristics and limitations
- Other SSI analysis approaches and implementations could be used

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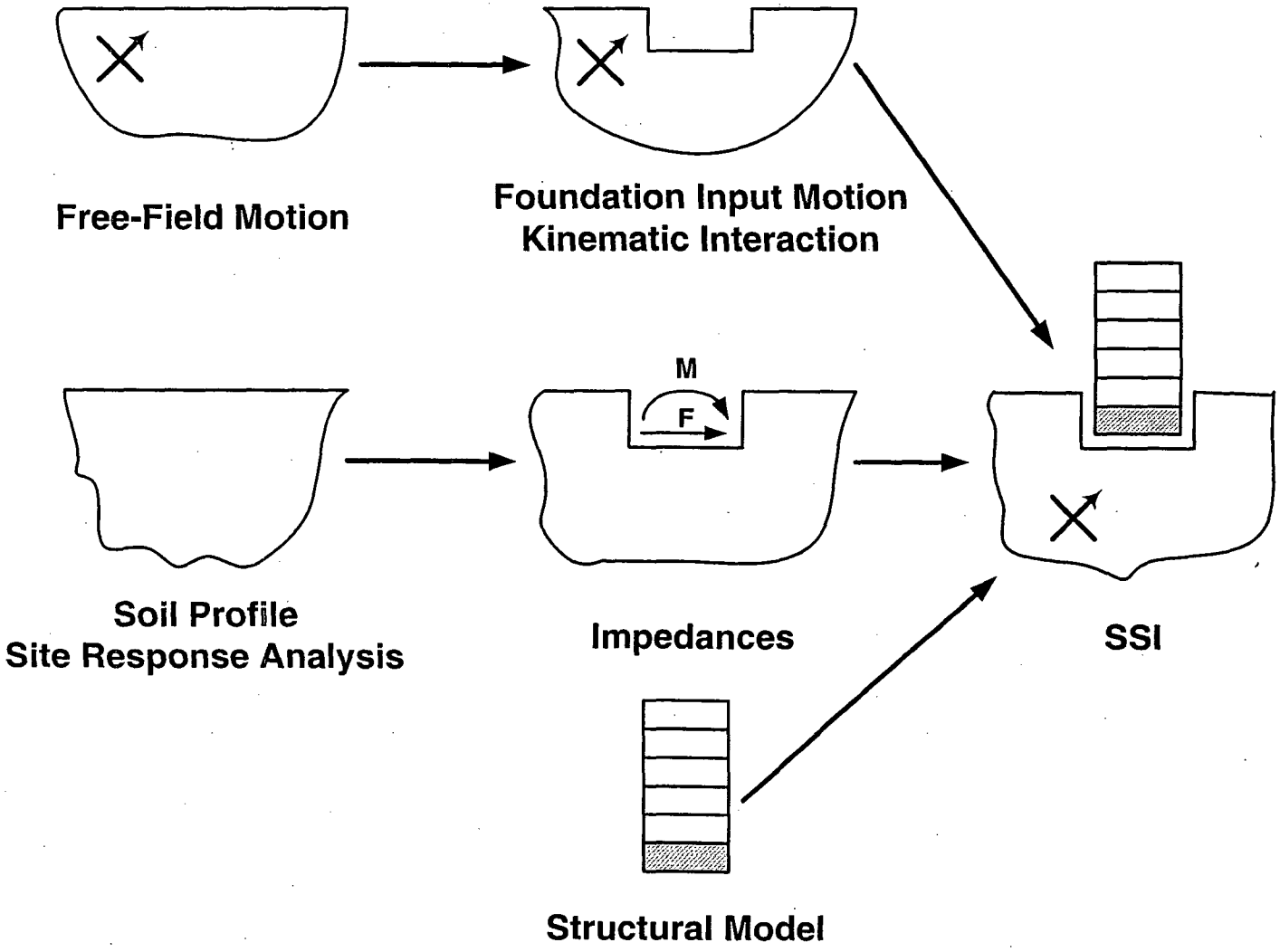
Elements of the Substructure SSI Analysis as Implemented in CLASSI Programs



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Characteristics and Limitations of the Current CLASSI Implementation of Incoherency Effects

- Characteristics
  - Foundations assumed to behave rigidly for overall dynamic response purposes
    - Effective foundation stiffness strongly dependent on stiffening effects of interconnecting walls and other structural elements
    - Commonly treat foundations of reactor containment structures (including internal structure and NSSS) and heavy shear wall structures as behaving rigidly
    - Design forces are developed from second stage structure analyses, which include structure element flexibility
  - Surface or near-surface founded

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Characteristics and Limitations of the Current CLASSI Implementation of Incoherency Effects (cont.)

- Embedded foundations treated through a hybrid approach using finite element representations of the embedded foundation shapes (SASSI or others)
- Limitations
  - Flexible foundations not practically treated

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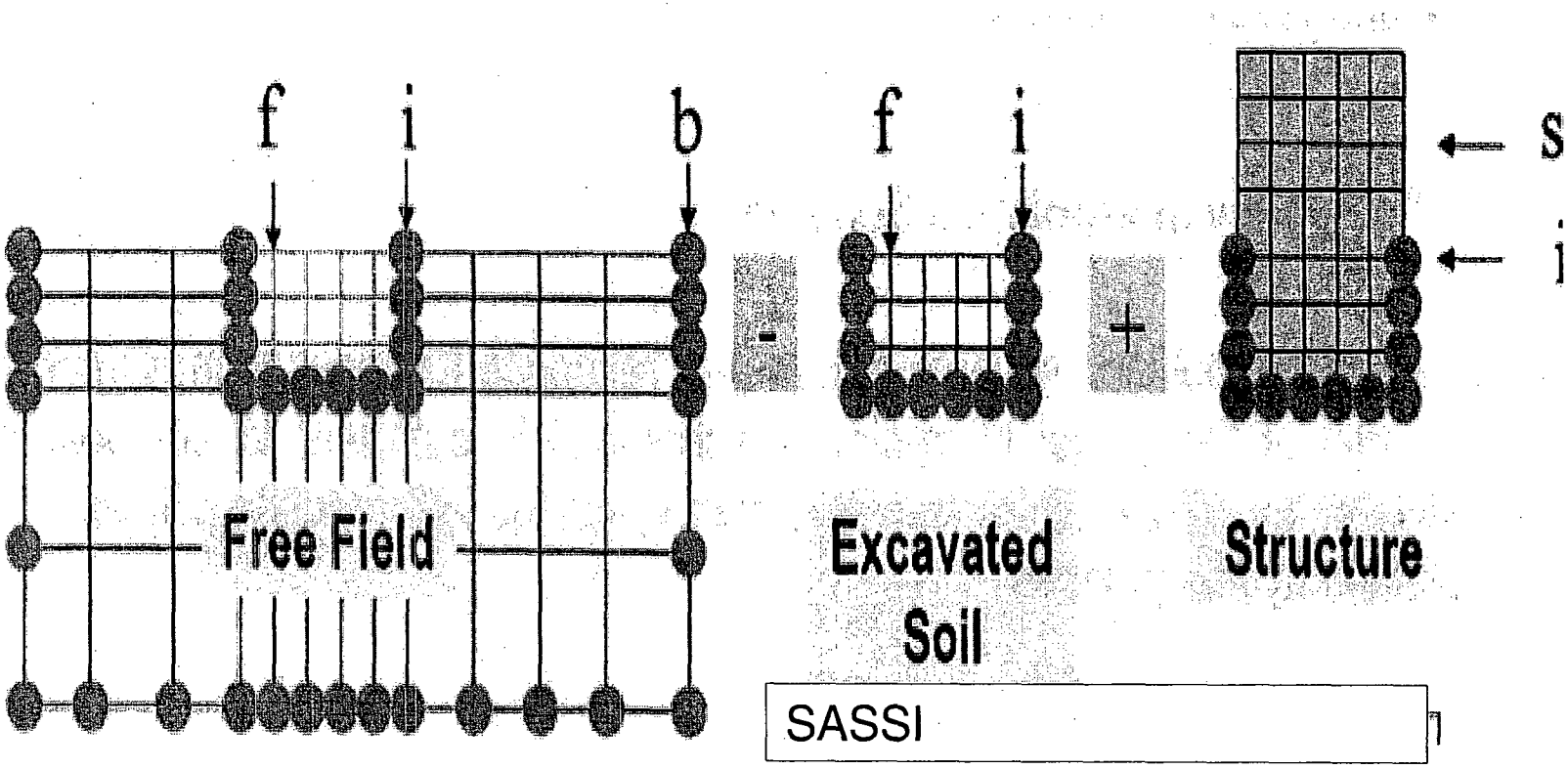
Schematic of SASSI Analysis Process



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Characteristics and Limitations of the Current SASSI Implementation of Incoherency Effects

- Characteristics
  - Foundations may be modeled to behave rigidly or flexible for overall dynamic response purposes
  - Surface-founded structures or structures with embedded foundations and partially embedded walls may be modeled
    - Current assumption is that NAA coherency functions apply equally to surface motions and motions on horizontal planes in the soil
- Limitations
  - Additional expertise required by analyst

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Incoherency Transfer Functions (ITFs): Approach

- Frequency-dependent functions to be applied to the Risk Informed Site Specific SSE Ground Motion (RISS-SSE) to account for the effects of incoherency of ground motion
  - Applied to the amplitude of the Fourier transform of the RISS-SSE; phase of the Fourier transform of the RISS-SSE is unchanged
  - Function of foundation size, shape, and site conditions (ongoing Phase 2 evaluation); different ITFs for different structures at the same site

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Incoherency Transfer Functions (ITFs): Advantages and Limitations

- Advantages
  - Provides transparency to the effects of incoherency of ground motion on soil-structure response
  - Easily applied
  - Existing SSI/dynamic structure response analysis programs may be used directly – no requirement for extensive code modification and validation
- Limitations
  - Engineering rules that apply to all foundation shapes may be difficult to develop and validate
  - Potential effect of the necessity to account for additional rotations (torsion and rocking) being evaluated (Phase 2) – may add complications
  - For foundation-structure systems whose foundation behaves flexibly additional rules may need to be developed

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S2.1 Phase 2 Studies

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Phase 2 : Foundation and Building Response to Incoherence

- Re-evaluate the potential for induced rotations (torsion and rocking) of the rigid massless foundation due to the incoherency of the ground motion
  - Compare with literature, e.g., Kim and Stewart
  - No effect on Phase 1 translational response of rigid massless foundations – translational ITFs
  - Evaluate impact, if any, on calculation of in-structure response
  - Evaluate impact, if any, on conclusions for rock and soil sites
- Effect of coherency function uncertainty on Incoherence Transfer Functions (ITFs)
- Compute incoherence at Diablo Canyon and compare to data from recent small earthquakes
- Review Perry Nuclear Power Plant recordings from the Leroy earthquake (previously presented on Thursday with S2.2)
- Analyze additional foundation shape (Circular)

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Induced Rotations

- Re-evaluate induced rotations due to incoherence of ground motions in Phase 2
- Torsion due to horizontal ground motion
- Rocking due to vertical ground motion
- Compare rigid, massless foundation response with published data
  - Kim and Stewart
  - Veletsos

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Kim and Stewart

- "Kinematic Soil-Structure Interaction from Strong Motion Recordings," ASCE, Journal of Geotechnical and Geoenvironmental, April 2003.
- Evaluation between free-field and foundation response
  - 29 instrumented sites considered - 14 near surface/15 pile or shaft foundations - some multiple earthquake records
  - Transfer functions between free-field and foundation motion developed based on Veletsos and validated
    - Approximately corrected for a representative structure
    - Approximately corrected for inertial interaction effects

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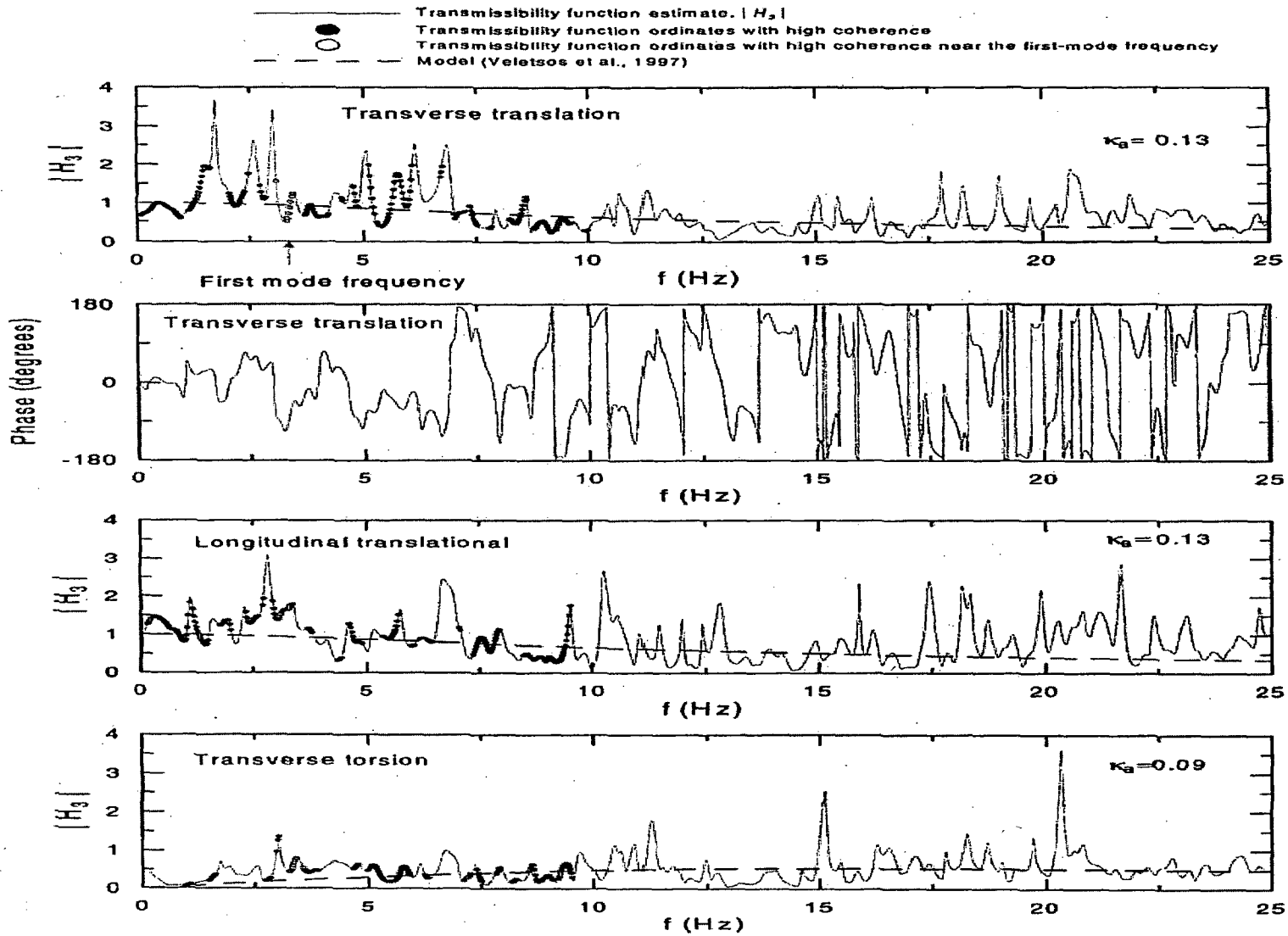
Kim/Stewart Estimation of Incoherence Parameter Ka for Site 44 (Whittier Earthquake)



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Kim and Stewart

- Recorded data evaluated for reliability - only data at frequencies less than 10 Hz. considered
- Translation and rotations
  - Translations derived from single or averaged over multiple recordings on foundation
  - Rotations derived from differences in motion from multiple recordings on the foundation
- Transfer functions developed and verified - highest confidence in frequencies less than 10 Hz. and for translations
- Transfer functions defined identically to the Phase 1 approach

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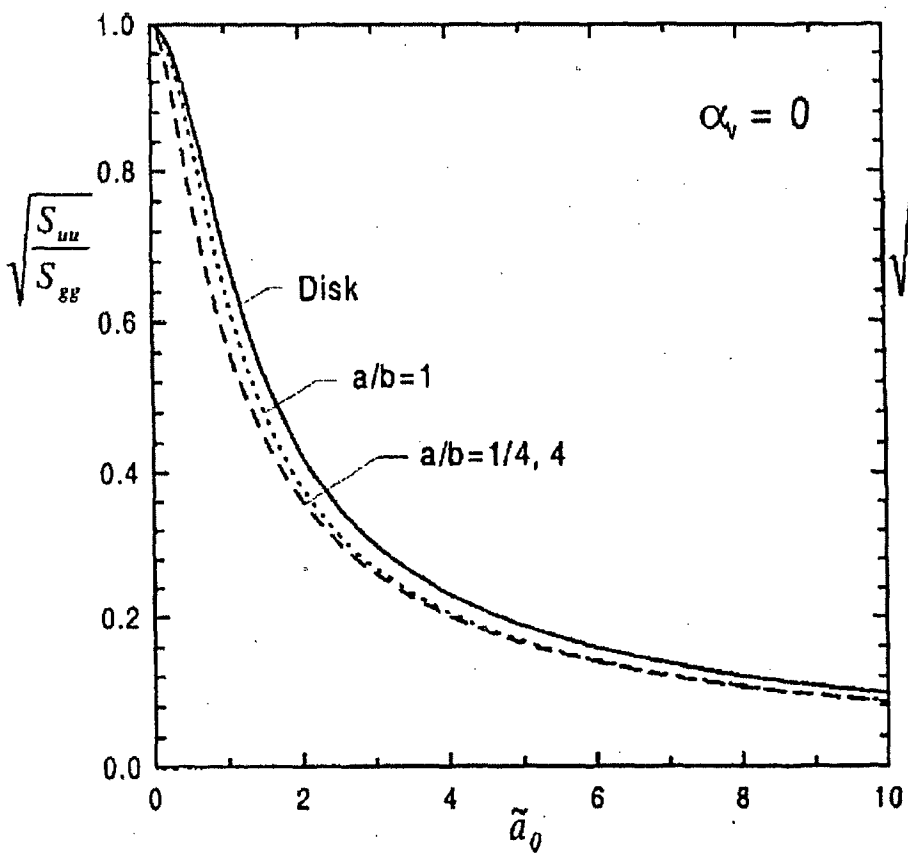
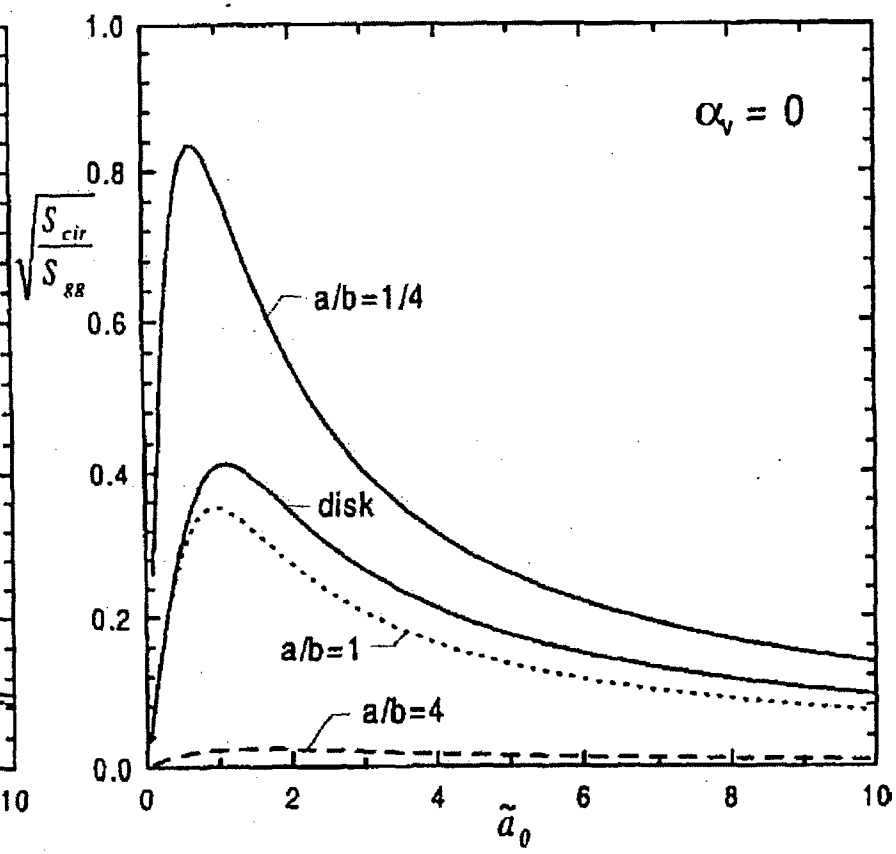
Kim and Stewart Translation and Torsion Transfer Functions





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Kim - Stewart Recommendations for Implementation in SSI Analysis Procedure

- Identical approach to the Phase 1 derivation of the Incoherency Transfer Function (ITF) - Apply to translational input only
- No recommended additional treatment of induced rotations
- Phase 2 - continue verification with other published studies

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Phase 2 Foundation Responses - Transfer Functions and PSDs

- Transfer functions similar to Kim and Stewart
  - Different coherency functions (NAA)
- Foundation PSD functions
  - **Translations due to torsion are small for rock and soil sites**
  - Translations due to torsion on rock greater than on soil due to site specific ground motion frequency content
    - Soil site specific ground motion - low frequency (less than 10 Hz.) - minimal incoherency effect
    - Rock site specific ground motion - high frequency (greater than 10 Hz.)

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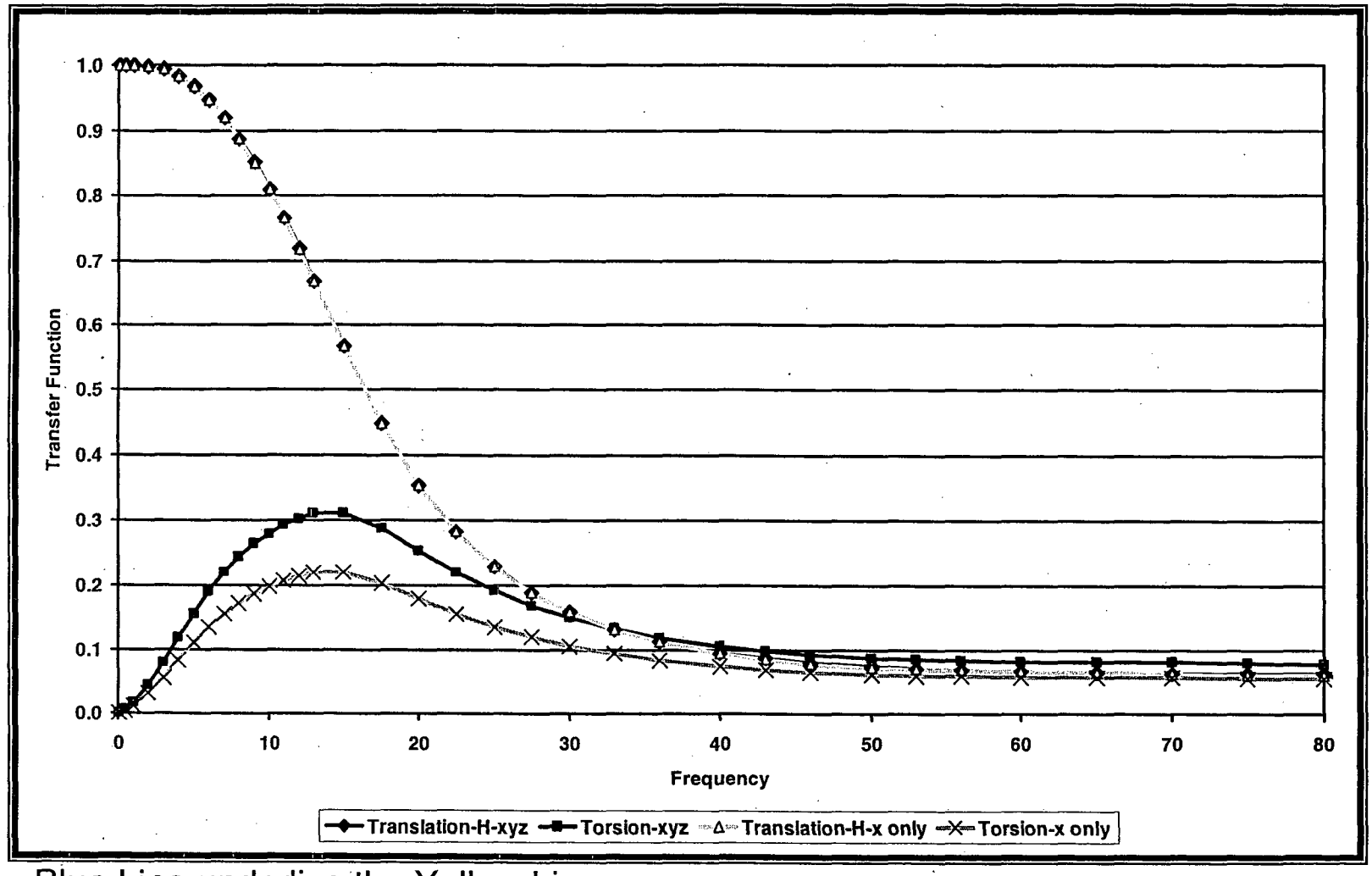
Transfer Function – Horizontal Translation and Torsion – Rock



Blue Line underlies the Yellow Line

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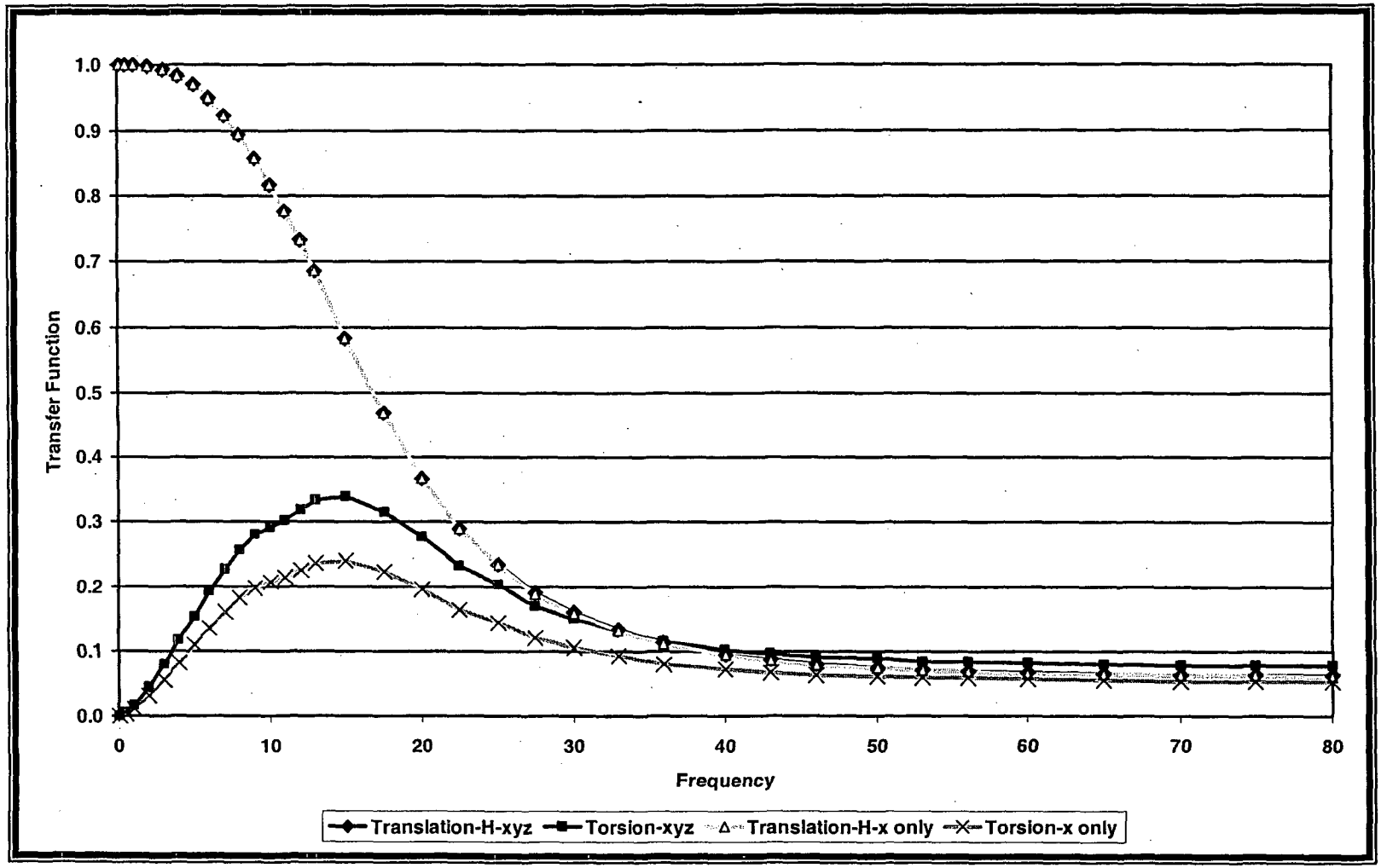
Transfer Function – Horizontal Translation and Torsion – Soil



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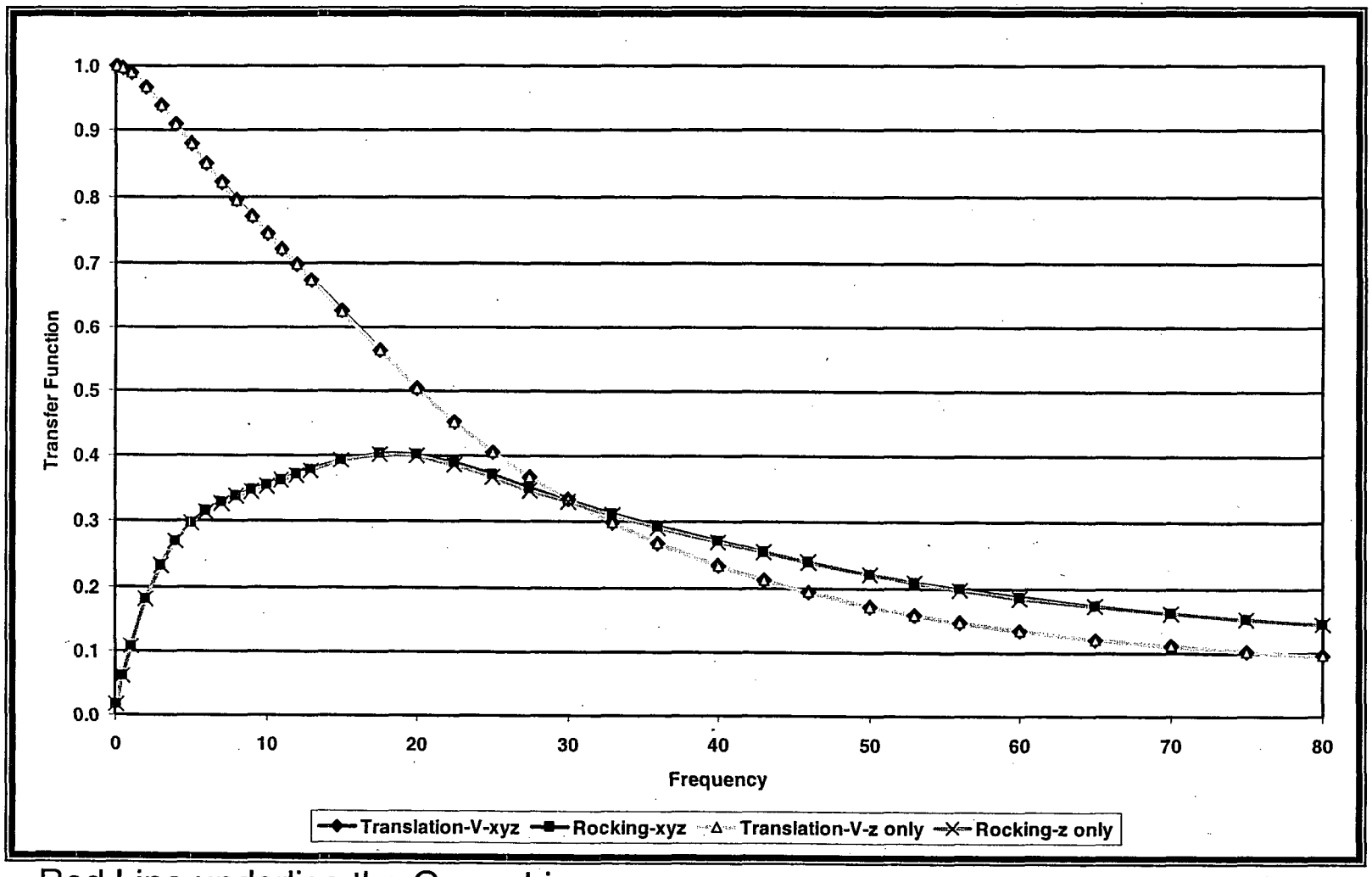
Transfer Function – Vertical Translation and Rocking – Rock



Red Line underlies the Green Line

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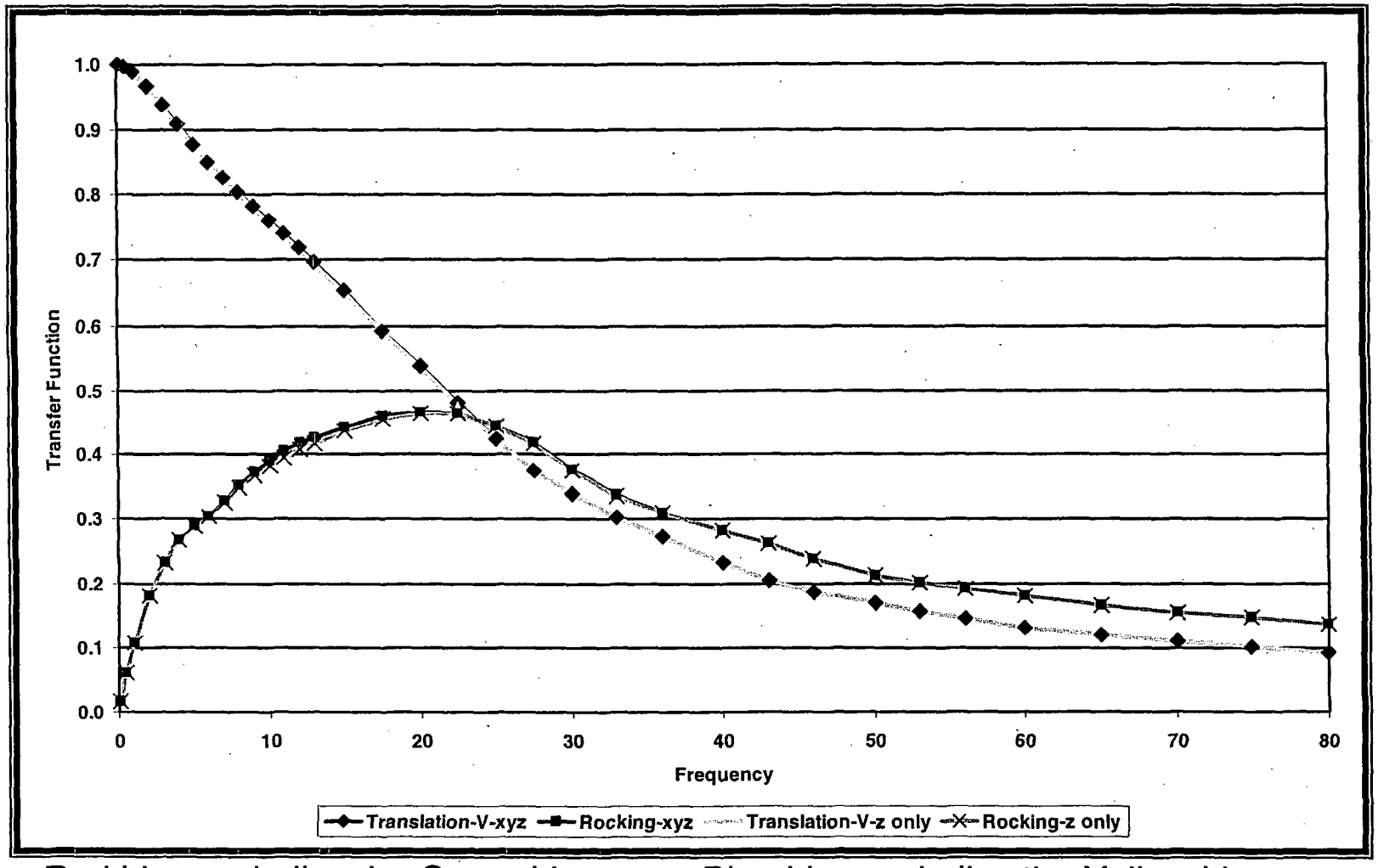
Transfer Function – Vertical Translation and Rocking – Soil



Red Line underlies the Green Line

Blue Line underlies the Yellow Line

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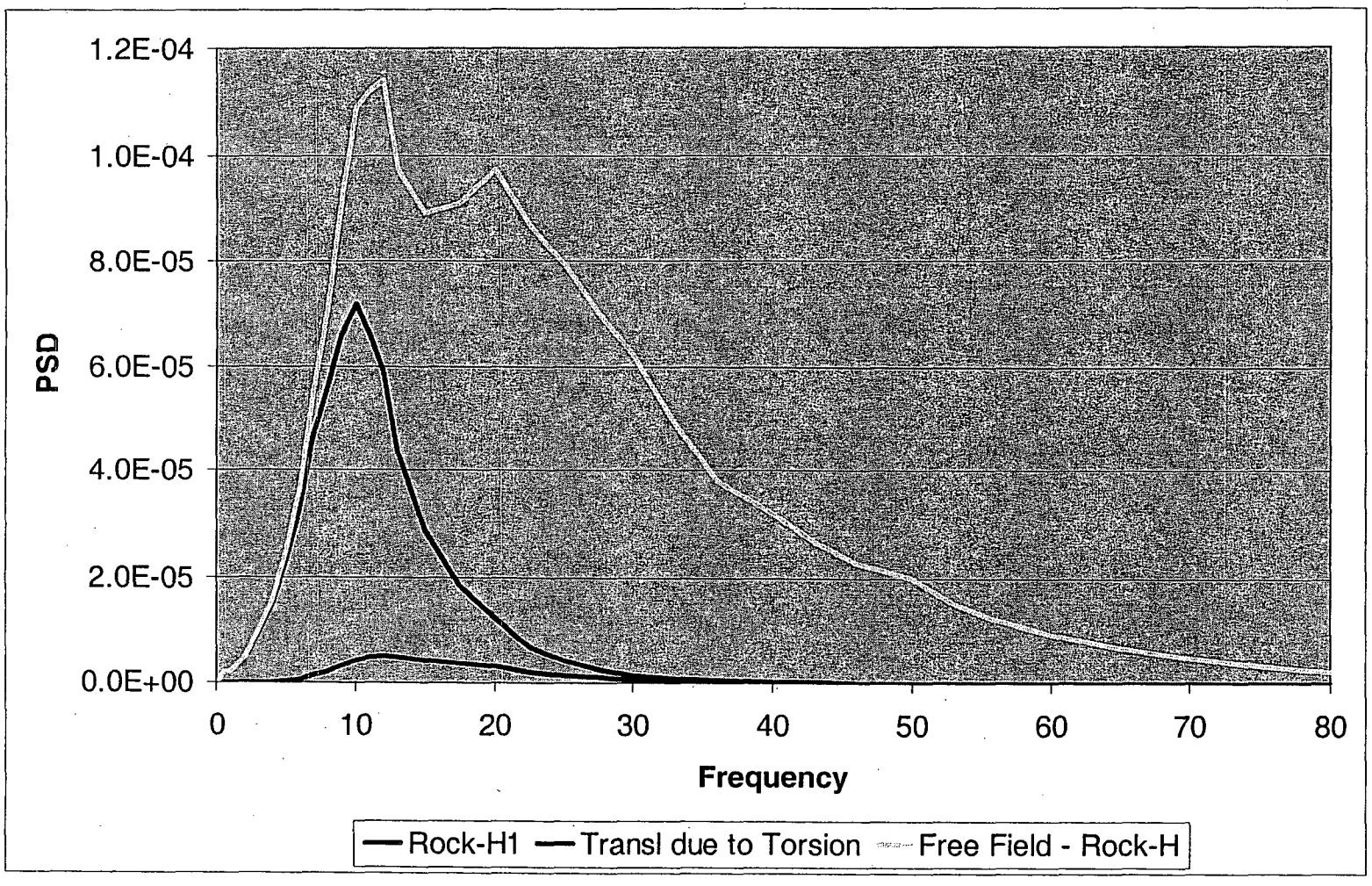
PSD - Foundation Response - Rock



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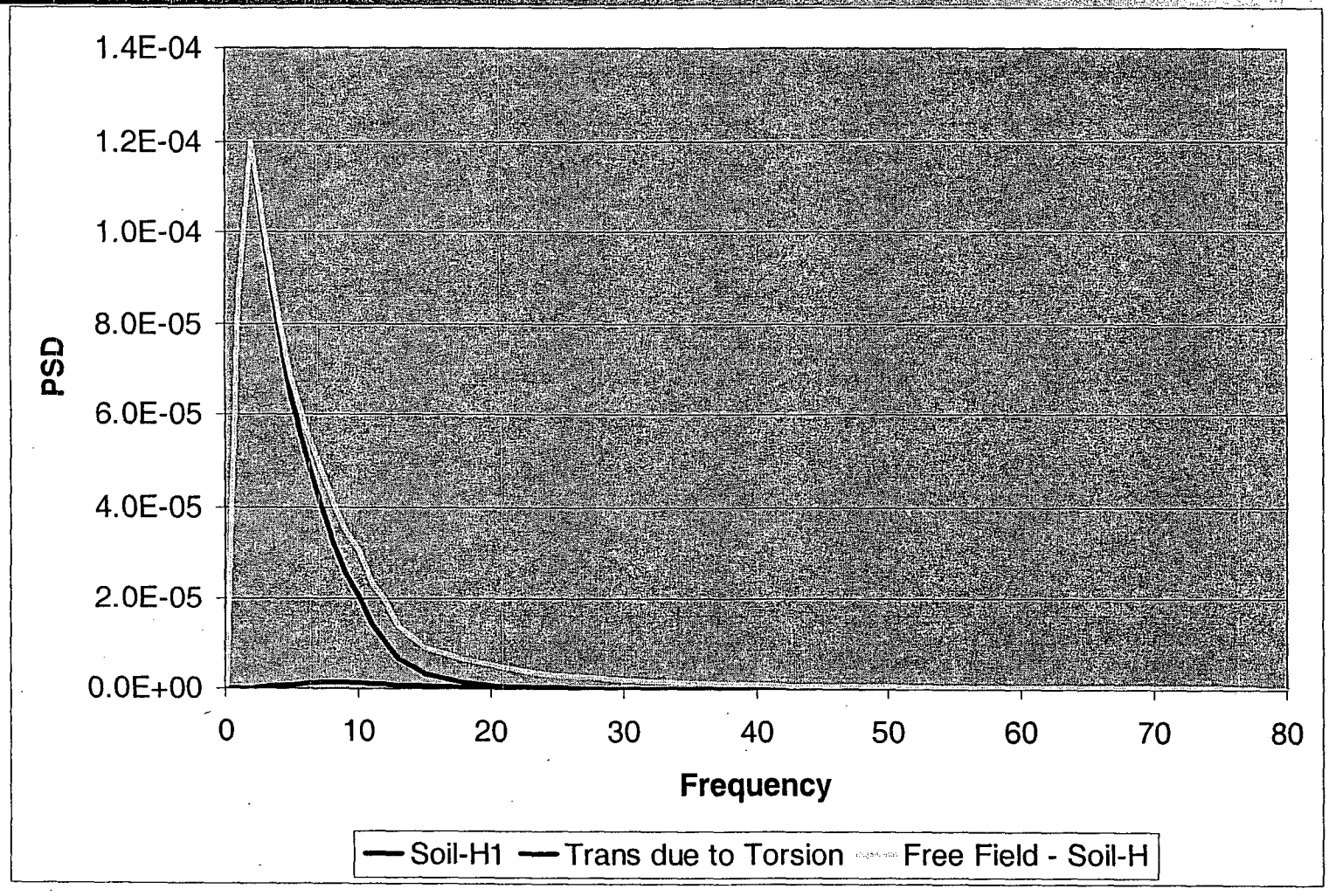
PSD - Foundation Response - Soil



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Effect of Coherency Function Uncertainty on Foundation Response

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Effect of Uncertainty in the Coherency Function on Foundation Response

- Phase 1 study focused on the median coherency function
  - Approximated the mean coherency function
  - Generated Incoherency Transfer Functions (ITFs) approximating the median values
- Phase 2 objective
  - Perform a sensitivity study to establish a reasonable estimate of the effects of coherency uncertainty on ITFs
  - Generate an approximation of the 84% ITF and the 84% NEP of the foundation response for the rigid massless foundation (150 foot square)
  - Evaluate the potential effect on the approach to defining the ITFs for application to the RISS-SSE

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Coherency Function

- Median coherency function has been used for Phase 1 analyses
- The 84th percentile coherency function is defined for horizontal motion

$$\gamma_{PW\,84}(f,\xi) = \tanh\left[\tanh^{-1}(\gamma_{PW}(f,\xi) + \sigma(f,\xi)\right]$$

- Where for frequencies greater than 20 Hz

$$\sigma_H(f,\xi) = 0.4$$

- And for frequencies less than or equal to 20 Hz

$$\sigma_H(f,\xi) = 0.4 + (f - 20)(-0.0065 - 1.9x10^{-6}\xi^2)$$

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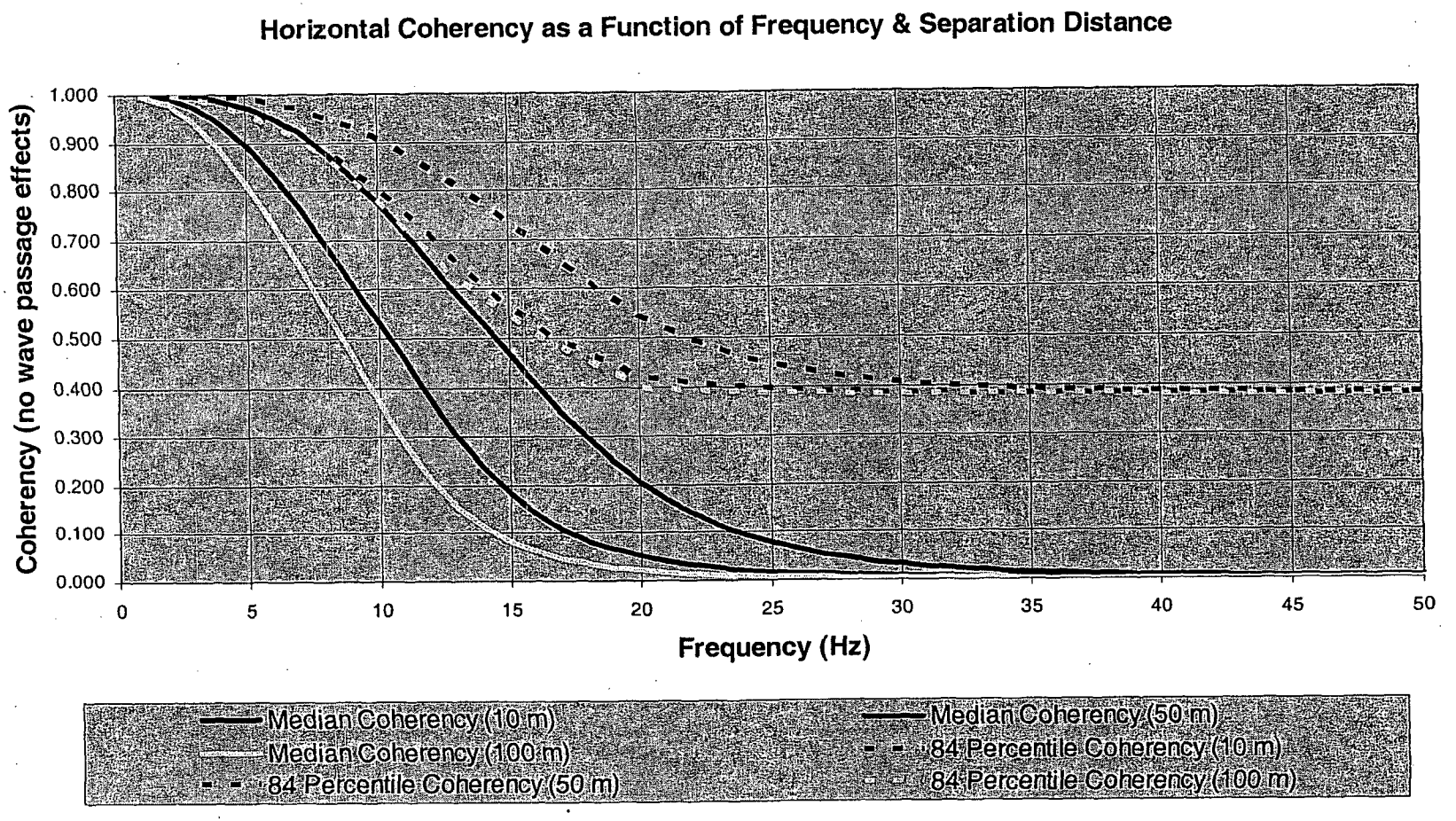
Median & 84 Percentile Coherency for Horizontal Motion



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Phase 2 Study on Uncertainty in Coherency Functions: Assumptions

- Coherency functions and Incoherency Transfer Functions may be assumed to be independent of frequency. Analyze each frequency of interest independently.
- Point-to-point coherency functions are assumed to be independent. That is, no correlation of coherency functions for points equi-distant or for points within defined radii.

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Phase 2 Study on Uncertainty in Coherency Functions: Approach

- Assume a distribution for $\gamma_{pw,p}$ defined by the median and sigma values. The resulting coherency, $\gamma_{pw,p}$ will be permitted in the range of -1.0 to +1.0.
- Perform Monte Carlo simulations, sampling on γpw,p, and calculating values of ITF. Analyze each frequency of interest independently.
- From the resulting 84% NEP ITFs, evaluate response spectra for the rigid massless foundation on a rock site to estimate the 84% NEP response spectra.
- Compare the incoherency transfer functions and rock foundation response spectra
  - Phase 1 ITFs and foundation response spectra generated assuming median coherency functions
  - Phase 2 "reasonable estimate of uncertainty" of ITFs and foundation response spectra

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Diablo Canyon Earthquakes

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Diablo Canyon Earthquake Recordings Evaluation

- There are recordings in the free field and on the foundation
  - Magnitude 3.4 Deer Canyon Earthquake – 10/18/2003
  - Magnitude 6.5 San Simeon Earthquake – 12/22/2003
- Opportunity to compare calculated and measured incoherency effects
  - The lower magnitude Deer Canyon motion is narrow banded with high frequencies in the 10 to 20 Hz range; PGA is between 0.01 and 0.02g depending on the component
  - The larger magnitude San Simeon motion is broad banded with largest amplification in the 2 to 8 Hz range but significant content at 10 Hz; PGA is 0.02 to 0.05g depending on the component

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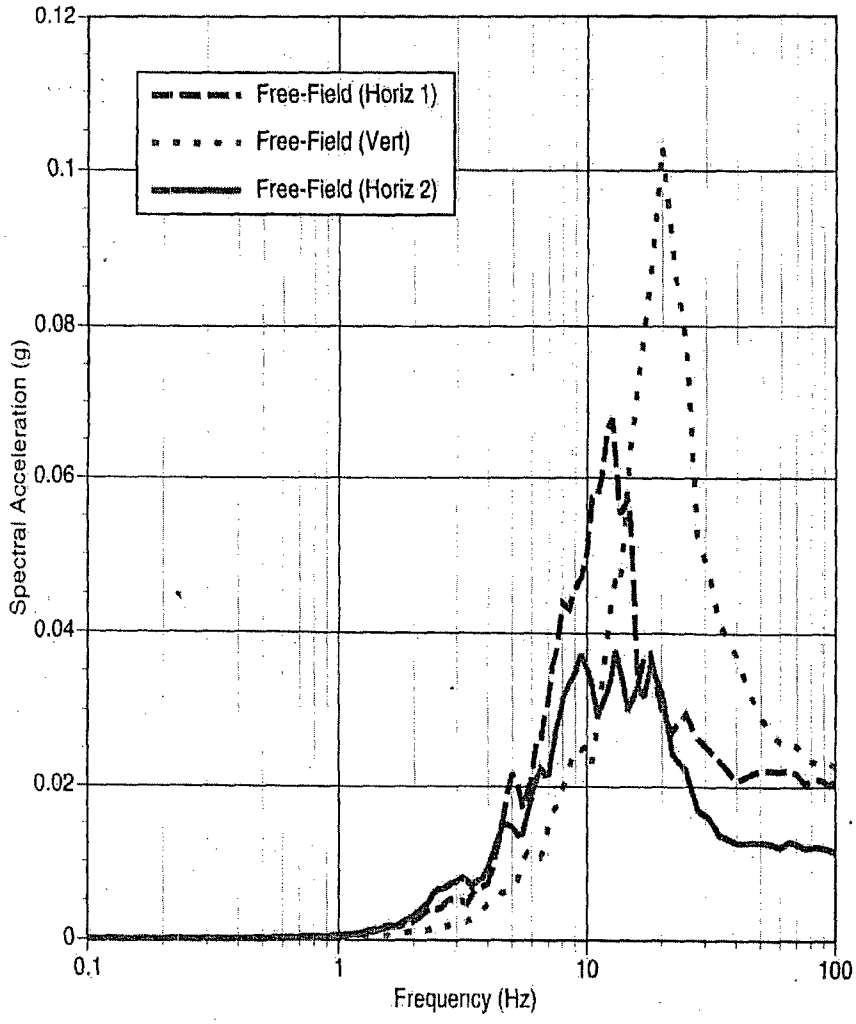
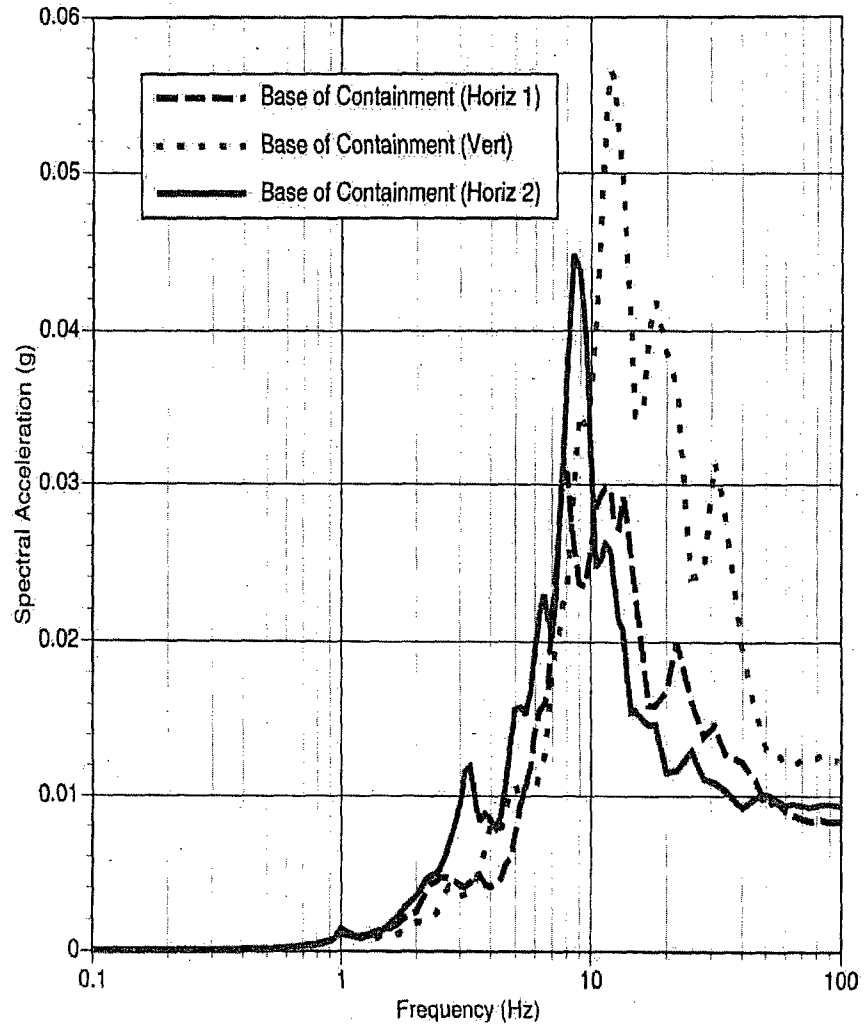
10/18/2003 Deer Canyon Earthquake





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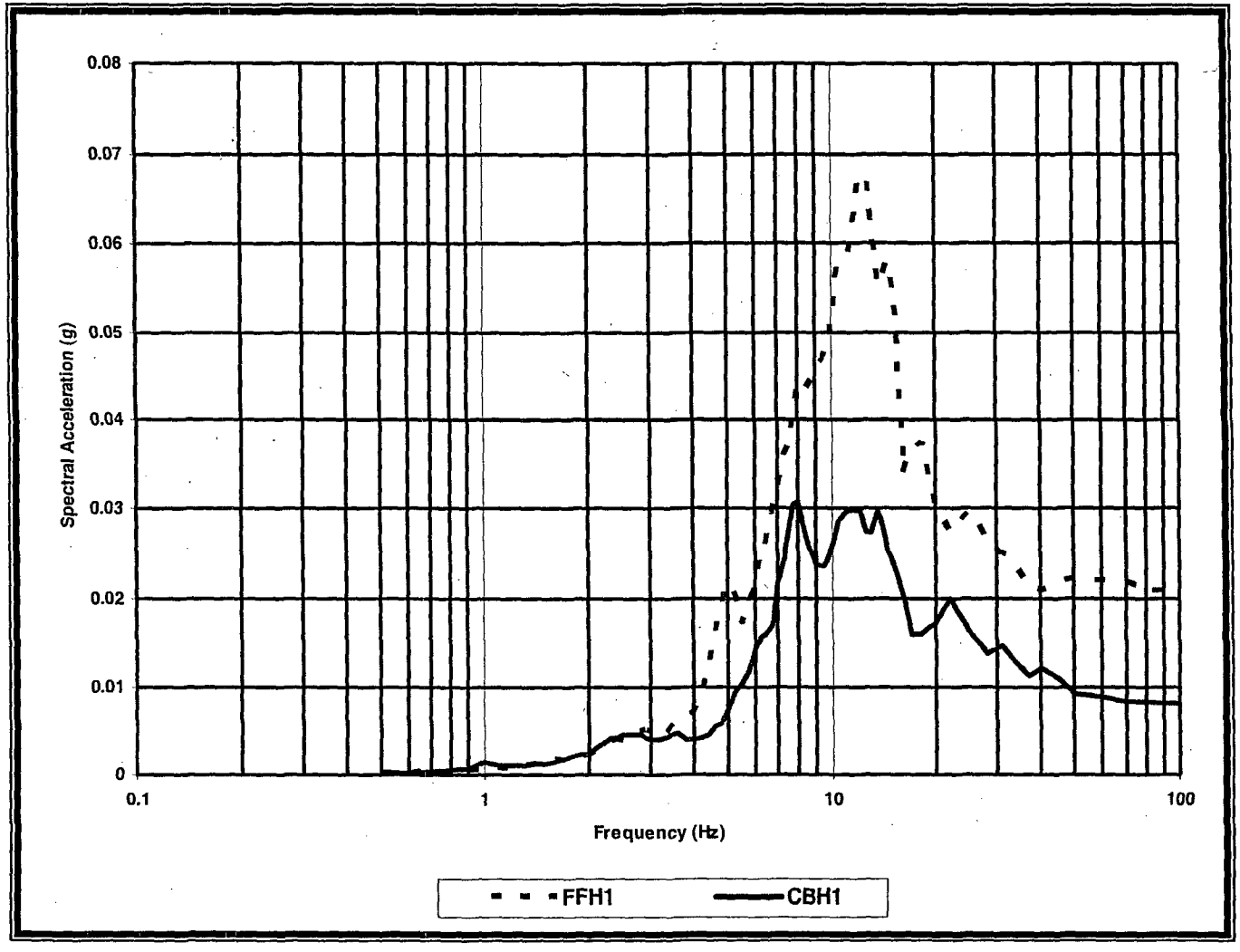
Deer Canyon Horizontal #1 Response



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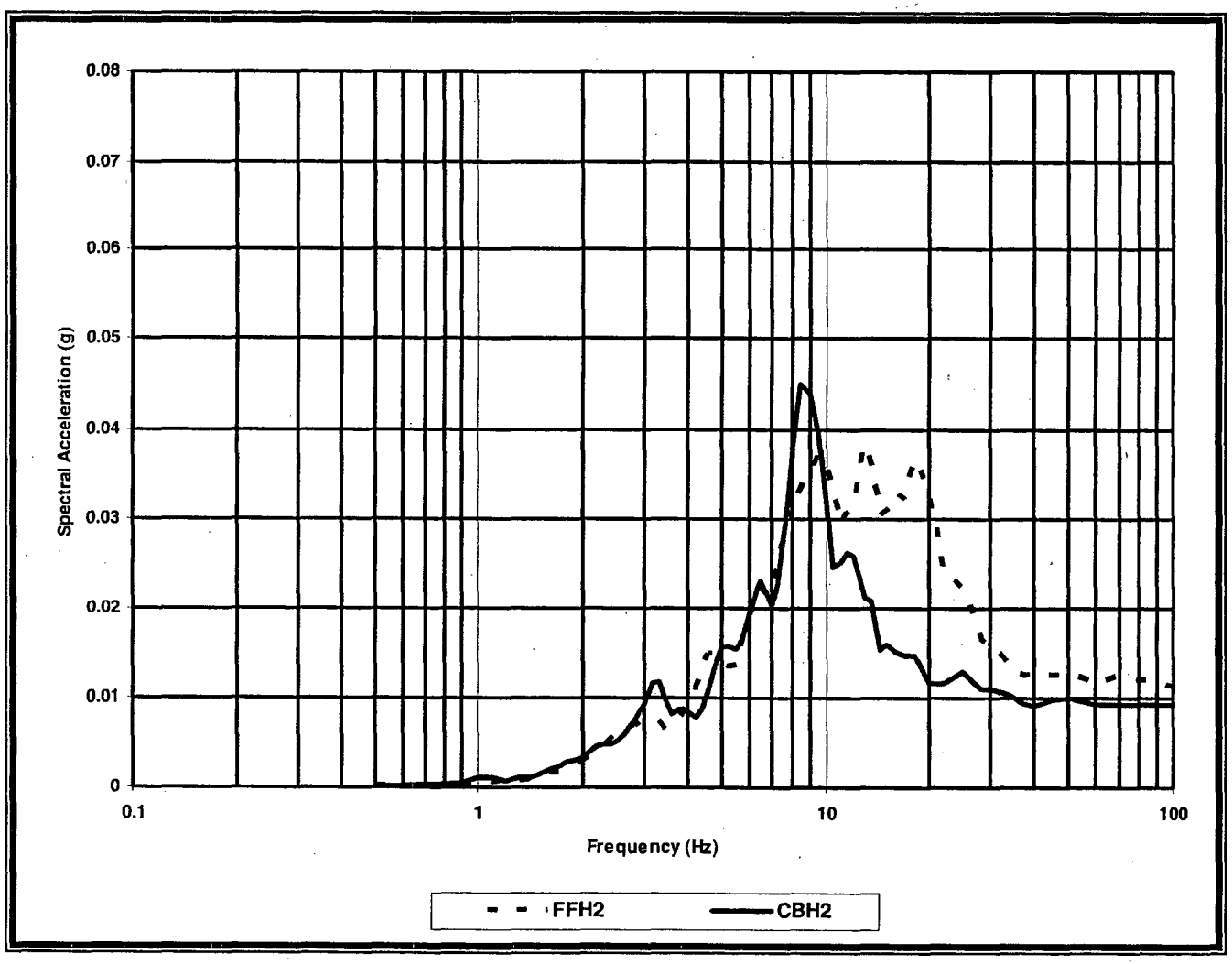
Deer Canyon Horizontal #2 Response



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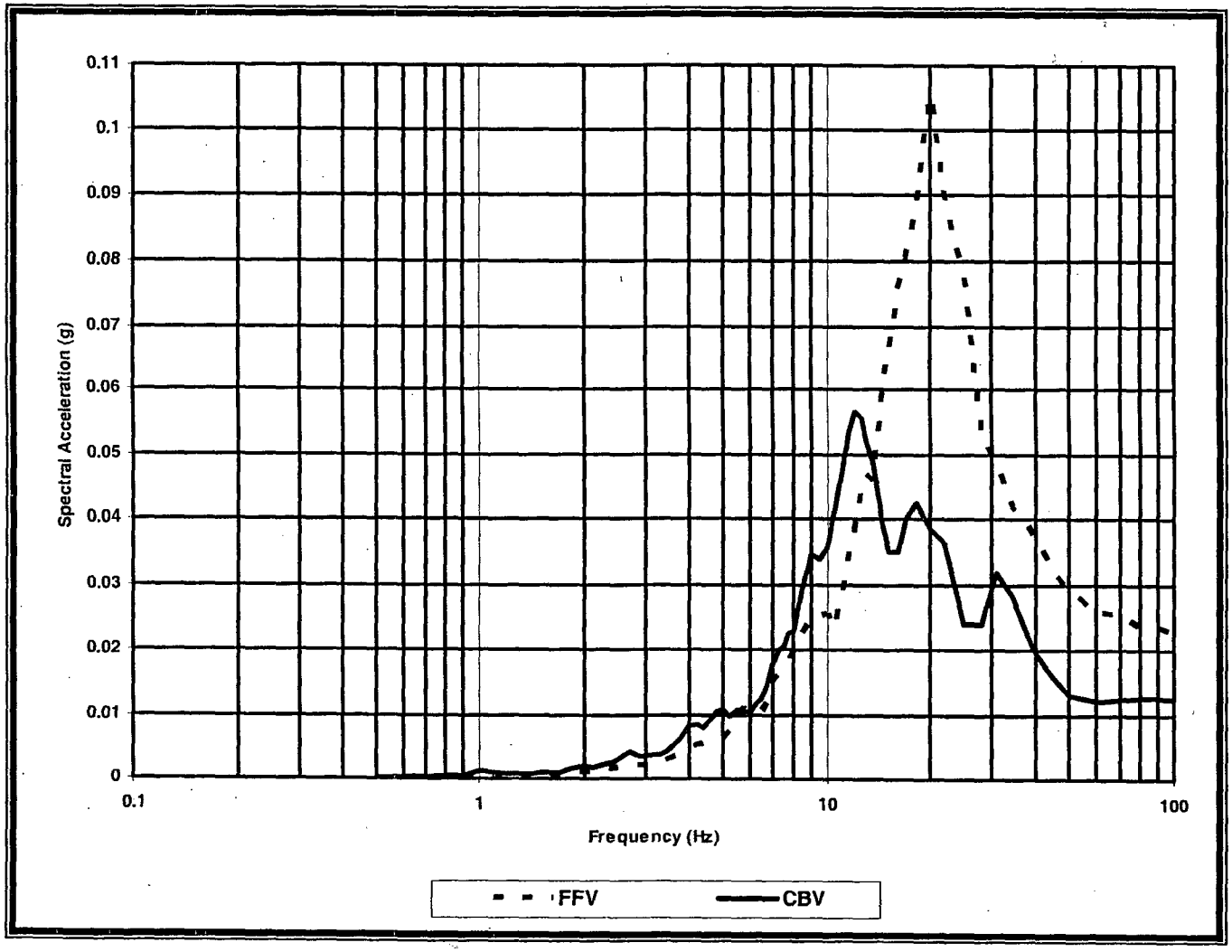
Deer Canyon Vertical Response



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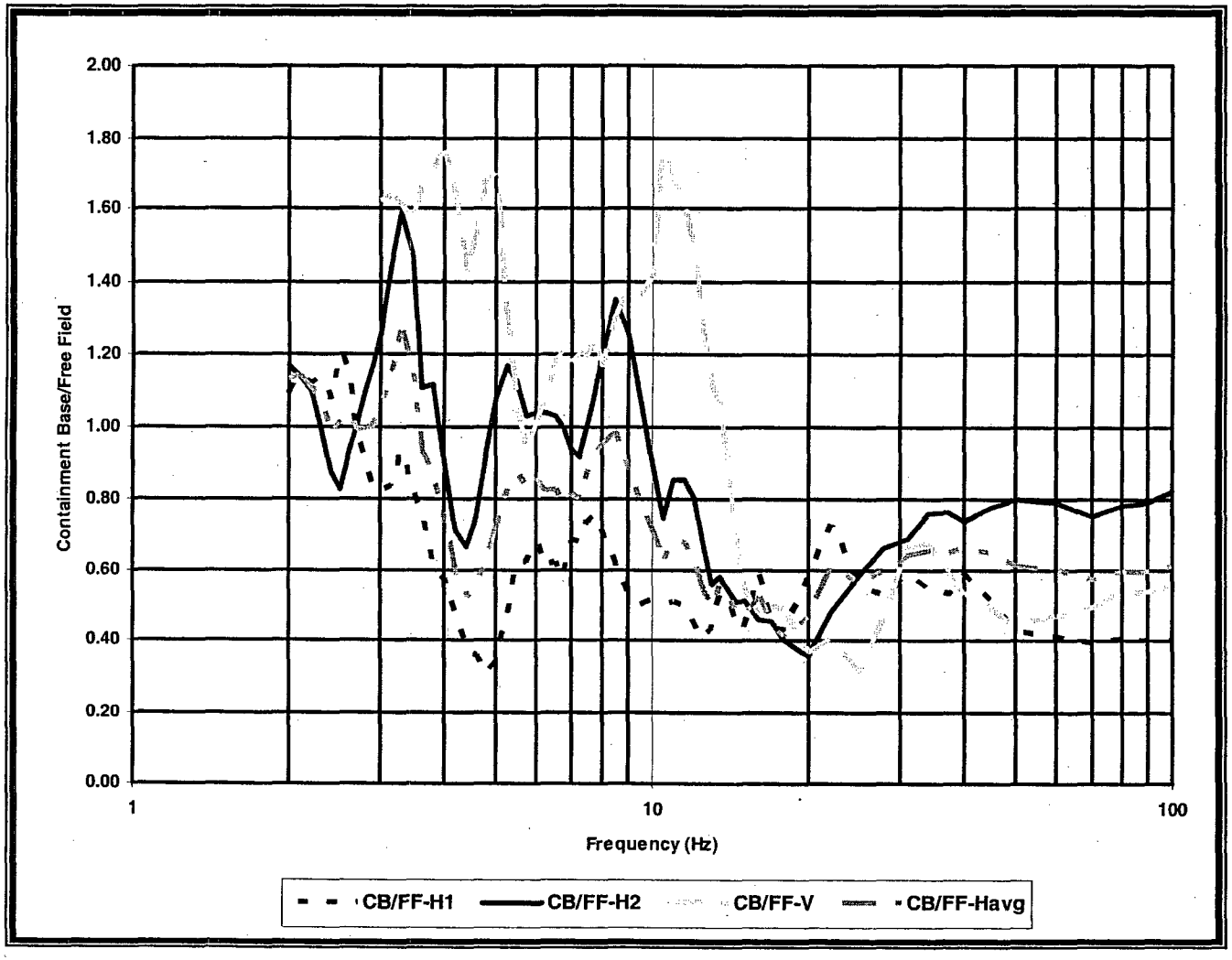
Deer Canyon Spectral Reductions



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Diablo Canyon Earthquake Recordings Evaluation Approach

- Input free field ground response spectra to the CLASSI RVT approach to compute response of a rigid, massless 153 foot diameter circular foundation and compare to measured response spectra
- Isolate the effects of incoherency from other SSI effects (i.e., inertial interaction, embedment) using Diablo Canyon existing SSI transfer functions to develop incoherence only response spectra and compare to measured response spectra
- Determine whether calculated spectra and measured spectra match sufficiently close considering results from the uncertainty task

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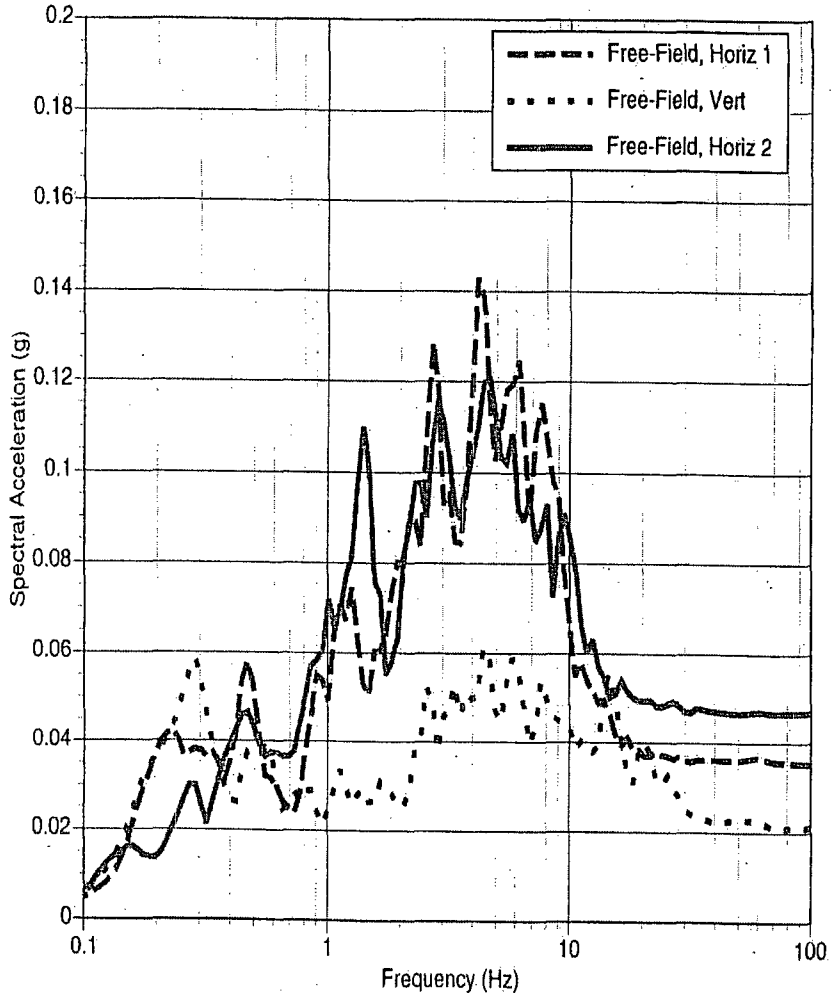
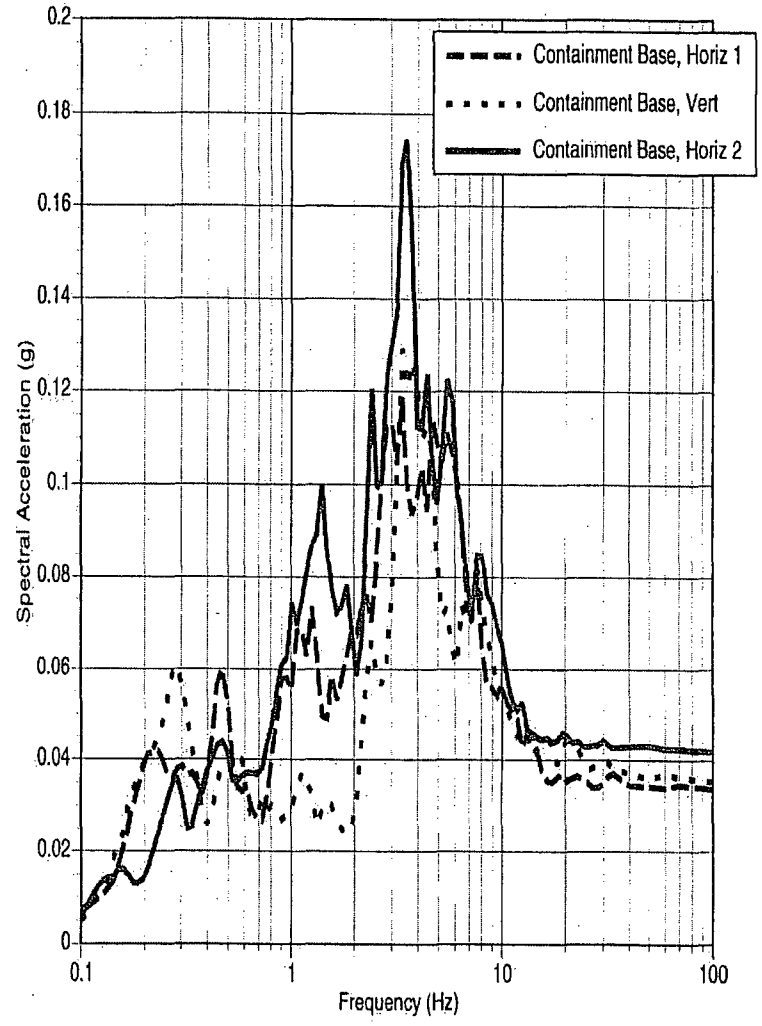
12/22/2003 San Simeon Earthquake





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ESP Task S2.1 Status and Schedule

- NRC/TRAG Technical Working Meetings
  - ARES So Cal June 22/23
  - ARES So Cal August 22-23
- NEI/NRC Meeting in October in Washington DC
- Completion of Phase 1 Structural Tasks November 2005
- Final Report Submitted to NRC January 2006
- NRC Comments Received April 24, 2006
- NEI/NRC Meeting in Washington DC May 11-12, 2006
  - Discuss Phase 2 Status
  - Discuss NRC Comments
- Future Activities
  - Phase 2 Draft June 30 2006
  - S Task Incorporation into Integration Document October 2006
  - Respond to NRC RAIs (schedule TBD)

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