Efficient Probabilistic Seismic SSI for Nuclear Structures Using Reduced-Order Models in Probability Space

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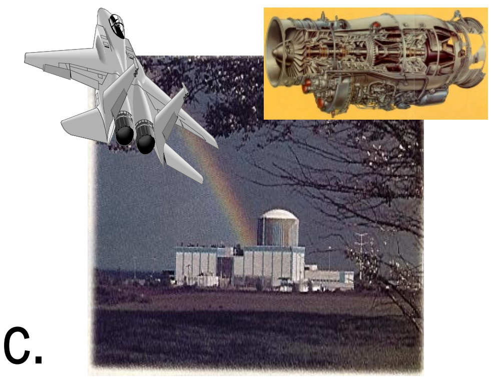

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Purpose of This Presentation:

To present different reduced-order modeling (ROM) approaches for performing efficient probabilistic SSI analyses.

To review three types of ROM approaches:

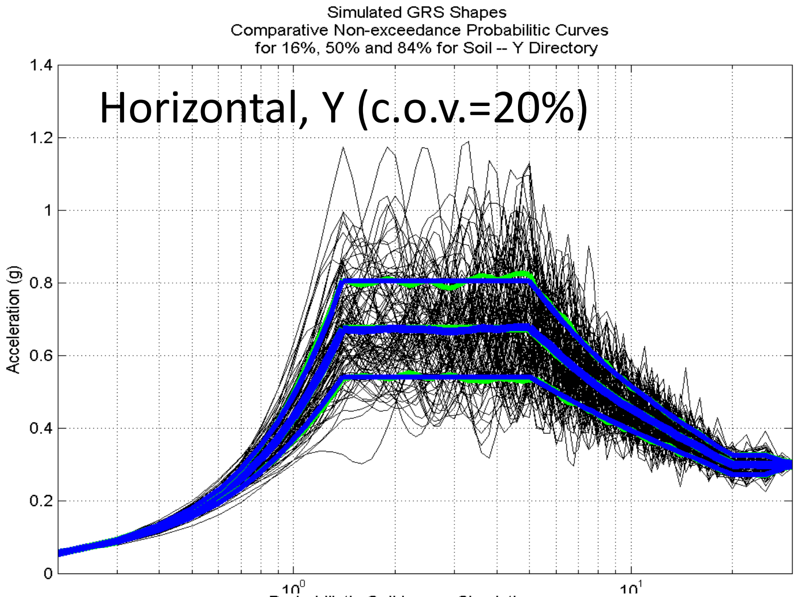
- Latin Hypercube Sampling (LHS) used extensively for probabilistic SSI simulations. Recommended by ASCE 04-2013 (30 LHS vs. 200 MCS)

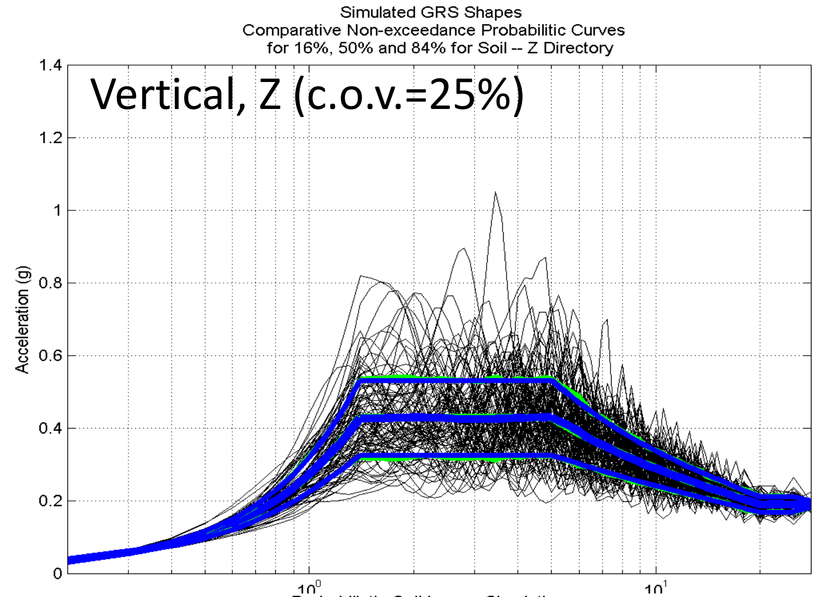
- Random Vibration Theory (RVT) based approach used only very limited for probabilistic SSI analysis. Recommended by ASCE 04-2013, but it needs more user guidance in future.

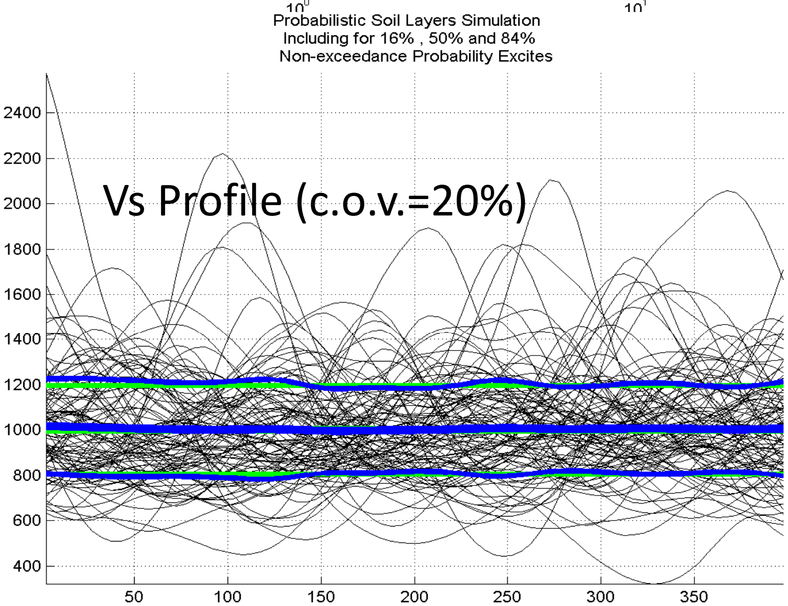
- Stochastic Reduced-Order Model (SROM) approach, new efficient computational simulation approach, state-of-the-art approach applicable to any probabilistic FEA analysis. Not included in ASCE 04-2013.

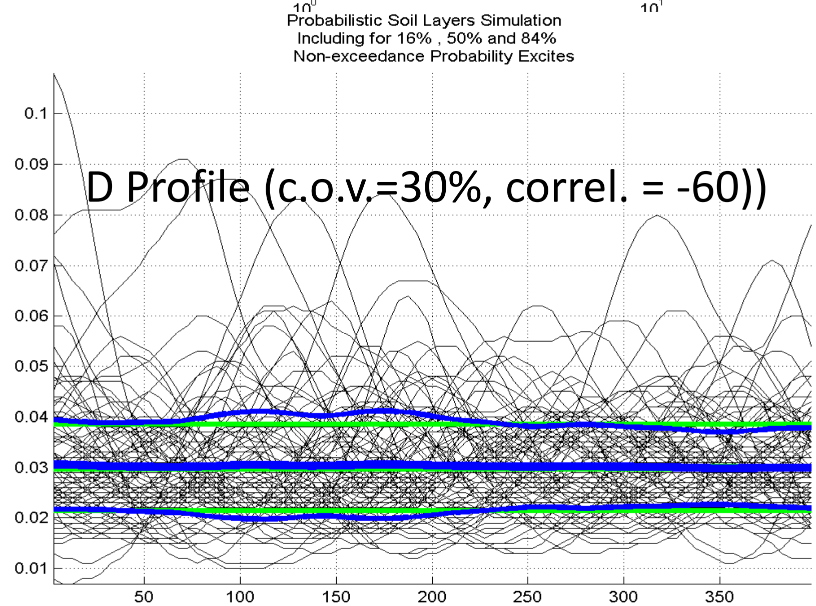
ACS SASSI V230 Options Pro and RVT were used for LHS and RVT results.

Seismic GRS and Soil Profiles Using LHS Simulation
100 LHS Simulations



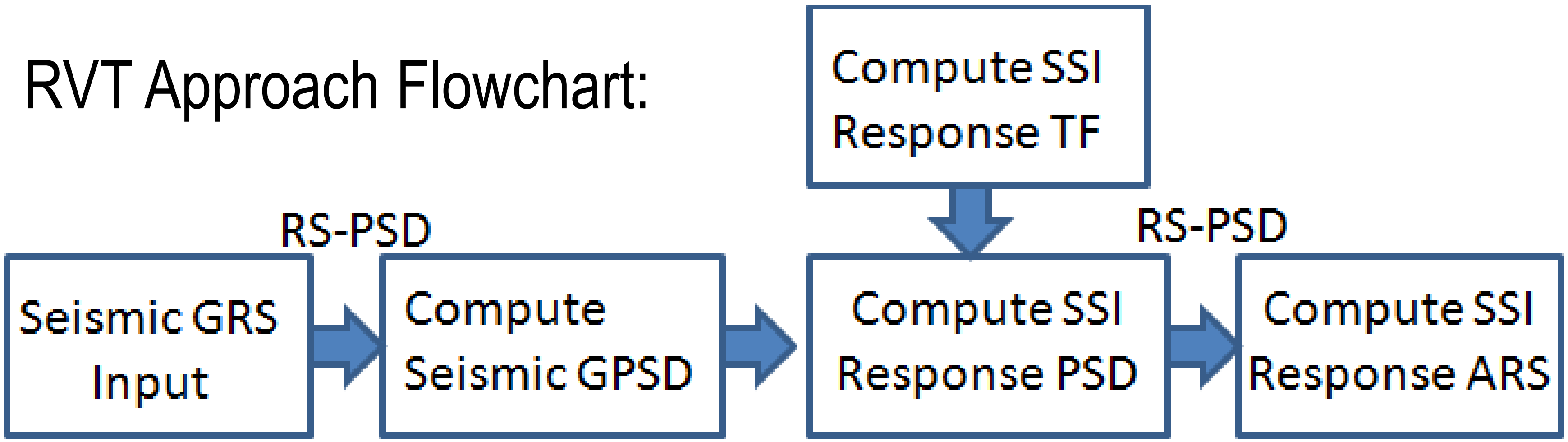






RVT Approach for Seismic SSI Analysis

RVT Approach Flowchart:



SDOF Transfer Functions:

$$H_0(\omega) = \frac{\omega_0^2 + 2i\omega_0\xi_0\omega}{\left(\omega_0^2 - \omega^2\right) + 2i\omega_0\xi_0}$$

Absolute Accelerations (ARS-APSD)

$$H_0(\omega) = \frac{\omega}{\left(\omega_0^2 - \omega^2\right) + 2i\omega_0\xi_0}$$

Relative Velocities (VRS-VPSD)

$$H_0(\omega) = \frac{1}{\left(\omega_0^2 - \omega^2\right) + 2i\omega_0\xi_0}$$

Relative Displacements (DRS-RPSD)

RVT Approach for SSI Analysis (Only Seismic Input)

The RVT based approach uses frequency domain convolution computations (no need to use time-histories) assuming a Gaussian seismic input:

$$S_X(\omega) = \left|H(\omega)\right|^2 \left|H_0(\omega)\right|^2 S_u(\omega)$$

Response SSI SDOF Input

The RVT-based approaches include several options related to the *PSD-RS transformation*. These options are related to the stochastic approximation models used for computing the maximum SSI response overt a time period T, i.e. during the earthquake intense motion time interval.

The maximum SSI response can be expressed by using peak factors that are applied to the stochastic motion standard deviation (RMS). These quantities depend on the duration T, the mean crossing rate of the motion and probability level associated to the maximum response (“first passage problem”).

Computation of Maximum SSI Response (RS)

$$\overline{X}_{\max} = p\,\sigma_X$$
$$\sigma_{X_{\max}} = q\,\sigma_X$$

1) M Kaul-Unruh-Kana stochastic model (MK-UK) (1978, 1981) :

$$p = \left[-2\ln\left(-\left(\frac{\pi}{T}\right)\left(\frac{\sigma_X}{\sigma_{\dot{X}}}\right)\ln(P)\right)\right]^{1/2}$$

Please note that this *p* is not the mean peak factor, since it provides maximum peak factor for any given NEP P

2) A Davenport (AD) (1964) for p and Der Kiureghian (1980) for q

$$p = \sqrt{2\ln(\nu_0 T)} + \frac{0.5772}{\sqrt{2\ln(\nu_0 T)}} \qquad q = \frac{1.2}{\sqrt{2\ln(\nu_0 T)}} - \frac{5.4}{\left[13 + \left(2\ln(\nu_0 T)\right)^{3.2}\right]}$$

3) A Davenport Modified by Der Kiureghian (AD-DK) (1981,1983)

$$\nu_e T = \begin{cases} \max\left(2.1, 2\delta\nu_0 T\right) & ;0 < \delta \le 0.1 \\ \left(1.63\delta^{0.45} - 0.38\right)\nu_0 T & ;0.1 < \delta < 0.69 \\ \nu_0 T & ;0.69 \le \delta < 1 \end{cases} \qquad \delta = \sqrt{1 - \frac{\lambda_1^2}{\lambda_0 \lambda_2}}$$

Warning Remarks on RVT Approach

1) It is based on the assumption that the seismic ground motion is a Gaussian stationary stochastic process.

This assumption might not be true if highly non-Gaussian “seed” records are used to generate the design-basis input time histories. Unfortunately, some recent publications show inconsistent results by comparing the RVT-based approach ISRS results with time-domain statistical ISRS results for highly non-Gaussian seismic input histories. If the Gaussianity modeling aspect is ignored, the RVT-based approach application becomes quite arbitrary, with results based on a case-by-case luck, and without a sound theoretical basis.

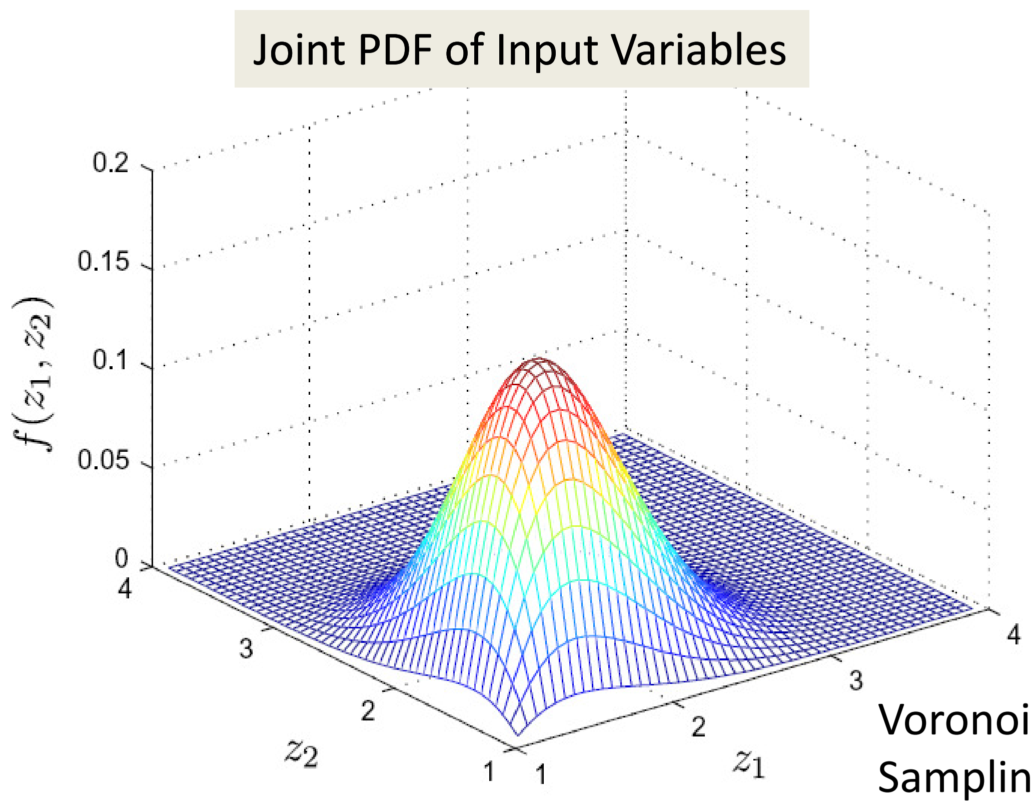
2) The ASCE 04-2013 referenced RVT approaches do not include the cross-correlations between the SSI response motions at different locations. Innaplicable to mutiple support time domain analysis of piping systems.

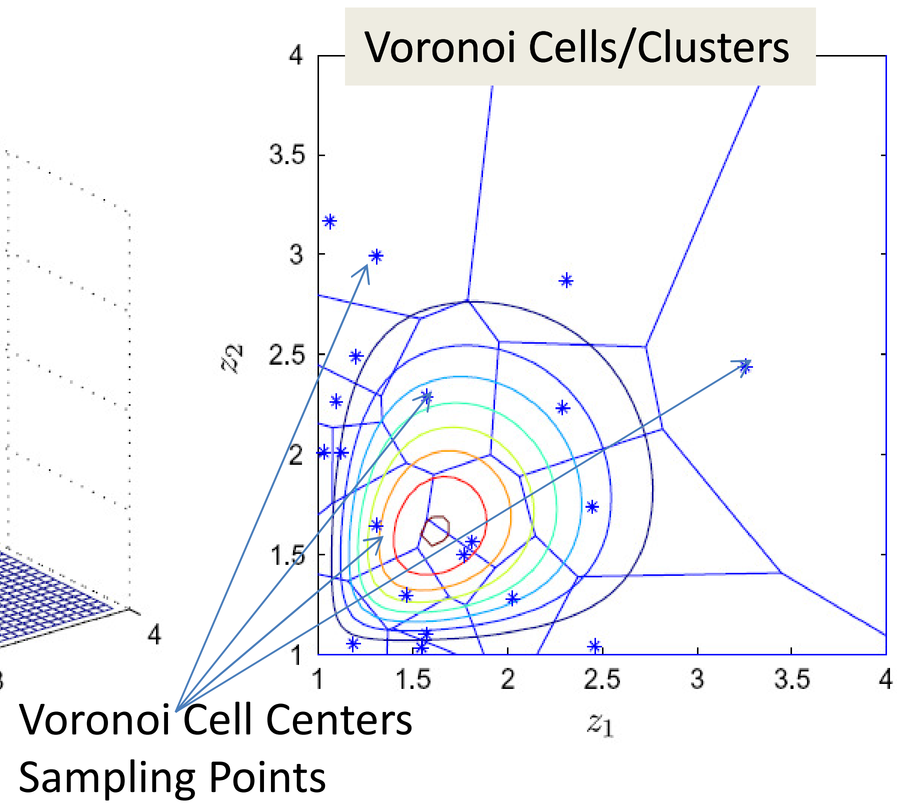
Stochastic Reduced Order Model (SROM)

The proposed method combines features of

(1) "Smart" Monte Carlo simulation, in the sense that it uses a relatively small number of samples zk of Z to characterize this random vector in an optimal manner and

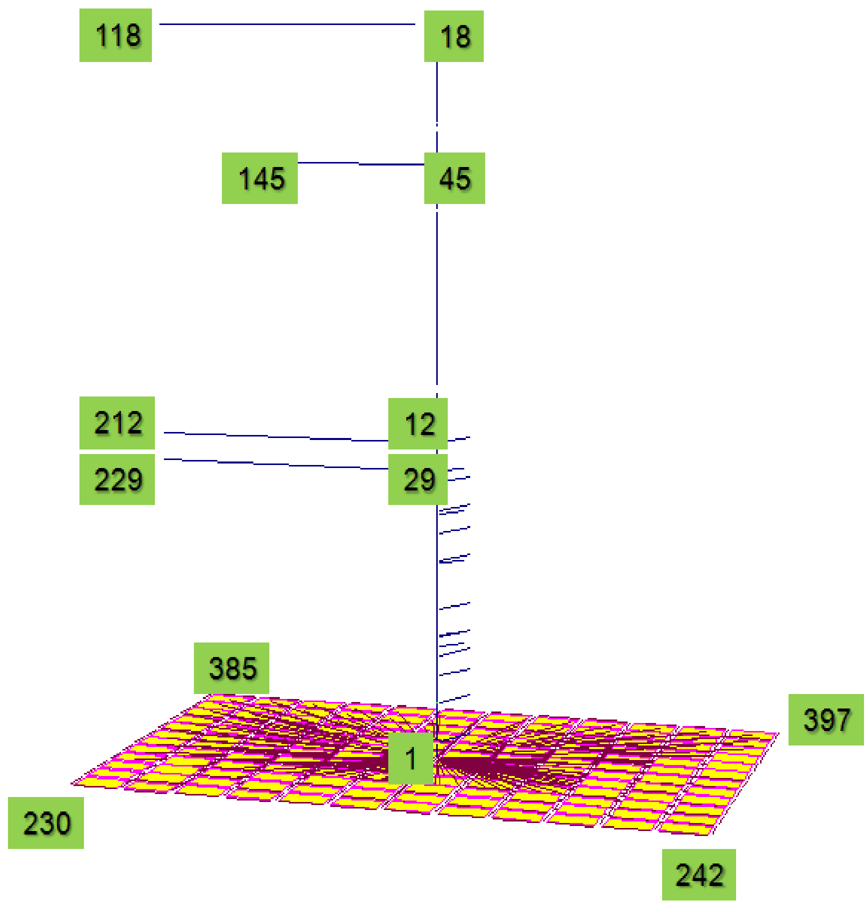
(2) Collocation method, in the sense that it interpolates between deterministic responses uk corresponding to Z=zk.



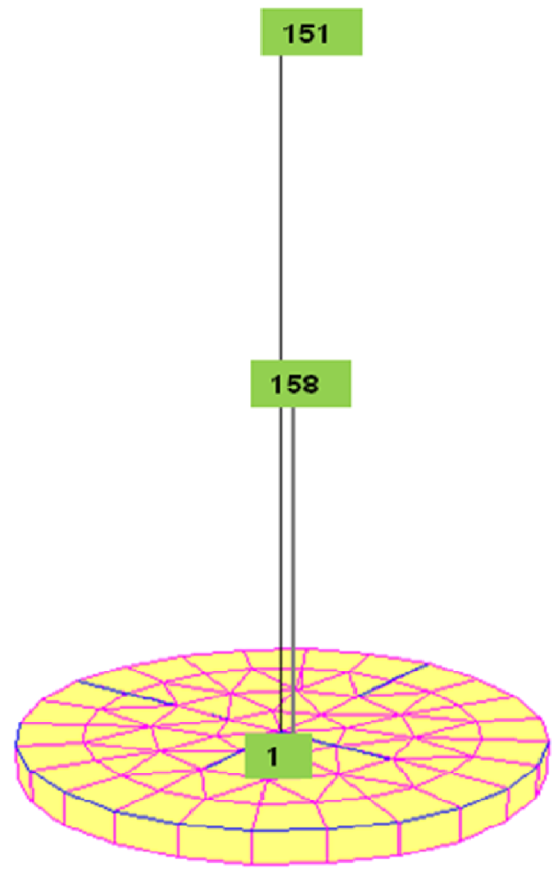


Case Studies: 1) EPRI AP1000 NI & 2) PWR RB Sticks

EPRI AP1000 NI Stick Model

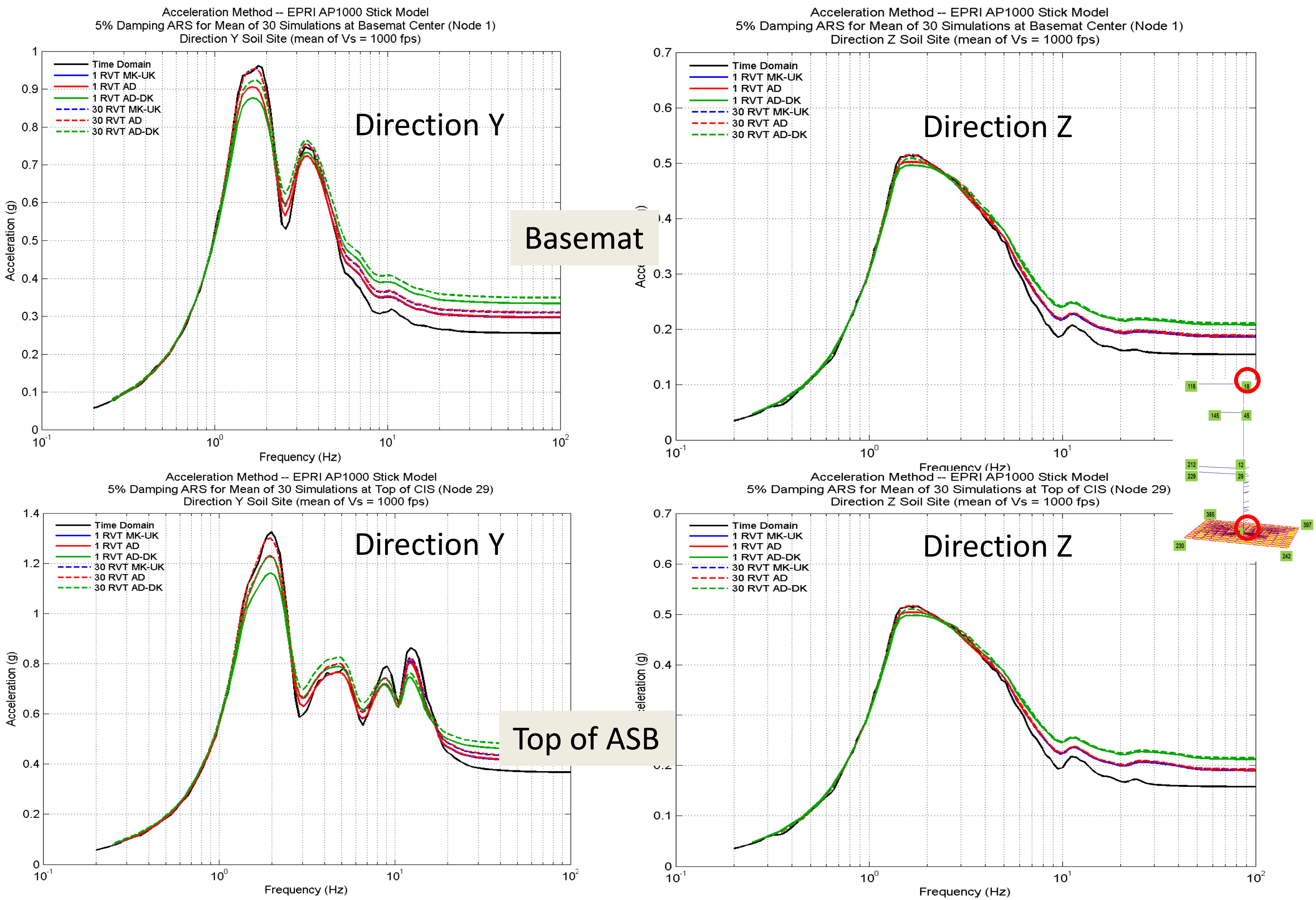


PWR RB Stick Model

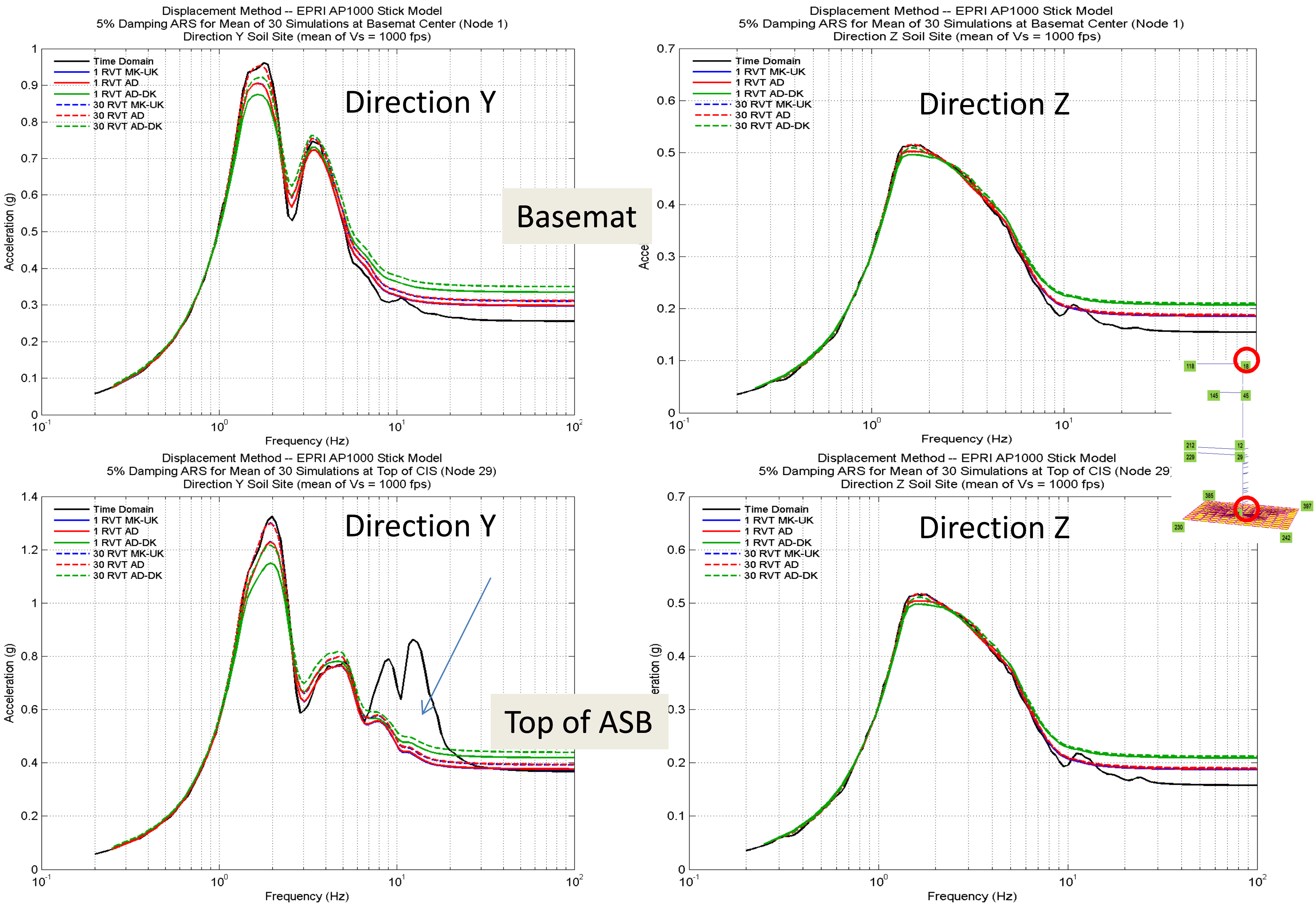


Case 1: Soil Site (BE Soil and Random Soil), Vs = 1,000 fps
Case 2: Rock Site (BE Soil and Random Soil), Vs = 6,000 fps

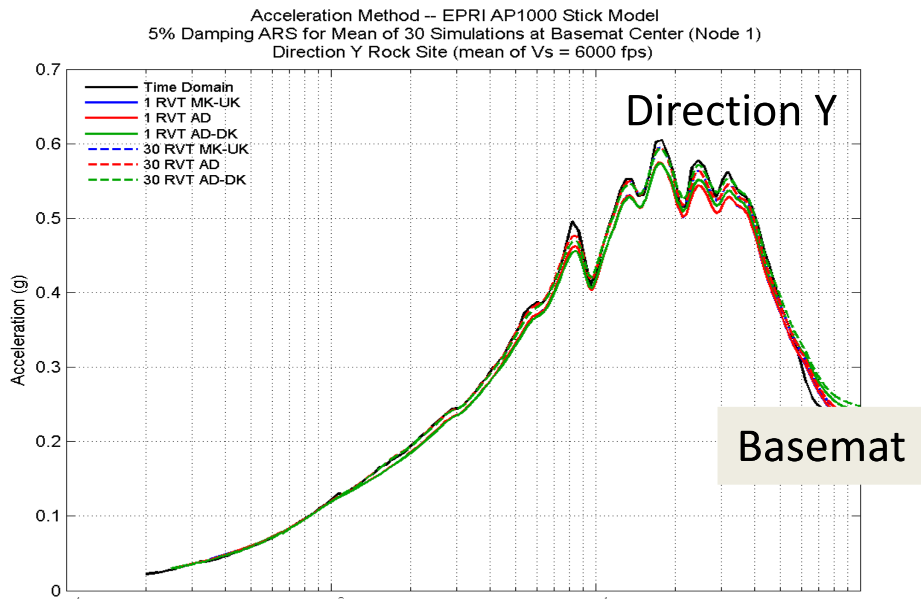
RVT Approach (ACC) vs. LHS for BE Soil – Mean ISRS

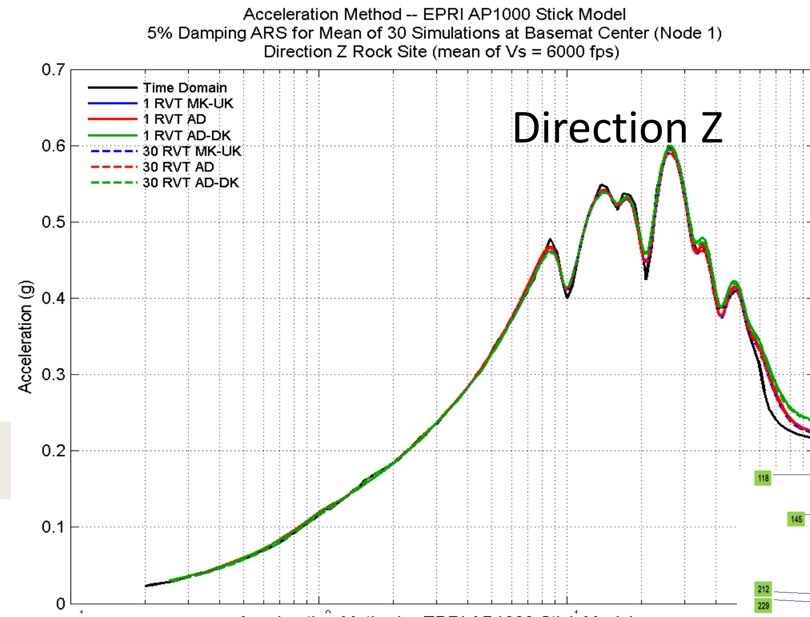


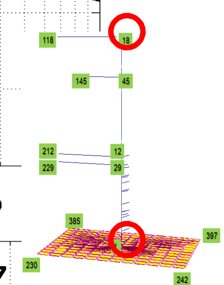
RVT Approach (DIS) vs. LHS for BE Soil – Mean ISRS

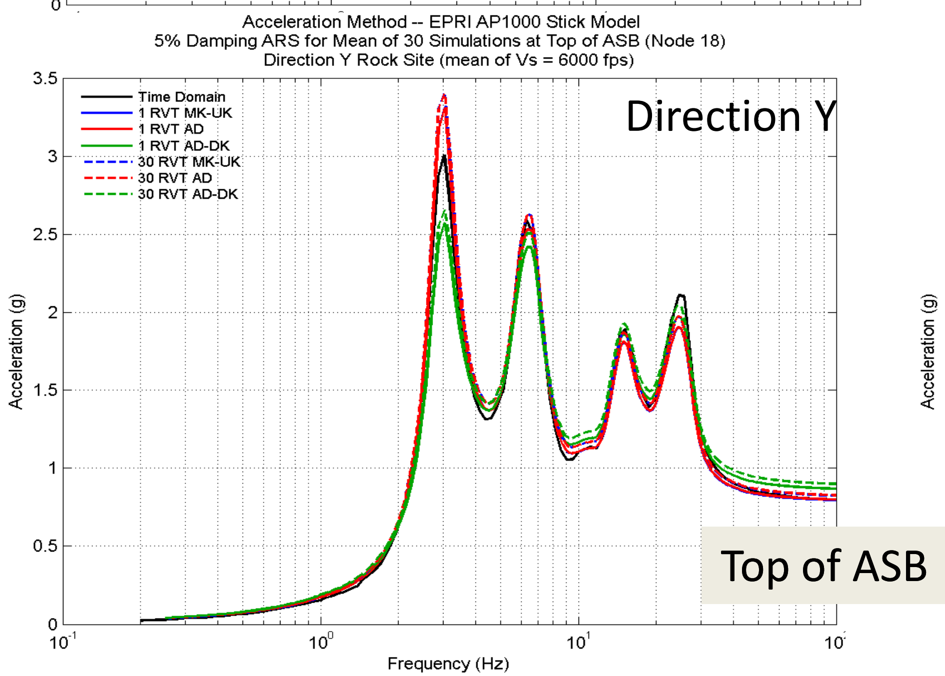


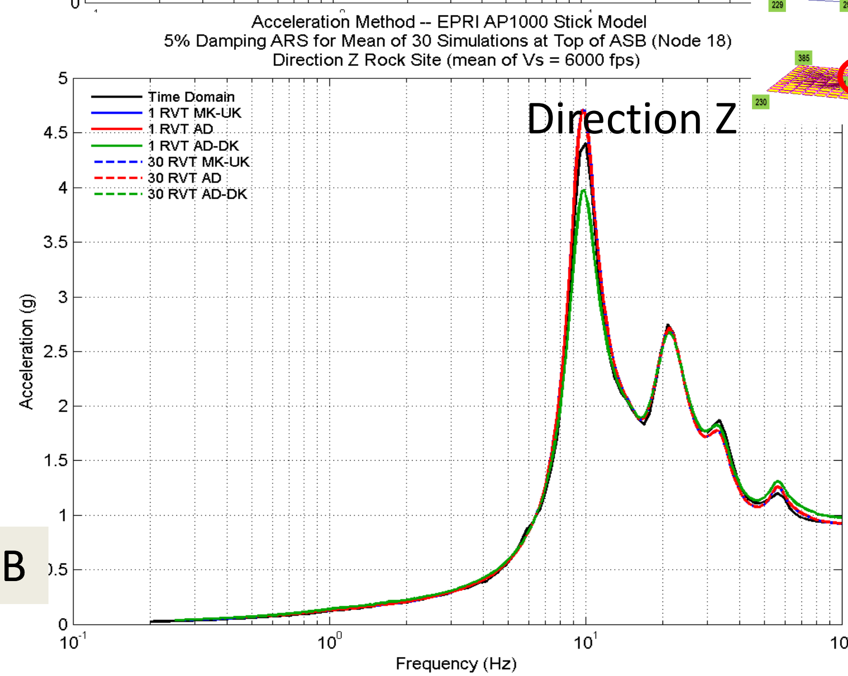
RVT Approach (ACC) vs. LHS for BE Rock – Mean ISRS



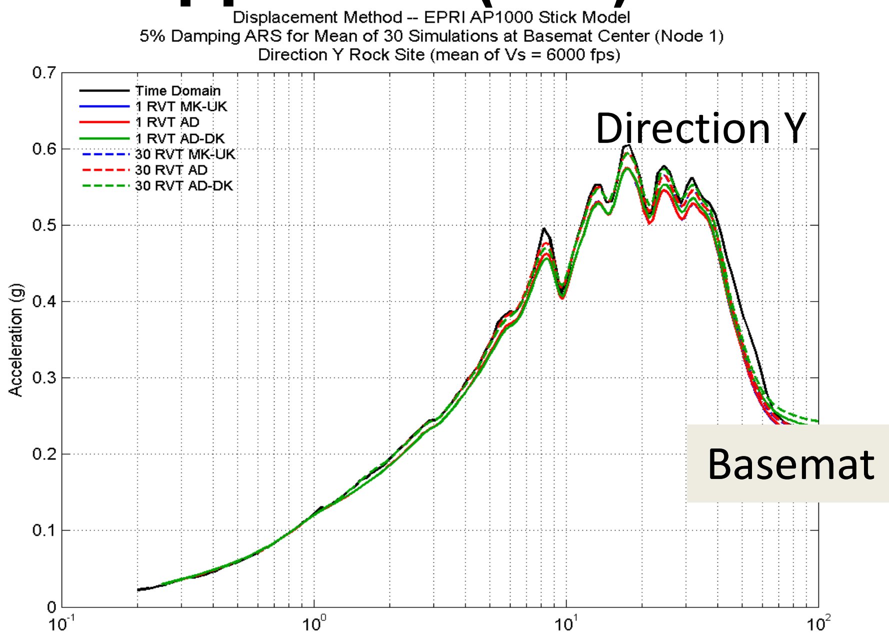


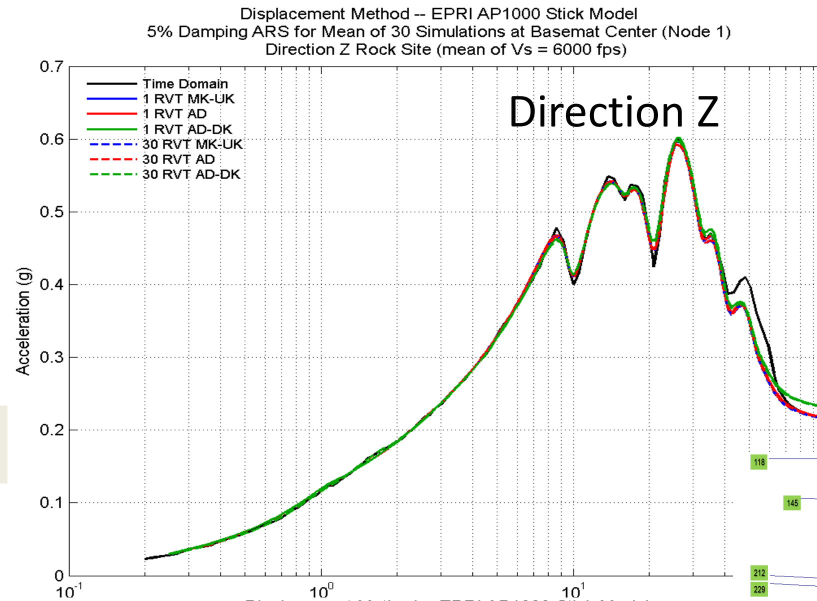


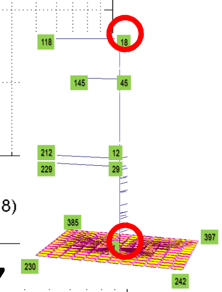


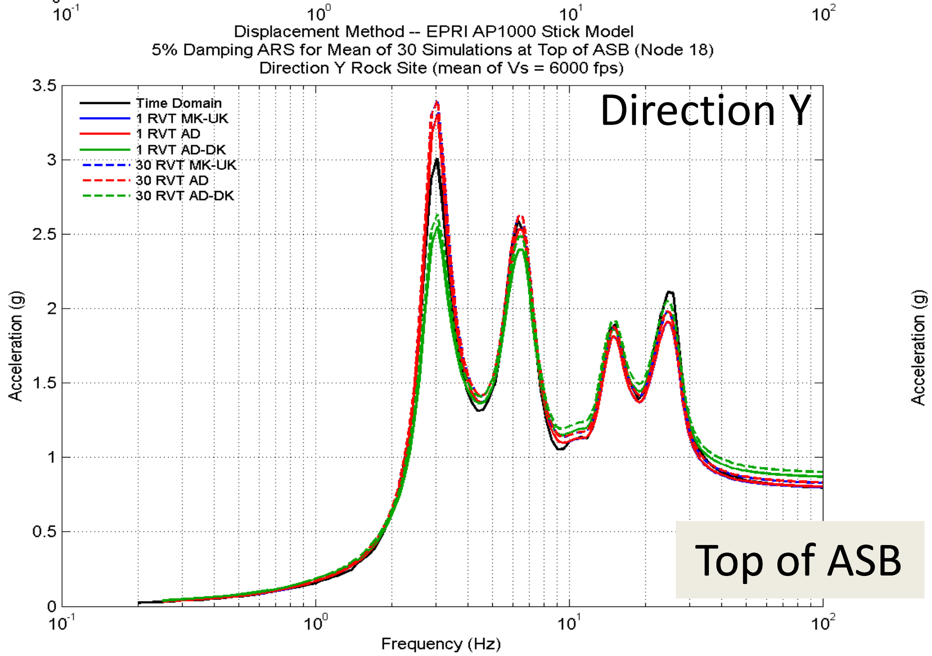


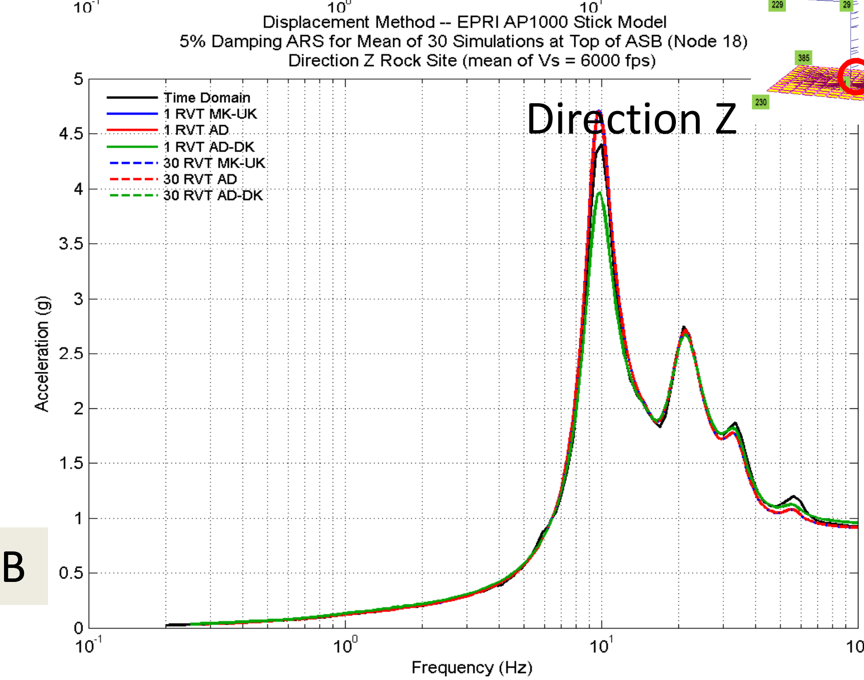
RVT Approach (DIS) vs. LHS for BE Rock – Mean ISRS



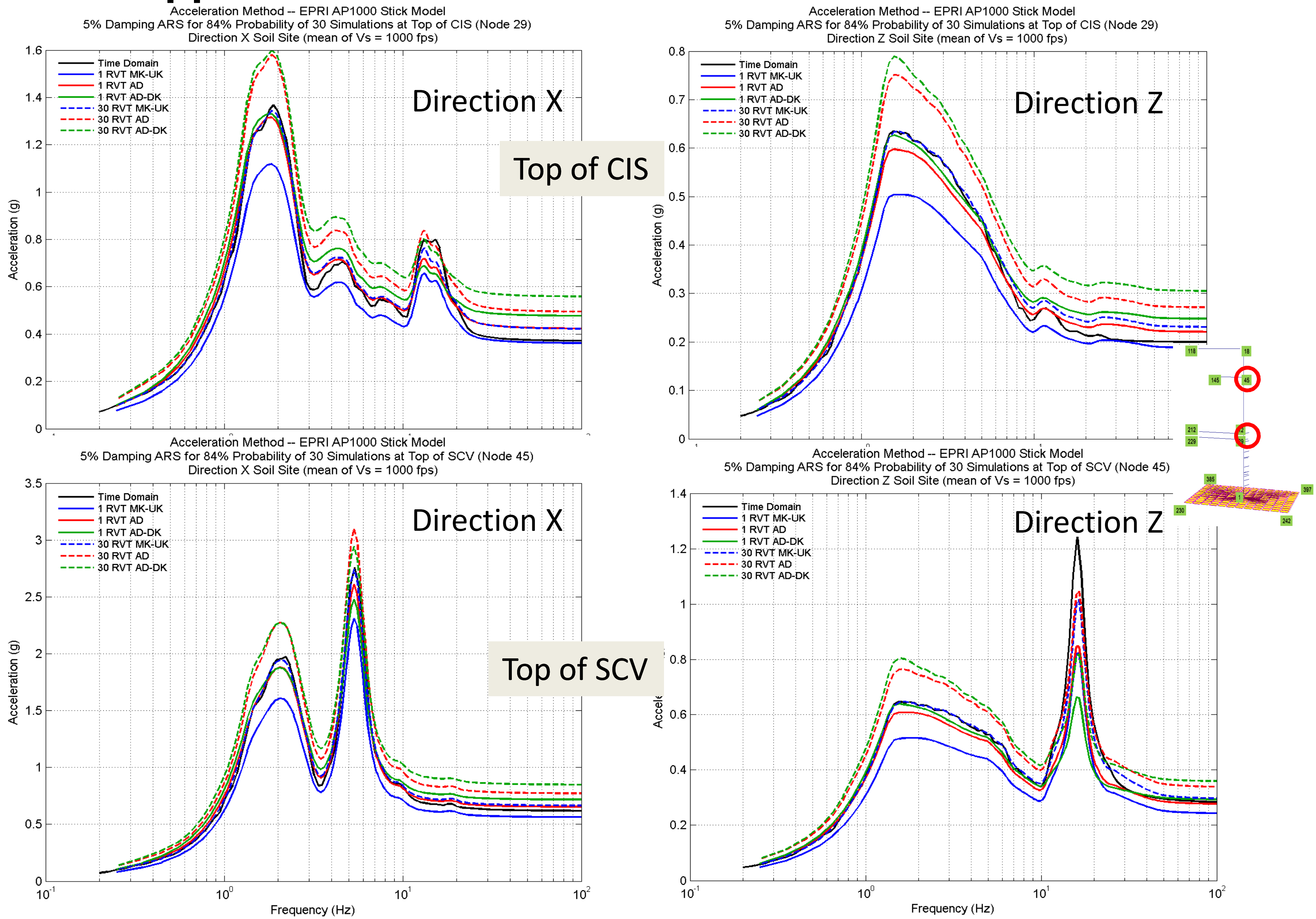




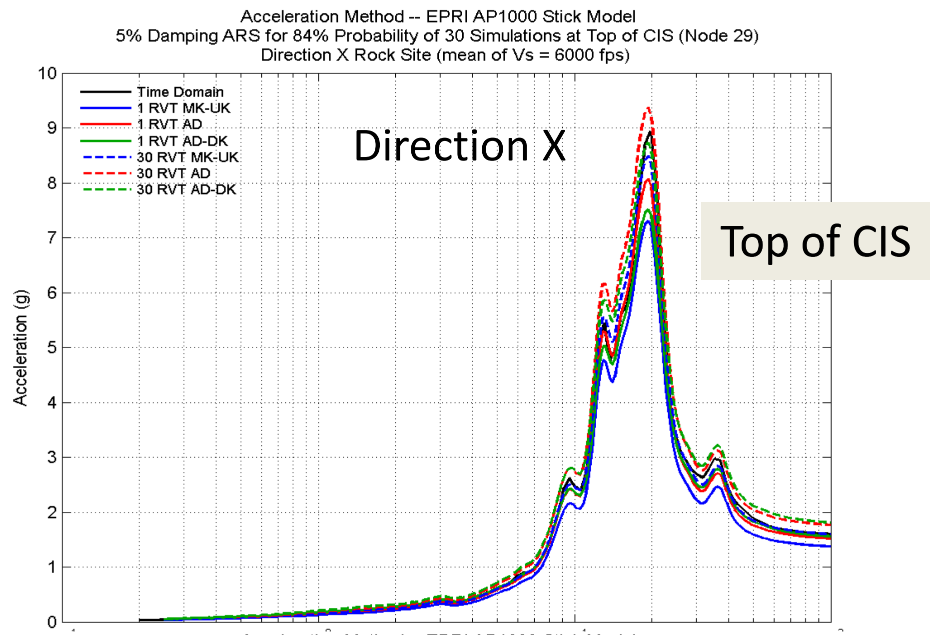


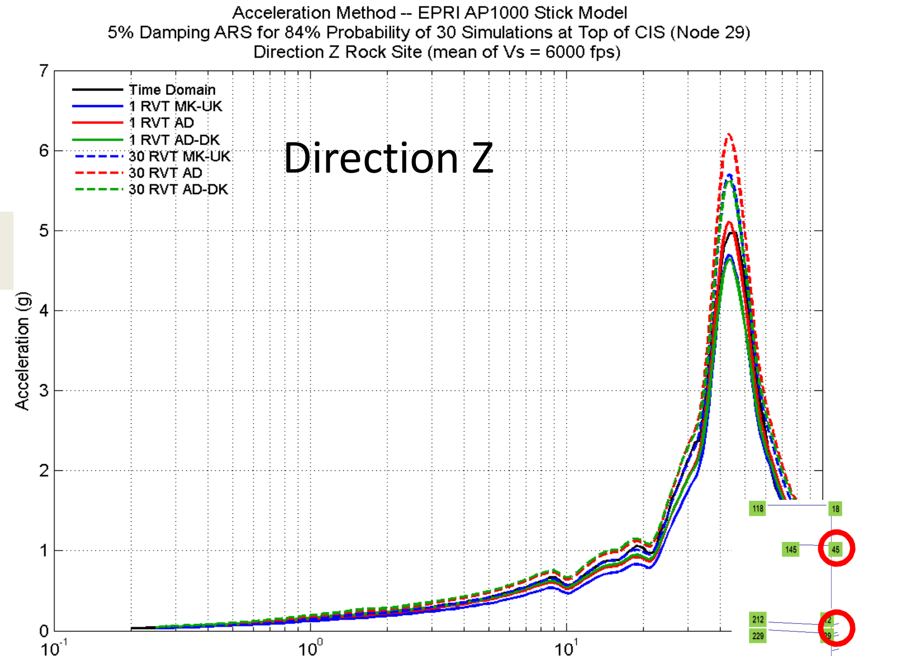


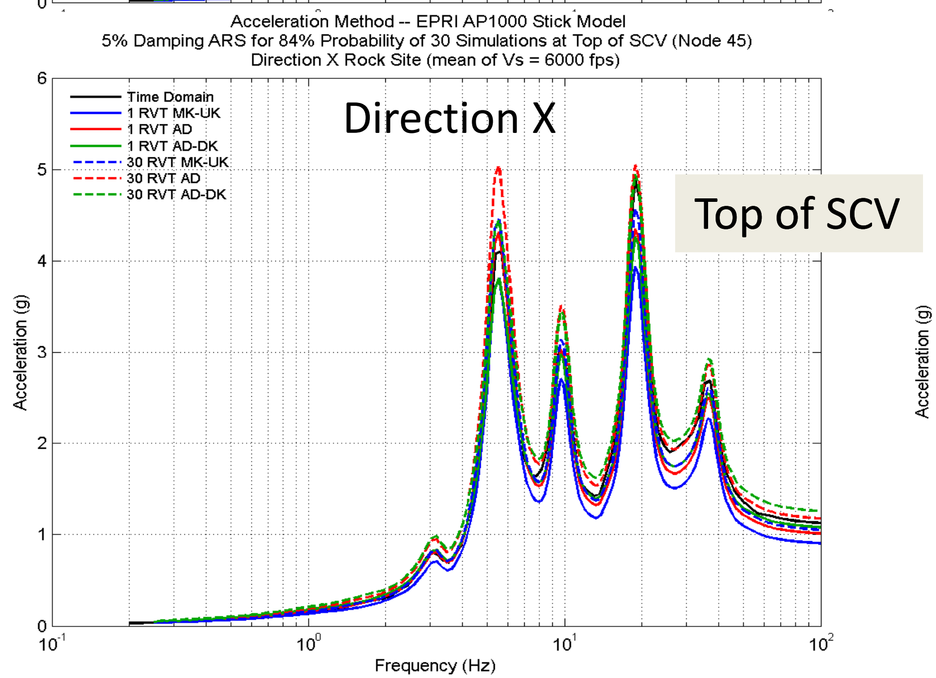
RVT Approach vs. LHS Results for BE Soil – 84% NEP ISRS

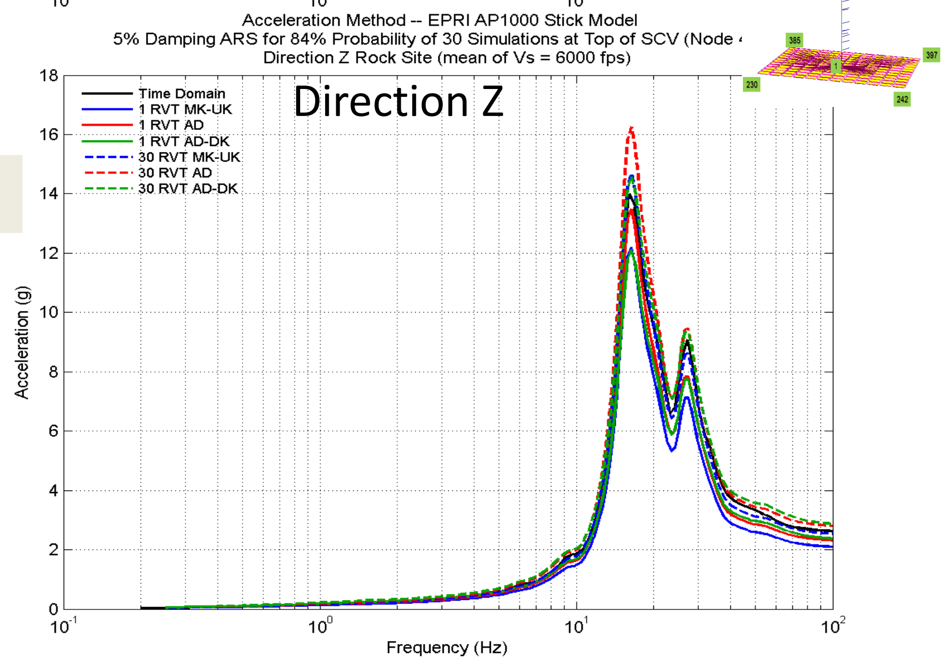


RVT Approach vs. LHS Results for BE Rock – 84% NEP ISRS

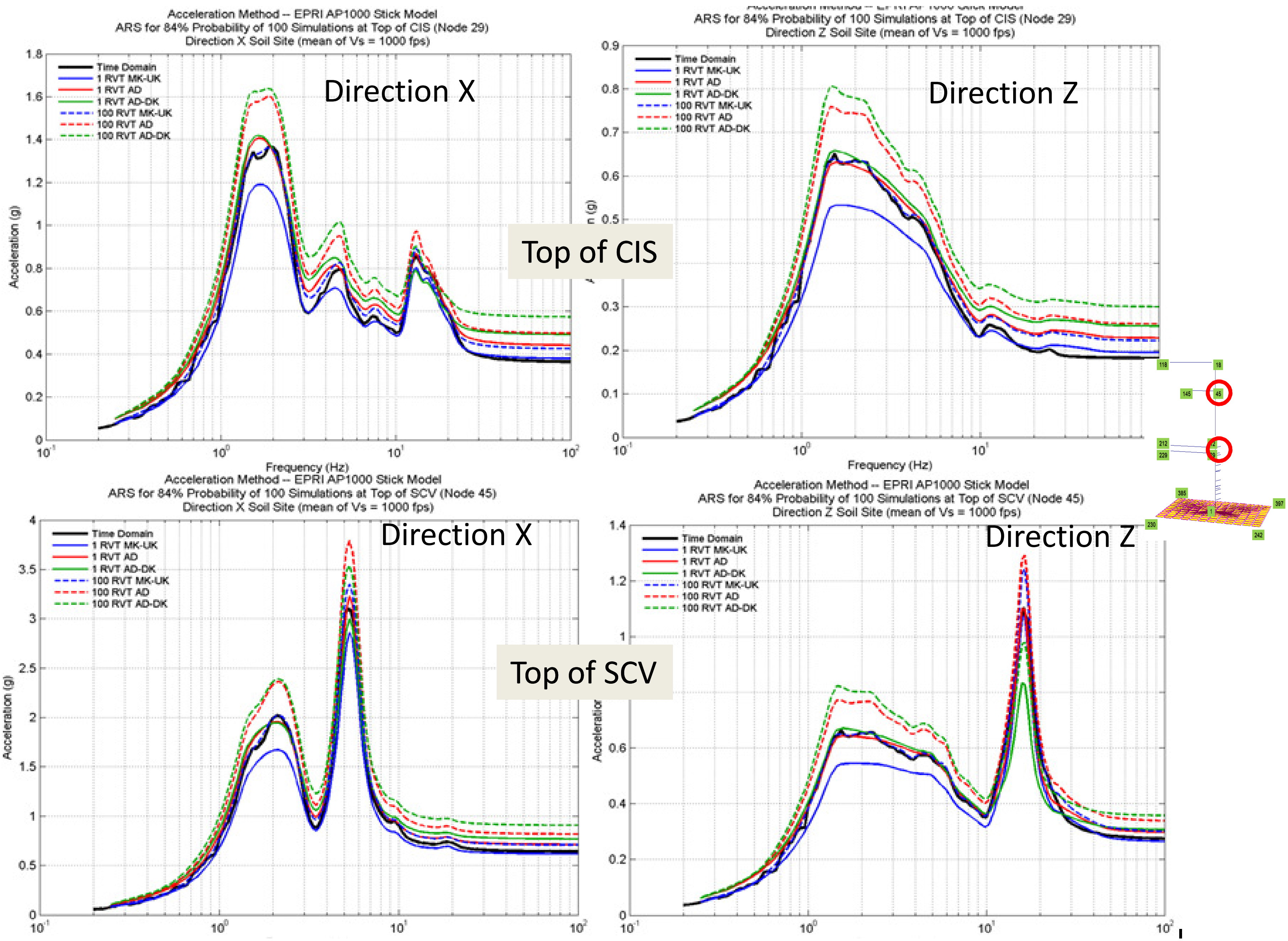




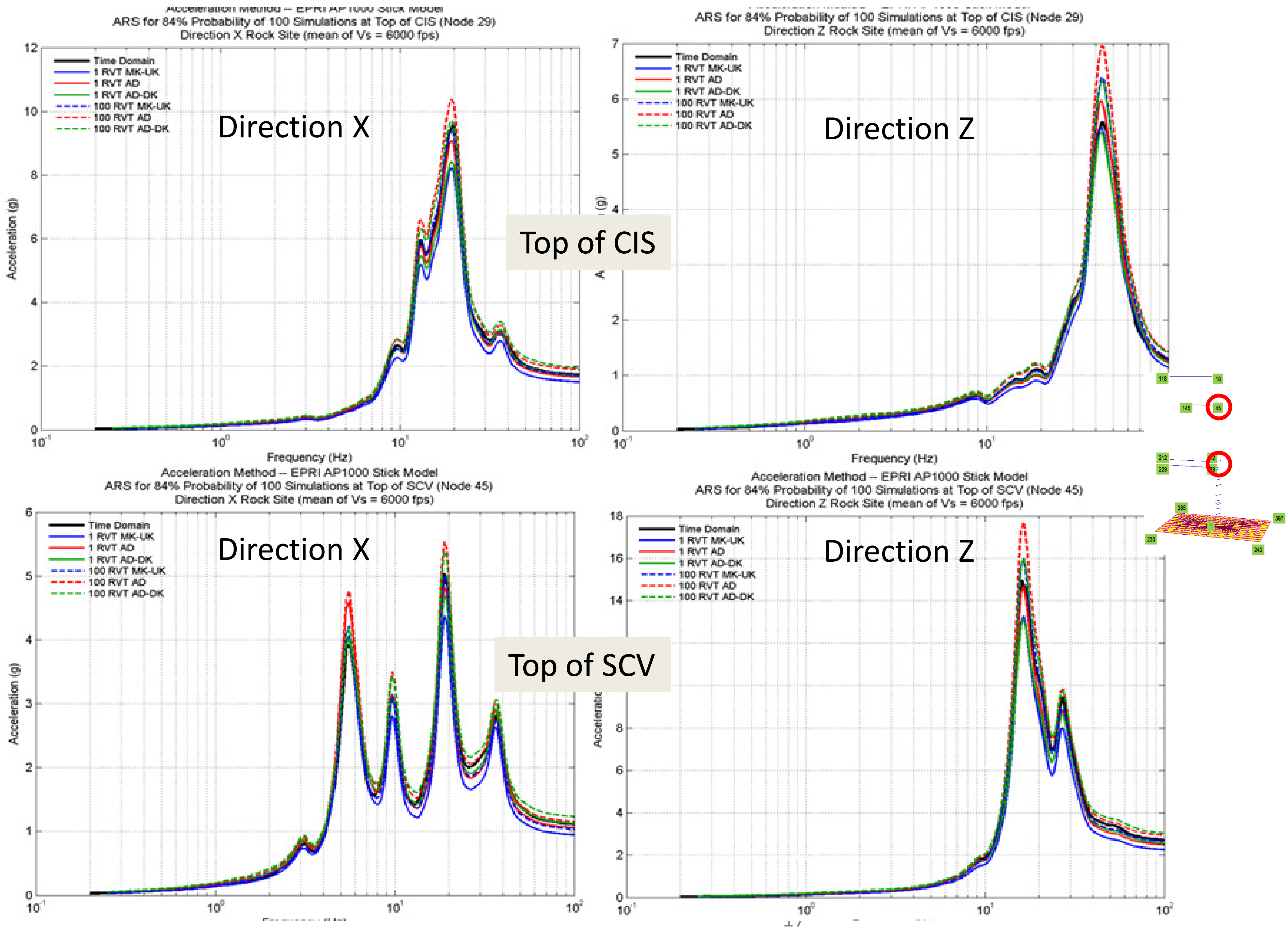




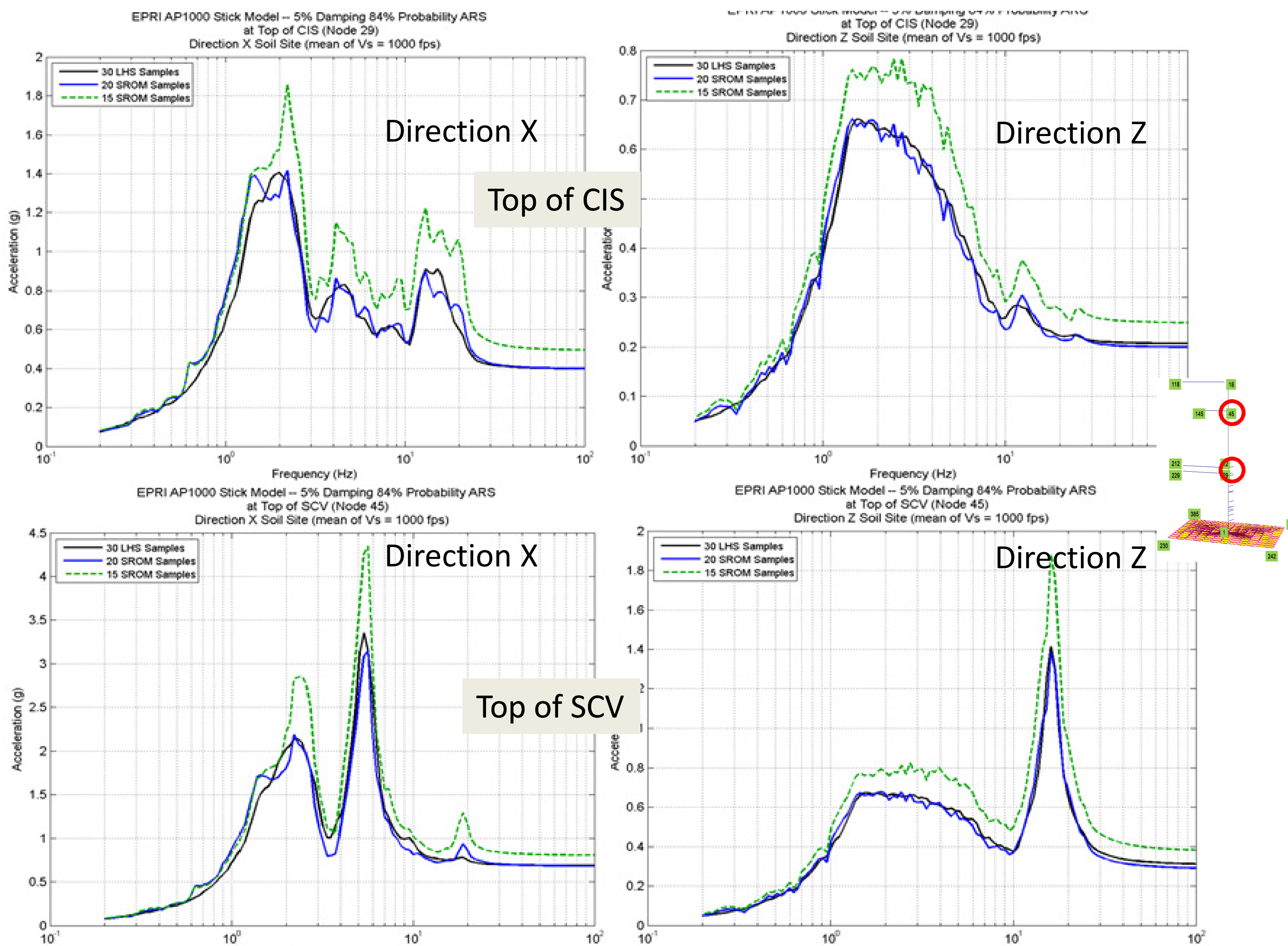
RVT vs. LHS Results for Random Soil – 84% NEP ISRS



RVT vs. LHS Results for Random Rock – 84% NEP ISRS



SROM vs. LHS for Random Soil – 84% NEP ISRS



Conclusions

- The LHS approach is the reference method for "Probabilistic SSI Analysis" that is recommended by the ASCE 04-2013 standard. LSH is much faster than MCS (30 LHS samples vs. 200 MCS samples). It is accurate and robust.

- The RVT approach can provide reasonably accurate results, if appropriately used. Unfortunately, there are no engineering guidelines by EPRI, ASCE or NRC on which method is most accurate, and what is the impact on accuracy, if other methods are used.
  - The accuracy RVT results varies significantly from method to method (MK-UK, AD and AD-DK). The RVT results variability is more drastically for the soil sites than for the rock sites as shown in the paper.
  - For non-Gaussian seismic inputs (could occur when "seed" records are used), the RVT approach could become arbitrary, potentially inaccurate. The RVT approach is expected to provide reasonably accurate results for Gaussian inputs, but not for non-Gaussian.
  - Based on limited investigations, the MK-UK100 appears to out outperform the other methods in terms of accuracy. AD1 appears to be reasonable accurate and robust. Carefulness is need when using other RVT methods, and displacement-based approach.

- The SROM approach is an efficient and accurate approach that has open future for fast probabilistic FEA analysis, including both linear and nonlinear analyses with complex FEA SSI models.