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

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**

**INCOHERENT**

**IDEALISTIC MOTION**
(1D DETERMINISTIC WAVE MODEL)

Assume vertically propagating S and P Waves in horizontal soil layering

**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)

3D Random Wave Field Motion (Realistic)

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 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 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):

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

Power Spectral Density (PSD):

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

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

\[ \gamma_{\text{PW}}(\omega, \xi_{x,x'}, \xi_{x,x'}^{\text{PW}}) = |\gamma(\omega, \xi_{x,x'})| \alpha(\omega, \xi_{x,x'}^{\text{PW}}) \exp(-\omega \xi_{x,x'}^{\text{PW}} / V_{\text{pw}}) \]

Abrahamson Lagged and Plane-Wave Coherence Functions

Lagged Coherence Function Estimates Using Different Smoothing Bandwidths of Hamming Window

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:

Abrahamson Coherence Function (Fitted) Analytical Form:

\[ \gamma_{pw}(f, \xi) = \left[ 1 + \left( \frac{f \ Tanh(a_3\xi)}{a_1f_c(\xi)} \right)^{n1(\xi)} \right]^{-1/2} \left[ 1 + \left( \frac{f \ Tanh(a_3\xi)}{a_2} \right)^{n2} \right]^{-1/2} \]

(EPRI TR # 1015110, December 2007)
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

Coherence Functions for Same Distance, Different Directions

Distance

2007 EPRI Studies Used
Only Coherency Radial Models

Coherence Function Directional (or Anisotropic) Models

Coherence Functions for Same Distance, Different Directions

Distance
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:

\[ R_{U}[u(x), u(x')] = \sum_{n=0}^{\infty} \lambda_n \Phi_n(x) \Phi_n(x') \]

Karhunen-Loeve Expansion:

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

\[ z_i(\theta) = \frac{1}{\sqrt{\lambda_i}} \int_{D} \Phi_n(\theta) u(x, \theta) \, dx \]

Spatial correlation coefficient for non-Gaussian soil profiles:

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


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 Engineering, Madrid, Spain


Any Questions?