Probabilistic Simulation Procedure for Developing Site-Specific Plane-Wave Coherence Functions

Ghiocel Predictive Technologies Inc.

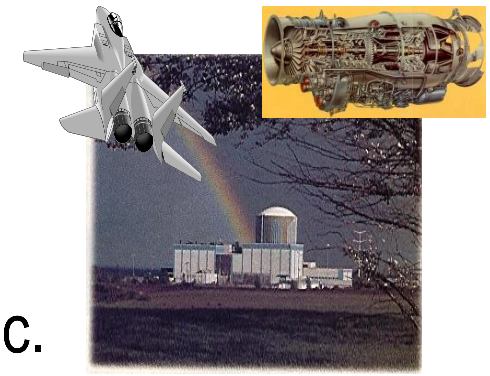
Dr. Dan M. Ghiocel

Email: dan.ghiocel@ghiocel-tech.com

Phone: 585-641-0379

Ghiocel Predictive Technologies Inc.

http://www.ghiocel-tech.com



DOE/NRC Natural Phenomena Hazards Meeting

US NRC Headquarters, Rockville, MD

October 23-24, 2018

Purpose of This Presentation:

To show the possibility of using probabilistic simulation to compute the site-specific coherence functions using 2D probabilistic site-responses. Only horizontal site-specific coherence functions were considered so far.

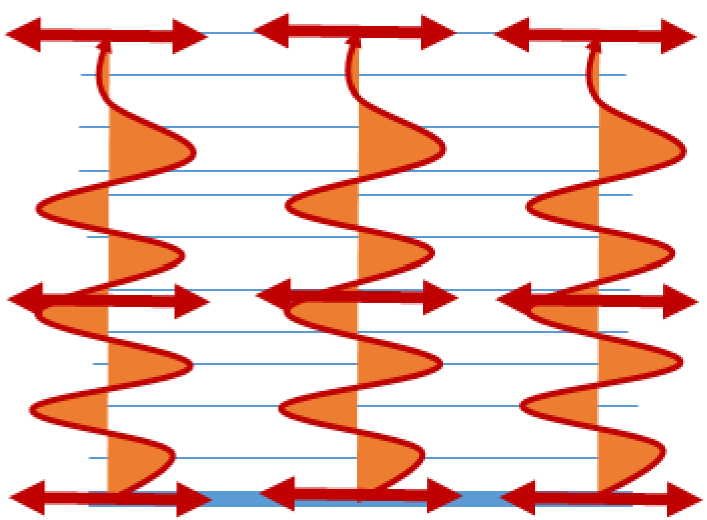
Results are promising and in tone with the research work in EDF that uses 2D probabilistic site-responses to compute site-specific coherence functions for soil deposits with horizontal layering or inclined layering or topographic features.

Content:

1. Introduction to Motion Incoherency Modeling
2. Site-Specific Plane-Wave Coherence Functions.
3. Probabilistic Simulation of Soil Layering

1. Introduction to Motion Incoherency

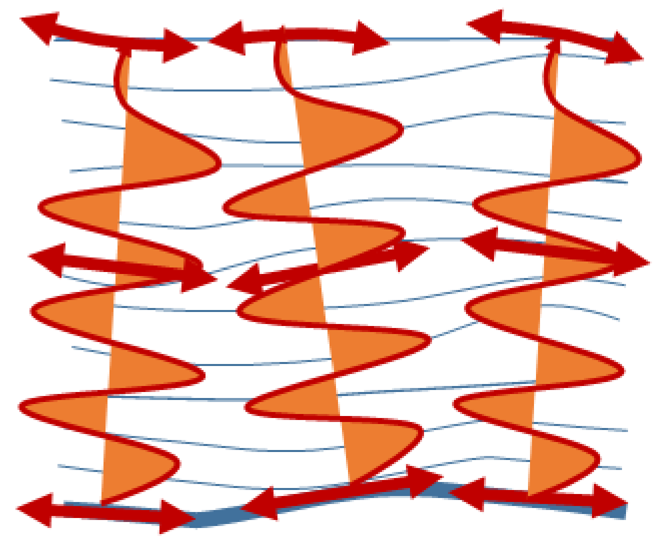
COHERENT



IDEALISTIC MOTION
(1D DETERMINISTIC WAVE MODEL)

Assume vertically propagating S and P Waves in horizontal soil layering

INCOHERENT



REALISTIC MOTION
(3D RANDOM WAVE MODEL)

Based on stochastic models developed from real record dense array databases (Chiba, Lotung, Pinyon Flat, etc.)

Factors Influencing Motion Incoherency

Spatial incoherency is caused by the complex wave propagation random pattern at the site. The main cause of incoherency observed over distances of tens of meters is caused by wave scattering in the top 500 m of the soil/rock deposit (Abrahamson, 2007)

Influential Factors:

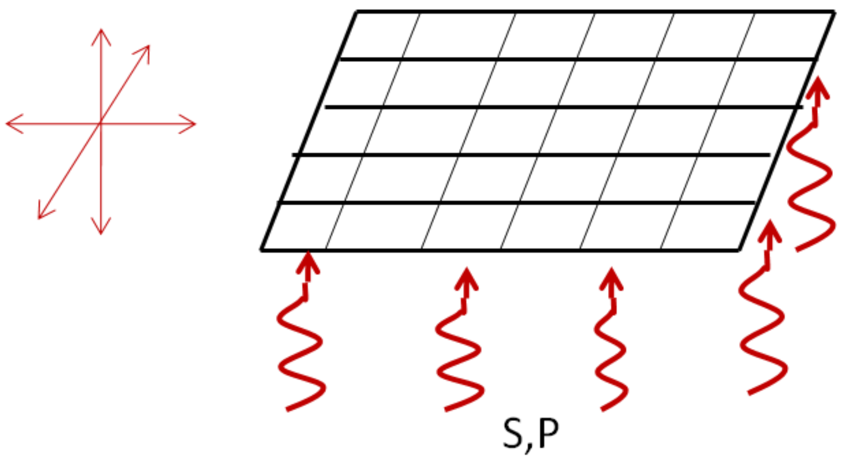
- Soil profile stiffness variation in horizontal directions increases incoherency
- Soil layer inclination, local discontinuities, faults increase incoherency
- Topography features in vicinity could significantly increase incoherency
- Earthquake magnitude is less influential especially for single point source
- For short distances near faults, the multiple wave paths from different parts of fault rupture may drastically increase the spatial variations, both the motion incoherency and wave passage effects
- Focal mechanism and directivity apparently affect less incoherency

Modeling Parameters:

The main parameters for capturing the motion incoherency is its dependence on relative distances between locations and frequency. The latter is stronger.

Coherent vs. Incoherent Wave Propagation Models

3D Rigid Body Motion (Idealized)



1 D Wave Propagation Analytical Model (Coherent)

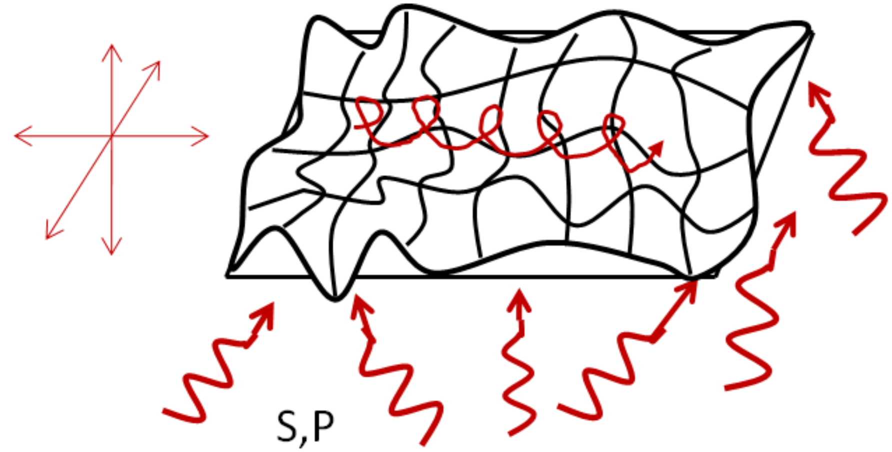
- Vertically Propagating S and P waves (1D)

- No other waves types included

- No heterogeneity random orientation and arrivals included

- Results in a rigid body soil motion, even for large-size foundations

3D Random Wave Field Motion (Realistic)

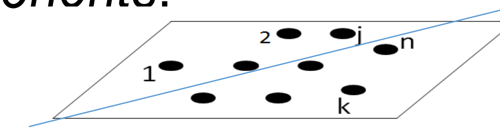


3D Wave Propagation Data-Based Model (Incoherent – Database-Driven Adjusted Coherent)

- Includes real field records information, including implicitly motion field heterogeneity, random arrivals of different wave types under random incident angles.

Motion Incoherency Includes Two Contributing Random Variations; Incoherency & Wave Passage

The motion spatial random variation is a mix of *two components*:



INCOHERENCY (Non-Directional Phenomena):

Measures the lack of similarity of two motions at two separated locations. This lack of similarity is expressed in terms of “correlation coefficient” between the amplitudes of the two motions at each frequency (coherence function).

If relative distance between locations is small, motions are highly correlated.

If relative distance between locations is large, motions are almost uncorrelated.

WAVE PASSAGE (Directional Phenomena):

Produced by the time delay (lag, shift) between two identical motions in a given direction.

If relative time delay locations is small, motions are highly correlated.

If relative time delay is larger, motions are almost uncorrelated.

REMARK: The incoherency and wave passage SSI effects of are qualitatively similar since they both produce lack of spatial correlation between two motions. For NPP structures incoherency is important, for large-span bridges both are important.

Coherence Function Definition for Two Time Series

Cross-Spectral Density (CSD):

$$S_{XY}(\omega) = \frac{2\left|X^*(\omega)Y(\omega)\right|}{2\pi T} = \frac{2}{2\pi T}\sum_{j=1}^{K}\left|\mathrm{Conj}\left[\sum_{t_j=T_{j-1}+dt}^{T_j} W(t_j - T_{j-1})X(t_j)e^{-i\omega t_j}\right]\sum_{t_j=T_{j-1}+dt}^{T_j} W(t_j - T_{j-1})Y(t_j)e^{-i\omega t_j}\right|$$

=

Power Spectral Density (PSD):

$$S_X(\omega) = \frac{2\left|X^*(\omega)X(\omega)\right|}{2\pi T} = \frac{2\left|X(\omega)\right|^2}{2\pi T} = \frac{2}{2\pi T}\sum_{j=1}^{K}\left|\sum_{t_j=T_{j-1}+dt}^{T_j} W(t_j - T_{j-1})X(t_j)e^{-i\omega t_j}\right|^2$$

Coherence Function is defined by:

$$\gamma_{X,Y}(\omega) = \frac{S_{X,Y}(\omega)}{S_X(\omega)S_Y(\omega)}$$

The quality of the coherence spectrum estimates deteriorate inversely proportional with its value between from 0 to 1.

(Ghiocel, 1996)

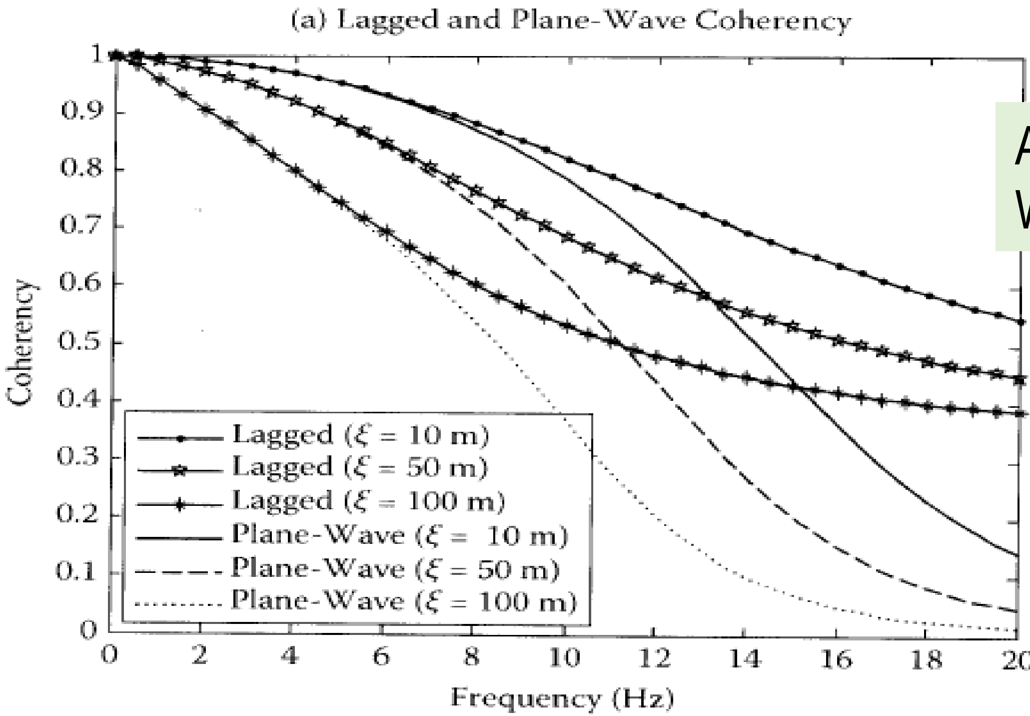
Lagged and Plane-Wave Coherence Functions

Unlagged and Lagged Coherence Functions:

$$\gamma(\omega, x, x') = |\gamma(\omega, x, x')| \exp(i\phi(\omega, x, x'))$$

Plane-Wave (P-W) Coherence Function is defined by

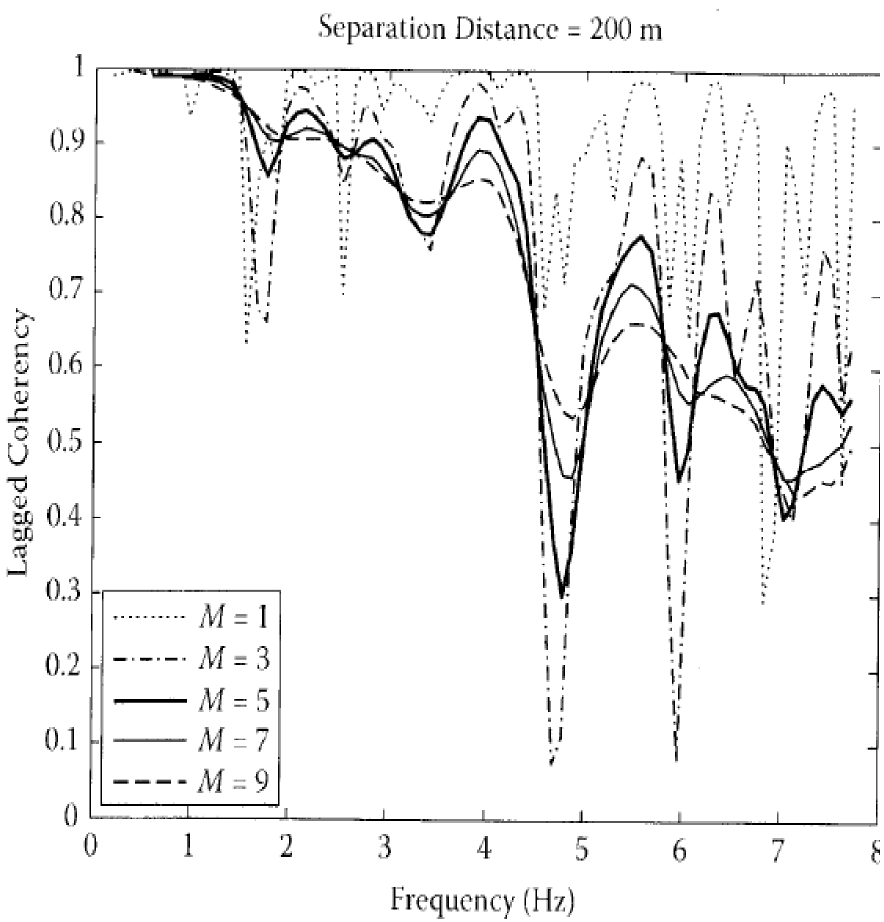
$$\gamma_{PW}\left(\omega, \xi_{x,x'}, \xi^{pw}_{x,x'}\right) = \left|\gamma\left(\omega, \xi_{x,x'}\right)\right| \alpha\left(\omega, \xi^{pw}_{x,x'}\right) \exp\left(-\omega \xi^{pw}_{x,x'} / V_{pw}\right)$$

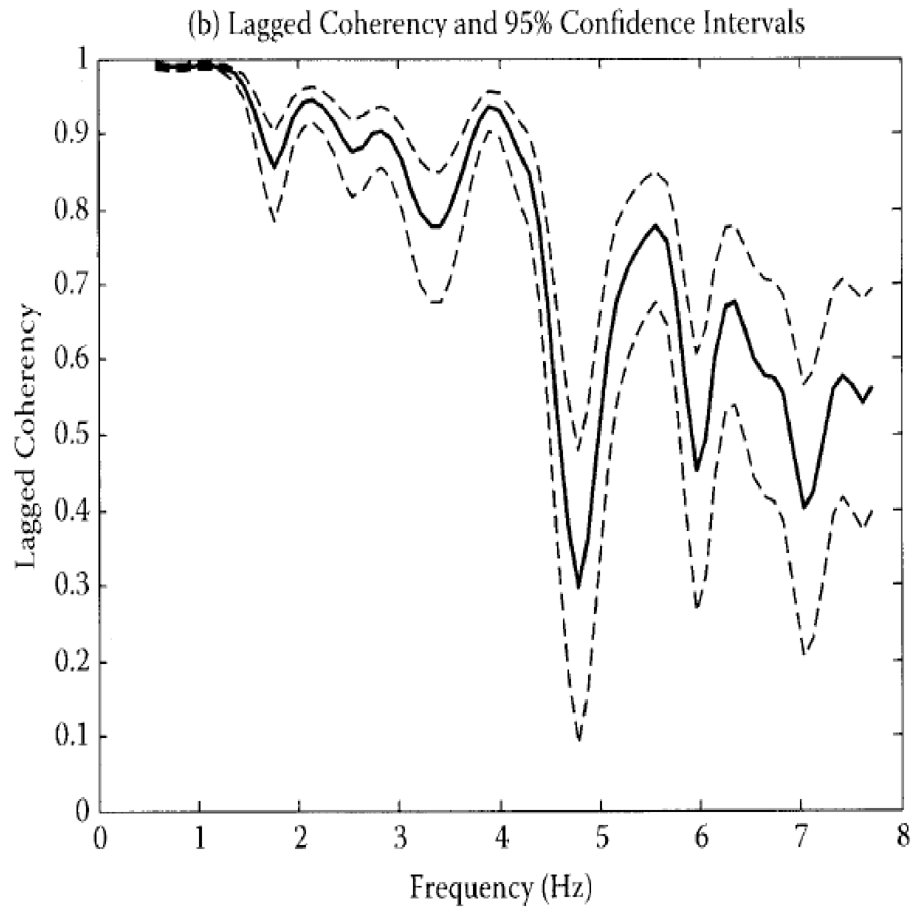


Abrahamson Lagged and Plane-Wave Coherence Functions

(Abrahamson, 1991, Zerva, 2008)

Lagged Coherence Function Estimates Using Different Smoothing Bandwidths of Hamming Window



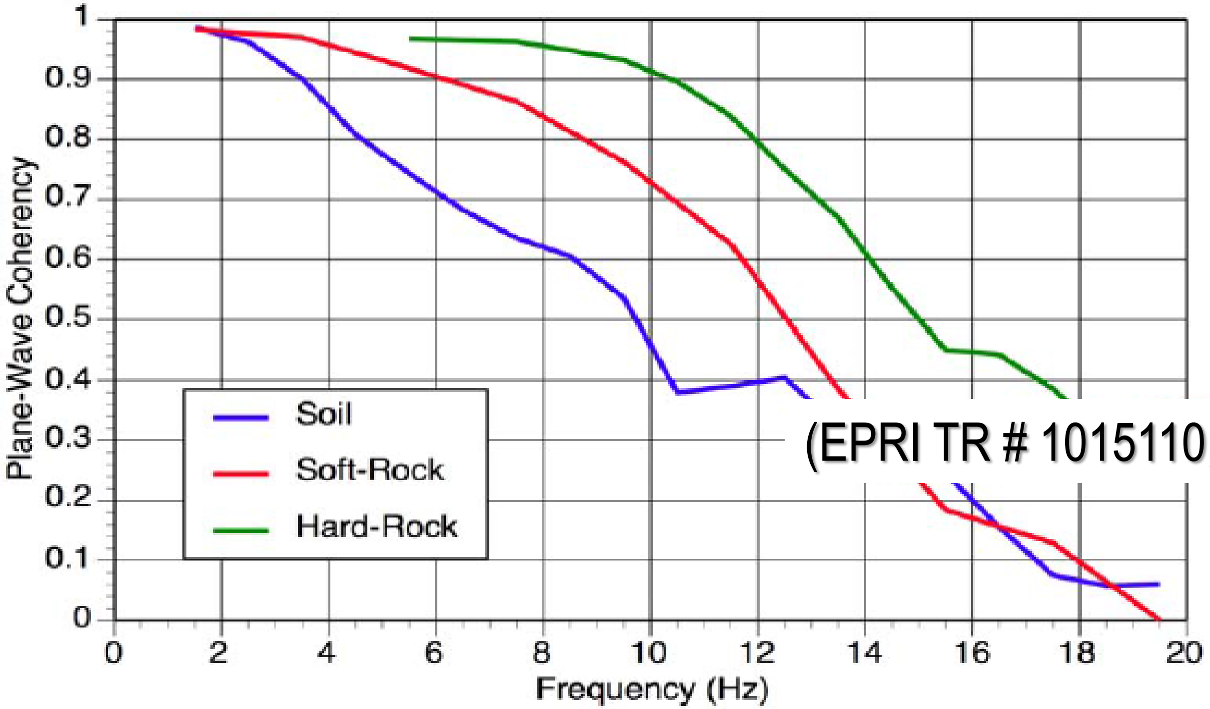


(Zerva, 2008)

Abrahamson recommends using 11-point Hamming window (M=5)

P-W Coherency Functions for Different Soil Sites

Coherence Function from many records in different dense arrays:



(EPRI TR # 1015110, December 2007)

Abrahamson Coherence Function (Fitted) Analytical Form:

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

Abrahamson Generic Coherence Functions for Rock & Soil Sites

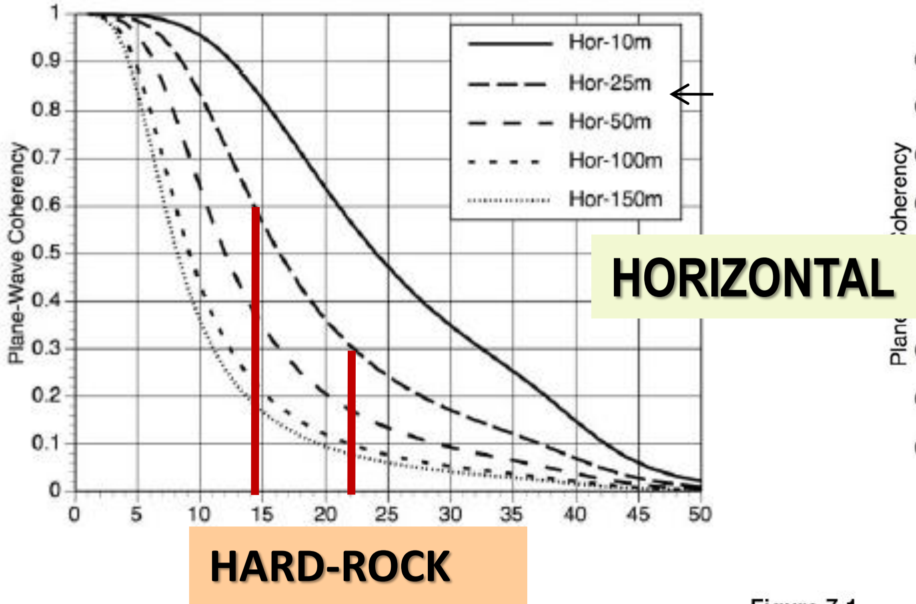


Figure 6-1
Plane-Wave Coherency for the Horizontal Component

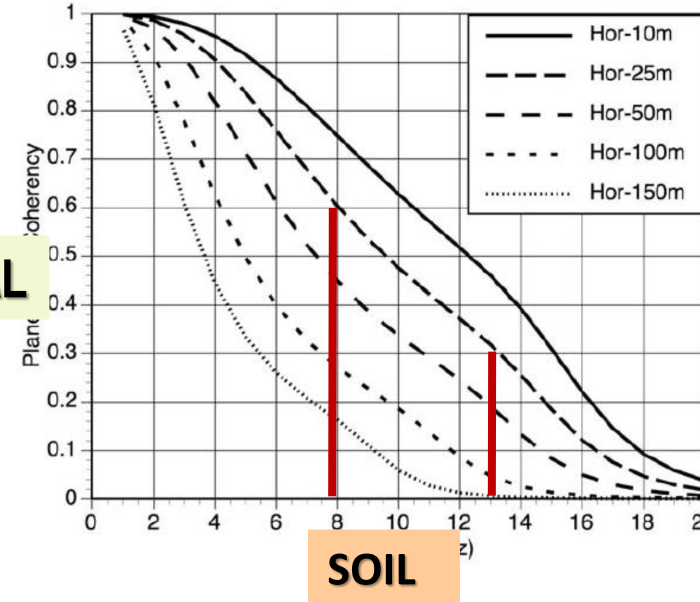


Figure 7-1
Plane-Wave Coherency for the Horizontal Component for Soil Sites

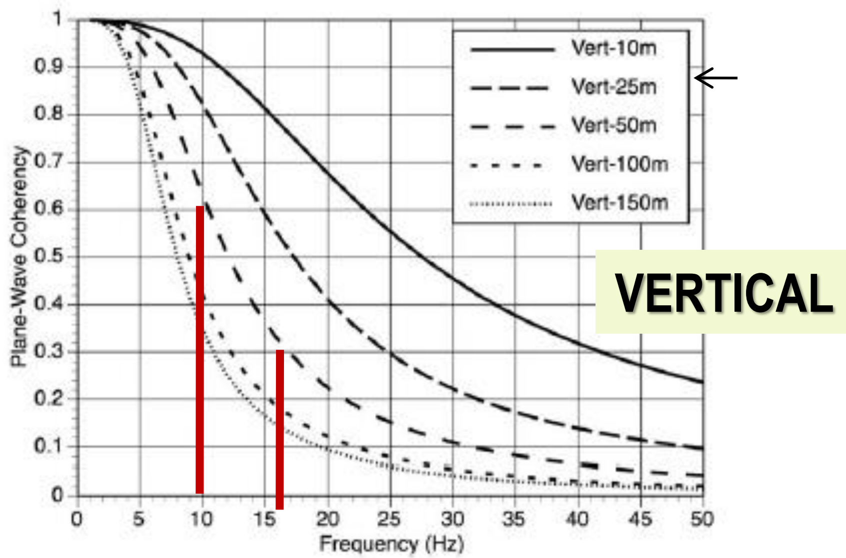


Figure 6-2
Plane-Wave Coherency for the Vertical Component

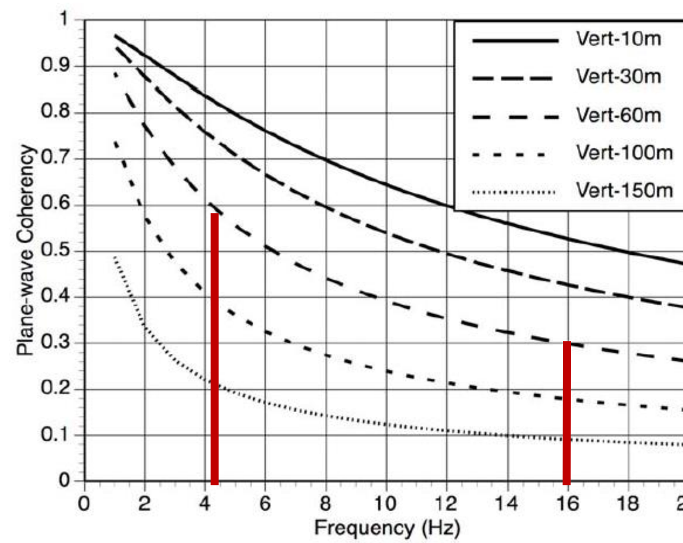
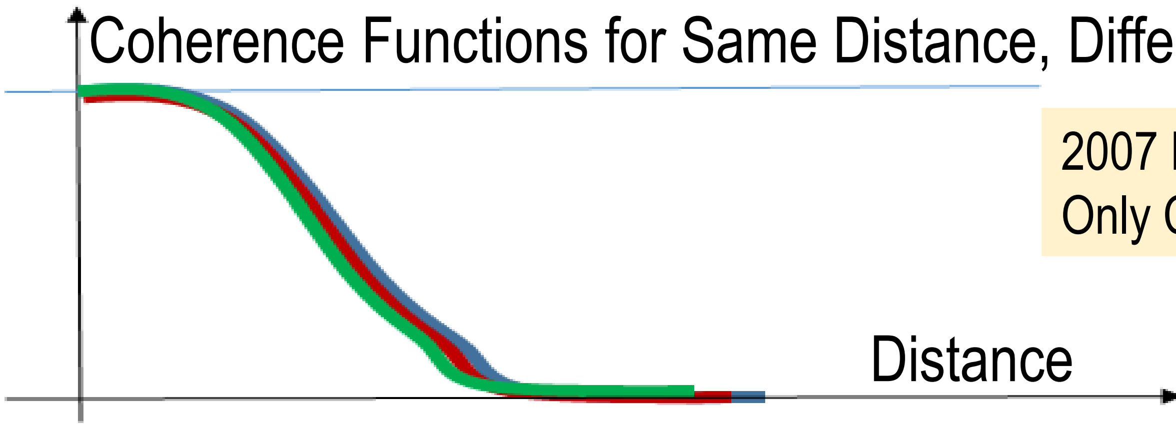


Figure 7-2
Plane-Wave Coherency for the Vertical Component for Soil Sites

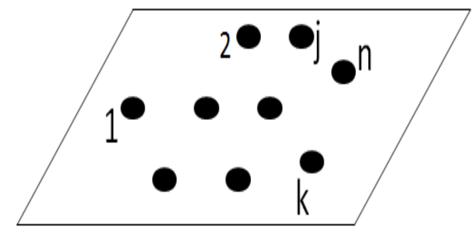
(EPRI TR # 1015110, December 2007)

P-W Coherence Function for Different Models

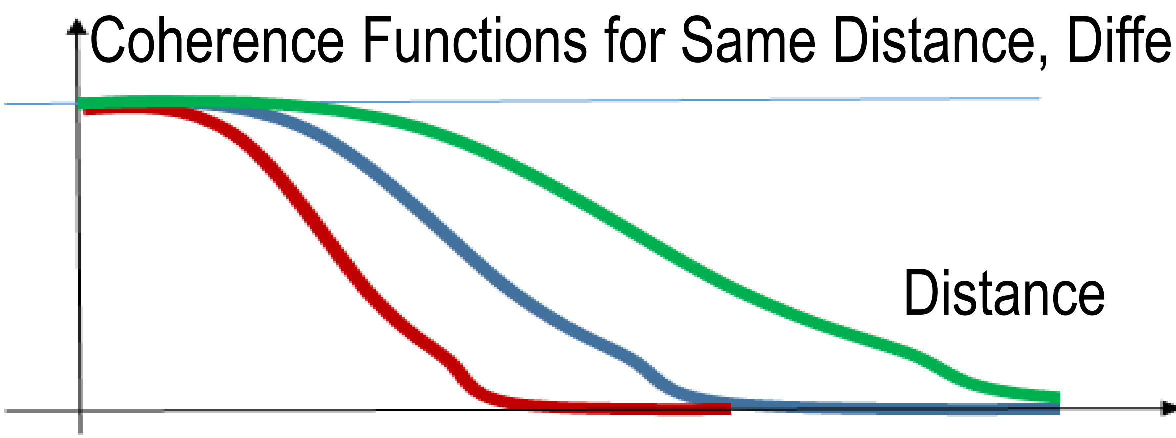
Coherence Function Radial (or Isotropic) Models



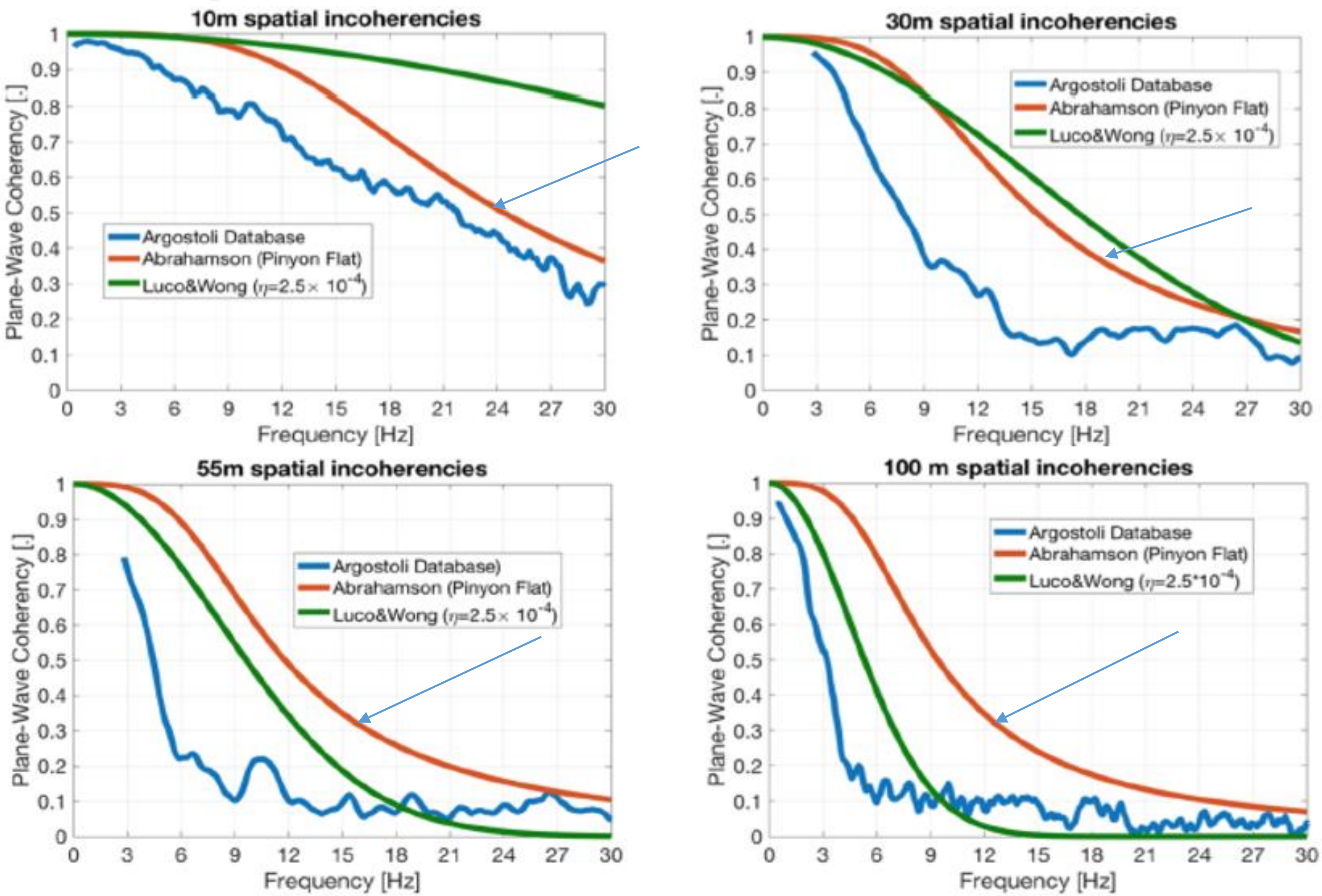
2007 EPRI Studies Used
Only Coherency Radial Models



Coherence Function Directional (or Anisotropic) Models



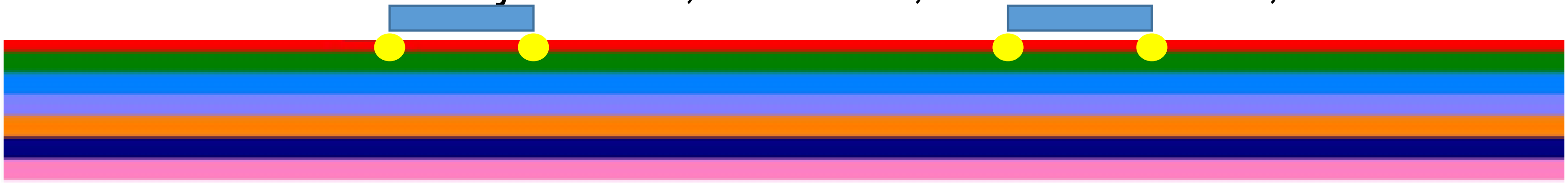
2. Site-Specific Plane-Wave Coherence Functions



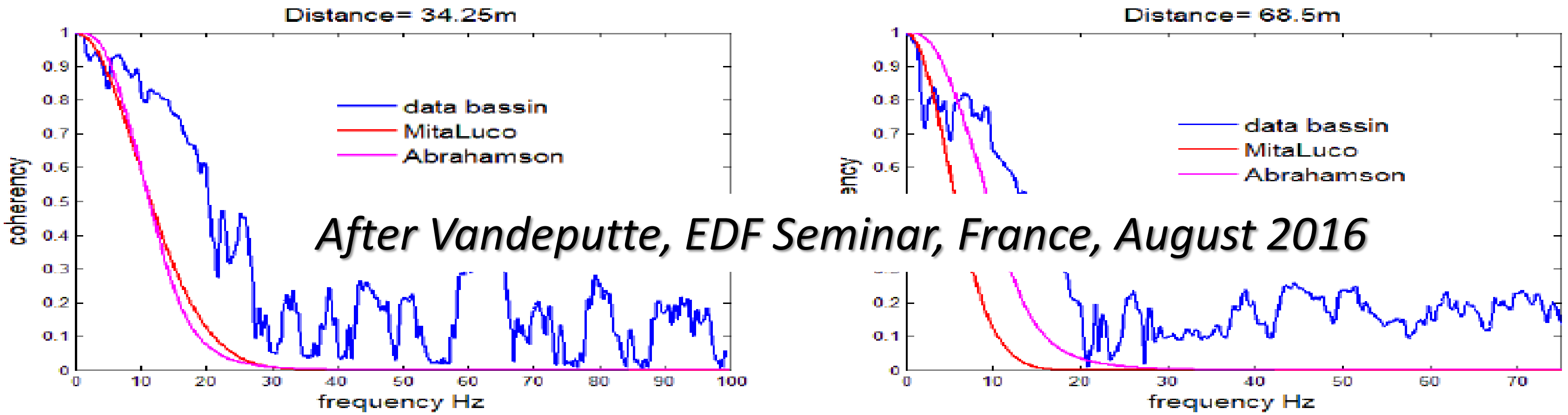
Site-Specific Coherence Function for Argostoli Site (after Svay et al., 2016, EDF)

Developing Site-Specific Coherency Function Models for NPP Site Using 2D/2V Probabilistic Soil Profiles (Vs, D)

Horizontal Mean Soil Layering (2D/2V Homogeneous Correlated Fields)
>>> Generic Coherency Models, Statistical, as Abrahamson, Luco



Slopped Mean Soil Layering (2D/2V NonHomogeneous Correlated Fields)
>>> Site-Specific Coherency Models, Physics-based Modeling



After Vandeputte, EDF Seminar, France, August 2016

3. Probabilistic Simulation of Soil Layering As 2D/2v Stochastic Field Models

Spatial Correlation:

$$R_U[u(\mathbf{x}),u(\mathbf{x}')] = \sum_{n=0}^{\infty} \lambda_n \Phi_n(\mathbf{x}) \Phi_n(\mathbf{x}')$$

In engineering applications, usually, independent correlation structures for horizontal and vertical directions Can be assumed.

Karhunen-Loeve Expansion:

$$u(\mathbf{x},\theta) = \sum_{i=0}^{n} \sqrt{\lambda_i}\, \Phi_i(\mathbf{x}) z_i(\theta)$$

$$z_i(\theta) = \frac{1}{\sqrt{\lambda_i}} \int_D \Phi_n(\theta)\, u(\mathbf{x},\theta)\, d\mathbf{x}$$

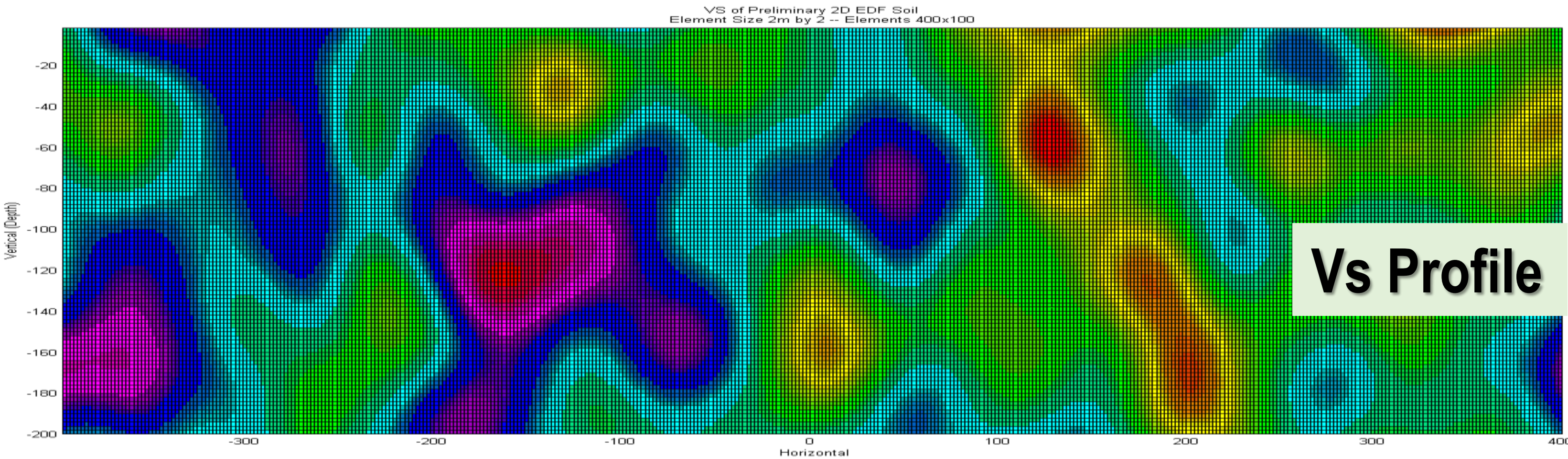
Can be used to identify the Zi random variable simulation values based on available measurements. Applicable to Gaussian and non-Gaussian stochastic fields.

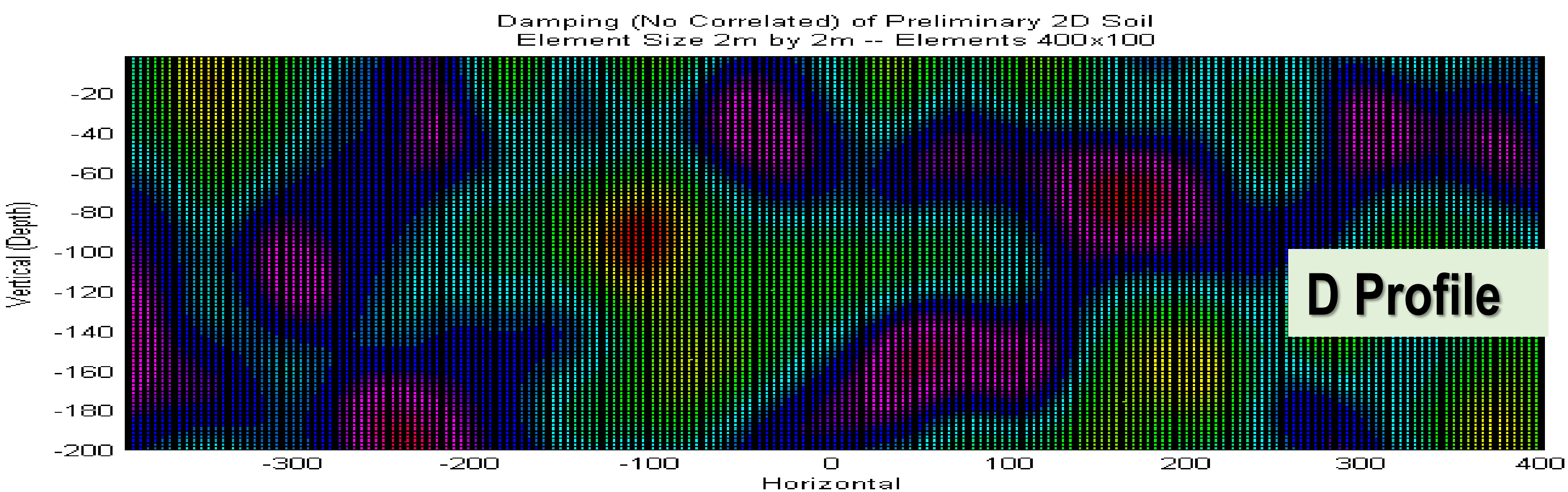
Spatial correlation coefficient for non-Gaussian soil profiles:

$$\rho_{yi,yj} = \frac{1}{\sigma_{yi}\sigma_{yj}} \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} [F_i^{-1}\Phi(x_i) - \mu_{yi}][F_i^{-1}\Phi(x_j) - \mu_{yj}]\phi(x_i, x_j) dx_i dx_j$$

Simulated Vs and D Profiles for Uniform Deep Soil

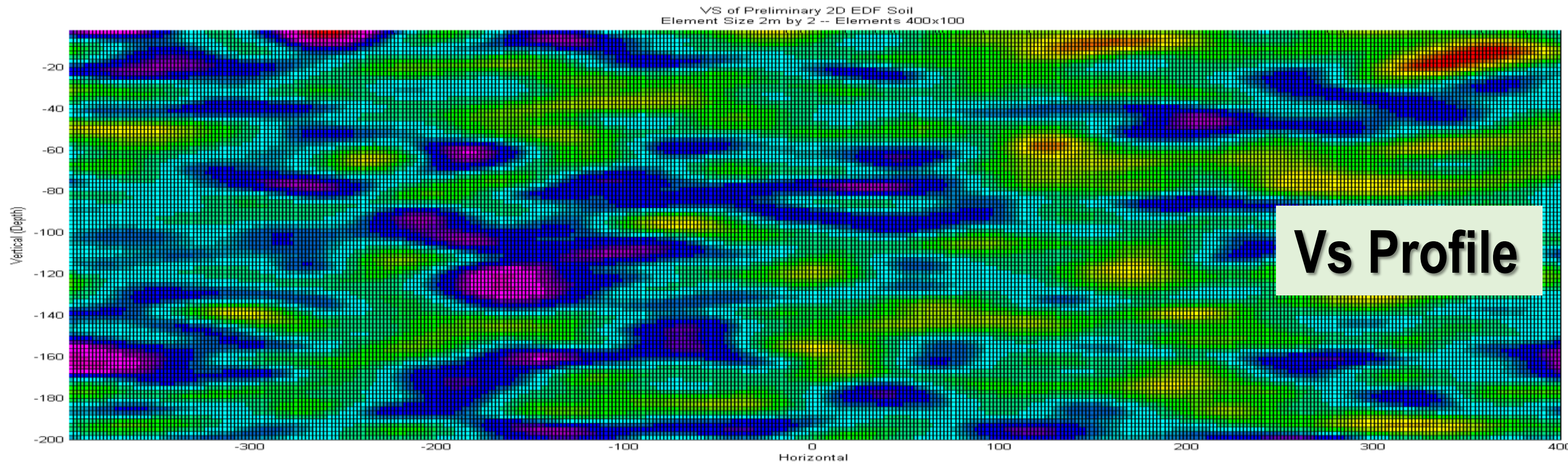
Vs and D Simulated Profiles for Correlation Lengths of 60m x 60m

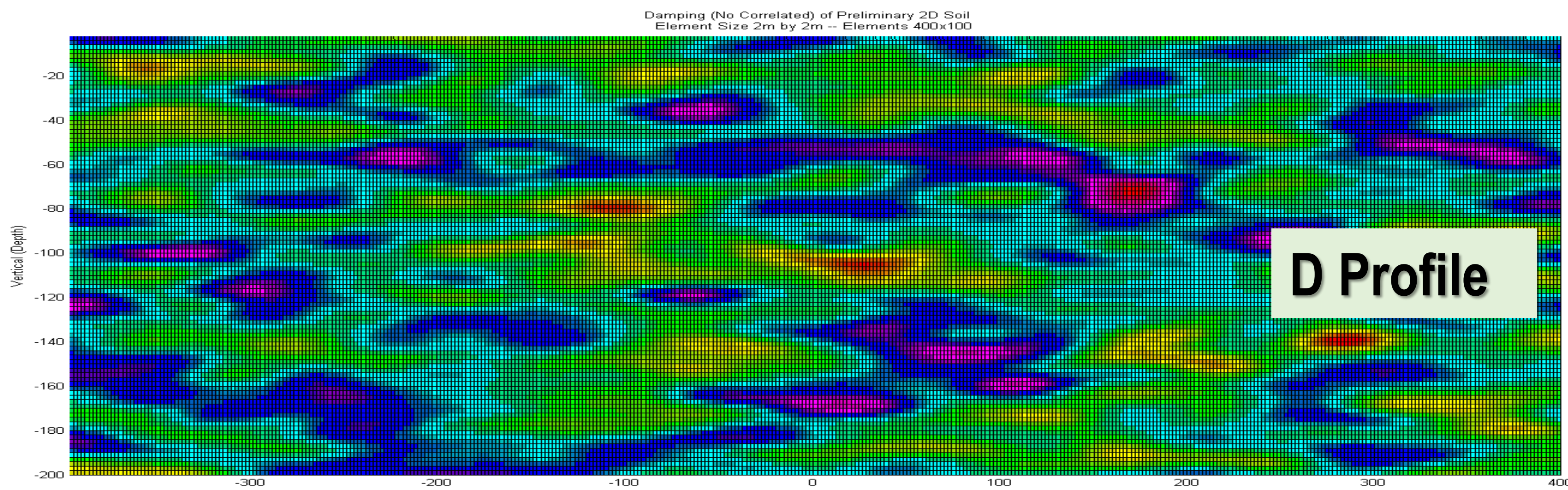




Simulated Vs and D Profiles for Uniform Deep Soil

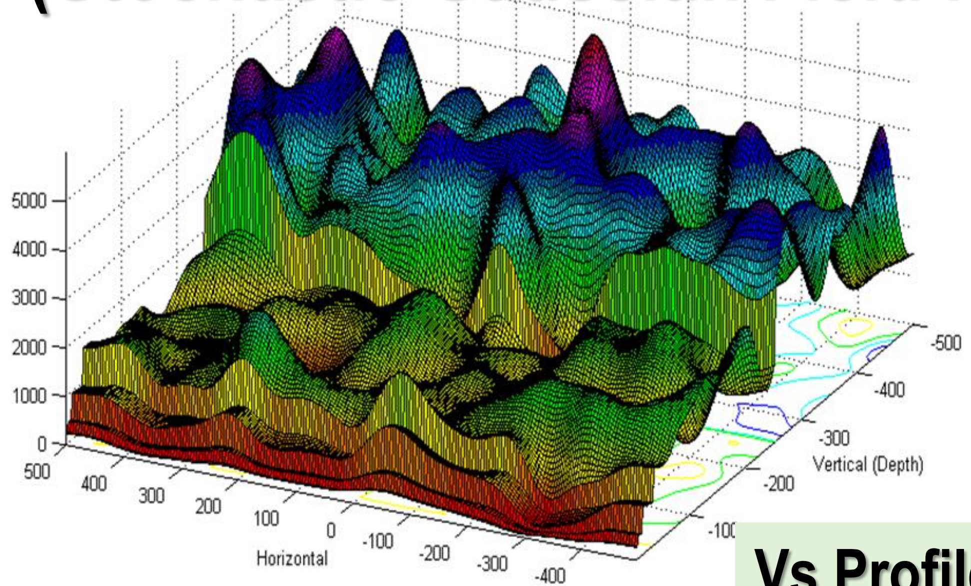
Vs and D Simulated Profiles for Correlation Lengths of 60m x 10m (EDF site)

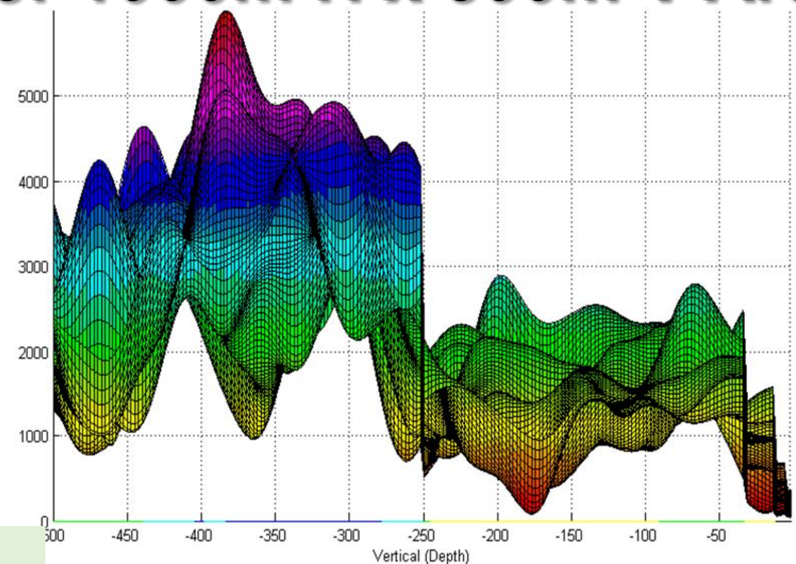




Pinyon Flat Rock Site Validation Study

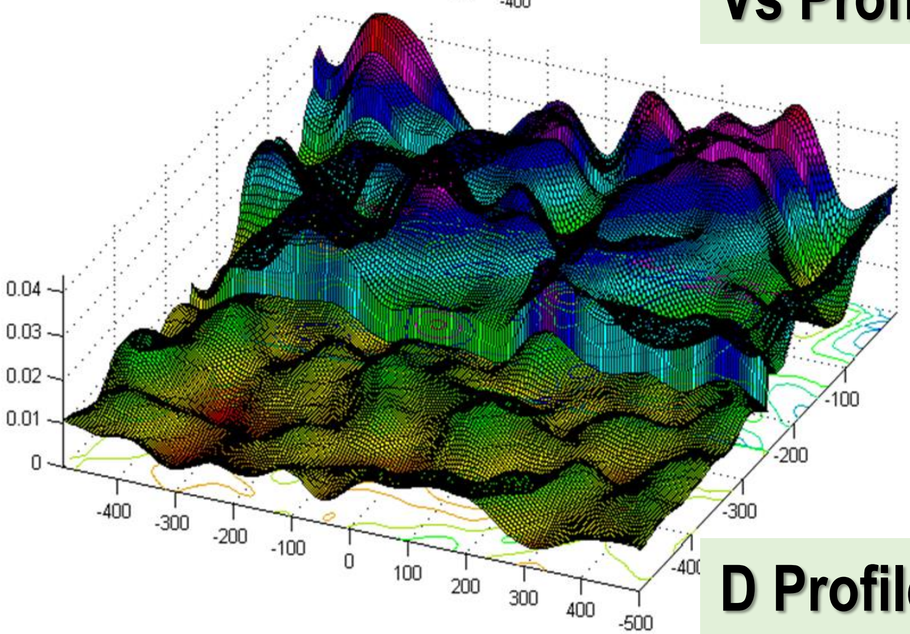
Simulated Vs and D Soil Profiles for Pinyon Flat Site (Stochastic Gaussian Field for 1000m H x 500m V Area)

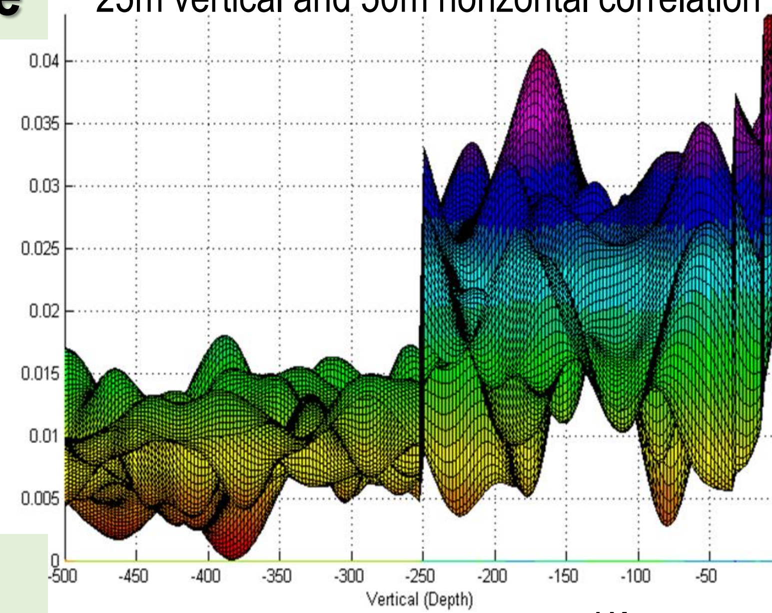




Vs Profile

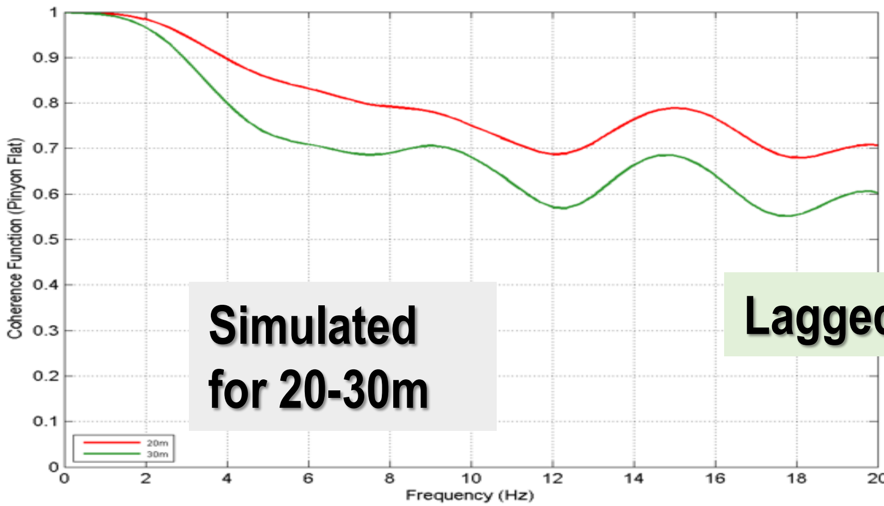
25m vertical and 50m horizontal correlation length





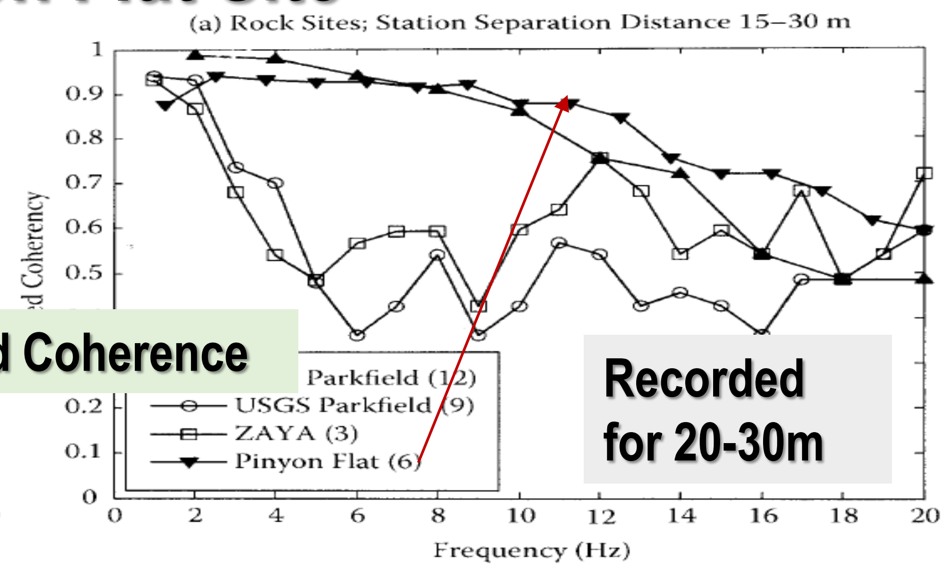
D Profile

Estimation of Site-Specific Coherence Functions for Pinyon Flat Site

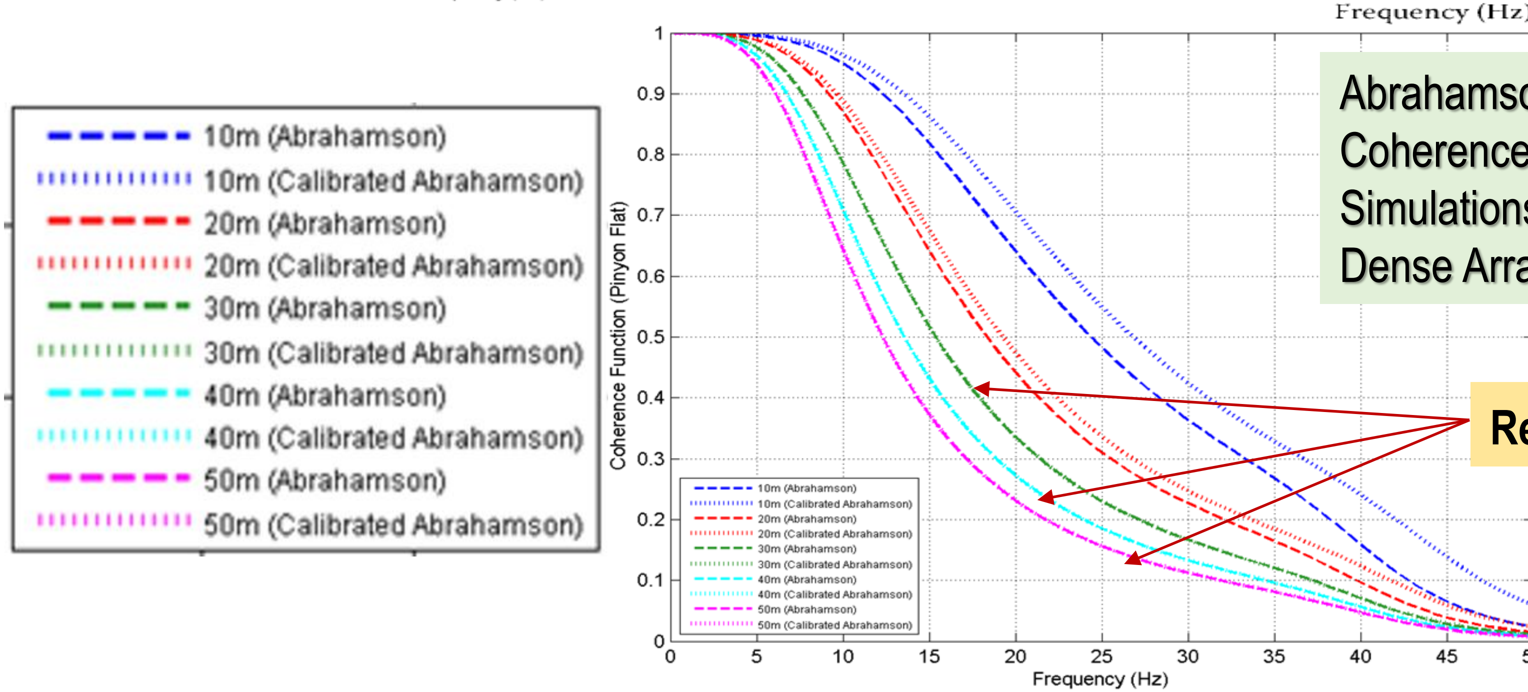


Simulated for 20-30m

Lagged Coherence



Recorded for 20-30m

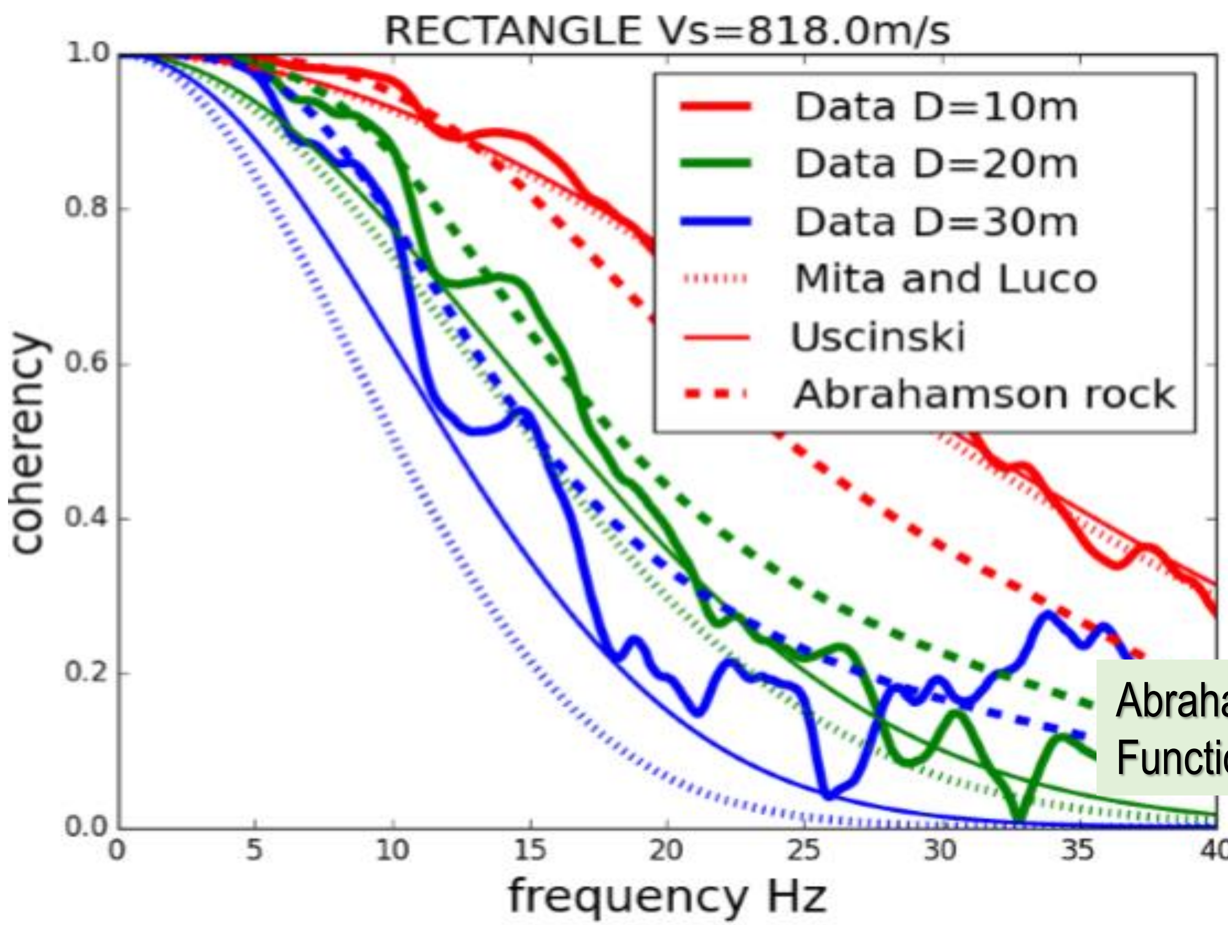


Abrahamson Plane-Wave Coherence Computed from Simulations and Pinyon Flat Dense Arrays Records

Results overlap

EDF Digital Uniform Deep Soil Site (Vs=818m/s) Validation Study

Site-Specific Coherence Functions for *EDF Digital Site* with An Uniform Soil with Vs=818m/s

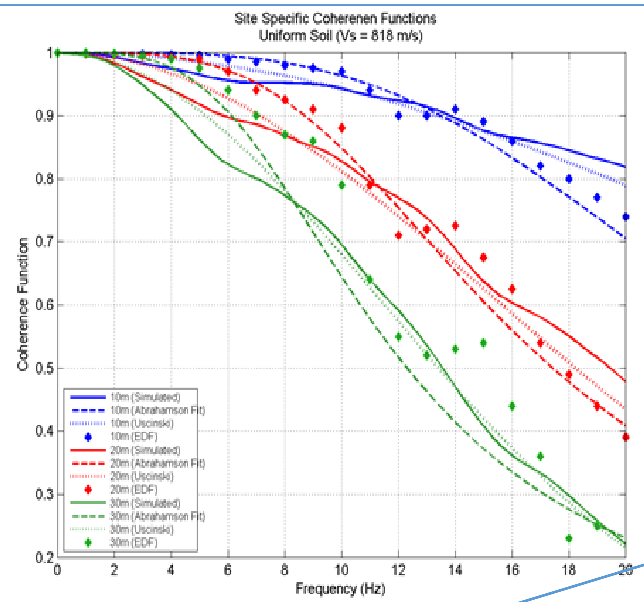


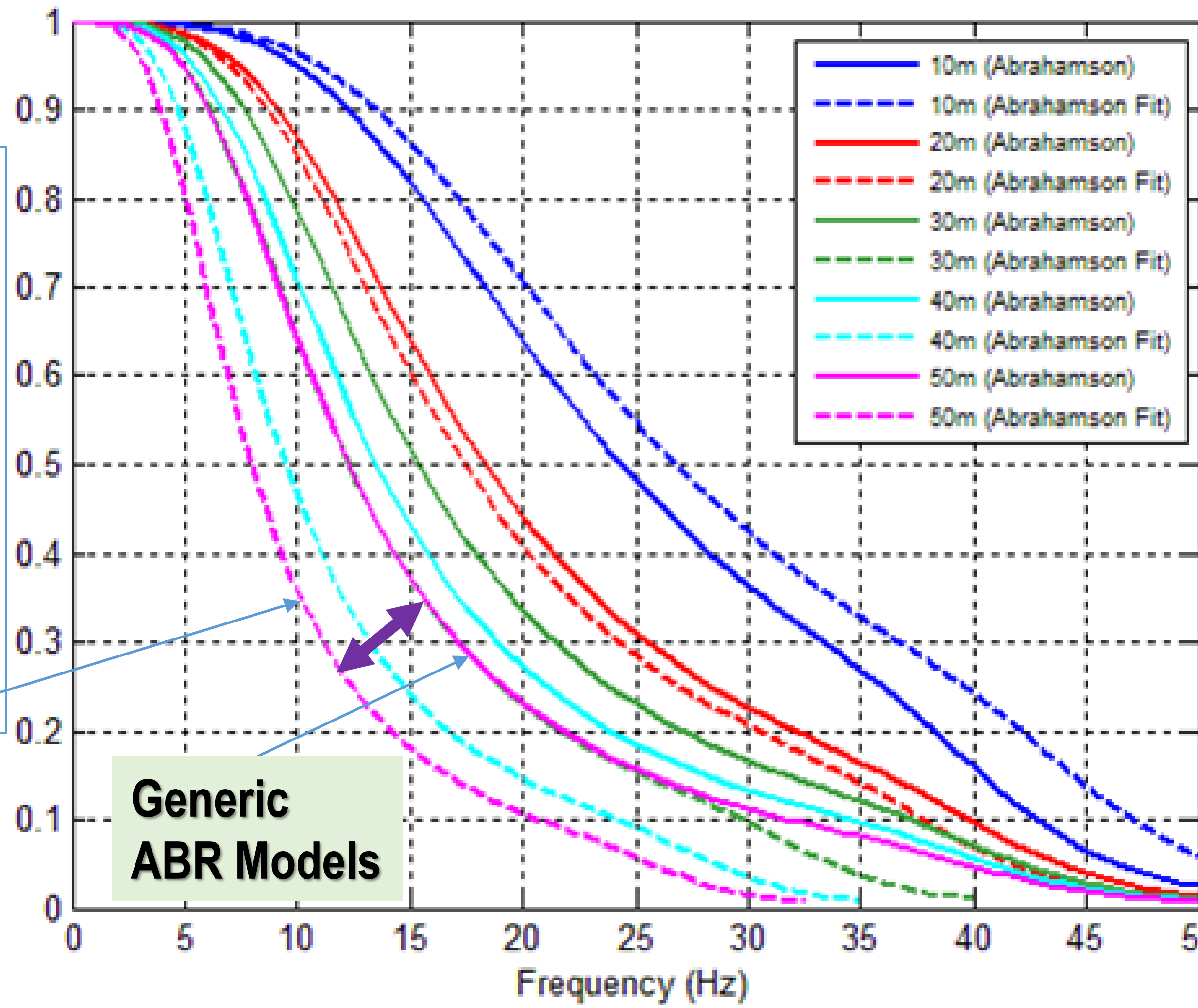
Abrahamson P-W coherence Function significantly different

Zentner, 2016

Site-Specific Coherence Functions Computed for *EDF Digital Site* with An Uniform Soil with Vs=818m/s

Comparative Results For EDF Digital Site





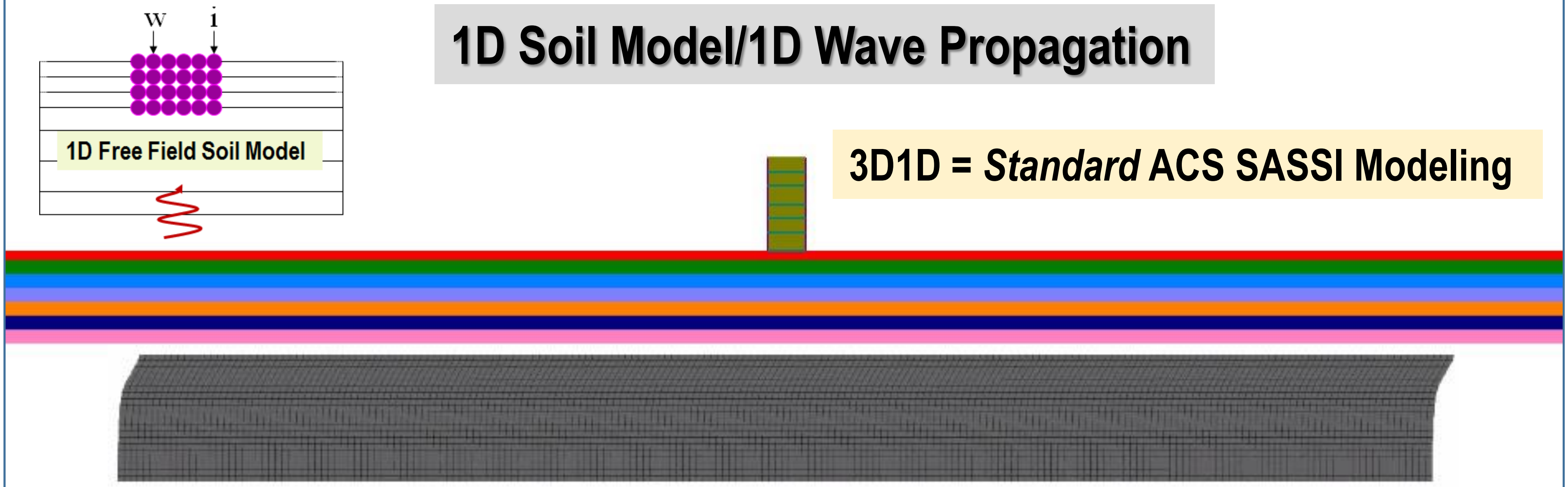
Site-Specific ABR Models

Generic ABR Models

ACS SASSI SSI Modeling Extended to 2D Soil Models

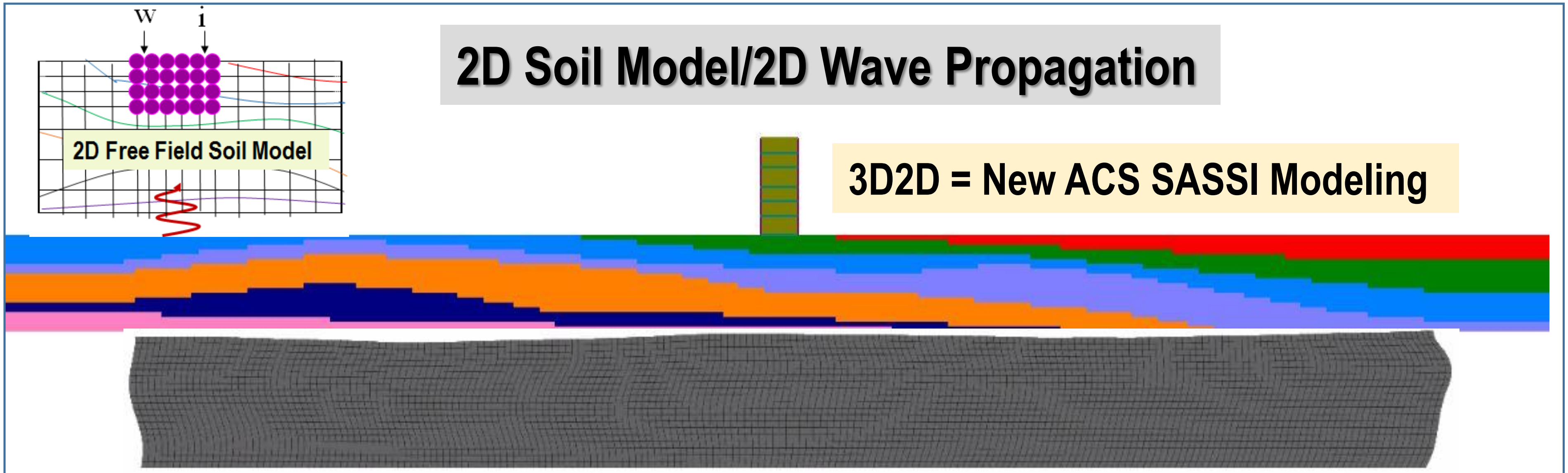
Option 2DSOIL - Soil Impedances & Motions for 2D Models

1D Soil Model/1D Wave Propagation



3D1D = *Standard* ACS SASSI Modeling

2D Soil Model/2D Wave Propagation



3D2D = New ACS SASSI Modeling

 DOE/NRC NPH Meeting, Oct 23-24, 2018

4. Conclusions

It was shown that probabilistic simulations can be site-specific coherence functions using the 2D probabilistic site responses.

Only horizontal site-specific coherence functions were considered so far.

On-going Efforts:

Additional studies are performed for comparing the probabilistic simulation results of the incoherent 3D2D SASSI analyses based on the 2D1D or 2D2D probabilistic soil profiles against the probabilistic SSI simulation results obtained directly using the 3D2D SASSI analyses.

These result comparisons will confirm if the currently used coherence functions, which are decoupled for the horizontal and vertical directions are reasonable for performing accurate incoherent SSI analyses.

5. References

Abrahamson, N. (2007).”Effects of Spatial Incoherence on Seismic Ground Motions”, Electric Power Research Institute, Palo Alto, CA and US Department of Energy, Germantown, MD, Report No. TR-1015110, December 20

Abrahamson, N., Schneider, J.F. and Stepp, J.C.(1991).” Empirical Spatial Coherency Functions for Application to Soil-Structure Interaction Analysis”, Earthquake Spectra, Vol. 7, pp. 1-27

Ghiocel, D.M., (2004). “Stochastic Simulation Methods for Engineering Predictions”, Chapter 20 of the CRC Press “Engineering Design Reliability Handbook”, Eds. Nikolaidis, Ghiocel and Singhal, Taylor and Francis, CRC Press, December

Ghiocel, D.M. (1996) " On Accuracy of Coherency Spectrum Estimation for Broad and Narrow Band Stationary Processes", Proceedings of the 7th International Conference on Applied Statistics and Probability, Paris, July

Schneider J.F., Stepp, J.C. Stepp and Abrahamson, N.A. (1992).”The Spatial Variation of Earthquake Ground Motion and Effects of Local Site Conditions”, Proceedings on the 10th World Conference on Earthquake Engineeing, Madrid, Spain

Svay, A., Zentner, I., Clouteau, D., Cottereau, J.(2016) “Spatial Coherency Analysis of Seismic Ground Motions from a Rock Site Dense Array Implemented during the Kefalonia 2014 Aftershock Sequence”, LOSSVAR Seminar, EDF Lab, Paris-Saclay, August 26.

Zentner, I. (2016) “Stochastic Representation of Soil Variability and Implementation for Efficient SSI Analysis with EDF Code Aster”, LOSSVAR Seminar, EDF Lab, Paris-Saclay, August 26

Zerva, A. (2008). “Spatial Variation of Seismic Ground Motions: Modelling and Engineering Applications”, CRC Press, Taylor & Francis, Boca Raton, London, New York

Any Questions?

