Uncertainties in In-Structural Response Spectra Estimated by Using Multiple Acceleration Time Histories

October 20-22, 2020

DOE/NRC Natural Phenomena Hazards Meeting

Virtual

Jinsuo Nie, Jim Xu, Vladimir Graizer, and Dogan Seber

Division of Engineering
Office of Regulatory Research
Nuclear Regulatory Commission

DISCLAIMER NOTICE

The findings and opinions expressed in this presentation are those of the authors, and do not necessarily reflect the view of the U.S. Nuclear Regulatory Commission.

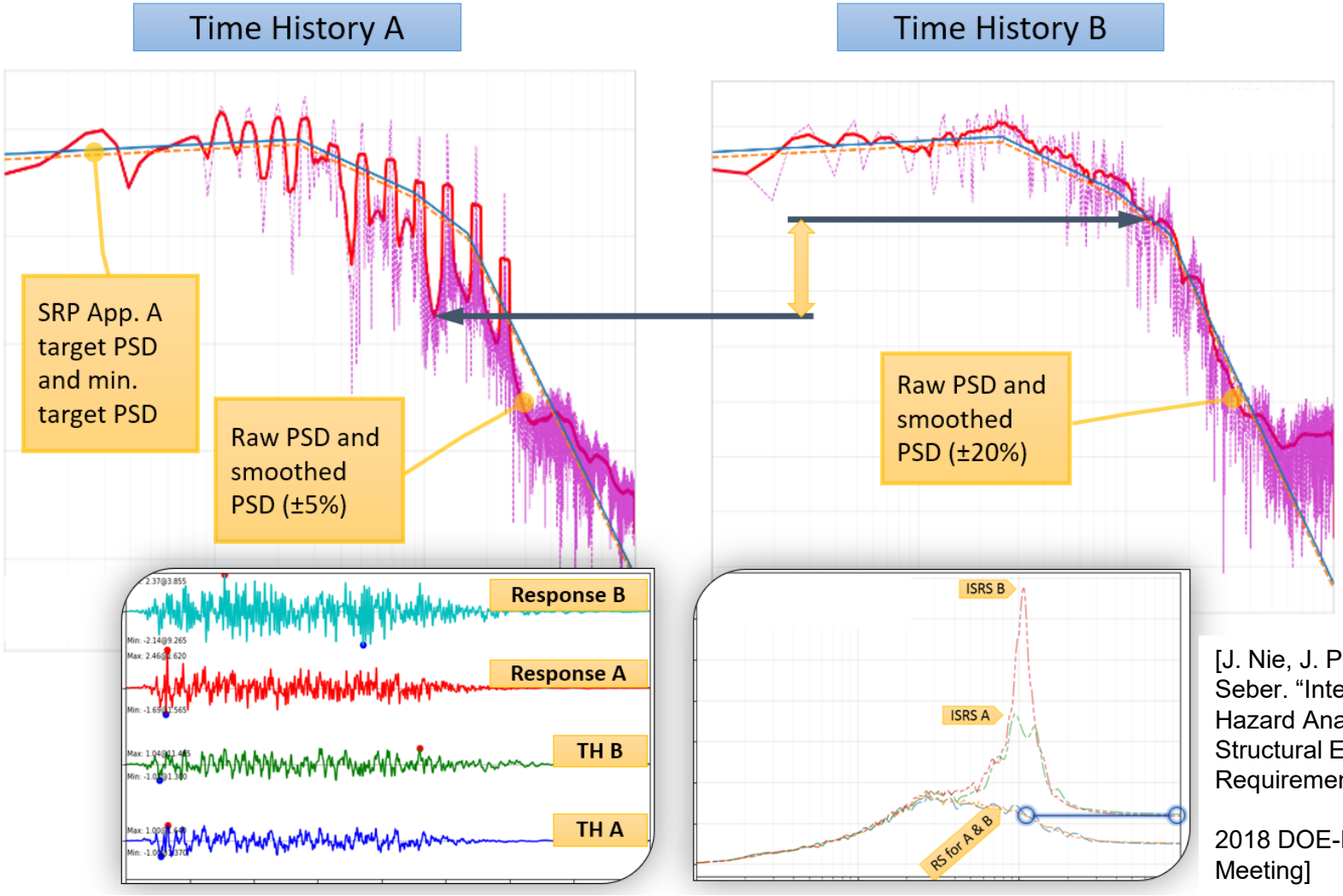
Topics of This Presentation

- In-Structure Response Spectra (ISRS) as a Better Representation of Input Power Distribution
- ISRS as Acceptance Criteria To Determine the Number of Input Time Histories
- Uncertainties in Input Time Histories and Coefficient of Variation in ISRS
- Effect of Phase Uncertainty on the Number of Input Time Histories
- Major conclusion: four or five time histories in the current practices may not be sufficient, especially for soil-structure systems with very low frequencies.

ISRS Is Better than Input RS to Represent Input Power Distribution

Comparison of Time History A consisting of mainly 15 frequencies and a broadband Time History B.

PSD – Power spectral density
RS – Response spectrum
SRP – Standard Review Plan
TH – Time history

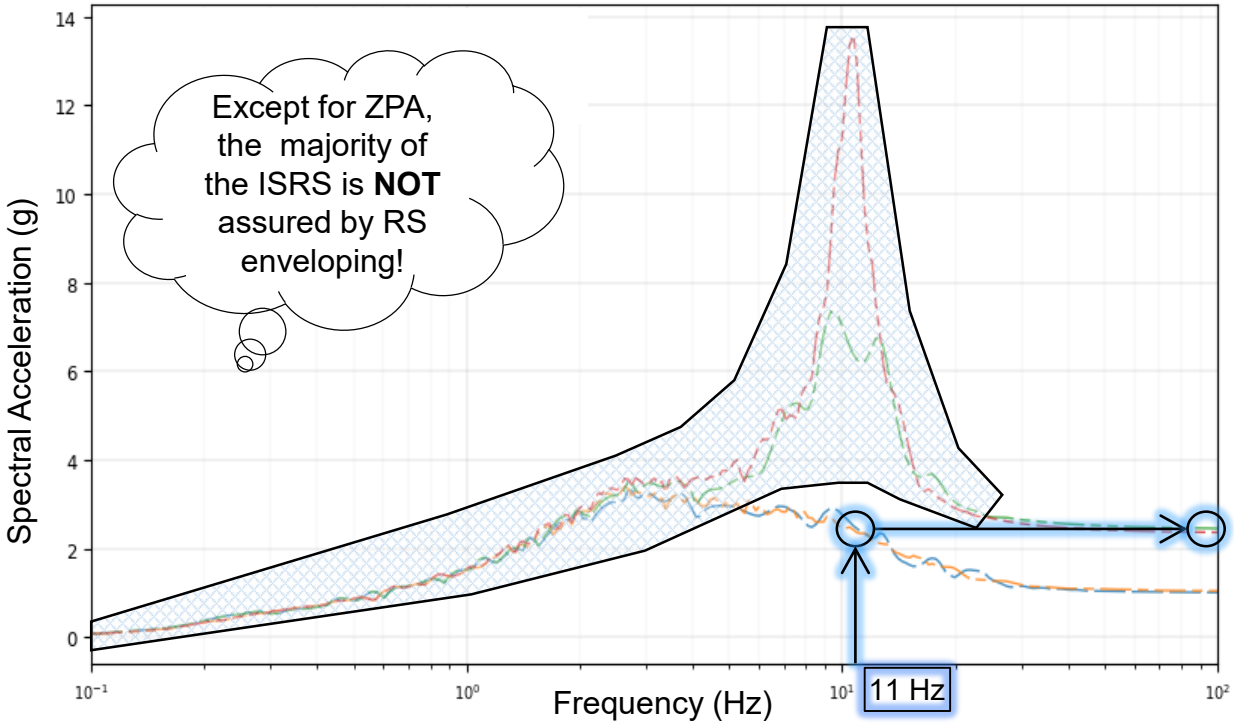


[J. Nie, J. Pires, and D. Seber. "Interfacing Seismic Hazard Analysis with Structural Engineering Requirements,"

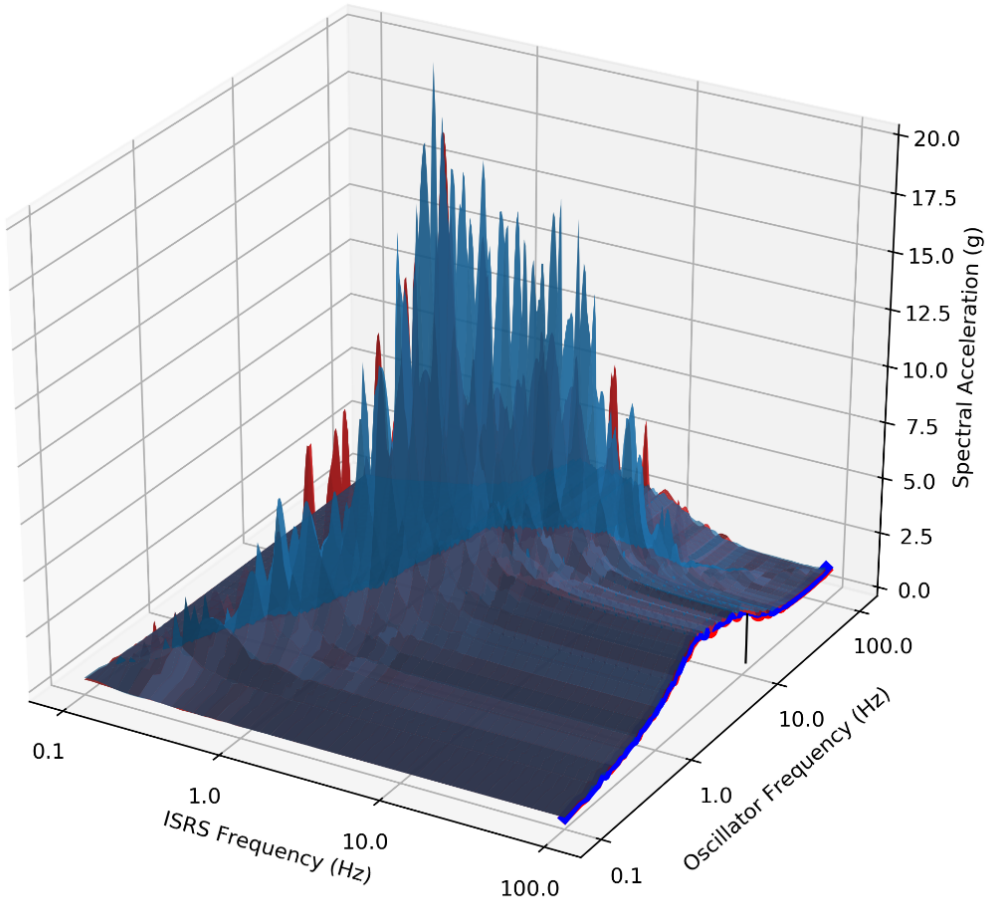
2018 DOE-NRC NPH Meeting]

ISRS for Multiple Oscillators

Assurance from RS Enveloping



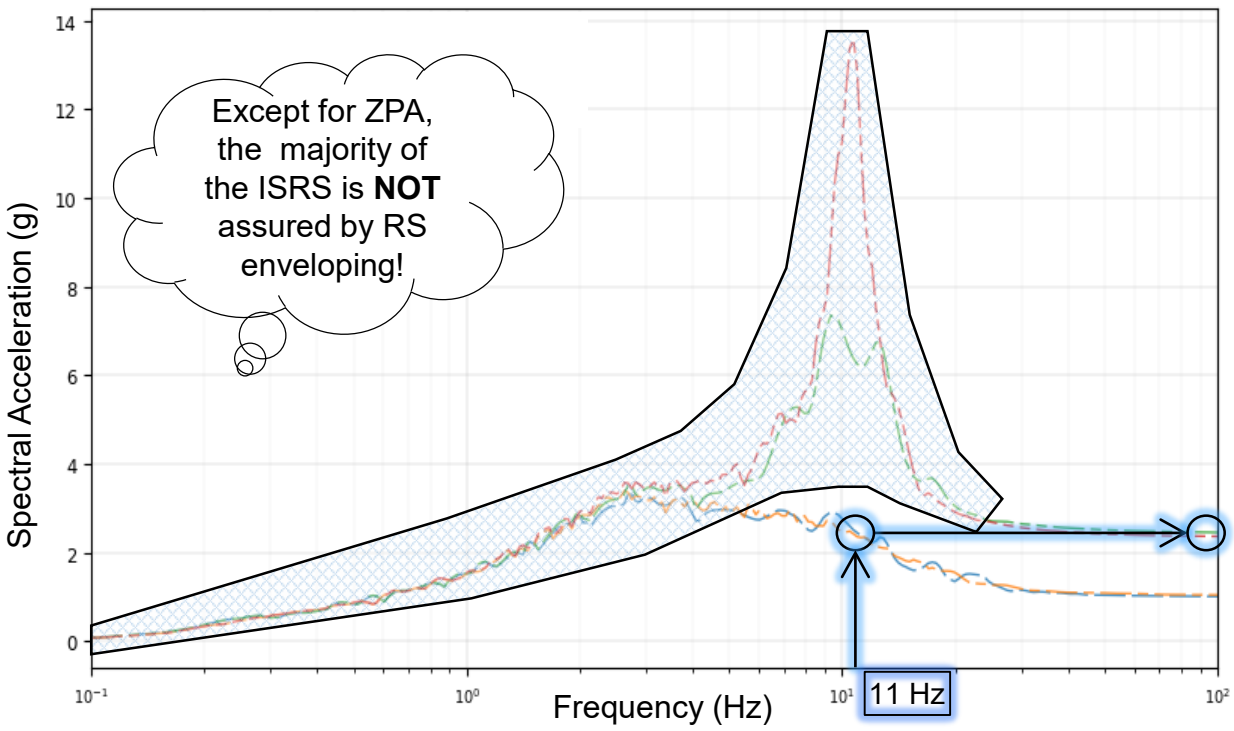
[J. Nie, J. Pires, and D. Seber (2019). "Understanding the assumptions in input response spectra for seismic time history analyses." Transactions, the 25th Structural Mechanics in Reactor Technology, SMiRT25.]

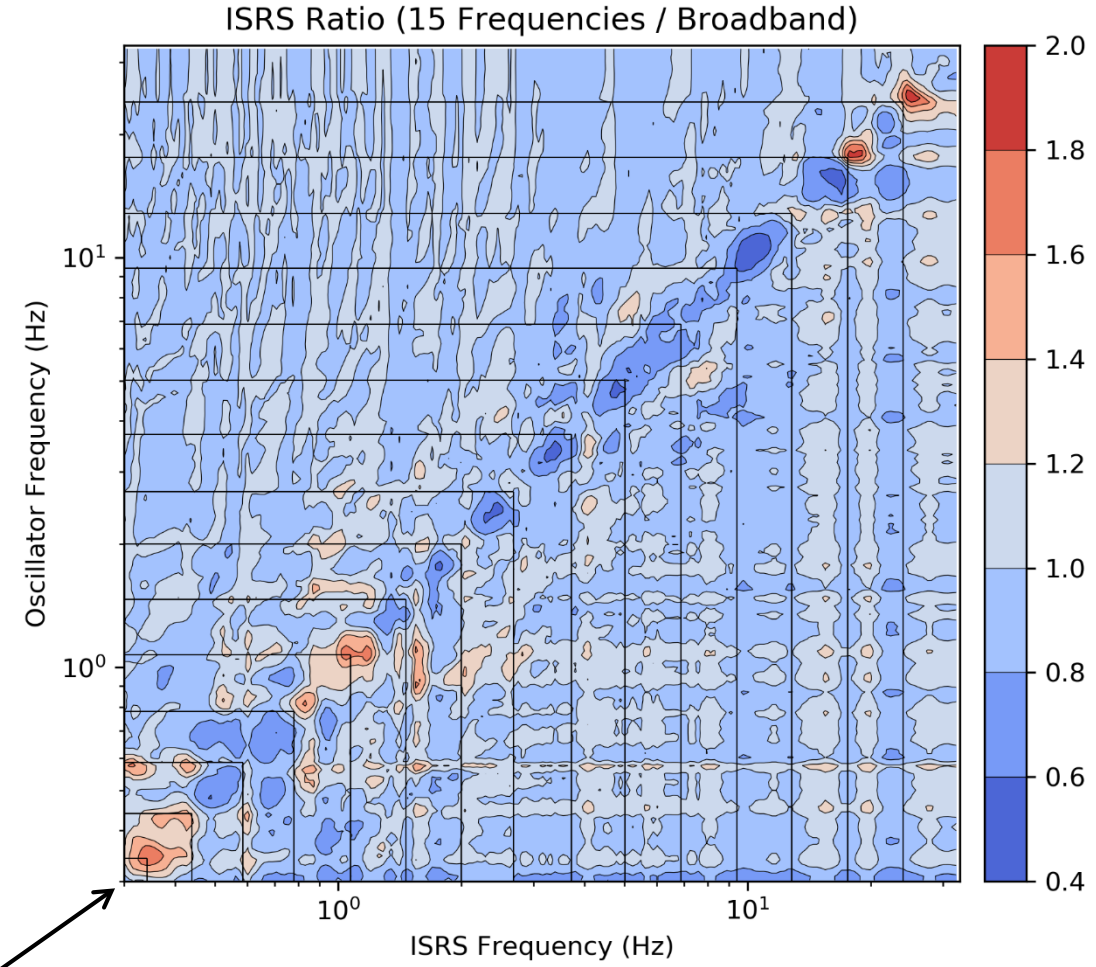


ISRS for Oscillators of Frequencies from 0.1 Hz to 100 Hz

ISRS Ratio Showing Different Power Distribution

Assurance from RS Enveloping





ISRS ratio is used to minimize the effect of minor differences in the input RS.

Contour Plot of ISRS Ratio (ISRS / Input RS)

ISRS as Acceptance Criteria To Determine the Number of Input Time Histories

- For linear analyses, the current practices are at least 5 time histories (ASCE 4-16) or 4 (SRP 3.7.1).
- Use a relatively large number of input acceleration time histories to estimate the “true” mean and Coefficient of Variation (CV) of the ISRS.
- Use CV_{ISRS} to determine the number of input time histories required to achieve a stable mean ISRS which falls within ±10% of the true mean for a given confidence level (CL).
- Assumptions: (1) input acceleration time histories are statistically independent, (2) ISRS relative to their mean are statistically independent, and (3) they have identical distribution.

ISRS as Acceptance Criteria

- The sample mean M and sample CV of the RS (i.e., M_{RS}, M_{ISRS}, CV_{RS}, and CV_{ISRS}) are estimated from 500 input time histories.
- The CV of M_{RS} and M_{ISRS} can be found as:

$$CV_{M_{RS}} = \frac{CV_{RS}}{\sqrt{N}}; \quad CV_{M_{ISRS}} = \frac{CV_{ISRS}}{\sqrt{N}};$$ for *N* time histories

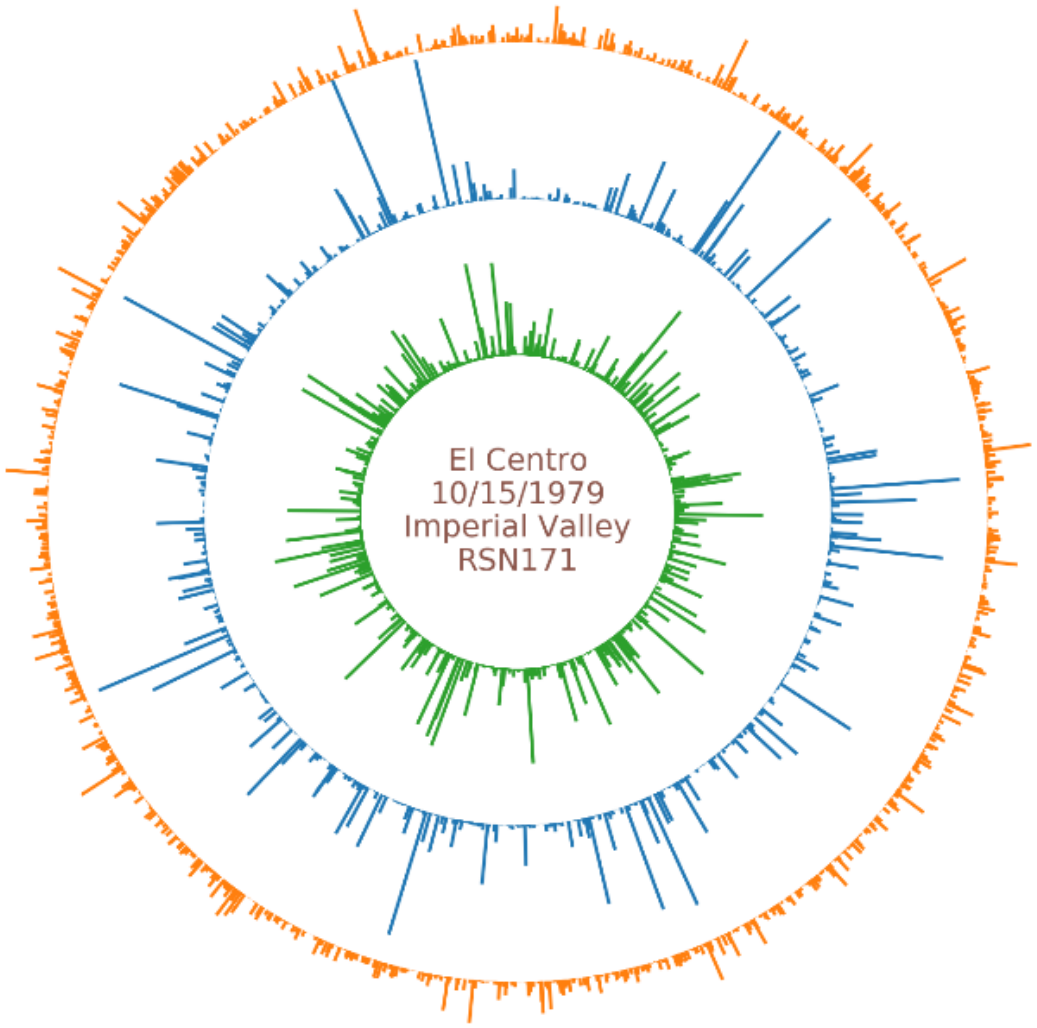
- Using the sample CV_{ISRS}, N_s time histories to achieve a M_{ISRS} within ±10% of the true mean can be determined by:

$$N_s \geq 100\, CV_{ISRS}^2, \text{ CL=68\%}; \quad N_s \geq 384\, CV_{ISRS}^2, \text{ CL=95\%}$$

- The essential task becomes to estimate an **accurate sample CV_{ISRS}**.

Uncertainties in Input Time Histories

- We separate the uncertainty in Fourier amplitude spectra and the **uncertainty in Fourier phase spectra** of the acceleration time histories.
- Fourier phase spectra are commonly observed to be distributed uniformly in [0, 2π] and are considered **irreducible**.
- Fourier amplitude spectrum and Fourier phase spectrum are generally **uncorrelated**.
- The uncertainty in the Fourier amplitude spectra should increase CV_{RS} (*for non RS matched time histories*) and CV_{ISRS}, and will need to be addressed in a future study.

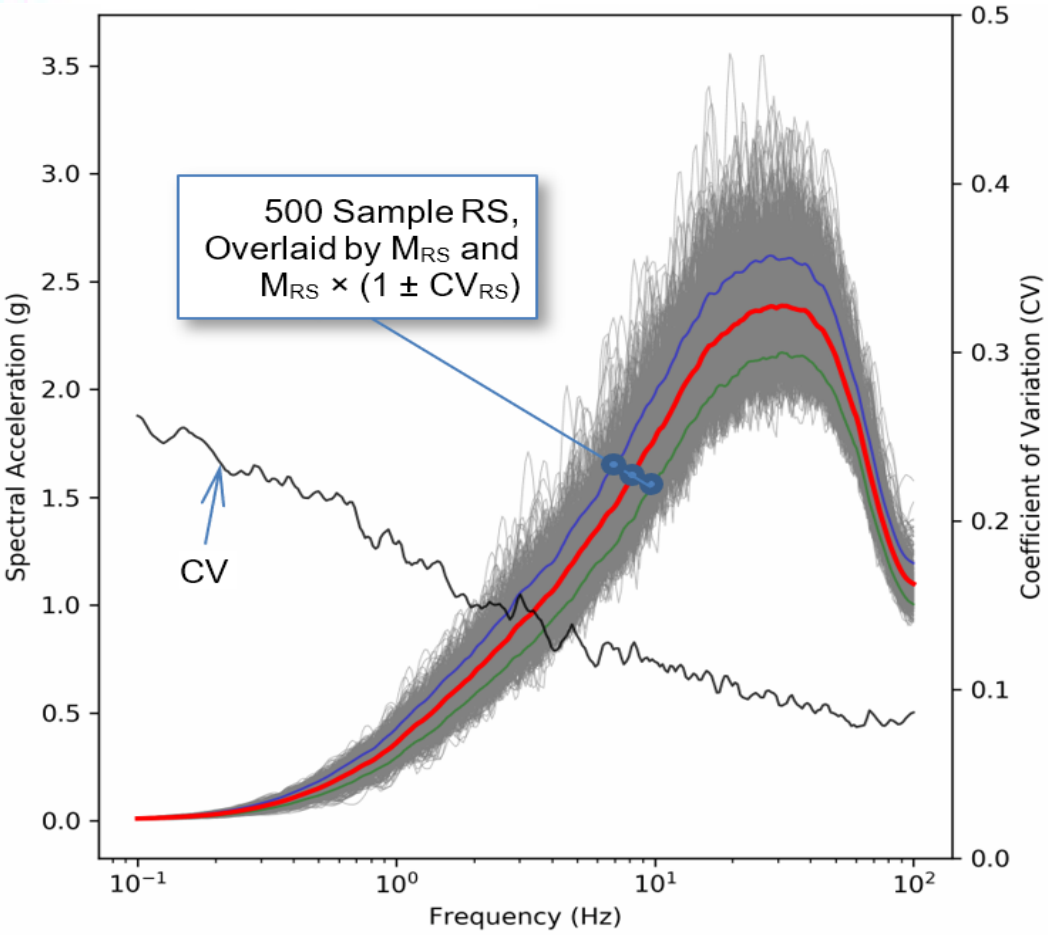


[J. Nie, J. Xu, V. Graizer, and D. Seber (2020). "Estimating stable mean responses for linear structural systems by using limited number of acceleration time histories." 2020 ASME Pressure Vessels and Piping Division Conference, PVP2020, Virtual Meeting. For this figure and those in the rest of this presentation. (ML20287A295)]

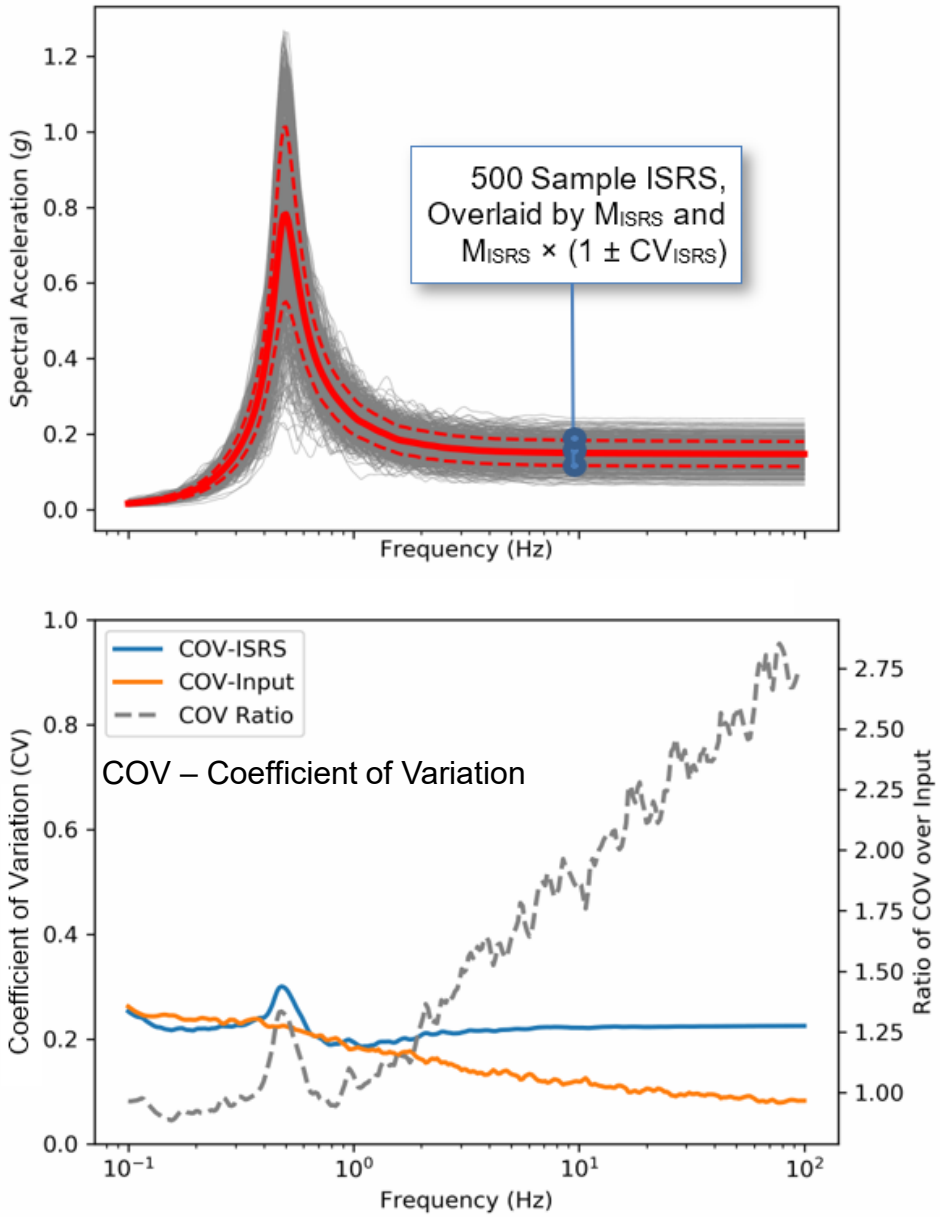
Procedure to Calculate CV_{ISRS}

- We analyzed 21 cases:
  - 20 target PSD functions from SRP Rev. 4, Section 3.7.1, Appendix B
  - One Phase Wave (i.e., a unit PSD function)
- For each PSD function:
  - Prescribe the Fourier amplitude spectrum **deterministically** based on the PSD function;
  - **Randomly** generate 500 sets of Fourier phase spectra over [0, 2π]; and
  - Invert these Fourier spectra to 500 acceleration time histories.
  - This procedure follows the RVT approach, and "exactly" produces the input response spectra as the average.
- 151 single-degree-of-freedom oscillators (0.1 Hz – 100 Hz) with a damping ratio of 5% were used to generate the response time histories.
- For each oscillator (conceptually a simple structure or a structural mode), the 500 response time histories were used to generate the ISRS and estimate the sample CV_{ISRS}.

Example Case of Input RS and ISRS



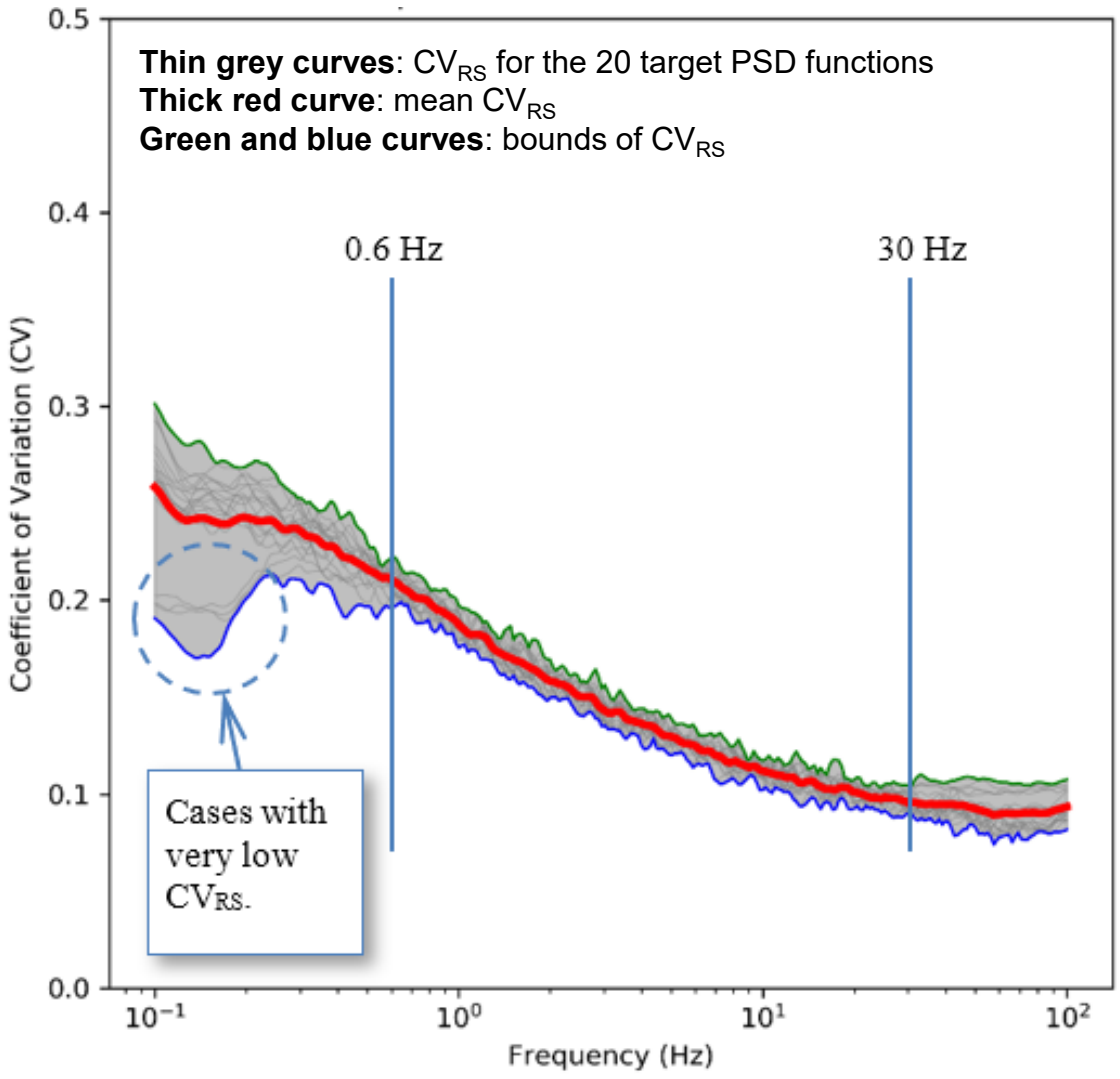
500 Sample Input RS, Mean RS, and Mean ± One Standard Deviation



500 Sample ISRS, Mean ISRS, Mean ± One Standard Deviation (top), and CV (bottom)

CV_{RS} of Input Time Histories

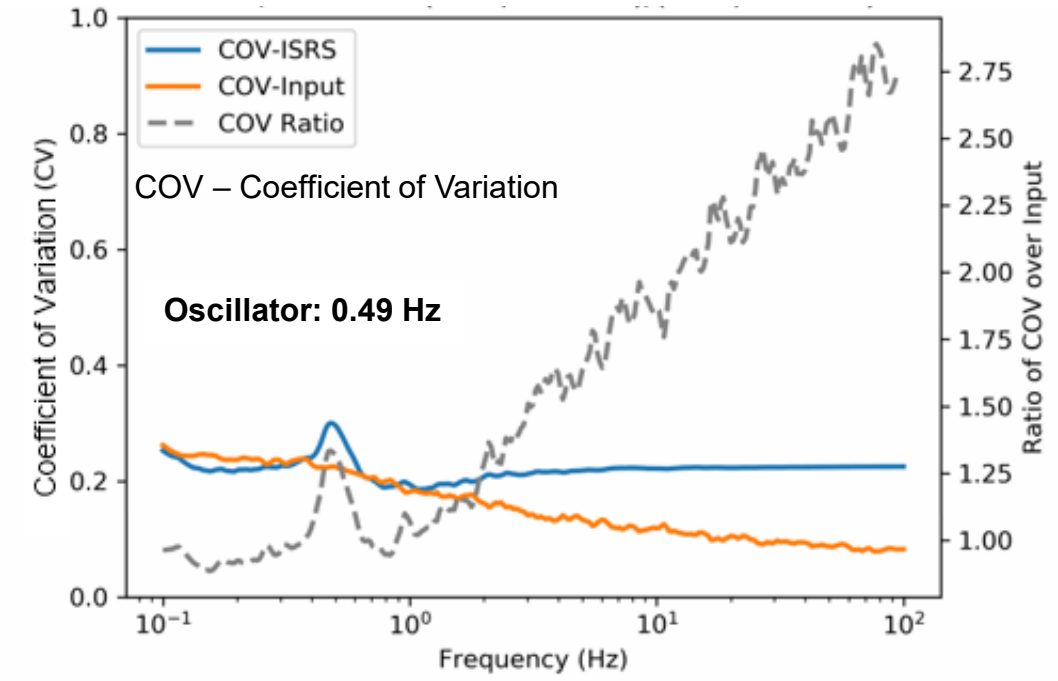
- Except for very low frequencies (below 0.2 Hz), the variations in the CV_{RS} are generally very small among the 20 different PSD functions.
- The spread in the CV_{RS} from 0.6 Hz to 30 Hz appears to be constant
  - Regardless of frequencies
  - Independent of the vastly different PSD functions
- The largest CV_{RS} is about 30% and the smallest CV_{RS} is 7%.
- All CV_{RS} curves are generally decreasing functions of frequency.

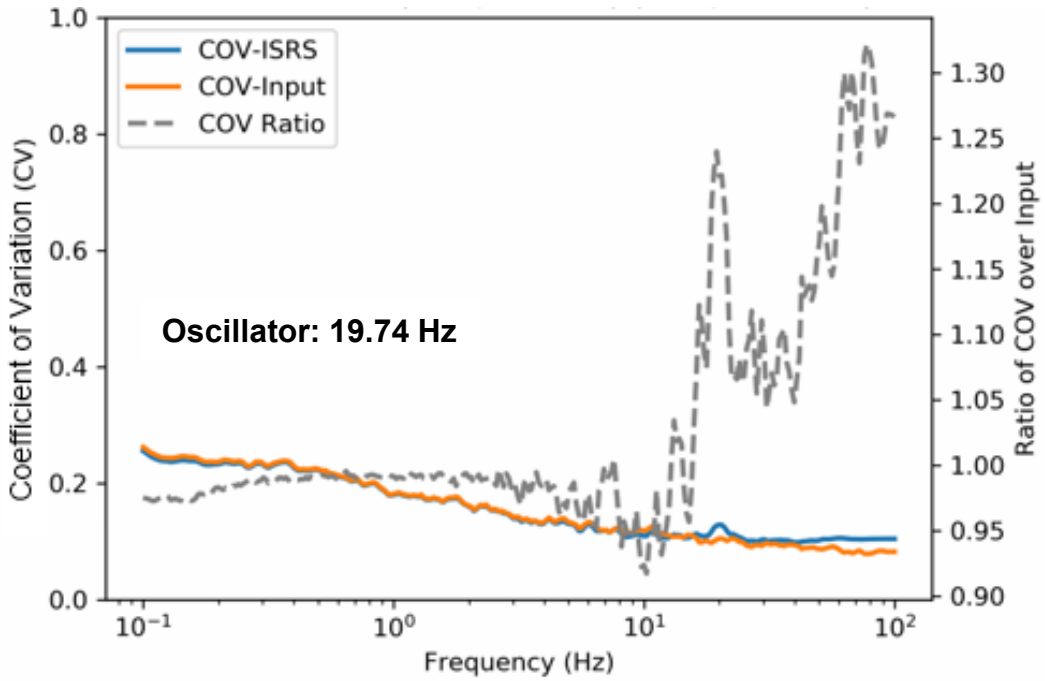


Observations in CV_{ISRS}

ZPA Effect: CV_{ISRS} maintains a higher level than CV_{RS} beyond the zero-period acceleration (ZPA) frequency of the response:

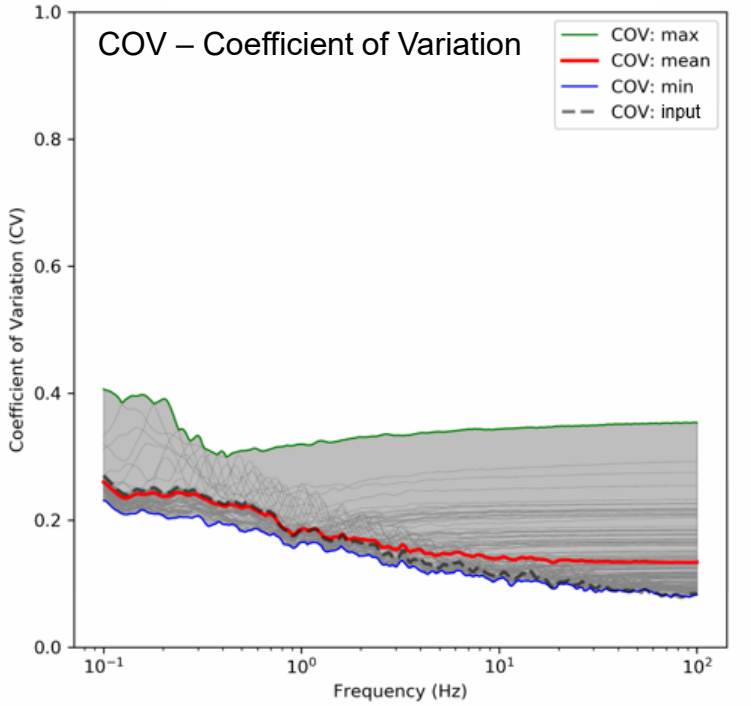
- Roughly reflects the CV_{RS} at the oscillator frequency.
- The ZPA on the ISRS is simply the RS of the input motion at the oscillator frequency.



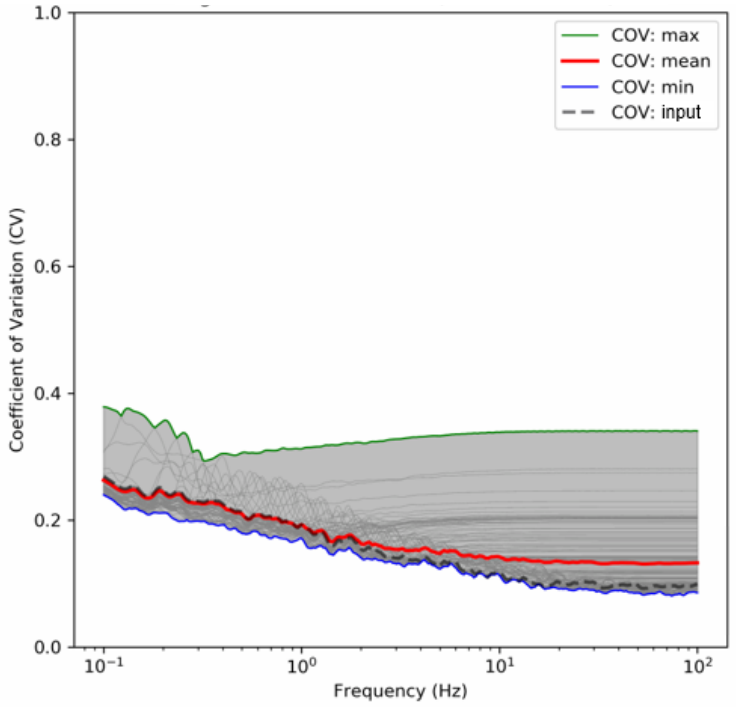


Example Cases of 151 CV_{ISRS}

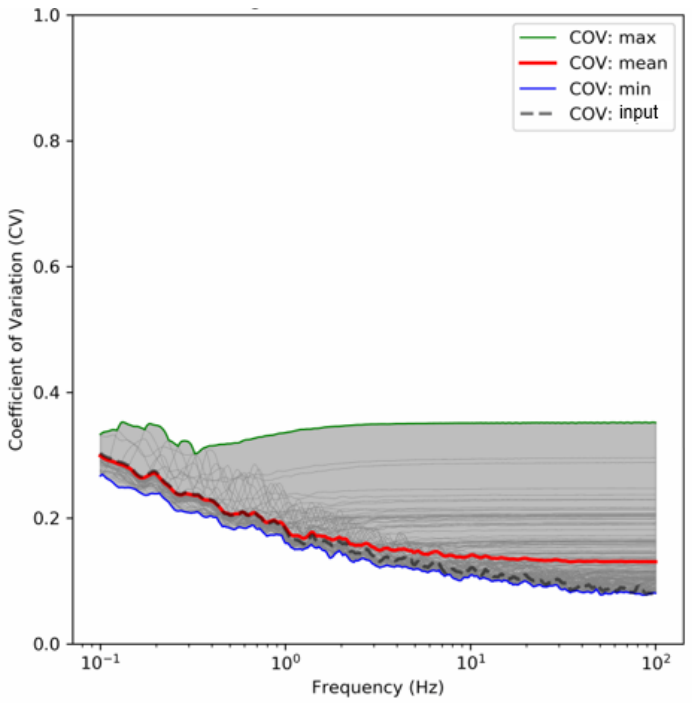
- Each of the 21 PSD functions represents an input motion with uncertain phase spectra.
- For each input motion, the 151 CV_{ISRS} are plotted together to assess how a complex structure of many modes would respond at various locations in the structure.
- The effect of modal combination would most likely increase the CV_{ISRS}.



CV_{ISRS} for 151 Oscillators for SRP Target PSD Function for Central and Eastern U.S., M_w 6-7, D: 0-10 km



CV_{ISRS} for 151 Oscillators for SRP Target PSD Function for Western U.S., M_w 7+, D10 km



CV_{ISRS} for 151 Oscillators for the Unit PSD Function

Effect of Phase Uncertainty on N_S

- The maximum CV_{ISRS} is around 0.4 for most of the 20 cases, except for the four low-magnitude cases (M_w 5-6) that have a maximum CV_{ISRS} above 0.53.
- For stiffer structural systems (for example, with a fundamental frequency of 5 Hz), the maximum CV_{ISRS} is about 30%, the same as that of the input motion.
- A higher structural mode would basically carry the CV_{RS} of the input motion at lower frequencies to CV_{ISRS}.

CV_{ISRS} (%)	N_S (CL=68%)	N_S (CL=95%)
20	4	15
22	5	19
26	7	26
30	9	35
40	16	61
50	25	96
70	49	188

Conclusions

- **We proposed an approach to explicitly use CV_{ISRS} to determine the minimum number of input acceleration time histories to estimate stable mean responses for linear structural systems.**
- **This study considered only the uncertainty in the phase spectrum but not: (1) the uncertainty in Fourier amplitude spectrum and (2) the effect of modal combination.**
- **The CV_{RS} of the input motion are generally a monotonically decreasing function of frequency and it does not vary much for significantly different PSD functions (for RVT type time histories).**
- **The maximum CV_{ISRS} across all frequencies is around 40%.**
  - N_S = 16 for CL = 68%, N_S = 61 for CL = 68% for low fundamental frequencies.
- **For stiffer systems (for example, 5 Hz), the maximum CV_{ISRS} is about 30%**
  - N_S = 9 for a CL of 68%, N_S = 35 for a CL of 95%.
- **This study indicates that the four or five time histories in the current practice may not be sufficient, especially for soil-structure systems with very low frequencies.**