New Plant Seismic Issues Resolution Program

Structural Tasks Working Meetings
Task G1.2 – Lower Bound Magnitude Characterization

by
Greg Hardy, ARES

June 23, 2005

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Task G1.2 - Revision of Lower Bound Magnitude for Hazard Integration

- **Lower bound magnitude (LBM) used in hazard computation (i.e., magnitude at which damage may occur) has major impact on computed hazard levels, particularly for higher frequencies**
- **Task 2.1 will study the correlation of earthquake magnitude with CAV in order to generate a more accurate and appropriate procedure for eliminating "non-damaging" earthquakes from the seismic hazard computation process**

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B-8

Motivation

- The lower bound magnitude used to integrate the earthquake frequency-magnitude relationship for hazard computation has a major impact on computed hazard level, particularly for high structural response frequencies
- Current practice uses a cutoff of Compressional Body Wave Magnitude (mb) 5, established as a conservative lower bound in the mid 1980s
- A mean-centered lower bound magnitude cut-off (or probabilistic treatment) would reduce high frequency ground motion hazard consistent with the damage potential of small magnitude earthquakes

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Background on the Lower Bound Magnitude Issue

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Hazard Study Assumptions

- Prior hazard studies (LLNL,1994; EPRI, 1989) used a low bound cut-off of body-wave magnitude $m_b = 5$
- This practice has continued to be used in current updated hazard studies
- This translates to an approximate moment magnitude of Mw = 4.6
- Studies have concluded that the threshold of damage to engineered structures is greater than Mw = 5.0

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Comparison of Hazard Results

- A hazard study conducted for the CEUS rock site computed the mean bedrock outcrop hazard spectrum for both values of low bound magnitude Mw =4.6 and Mw = 5.0
- As can be noted, a significant reduction of high frequency content resulted

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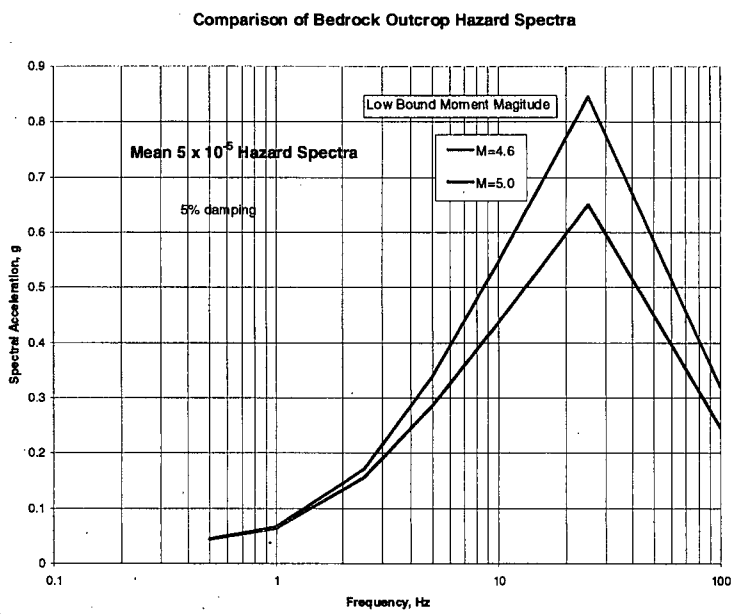

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G1.2 Task Alternatives Considered

- **Option 1 – Justify Higher Lower Bound Magnitude Cutoff**
  - Research new earthquake data
  - Integrate appropriate test data and IPEEE data
  - Update previous EPRI study with new data
- **Option 2 – Correlate Earthquake Magnitude with Associated CAV Data to Estimate the Probability that Ground Motions from Small Earthquakes are Potentially Damaging**
  - 0.16 g-sec criteria for non-damaging earthquakes
  - Regulatory Guide 1.166 (1997)
  - This procedure leads to a smooth transition in the magnitude contribution, rather than an abrupt cutoff

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G1.2 Status

- **Project Meeting April 7**
  - Second Approach using CAV may provide best/clearest path for dealing with lower bound magnitude events
  - Sample curves for Western US earthquakes developed for PGA by Dr. Norm Abrahamson
- **April 26 Meeting**
  - Consensus agreement for using CAV data and probabilistic definition of lower bound magnitude effects
- **June 23 Meeting (Move up of July Meeting)**
  - TRAG and NRC review of status
- **Future Scheduled Meetings**
  - July (ARES) and October (DC)

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CAV Approach for G1.2

- **Task 1 - Initial Trial Application**
  - Compute the 10 Hz and 20 Hz hazard curves for the North Anna site using the USGS source model and the Toro et al (1997) attenuation relation
  - Re-compute the hazard using the WUS Probability (CAV>0.16g-sec) model
  - Assess the impact of this approach
- **Task 2 - Document WUS Probability (CAV>0.16g-sec) Model**
  - Prepare documentation of the development of the Probability (CAV>0.16g-sec) model for PGA and spectral frequencies of 20 Hz, 10 Hz, and 5 Hz, 2.5 Hz, and 1 Hz

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CAV Approach for G1.2

- **Task 3 - Develop new Probability (CAV>0.16g-sec) model for EUS ground motions**
  - Ground motion models for the EUS are primarily based on the point source stochastic model
  - CAV can also be computed from the point source stochastic model
  - Develop/Calculate Probability (CAV>0.16g-sec) as a function of magnitude and spectral acceleration for the EUS
  - Consistent with the attenuation relations used in the hazard analysis

CAV Approach for G1.2

- **Task 4 - Compare EUS Probability (CAV>0.16g-sec) model with empirical data from the EUS**
  - Small number of strong motion recordings from EUS
  - Collect available EUS data
  - Calculate CAV values from this EUS data
  - Compare to the model from previous task as a check on the model

CAV Approach for G1.2

- **Task 5 - Trial Application**
  - Use the EUS Probability (CAV>0.16g-sec) model
  - Compute UHS spectra at 2 Example Sites in EUS
- **Task 6 - Documentation**
  - EPRI Report documenting results of task
- **Potential Phase 2**
  - Create new UHS spectra for 28 CEUS Sites

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New Plant Seismic Issues Resolution Program

Status

Task G1.2 – Lower Bound Magnitude Characterization

by
Norm Abrahamson

June 23, 2005

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Empirical Model of CAV

- **WUS Data Set (PEER Next Generation Attenuation)**
  - 2,395 recordings (shallow crustal earthquakes in active tectonic regions)
  - Magnitudes: 4.4 - 7.9
  - Distances: 0 - 300 km
  - Site Vs30: 160 - 2000 m/s (shear wave in top 30 meters)

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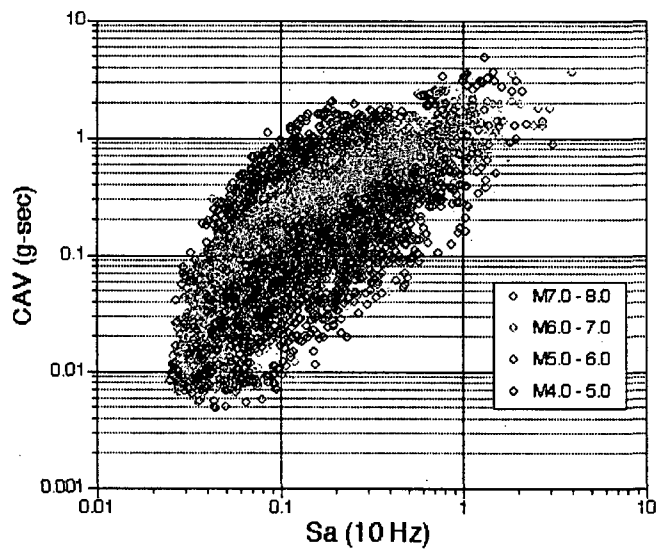
CAV from WUS Data



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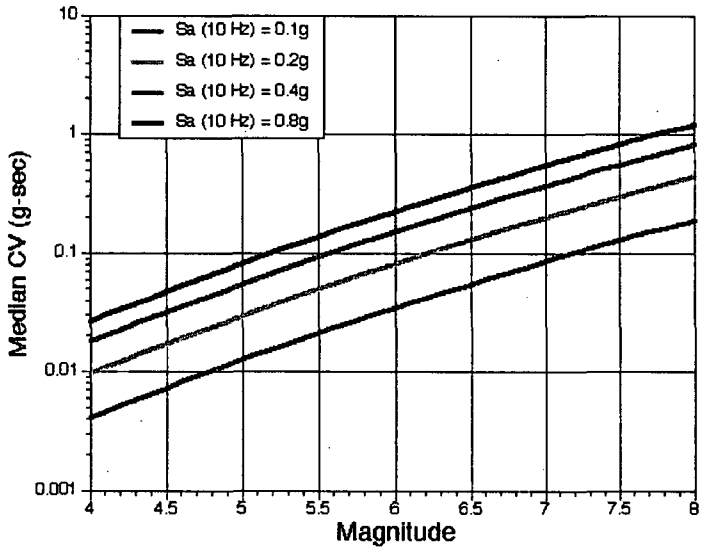
Median CAV Model from WUS Data for Hard Rock (Vs30-2800 m/s)



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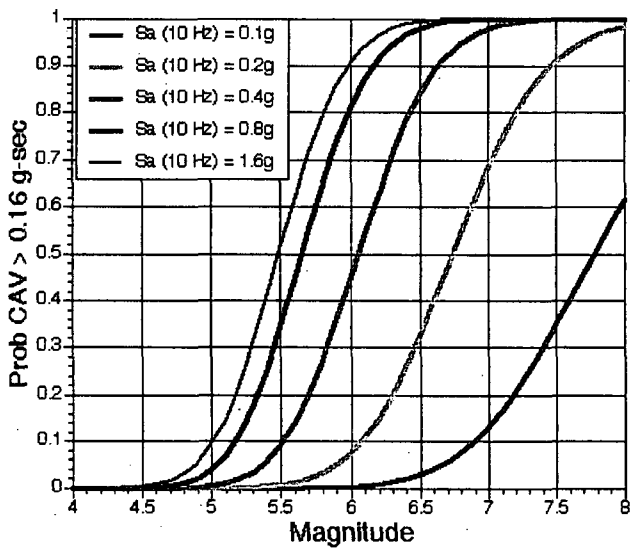
Probability of CAV Exceeding 0.16-g sec



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Probability of CAV Exceeding 0.16-g sec

- **Such functions are regressions of actual data and would be generated for:**
  - PGA
  - Spectral accelerations at 25 Hz, 10 Hz, 5 Hz, 2.5 Hz, and 1 Hz for use with Hazard attenuation models

CAV Filtered Hazard Curves

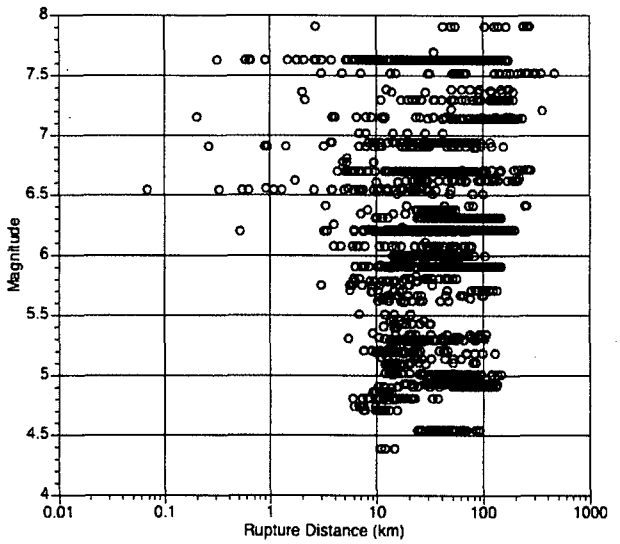
Norm Abrahamson

June 23, 2005

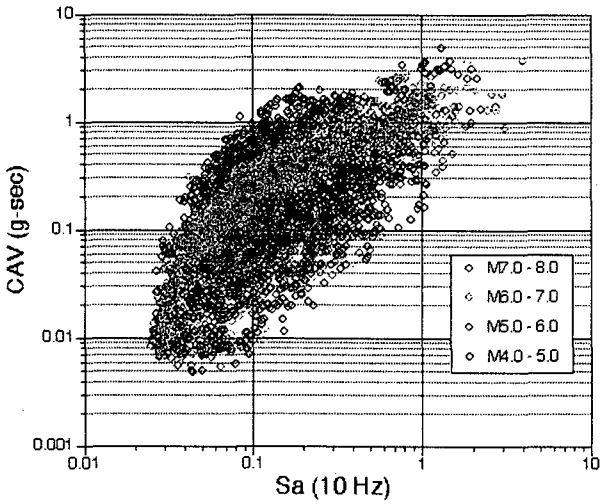
CAV Filtered Hazard

- Potentially Damaging Ground Motion
  - CAV > 0.16g-sec
- Develop a model that allows earthquakes that are not potentially damaging to be removed from the hazard curve
  - Remove earthquakes with CAV < 0.16g-sec

WUS Data Set

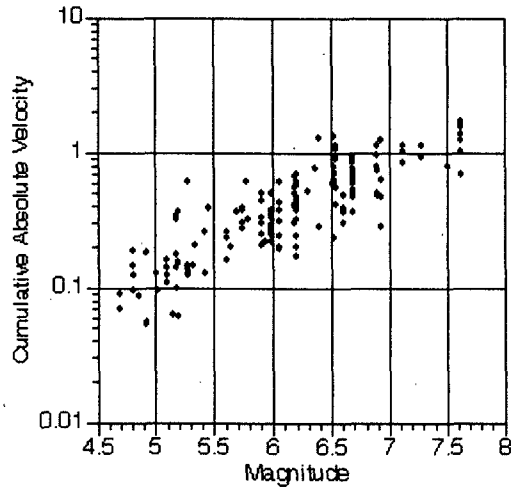


CAV from WUS Earthquakes



Magnitude Dependence

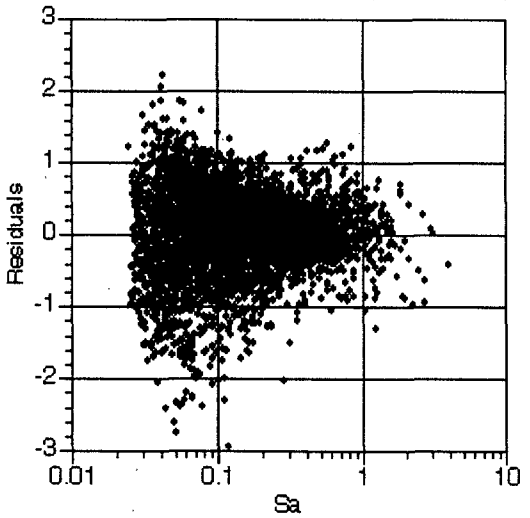
0.4g < Sa(10 Hz) < 0.5g



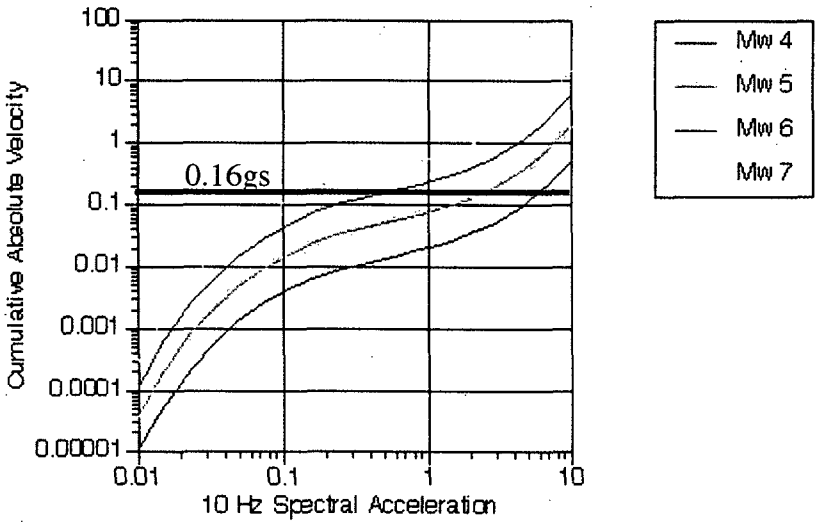
Preliminary Model

- CAV depends on
  - Magnitude
  - Distance (weak)
  - Spectral acceleration
  - Site Condition (Vs30)

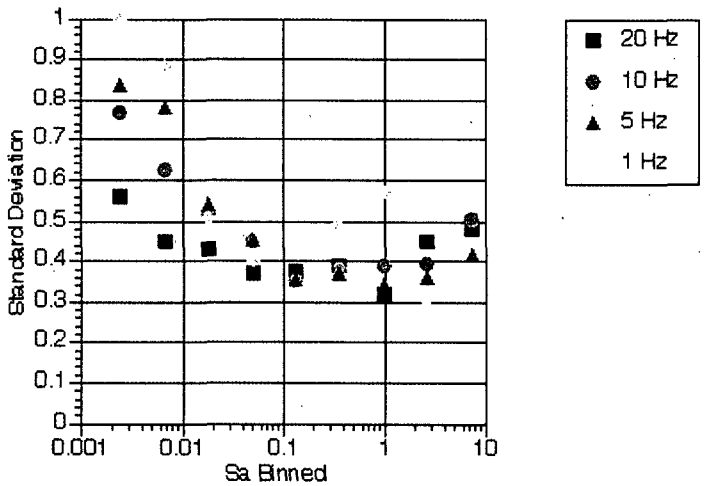
Residuals - Sa(10Hz)



Median CAV model results
Rrup = 15km and Vs30 = 2800 m/s



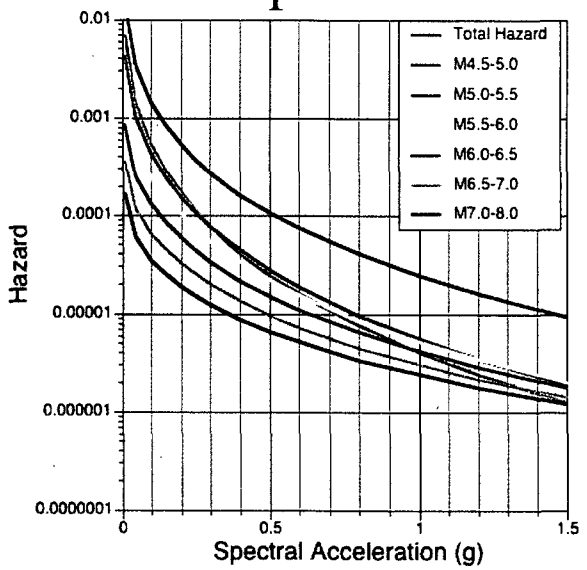
Standard Deviation of CAV depends on the Sa Level



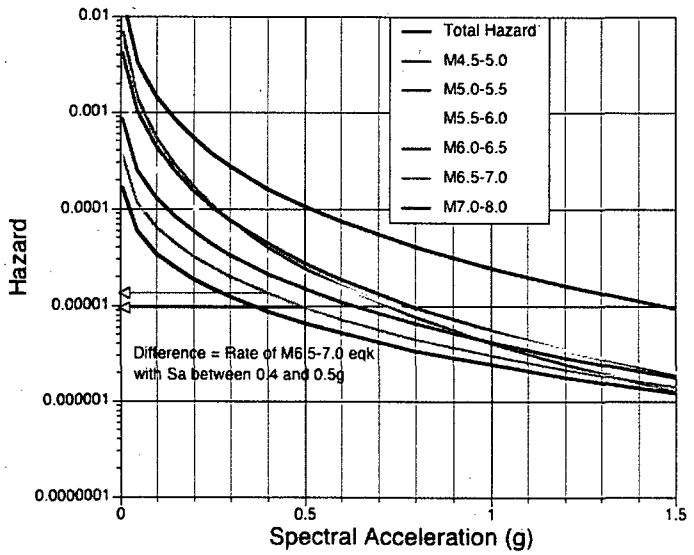
Application of CAV Filtering

- Given Rock Site Hazard
  - Hazard curve
  - Deaggregation
- Break hazard down into contribution from scenario events
  - Haz(z) * Deagg(M,R,z)
- Compute Rates of occurrence
  - M, R, z
- Remove events with CAV < 0.16g-s
- Re-Sum rates of events to get hazard curve

Example Hazard



Convert Hazard (rate of exceedance) to Rate of Occurrence



Build Table of Scenario Earthquakes

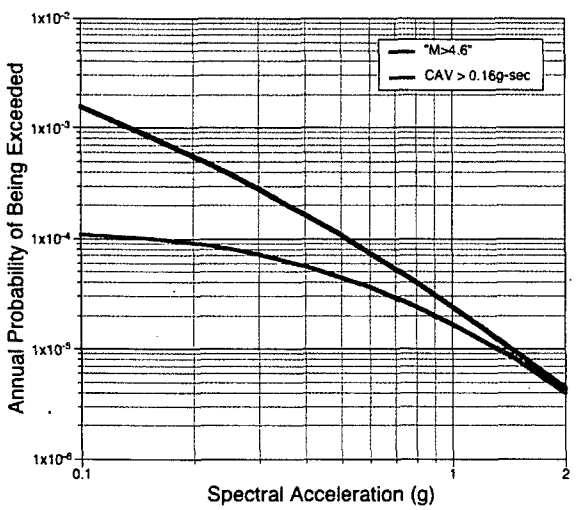
Mag	Dist	Sa (10 Hz)	Rate of Occur	P(CAV>0.16g-s)	Rate with CAV>0.16g-s
5.25	10	0.35	3E-5	0.008	2.4E-7
5.25	10	1.1	2E-6	0.35	7E-7
6.25	15	0.35	1E-5	0.49	4.9E-6
6.25	15	0.90	2E-6	0.95	1.9E-6

Example Hazard: 10 Hz

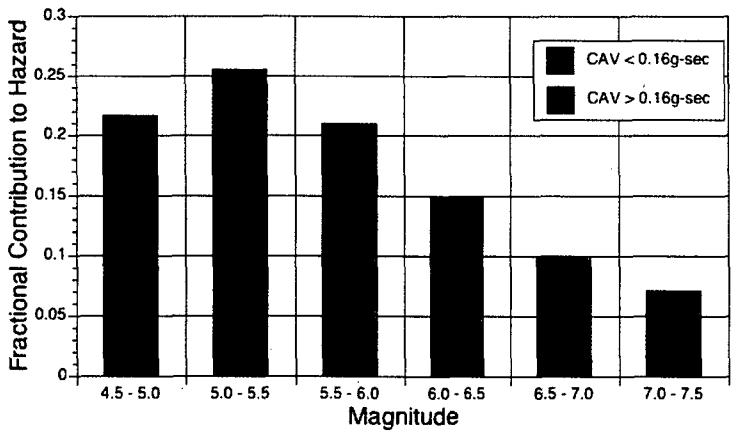
USGS (2002)
Smoothed seismicity

Toro et al (1997)
Attenuation

WUS CAV model



Contribution by Magnitude
Sa(10 Hz) >= 0.6g, M>4.6



Example: CAV Filtering for Soil Sites

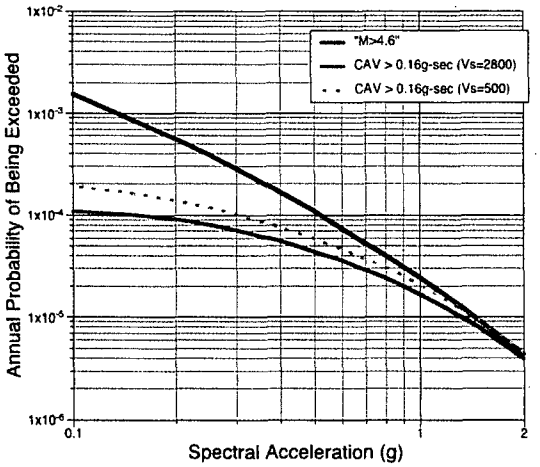
Mag	Dist	Sa Rock Vs=2800	Rate of Occur	Sa Soil Vs=500	P(CAV>0.16g-s) Using Sa Soil	Rate with CAV>0.16g-s
5.25	10	0.35	3E-5	0.50	0.03	9E-7
5.25	10	1.1	2E-6	1.60	0.7	1.4E-6
6.25	15	0.35	1E-5	0.50	0.7	7E-6
6.25	15	0.90	2E-6	1.30	1.0	2E-6

Example Hazard: 10 Hz

USGS (2002)
Smoothed seismicity

Toro et al (1997)
Attenuation

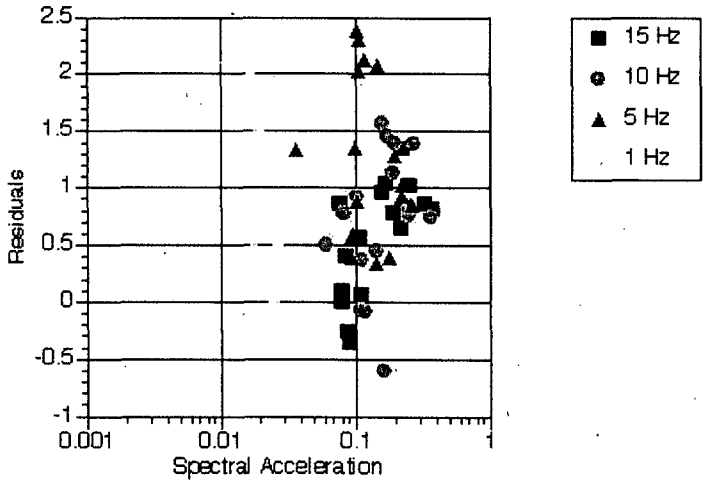
WUS CAV model



Test of the WUS CAV Model for EUS Earthquake

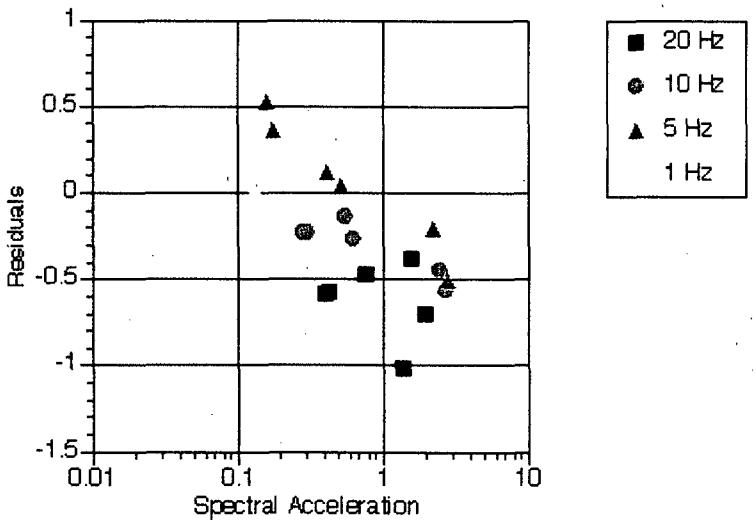
- Saguenay
  - M5.9
  - Distances ~60-200 km
- Nahanni
  - M6.8
  - Distances 8-16 km
  - Located in NW Territories but considered to be representative of EUS high frequency content

CAV Residuals for Saguenay



Res = Predicted − Observed

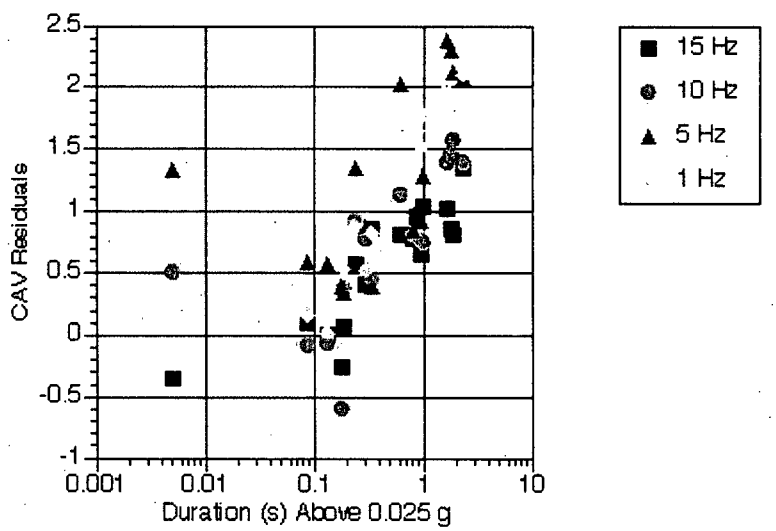
CAV Residuals for Nahanni



Need Revised CAV Model for EUS Earthquakes

- Preliminary model significantly underpredicts CAV for Saguenay
- Need to consider additional parameters
  - Duration
  - RMS acceleration

Duration Dependence from Saguenay



How to Use Additional Parameters

- Duration and RMS acceleration not directly available from hazard analysis
  - Develop empirical models for WUS earthquakes
  - Use seismological models to estimate duration and RMS acceleration for EUS
    - This is based on the same point source stochastic model this is the basis for the most attenuation relations used in the EUS

New Plant Seismic Issues Resolution Program

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

by
Greg Hardy, ARES

June 23, 2005

June 23rd S2.1 and G1.2 Meeting Agenda

- Welcome – Introductions (Hardy)
- ESP Task S2.1 Description & Goals – (Hardy)
- Summary of Diablo Canyon Use of Incoherence – (Short)
- Abrahamson Coherency Function – (Abrahamson)
- ARES Approach for Considering Coherency – (Short/Johnson)
- Bechtel Approach for Considering Coherency – (Ostadan)
- Benchmark Problem Comparison – (Short/Johnson/Ostadan)
- S2.1 Results, Schedule and Milestones – (Short/Johnson)
- G1.2 Task Description – (Hardy)
- G1.2 Status – (Abrahamson)

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**

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 (presentation by Dr. Norm Abrahamson)
  - Objective of this study is to systematically study the ground motion incoherency effects on typical NPP structures/foundations
  - Structures/foundations similar to those being considered for Advanced Reactor designs

Prior Incoherence Studies

- **NUREG/CR-3805, "Engineering Characterization of Ground Motion", Vols. 1-5, 1986 developed recommendations to account for incoherence**
- **Response spectrum reduction factors were developed as function of foundation plan dimension and frequency**
- **These recommendations were incorporated into EPRI NP-6041, "A Methodology for Assessment of Nuclear Power Plant Seismic Margin", 1991 and also DOE Standard 1020 and ASCE 4**
- **Probabilistic spectra were generated for the Diablo Canyon Long Term Seismic Program which used measured site coherency functions**

Summary – Diablo Canyon & Incoherency

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

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:**
    - **EPRI Parkfield**
    - **Chiba, Japan**
    - **Coalinga**
    - **UCSC ZIYA**
    - **Pinyon Flat**

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 knockdown factors to be applied to the seismologically defined seismic ground motion to account for the effects of incoherence on NPP structures/foundations as a function of foundation size, site conditions, and other relevant parameters (ARES)**
  - apply to the Fourier amplitude spectrum
  - develop an effective low-pass digital filter
- **The modified Fourier amplitude spectra and the original Fourier phase spectra will be used to develop new input ground motion time histories that account for incoherency**
- **Validate incoherence response knockdown factors and their implementation:**
  - CLASSI (ARES)
  - SASSI (Bechtel)
- **Verify that the approach gives accurate and reasonable seismic response**

Conclusions/Decisions from Past Meetings

- **Coherency functions are appropriate for all frequencies (including above 20 Hz)**
- **The slowness (s) of 0.00025 sec/m is conservative with respect to translation input but may tend to increase torsion/rocking input. A parametric case using s of 0.0005 sec/m will be performed to assess the effects of torsion/rocking input.**
- **For the purposes of this Task S2.1 study, Dr. Norm Abrahamson concluded:**
  - 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 and mean coherency will be used. A parametric case study will be run with an 84% NEP coherency function.**

Abrahamson Coherency Function

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

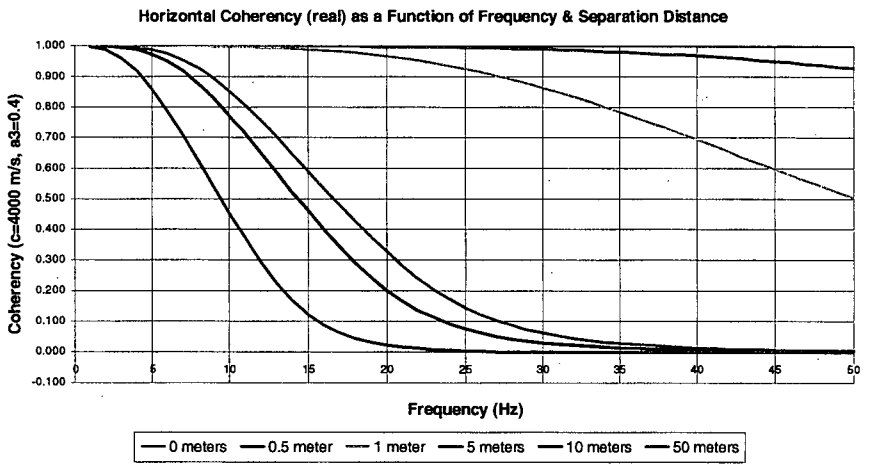
$$\gamma = |\gamma_{PW}|\left[\cos(2\pi\xi_R s) + i\sin(2\pi\xi_R s)\right] = |\gamma_{PW}|e^{i2\pi\xi_R s}$$

- **where γ is the total coherency function and γ_{PW} is the plane wave coherency function**
- **For horizontal ground motion : a_1=1.647; a_2=1.01; a_3=0.4; n1=7.02; n2=5.1-0.51ln(ξ+10); s=0.00025 s/m (c=4000 m/s); f_c=-1.886+2.221ln(4000/(ξ+1)+1.5)**
- **For vertical ground motion : a_1=3.15; a_2=1.0; a_3=0.4; n1=4.95; n2=1.685; s=0.00025 s/m (c=4000 m/s); f_c=exp(2.43-0.025 ln(ξ+1)-0.048 (ln(ξ+1))^2)**

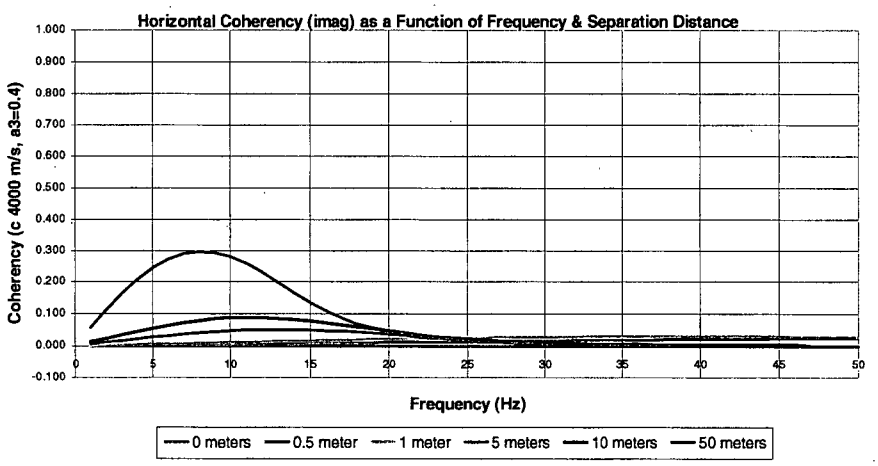
A median Coherency Function

A mean Coh Function will be derived – NRC will need to decide on use of mean vs median

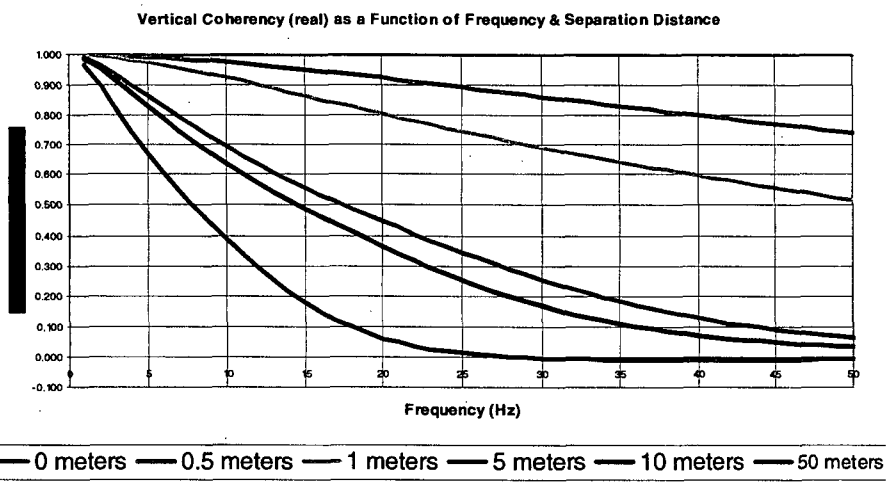
Abrahamson Coherency Function (cont.)



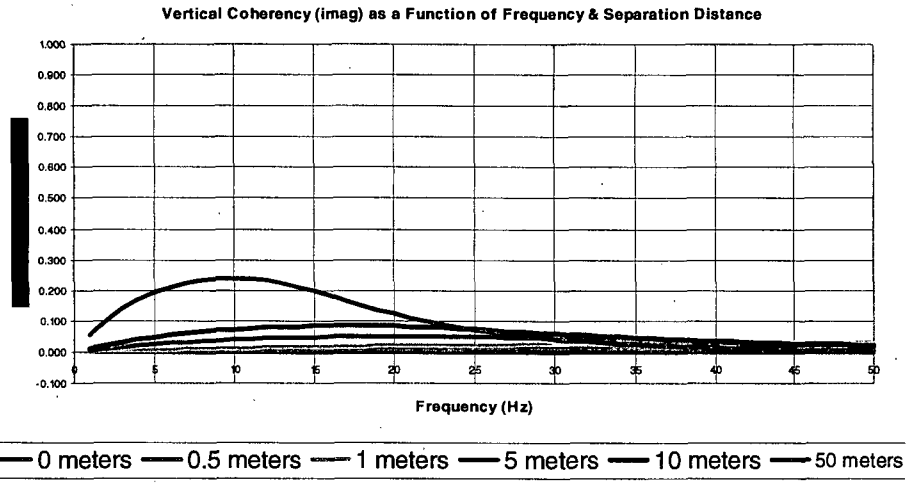
Abrahamson Coherency Function (cont.)



Abrahamson Coherency Function (cont.)



Abrahamson Coherency Function (cont.)



ARES Approach

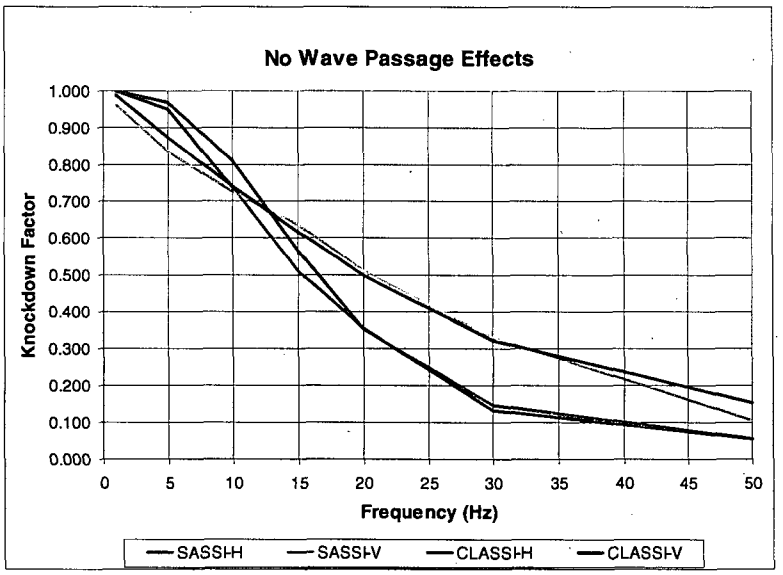
RPK prefers/insists of calling this Coherency Transfer Function

- **Stochastic Approach**
  - Knockdown factors developed for rigid massless, foundation & validated to be appropriate by evaluating structure response for a typical NPP structure
  - Initial effort is independent of ground motion definition
- **Power Spectral Density (PSD) - Response Spectra by Random Vibration Theory (RVT)**
- **Coherency as a function of separation distance, frequency, apparent wave velocity, and direction of motion from Dr. Norm Abrahamson**
- **Knockdown factors generated for rigid, massless foundation using CLASSI**
  - Intent is to apply knockdown factors to Fourier amplitude spectra in the free-field -- the end result being an engineering modified motion accounting for incoherency effects and to be used in subsequent SSI analyses to generate structure response
- **Knockdown factors validated for complete SSI using CLASSI**

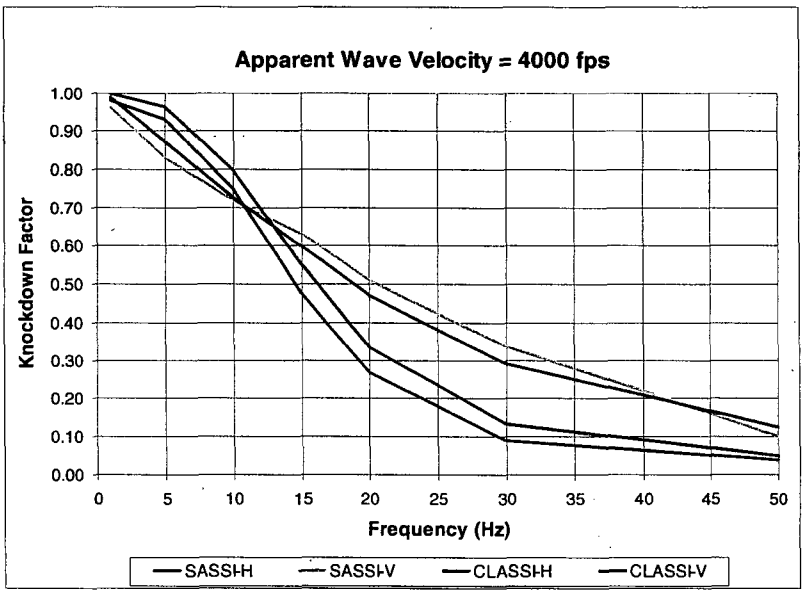
Bechtel Approach

- **SASSI Implementation**
  - Incorporate the ground motion incoherency model from Luco or Abrahamson
  - Develop the coherency matrix for all interaction nodes for each frequency of analysis,
  - Decompose the matrix (complex) to get eigen vectors (mode shapes) and eigen values (modal) weights
  - Combine the modes with respective weights (choice of few modes or all modes) to get free-field motion for all interacting nodes

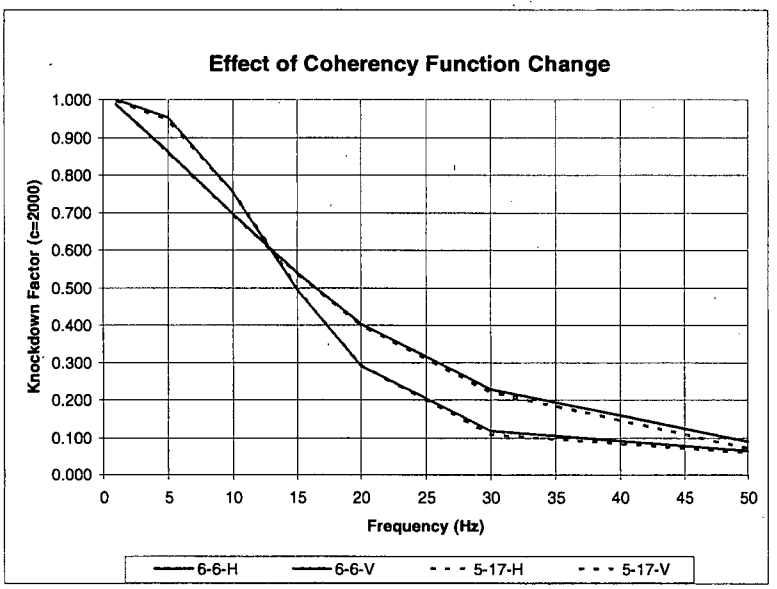
CLASSI-SASSI Comparisons



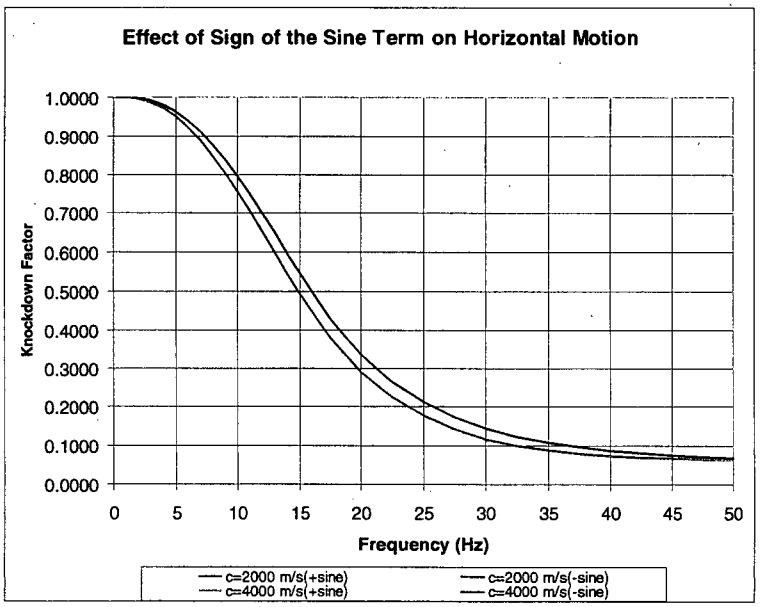
CLASSI-SASSI Comparisons (cont.)



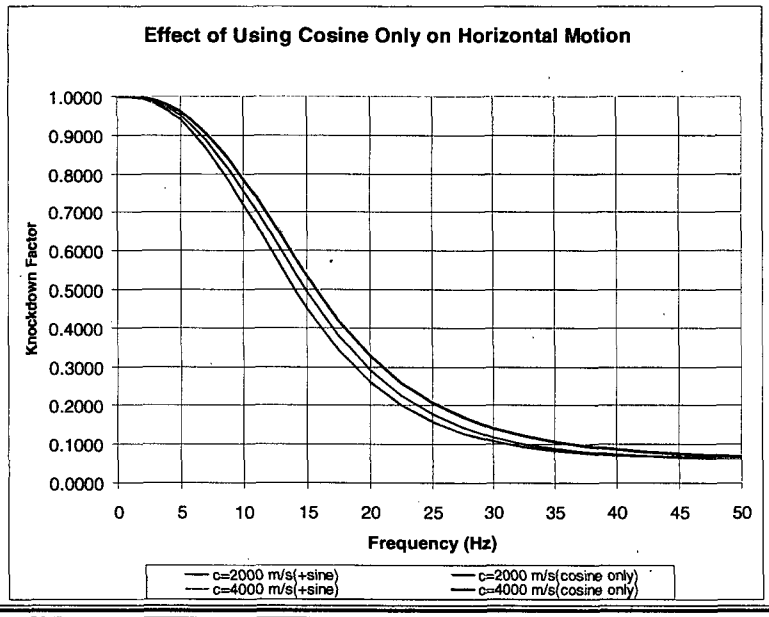
Effect of Coherency Function Change



Effect of Sign of the Wave Passage Sine Term



Effect of Using Wave Passage Cosine Term Only



S2.1 Analysis Cases

- Scattered incoherent rigid massless foundation input – 20 cases
  - 2 site conditions/ground motion
  - 2 foundation footprints
  - 3 directions – H1; H2 (rectangular fdn); V
  - 2 coherency functions; NAA, coherent;
  - Develop knockdown factors
- SSI inertial interaction foundation & structure response – 6 cases
  - 1 site condition/ground motion
  - 1 foundation footprint
  - 1 structural model
  - 3 directions - H1; H2; V
  - 2 coherency functions; NAA, coherent w/knockdown factors
- Parametric Studies – 3 cases
  - Another apparent wave velocity (2 km/s) for one case
  - 84% coherency function for one case
  - Benchmark with SASSI (surface rigid) NAA coherency function
  - Embedment; foundation flexibility performed in SASSI by Bechtel and compare knockdown factors with those of CLASSI surface rigid

S2.1 Analysis Cases (cont.)

Response Locations	H1	H2	V	Combined	Total
Rigid, massless Fdn - NAA	4	2	4	0	10
Rigid, massless Fdn - coherent	4	2	4	0	10
Fdn/Structure after SSI - NAA	1	1	1	0	3
Fdn/Structure after SSI - KD	1	1	1	0	3
2 km/s apparent wave velocity	1	0	0	0	1
84% coherency function	1	0	0	0	1
SASSI benchmark	1	0	0	0	1

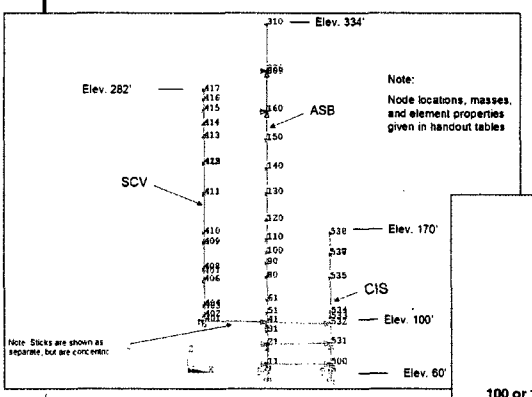
S2.1 Foundation Footprints

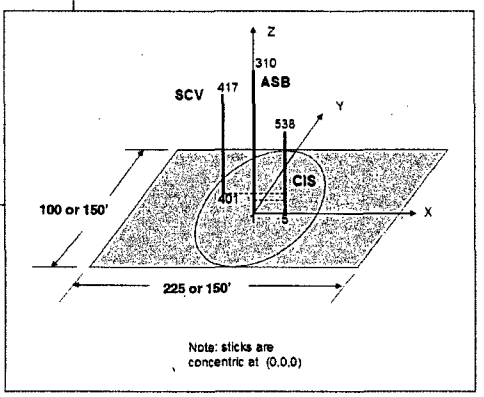
- A square and a rectangular foundation footprint will be considered
  - Rectangular foundation 225 feet by 100 feet
  - Square foundation 150 feet by 150 feet
- These are representative of potential advanced reactor designs (AP 1000 and ESBWR)
- These footprints are of equal area such that they will demonstrate the influence of foundation shape
- The 150 foot square foundation will be used for comparisons with the SASSI approach by Bechtel

S2.1 Structural Model

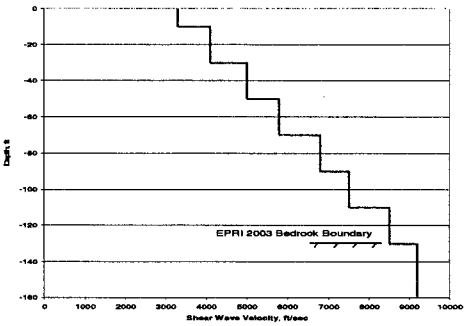
- The main containment/auxiliary building stick model for the AP 1000 design will be used.
- This model includes the following three sticks representing concentric parts of the AP 1000
  - Coupled Auxiliary & Shield Building (ASB) – 3 Hz horizontal; 6 Hz vertical
  - Steel Containment Vessel (SCV) – 6.3 Hz horizontal; 17 Hz vertical
  - Containment Internal Structure (CIS) – 10 Hz

S2.1 Structural Model (cont.)

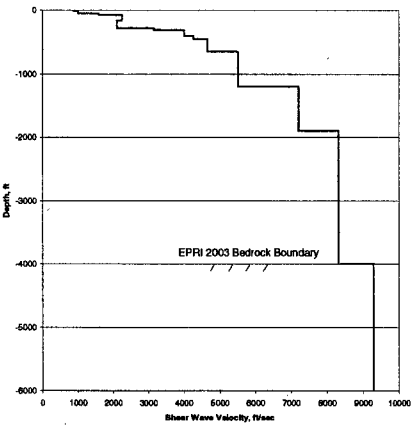




S2.1 Soil Profiles

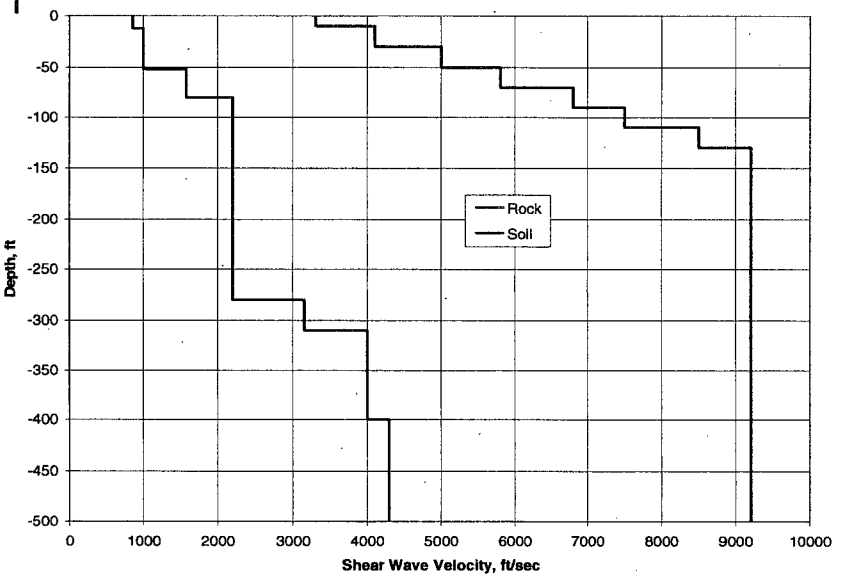


High Frequency Rock Site

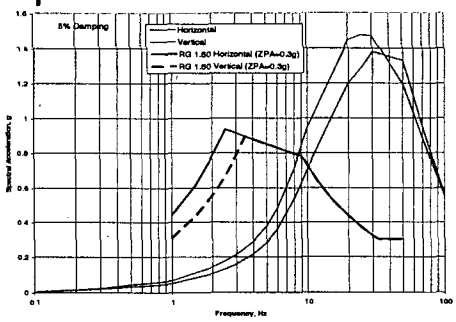


Lower Frequency Soil Site

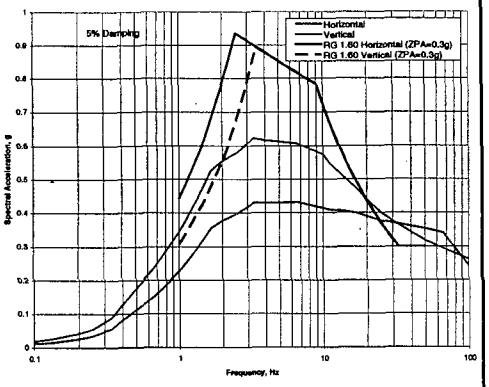
Rock and Soil Profiles within 500 feet of Surface



S2.1 Ground Response Spectra



Site specific response spectra for Rock Site

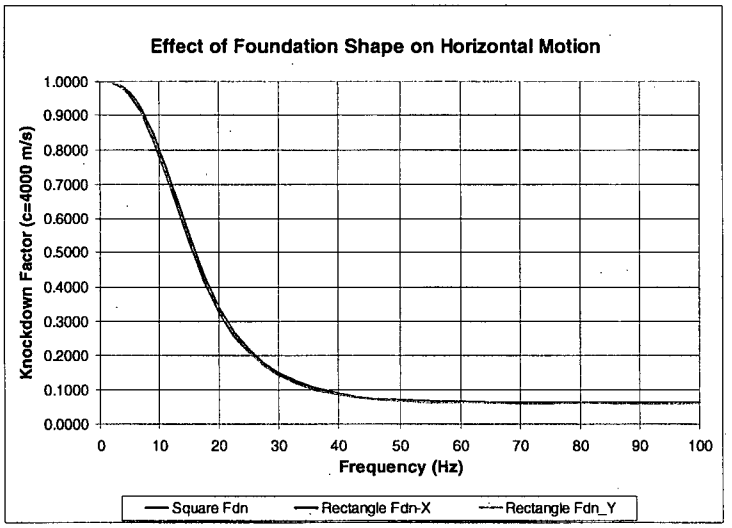


Site specific response spectra for Soil Site

S2.1 Project Milestones

- Define cases to be analyzed (4/21/2005)
  - Site conditions
  - Foundation characteristics
  - Structural characteristics
- Ground motion input (5/3/2005)
  - Response spectra
  - Coherency functions (all but uncertainty bands)
  - PSD by random vibration theory
- Knockdown Factor Development
  - Rigid-Massless Foundation Rock (6/17/2005)
  - Rigid Massless Foundation Soil (7/22/2005)
  - Knockdown Factor SSI Validation (9/1/2005)
- Sensitivity studies (6/17/2005)
  - 2 km/s apparent wave velocity
  - 84 % coherency function (not completed)

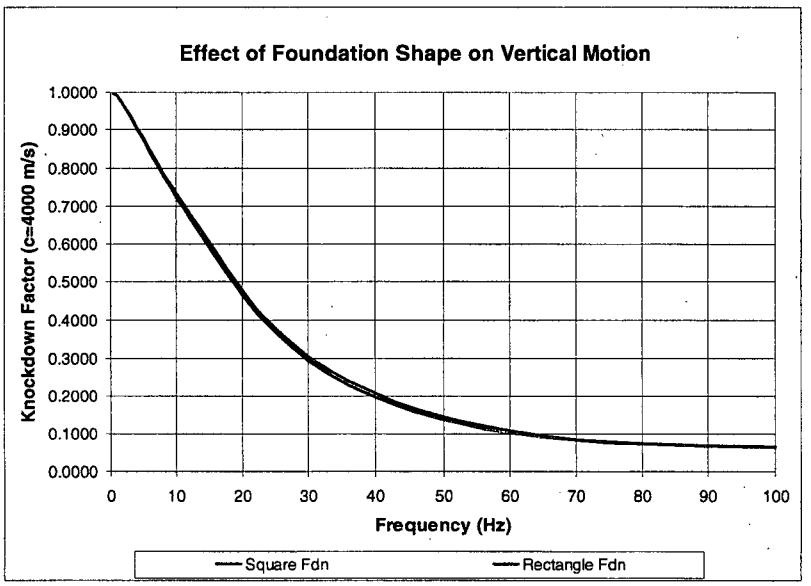
S2.1 Results – High Frequency Rock Site



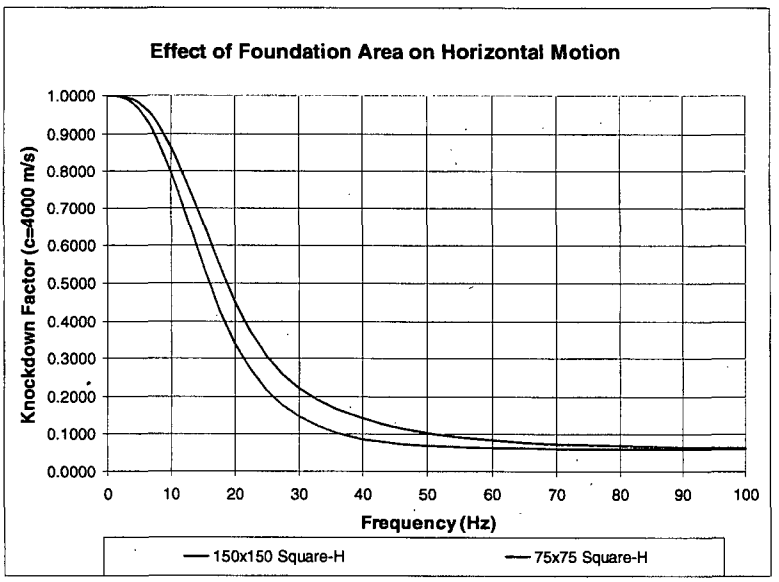
Rectangle and Square Foundations Have the Same Area

Foundation Shape Does Not Affect Knockdown Factors

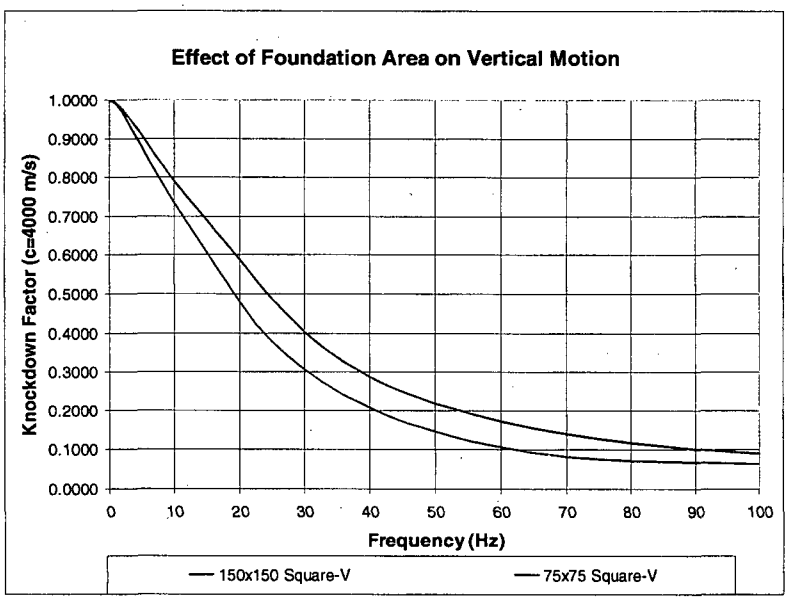
S2.1 Results – High Frequency Rock Site



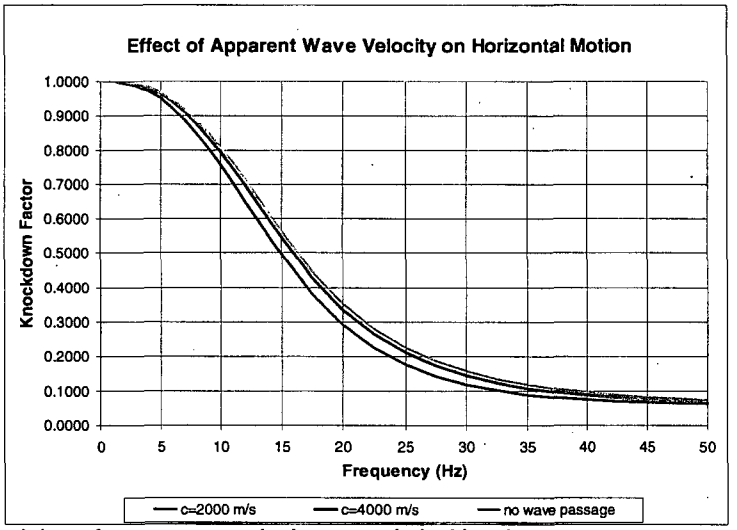
S2.1 Results – High Frequency Rock Site (cont.)



S2.1 Results – High Frequency Rock Site (cont.)



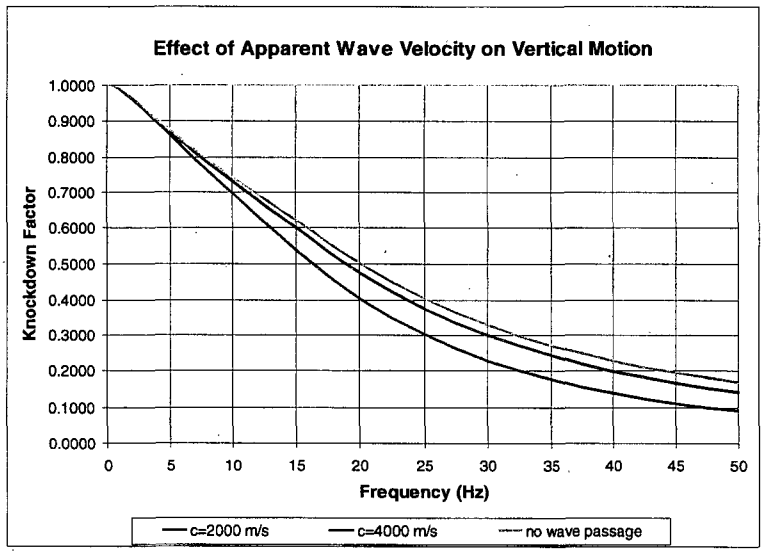
S2.1 Results – High Frequency Rock Site (cont.)



Knockdown factors are mostly due to statistical incoherence

Wave passage effects are small

S2.1 Results – High Frequency Rock Site (cont.)



Status/Schedule of S2.1 Tasks

- **Coherency function defined (report in process)**
- **Programming function into CLASSI in process (complete for rigid massless foundation; in progress for structure response by Random Vibration Theory)**
- **Parameters for response analysis defined**
  - Site conditions (soil site and rock site)
  - Ground motion characteristics representative of ESP sites
  - Foundation characteristics representative of Advanced Reactor Designs
  - Structure characteristics representative of Advanced Reactor Designs
- **Development of reduction factors in June/July**
- **Sensitivity Studies in August/September**
- **Final Report in November**

Spatial Coherency Models

Norm Abrahamson

June 23, 2005

Spatial Coherency

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

Spatial Coherency Measures

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

Estimation of Coherency

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

Dense Array Characteristics

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

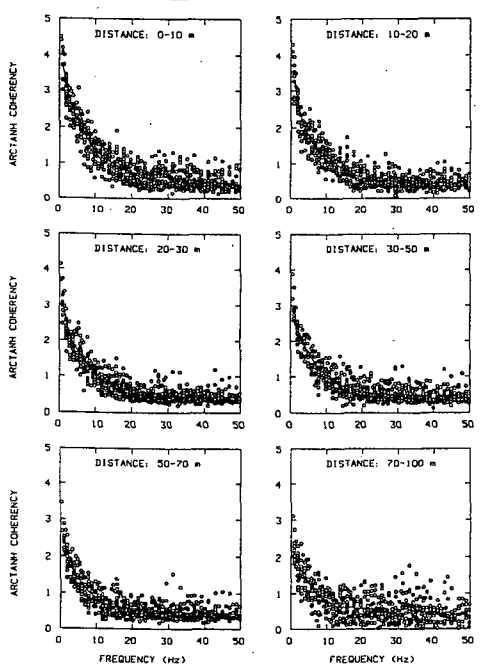
Dense Array Data Sets

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

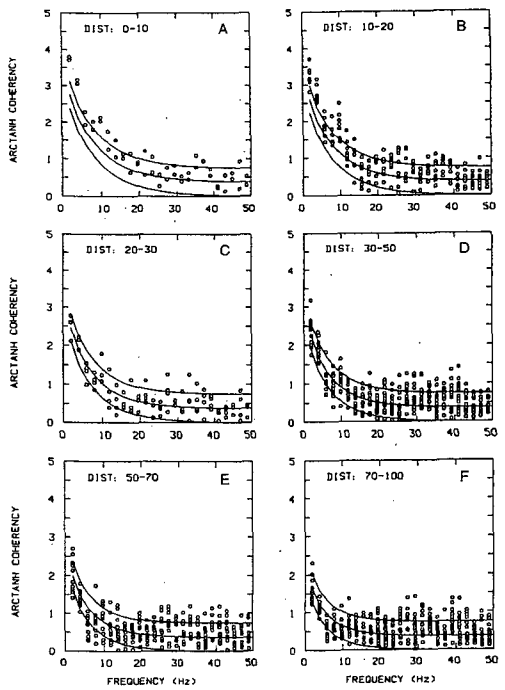
Site Dependence

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

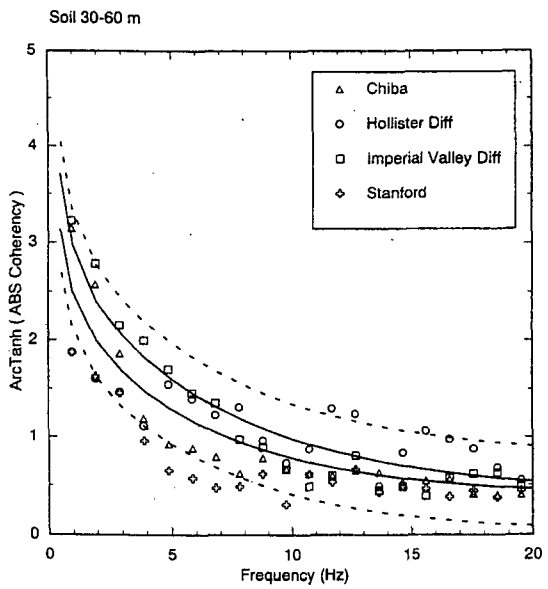
Lagged Coherency From the EPRI LSST Array



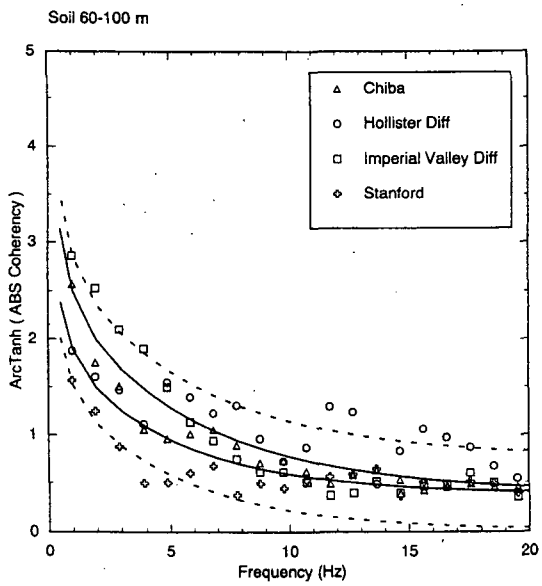
Comparison of EPRI Parkfield (Rock site) with the LSST Coherency Model



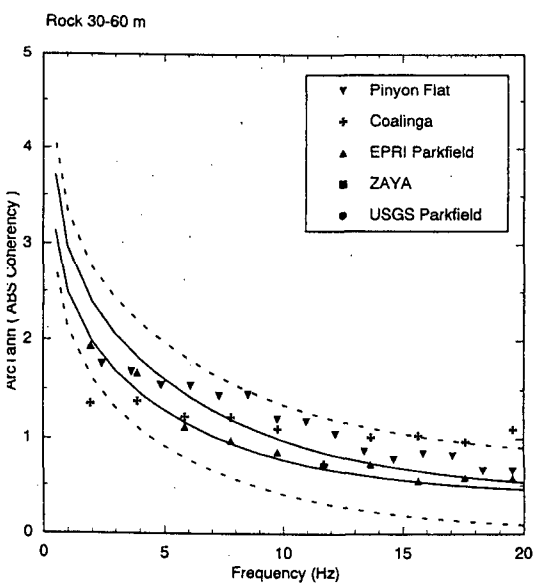
Comparison with Other Soil Sites 30-60m



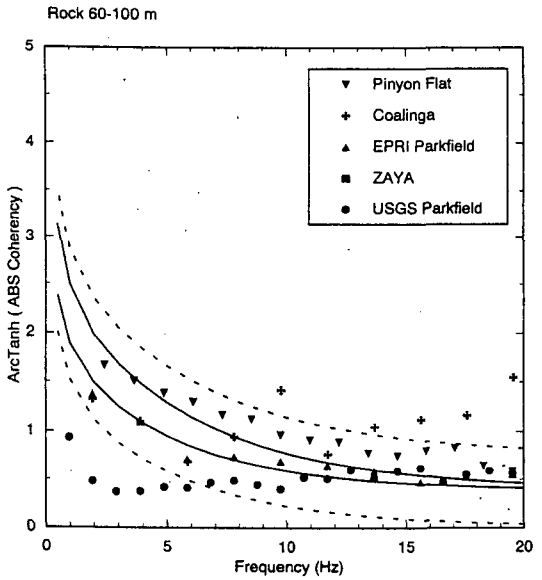
Comparison with Other Soil Sites 60-100m



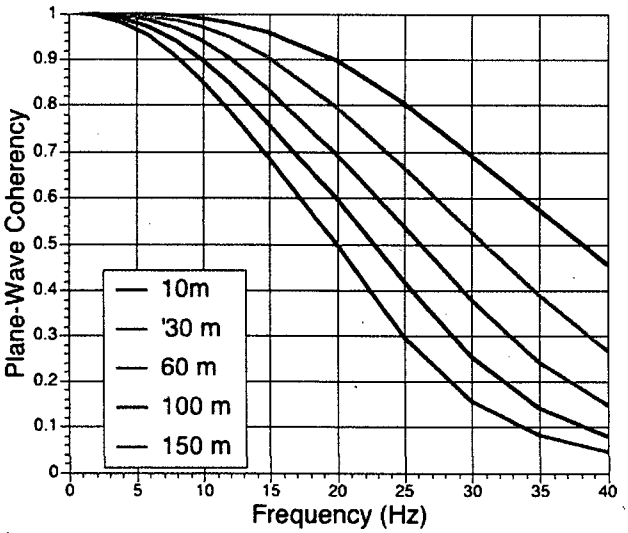
Comparison with Rock Sites 30-60m



Comparison with Rock Sites 60-100m



Median Horizontal Coherency



Summary

- Plane-wave coherency is the appropriate coherency measure for use in SSI
  - Requires wave-speed to be specified
- Coherency is not strongly affected by soil condition, but is affected by topography
- Need to check high frequency (e.g. 20 Hz) using shorter time windows
  - May lead to increase in coherency at high frequencies

norm will try shorter time windows