CONSISTENT SITE-RESPONSE/ SOIL-STRUCTURE INTERACTION CALCULATIONS

WORKSHOP ON SEISMIC ISSUES

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Consistent Motions at Various Elevations

- In most currently used methods, hazard curves are defined at 9200 fps Rock
- Must start with 9200 fps Rock Motions & Convolve through soil profile to the various elevations of interest
    - A) Obtain Mean 10^{-4} & 10^{-5} UHRS at each elevation of interest
    - B) Determine DRS from 10^{-4} & 10^{-5} UHRS at each elevation of interest
- This approach is the only rigorous approach to obtain DRS at various elevations when the hazard is defined initially at 9200 fps Rock
- See Section 2.3 and Commentary C2.3 of ASCE/SEI 43-05

Specification of Input for Deterministic SSI Analysis of Embedded Structure

- Most appropriate elevation for specifying seismic input is at the foundation level of the structure

- Specifying the seismic input at any other location can lead to unrealistic response spectra at the foundation level (either seriously unconservative, or unrealiazably high)

Heart of Issue

NUREG 0800 States:

- The site-specific GMRS need to be transferred to the foundation elevations (FIRS)
- Implies that can be done by LB, BE, UB deterministic convolution evaluations
- However, this process does not produce a mean 10^{-4}, 10^{-5}, or performance goal based FIRS at foundation elevation

Better to State:

- FIRS need to be defined at the foundation elevation consistent with the GMRS
- The change will enable the FIRS to be “Performance Goal Based” consistent with the GMRS

One Dimensional Wave Propagation Program SHAKE

- Analytical solution to 1-D wave propagation
- Maintain compatibility of displacement and stresses

$$\rho \frac{\partial^2 u}{\partial t^2} = G \frac{\partial^2 u}{\partial x^2} + \eta \frac{\partial^3 u}{\partial x^2 \partial t}$$

$$U(x) = Ee^{ikx} + Fe^{-ikx}$$

One Dimensional Wave Propagation Program SHAKE

- For system with m layers, the motion in each layer has two components

$$k^2 = \frac{\rho\omega^2}{G + i\omega\eta} = \frac{\rho\omega^2}{G^*}$$

$$\alpha_m = \frac{k_m G_m}{k_{m+1} G_{m+1}} = \sqrt{\frac{\rho_m G_m^*}{\rho_{m+1} G_{m+1}^*}}$$

$$E_{m+1} = \frac{1}{2} E_m (1+\alpha_m) e^{ik_m h_m} + \frac{1}{2} F_m (1-\alpha_m) e^{-ik_m h_m}$$

$$F_{m+1} = \frac{1}{2} E_m (1-\alpha_m) e^{ik_m h_m} + \frac{1}{2} F_m (1+\alpha_m) e^{-ik_m h_m}$$

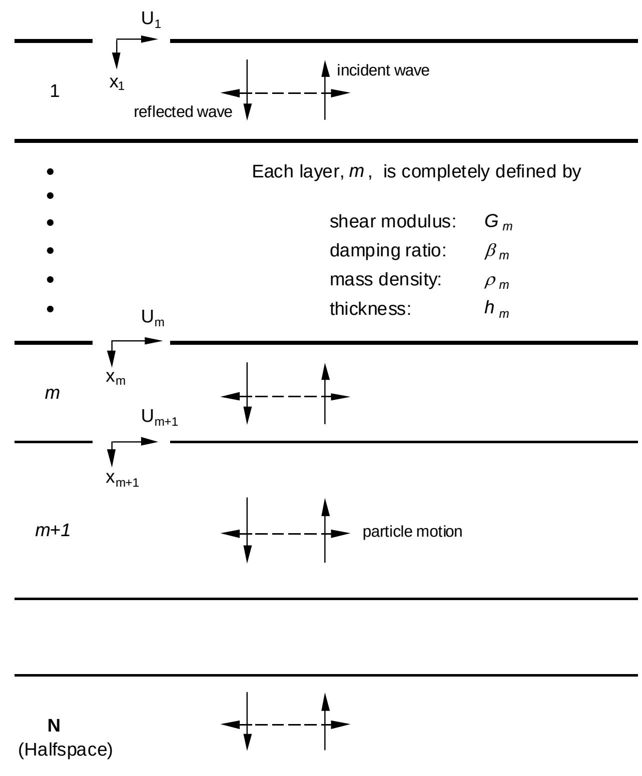


Figure 1 One-Dimensional Idealization of a Horizontally-Layered Soil Deposit Overlying a Uniform Halfspace

One Dimensional Wave Propagation Program SHAKE

Outcrop Definition in SHAKE

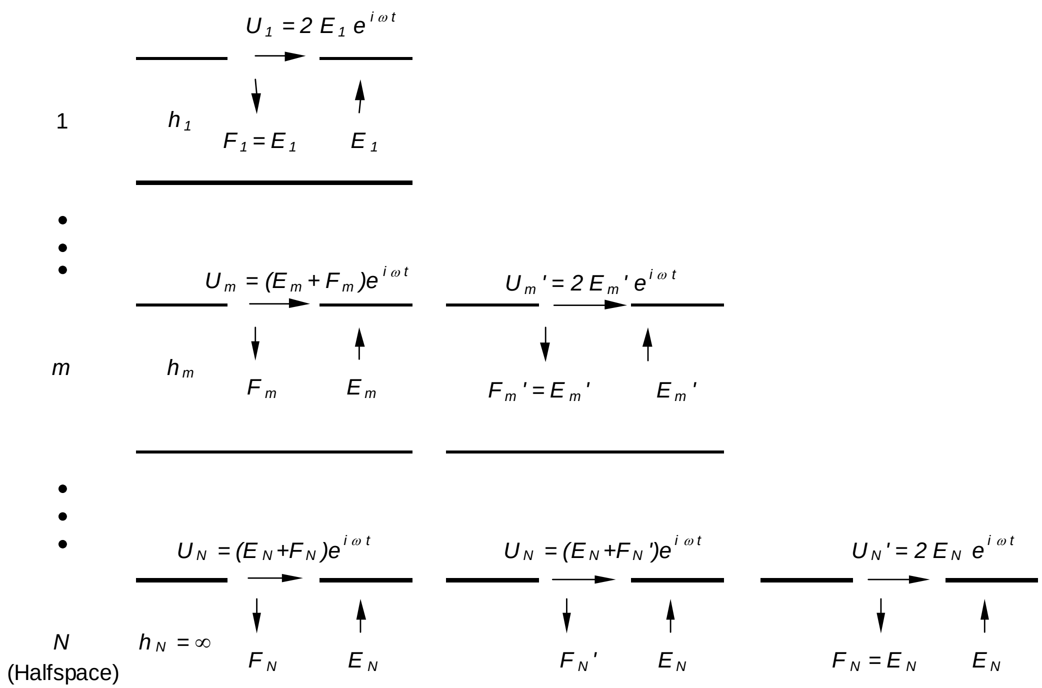


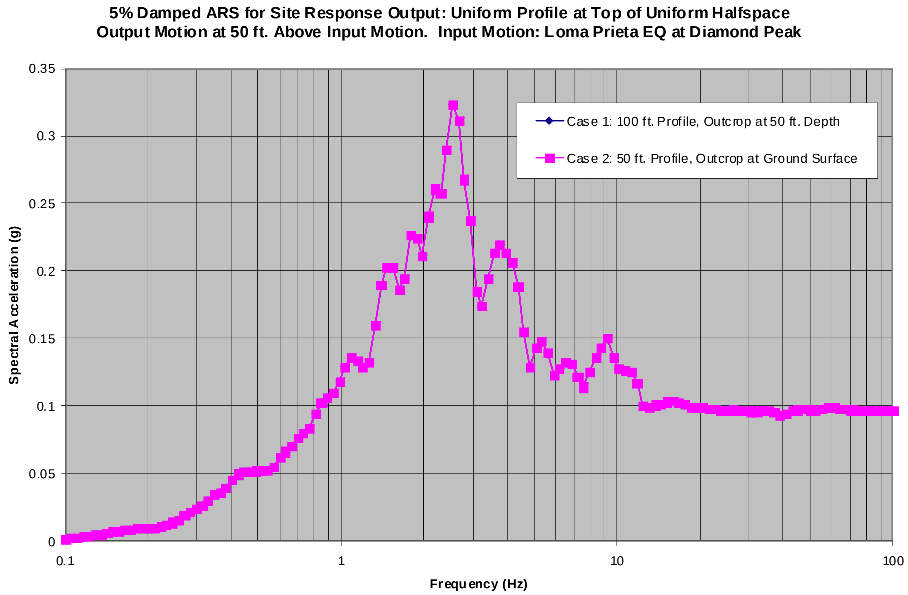
Figure 2 One-Dimensional Layered System with Outcropping Layers

EXAMPLE

- Case 1-100 ft. soil profile at top of a uniform halfspace with the same properties as the soil column, input motion is specified at 100 ft. outcrop, output ARS at 50 ft. outcrop.
- Case 2 is a 50 ft. soil profile at top of a uniform halfspace with the same properties as the soil column, input motion is specified at 50 ft. outcrop, output ARS at ground surface outcrop.
- Case 3 is a 100 ft. soil profile at top of a hard rock with Vs=10000 ft/s, input motion is specified at 100 ft depth as outcrop, output ARS at 50 ft. depth.
- Case 4 is a 50 ft. soil profile at top of a rigid rock with Vs=10000 ft/s, input motion is specified at 50 ft. outcrop, output ARS at ground surface outcrop.

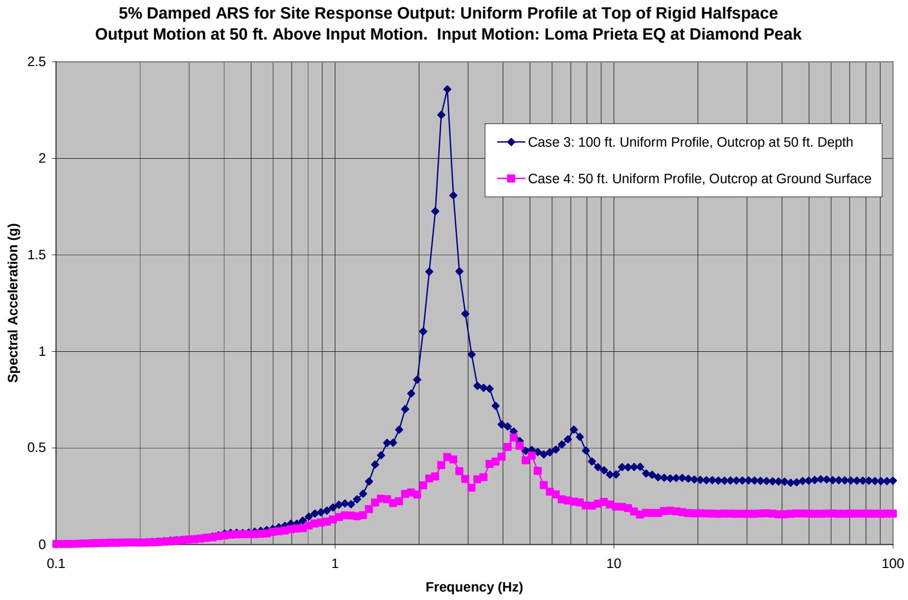
EXAMPLE-Cases 1 and 2

- Uniform Soil Profile (Halspace with no layering contrast)
- For a uniform Soil Profile with 100 ft thickness, response at 50 ft depth as outcrop is the same as running the 50 ft soil column (the upper 50 ft removed) and computing the response at the top of the soil column



EXAMPLE-Cases 3 and 4

- Layered site (100 ft of 1000 ft/sec over hard rock) with input motion specified as outcrop motion at the rock level
- Response motion at 50 ft depth as outcrop is different from the surface motion of 50-ft column (upper 50 ft removed) using the same input motion at the rock level as outcrop



Observation

- The notion that the SHAKE outcrop motion at a certain depth is the same as the surface motion of the same depth with the top soil removed is valid only for the uniform soil profile with no reflection from base

- For all real soil profiles (not uniform), the SHAKE outcrop motion at certain depth is different from the surface motion with top layers removed.

- If response motion is computed at surface with top layers removed, this response motion can not be used directly as input in the same profile with top layers added

- SHAKE outcrop response motion for any soil layer can be used as input outcrop motion in the same layer resulting in consistent and identical results

GMRS

Ground Motion Response Spectra (GMRS)—Site-specific ground motion response spectra characterized by horizontal and vertical response spectra determined as free-field motions on the ground surface or as free-field outcrop motions on the uppermost in-situ competent material using performance-based procedures in accordance with RG 1.208

- Currently GMRS is computed at the top of a competent soil layer with top layers removed
- The calculation includes PSHA analysis to get rock motion, soil column characterization and randomization of the data, convolution of de-aggregated HF and LF rock spectra, development of UHS at the GMRS horizon, and applying design factors to obtain design response spectra

GMRS-ISSUES

1. Removing the top layers is appealing since it seems to protect the GMRS from any changes that may take place in the soil profile above GMRS horizon during COLA. GMRS can never be free of the soil layers above it:
    - The initial velocity measured at the site has the effect of soil layers above on GMRS horizon on layers below
    - The nonlinear soil curves should include the effect of overburden
2. The site condition that defines the GMRS with top layers removed is not a realistic site condition and it never exists at the plant site
3. In spite of including the effect of overburden pressure on soil properties, the soil nonlinearity calculated as part of GMRS computation is an approximation of the nonlinearity since it does not have the effect of soil frequency of the soil layers above it

GMRS-ISSUES

4. GMRS with the above definition can not be used directly in the subsequent soil column that includes the top layers. It would require de-convolution to uniform halfspace in a separate de-convolution analysis and yet again convolved in a subsequent convolution analysis with the full soil column
5. GMRS is a broad band spectrum with high frequency controlled by stiffer soil profiles and low frequency by the softer soil profiles. De-convolution of a broad band spectrum is problematic and amounts to unrealistic motion, unconservative at some frequencies and overly excessive at other frequencies
6. GMRS is a design spectra and not UHS, de-convolution of GMRS and subsequent convolution does not yield the performance-based design motion at the horizon of interest

GMRS

It is suggested that GMRS to be computed as outcrop motion with soil layers above included. The soil layers above may be in-situ soil layers or backfill if it is an extended backfill. GMRS is not used for structural analysis, only FIRS is used. This approach maintains the effect of overburden from soil layers above and properly considers the effect of the soil column frequency above the GMRS horizon on GMRS. In addition this approach reduces the need to generate and randomize two soil columns, one for GMRS and one for FIRS

FIRS

Foundation Input Response Spectra (FIRS)—When the site-specific GMRS and the site-independent CSDRS are determined at different elevations, the site-specific GMRS need to be transferred to the base elevations of each Seismic Category I foundation. These site-specific GMRS at the foundation levels in the free field are referred to as FIRS and are derived as free-field outcrop spectra

FIRS use for SSI

- Any rigorous SSI model consists of two parts: the structural/foundation model and the free-field soil model
- The free field soil model must be consistent with the soil profile used to generate FIRS
- For SSI analysis including embedment, soil layers within the embedment depth of the SSI model should be included in the soil column analysis
- For SSI analysis with no embedment, the soil column model for FIRS should terminate at the base of the SSI model with no soil layers above it
- The input motion in SSI analysis is defined in the free-field model as control motion at control point
- Using consistent FIRS soil column and FIRS motion for free-field SSI model ensures application of performance-based motion for structural analysis

FIRS

The use of FIRS are as follows:

1. Comparison with CSDRS to evaluate applicability of the design to the site

   For this purpose FIRS should be computed compatible with use of CSDRS in SSI analysis.

   - For SSI analysis with no embedment, FIRS should be computed as a free surface motion (no soil layer above) at the foundation level.
   - For SSI analysis with embedment, FIRS should be computed as outcrop free-field motion including the soil layers above

   For standard designs that are based on CSDRS at the ground surface level and included embedment in the SSI analysis, the CSDRS-consistent motion in the free-field at the foundation level should be obtained from the generic profiles and compared with the site specific outcrop FIRS that includes the soil layer above the FIRS horizon

FIRS

2. Performing site specific SSI analysis

For this purpose FIRS should be computed compatible with its application for SSI analysis.

- For SSI analysis with no embedment, FIRS should be computed as a free surface motion (no soil layer above) at the foundation level
- For SSI analysis with embedment, FIRS should be computed as outcrop free-field motion including the soil layers above
- The soil profiles for SSI analysis should be obtained from the set of same profiles used for generation of FIRS to obtain upper, mean and lower bound profiles

FIRS

3. Checking with minimum 10% requirement

  - All standard designs are designed for RG 1.60 scaled to 0.30g as a minimum and this is not an issue
  - For other class I structures not covered by DCD, the requirement must be met
  - For this evaluation, the FIRS again should be consistent with its application for SSI (with either embedment or no embedment). It is suggested that the site specific FIRS consistent with its application to be compared with the minimum requirement

FIRS

Methodology for Computation of FIRS

- Once the application of the FIRS is determined and the decision on modeling of the top soil layers is made, the soil profile and the soil data will be randomized compatible with the method used for GMRS and soil column analysis will be performed using rock motion as input to obtain UHS and DRS at the FIRS horizon
- This approach provides performance-based motion for structural analysis
- The three soil profiles needed for SSI can be obtained from the strain-compatible soil properties generated from the FIRS computation
- This approach ensures consistent motion in site response and SSI analysis

Example of GMRS/FIRS

Soil Profile

- Deep profile (approximately 1500 ft to 2200 ft to base rock)
- Site specific measurement of velocity
- Upper 86 ft is engineered fill
- The velocity profile and soil nonlinear curves were randomized (60 sets)

Input Motion

- Rock motion is based on PSHA
- De-aggregated spectra (HF and LF) were computed at 10-4 and 10-5 levels
- Time histories were generated to match each response spectrum (30 time history for each spectrum)

Example of GMRS/FIRS

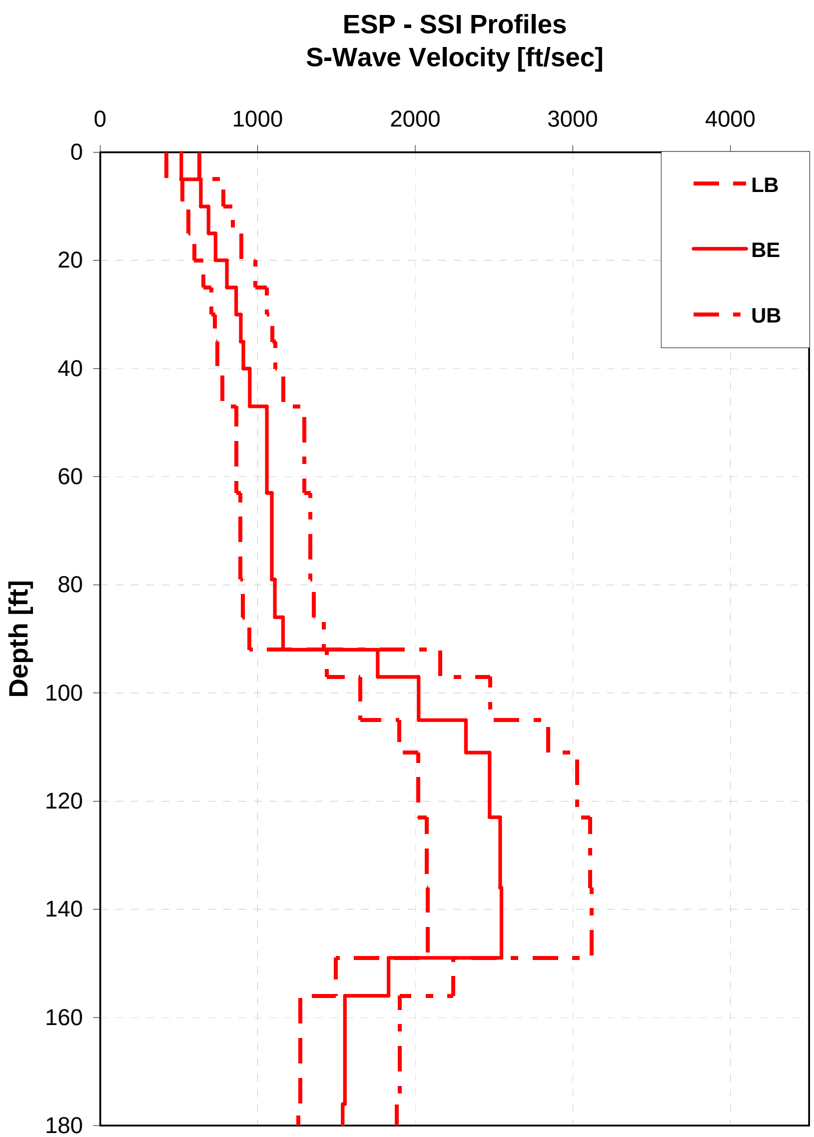
Soil Amplification

- Method 2A of NUREG 6728 was used to compute soil amplification factors
- The soil column used in the analysis is the full soil column from ground surface (top of backfill) to varying (randomized) base rock depth at about 1500 to 2200 ft depth
- Spectral amplification factors were computed at the ground surface level and at the foundation horizon at the depth of 40 ft as outcrop motion

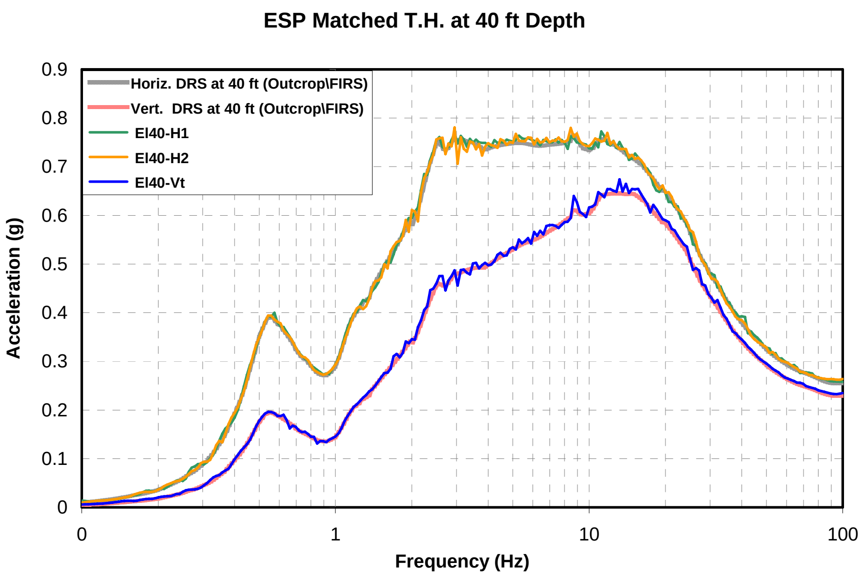
Design Spectra

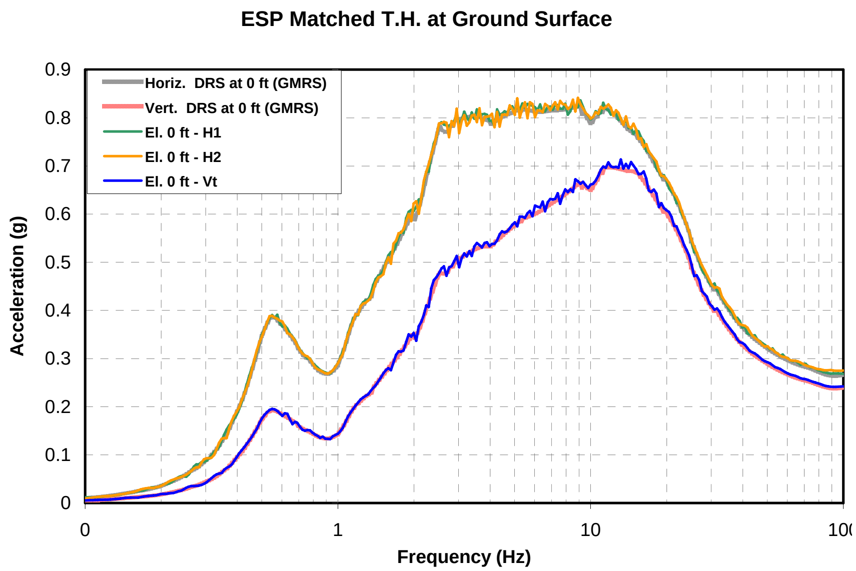
- The log-mean (median) of 60 soil amplification functions were used to develop soil uniform hazard spectra
- The design factors were applied to the uniform hazard spectra to obtain design spectra
- Vertical design spectra was obtained using V/H ratio
- The design spectra at the ground surface is labeled as GMRS, the design response spectra at the depth of 40 ft (the outcrop motion) is labeled as FIRS

Example of GMRS/FIRS



Example of GMRS/FIRS





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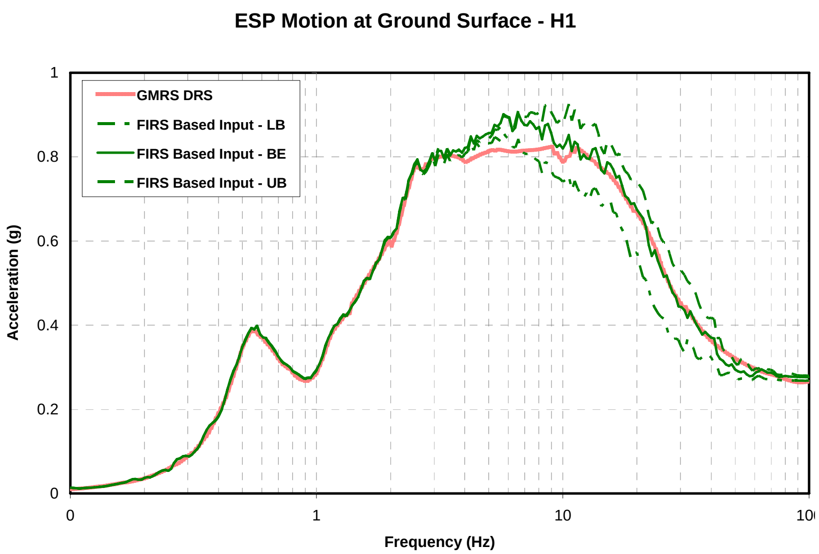
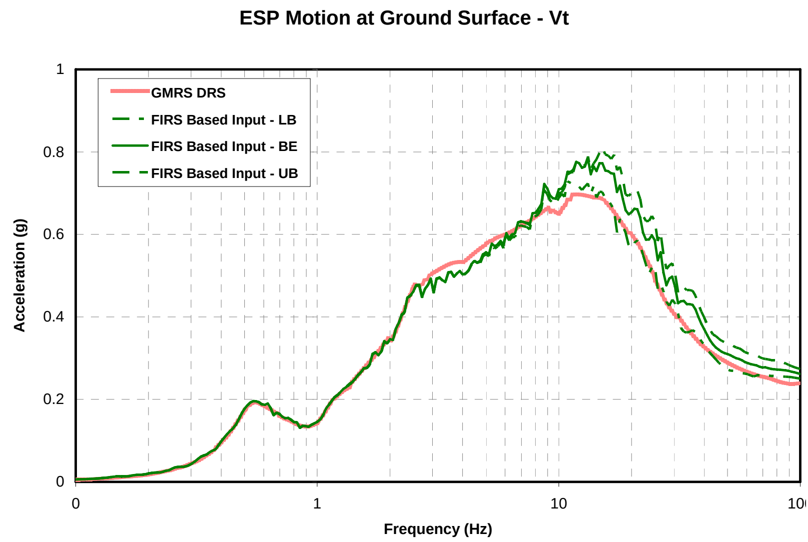
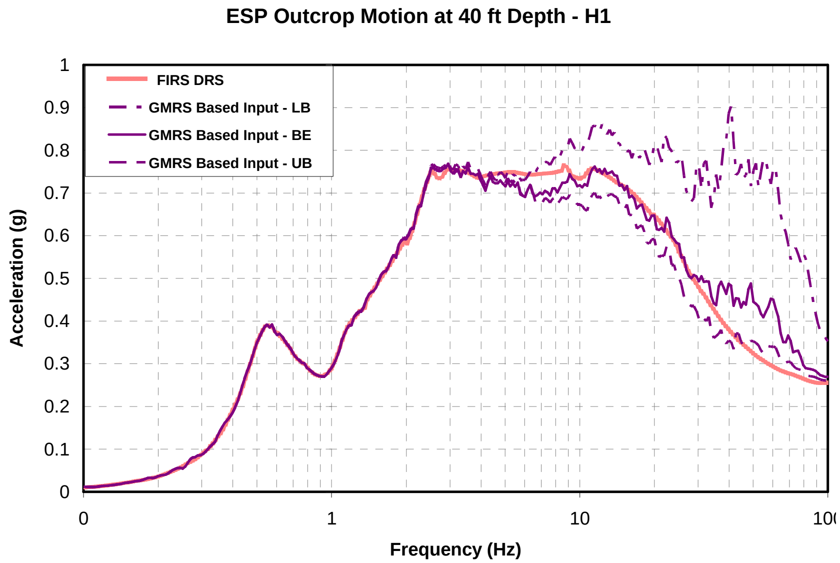
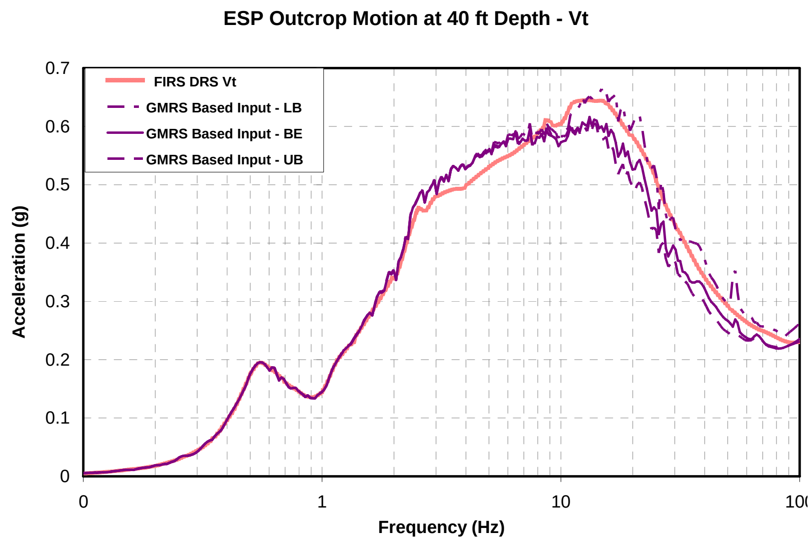




Green lines designate response motion at ground surface using FIRS-based time histories as input

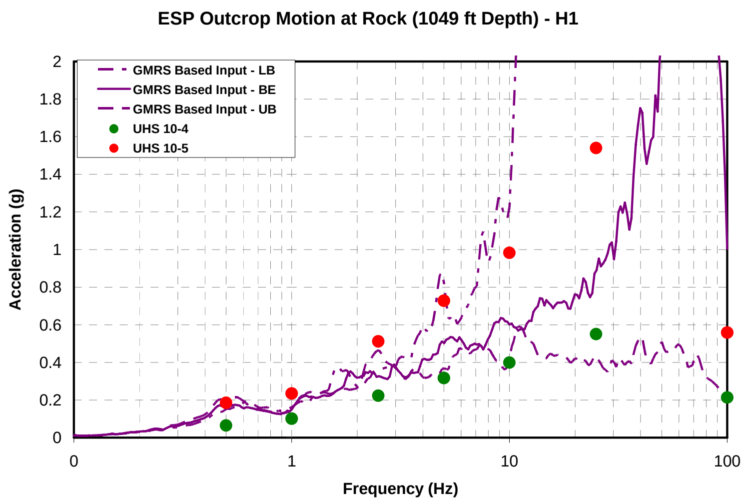
Example of GMRS/FIRS

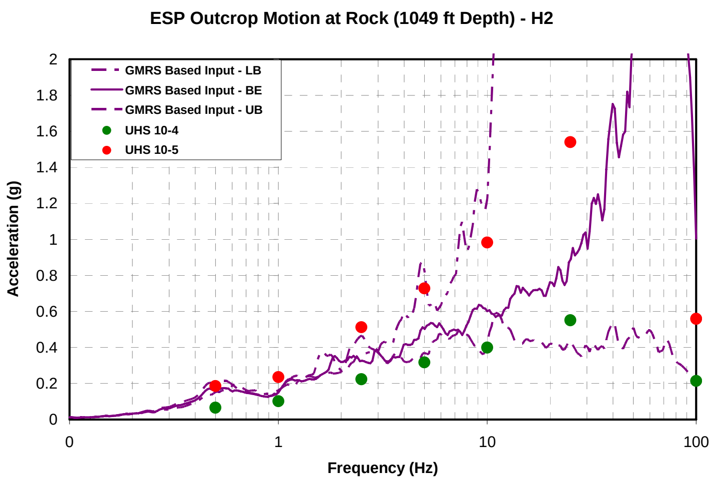




Purple lines designate response motion at 40 ft depth using GMRS time histories as input

Example of GMRS/FIRS





Purple lines designate response motion at 1049 ft depth using GMRS time histories as input

Example of GMRS/FIRS

OBSERVATION

- De-convolution of site specific smooth spectra results in unrealistic motion even at shallow depths. De-convolved motion can be lower or higher than the performance-based motion at foundation level of the structure
- De-convolved response motion is no longer a performance-based motion