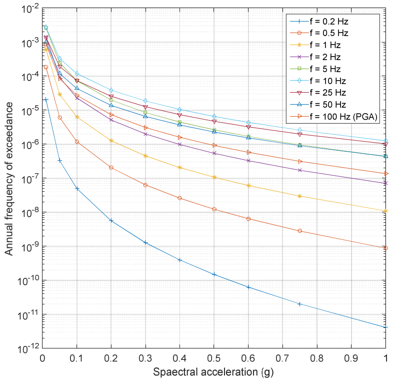
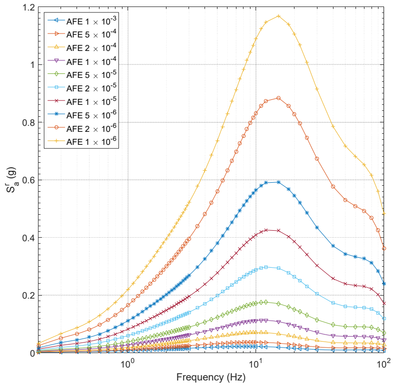
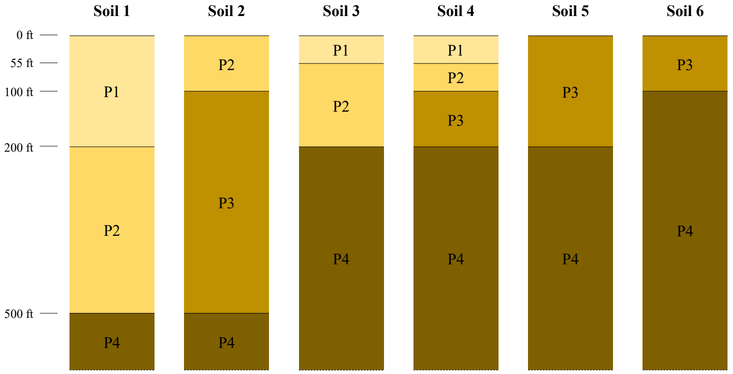
Probabilistic Site Response Analysis Considering Variability of Soil Properties

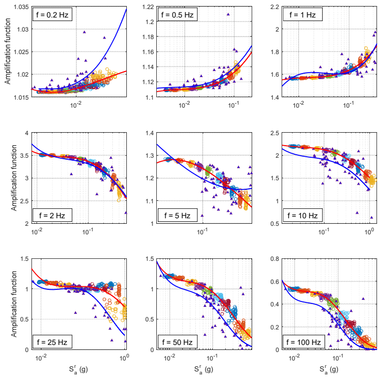
- **Hazard curves & UHRS at rock site**





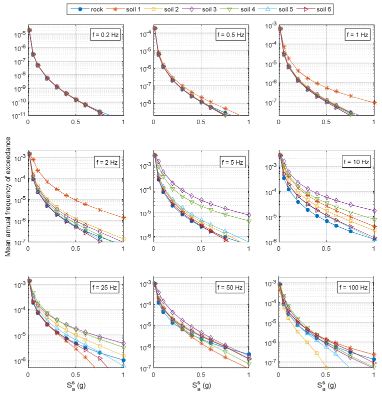
- **Soil sites and their amplification functions**

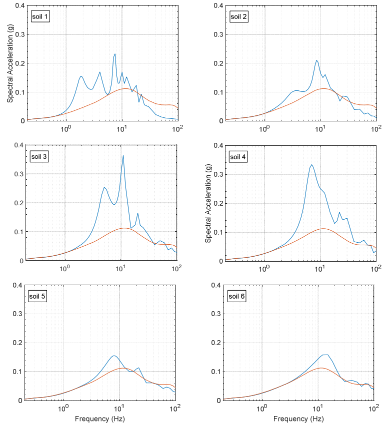




- **No time histories of earthquake ground motions are required.**

- **Hazard curves & UHRS at soil sites**





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2022. 7. 1.

Design Response Spectra for Nuclear Facilities at Rock Sites

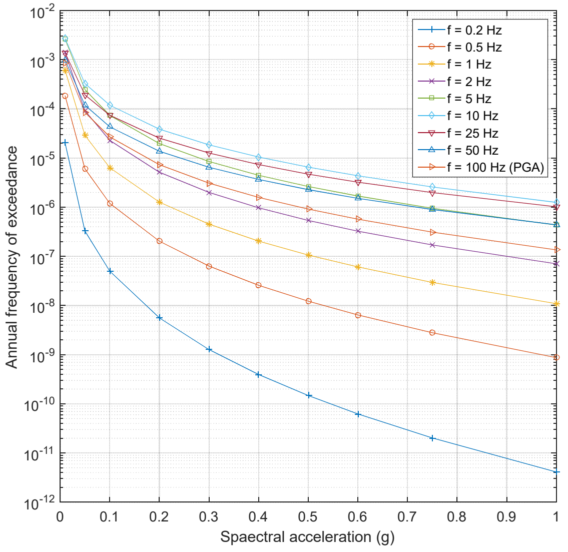
- **The seismic design of nuclear power plants (NPPs) is based on a design-basis earthquake (DBE).**
- **USNRC Regulatory Guide 1.60**
    - **Standard design response spectra**
- **USNRC Regulatory Guide 1.165**
    - **Safe shutdown earthquake ground motion based on the probabilistic seismic hazard analysis**
- **Uniform hazard response spectra (UHRS)**
- **USNRC Regulatory Guide 1.208**
    - **Uniform risk response spectra (URRS) or ground motion response spectra (GMRS) or with mean annual frequency of exceedance for unacceptable performance of 10^{-5}**
- **Earthquake responses of NPPs at soil sites are greatly affected by the soil-structure interaction. Therefore, various studies have been performed to obtain UHRS or GMRS at soil sites from those at the bedrock level considering the soil-amplification effects.**

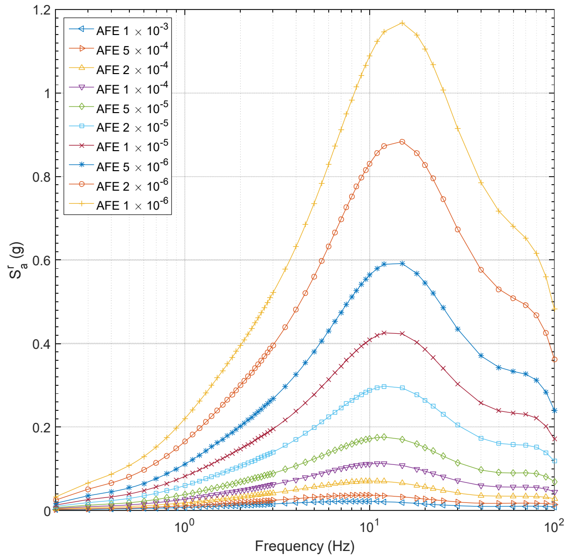
Design Response Spectra at Soil Sites

- Approach 4 (the truth)
  - UHRS computed directly from PSHA using site-specific soil attenuation relations.
  - Ground motion records at specific soil sites are very rare except for well-instrumented regions with high seismicity.
  - It is not easy to derive site-specific soil attenuation relations and evaluate seismic hazard curves for soil sites using Approach 4.
  - Therefore, seismic hazard curves and UHRS for soil sites can be obtained by Approach 4 only for very restricted regions.
- Approach 3 (near truth)
  - Convolution of seismic hazard curves at rock sites with soil transfer functions
  - Soil transfer functions can be obtained from well-established site response analysis.
  - Approach 3 is the best alternative among currently available approaches even for the regions where ground motion records at specific soil sites are rare.
  - Employed in probabilistic seismic hazard analysis for Swiss nuclear power plant sites
- Approach 2A (even bigger simplification)
  - Use scaled 1 Hz and 10 Hz design earthquakes as control motions to develop 1 Hz and 10 Hz soil motions or develop transfer function for 1 Hz and 10 Hz design earthquake, using a single control motion (scaled shape) for each frequency
  - Employed in ASCE/SEI Standard 43-05
- Approach 2B (a little less simplification)
  - Develop weighted mean transfer function for 1 Hz and 10 Hz design earthquakes accommodating magnitude distributions
- Approach 1 (greatest simplification)
  - Rock UHRS used as control motions to drive soil column

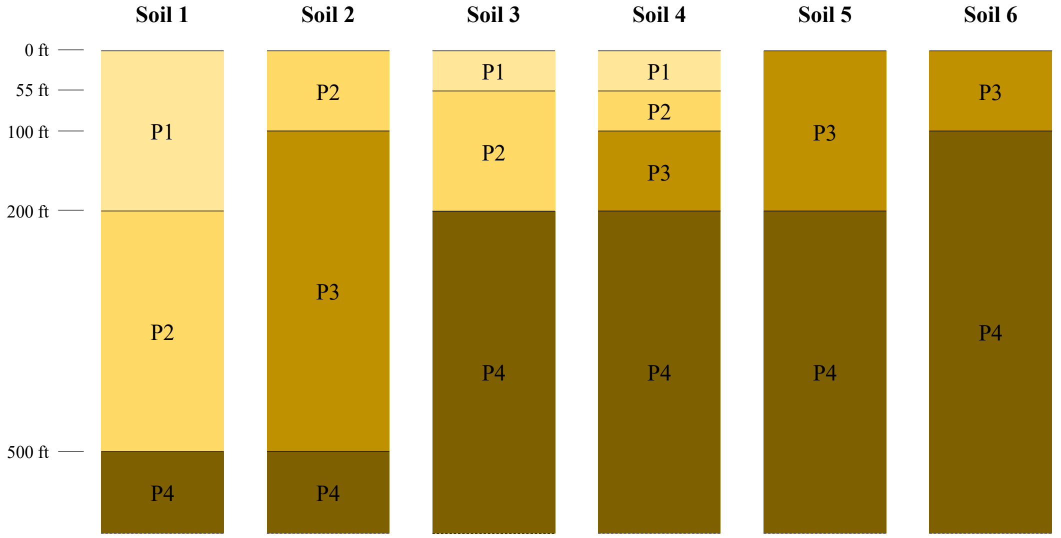
Response-history methodology

Hazard curves & UHRS at rock site





Soil sites and their amplification functions



Name	Station Name	Date	Comp.	Mag.	Dist. (km)	VS30 (m /sec)
Parkfield	Temblor	06-28-66	205	6.1	9.9	528
San Fernando	Cedar Springs, Allen Ranch	02-09-71	095	6.6	86.6	813
San Fernando	Santa Felita Dam (outlet)	02-09-71	172	6.6	27.5	376
San Fernando	Tehachapi Pump	02-09-71	090	6.6	68.0	669
Friuli	Feltre	05-06-76	000	6.5	97.1	587
Friuli	SanRocco	09-11-76	NS	5.5	17.9	587
Friuli	SanRocco	09-15-76	270	6.1	12.7	587
Santa Barbara	Cachuma Dam Toe	08-13-78	250	6.0	36.6	438
Tabas	Dayhook	09-16-78	LN	7.4	17.0	587
Tabas	Ferdows	09-16-78	L1	7.4	94.4	587
Imperial Valley	Superstition Mtn. Camera	10-15-79	045	6.5	26.0	362
Livermore	APEEL 3E Hayward	01-27-80	236	5.4	31.0	517
Mammoth Lakes	Bishop	05-27-80	070	6.0	43.7	345
Victoria	Cerro Prieto	06-09-80	045	6.1	34.8	587
Coalinga	VEW (temp)	05-09-83	005	5.0	12.6	376
Coalinga	Oil Fields Fire Station Pad	07-09-83	270	5.2	11.9	376
Coalinga	Transmitter Hill	07-09-83	270	5.2	10.4	376
Coalinga	Oil Fields Fire Sta.	07-22-83	360	5.8	10.9	376
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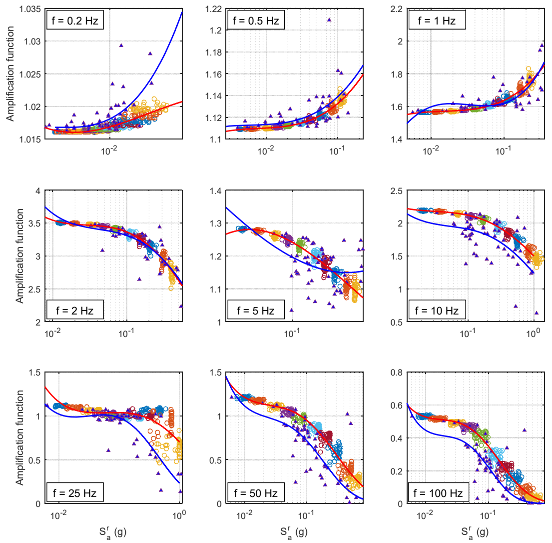
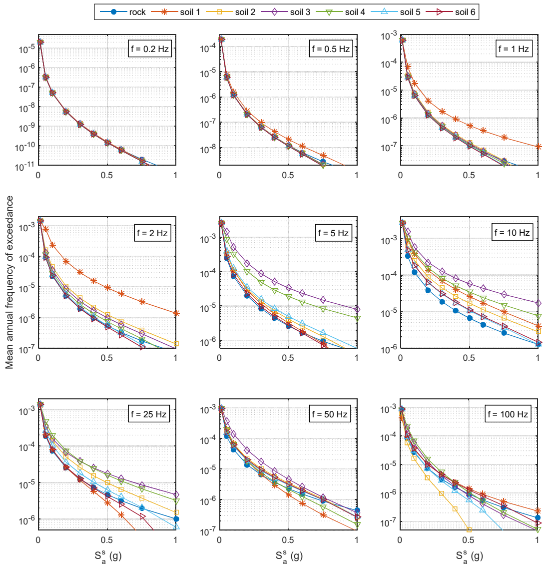
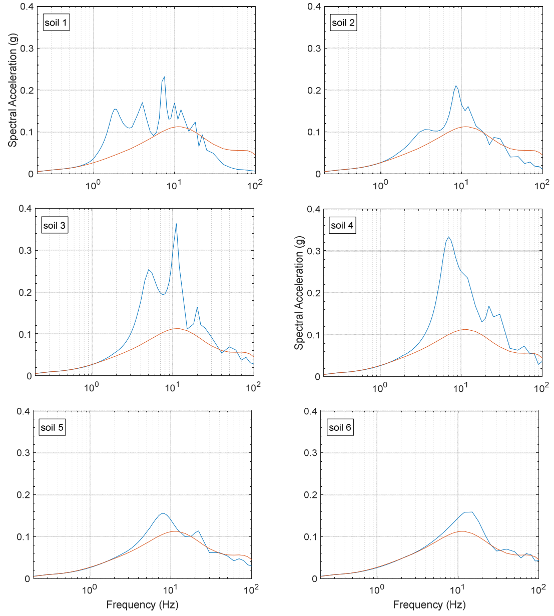
Nahanni	Site 3	12-23-85	270	6.8	16.0	587
Loma Prieta	Piedmont Jr. High	10-18-89	045	6.9	78.3	895
Loma Prieta	Point Bonita	10-18-89	207	6.9	88.6	1316
Loma Prieta	SF Cliff House	10-18-89	000	6.9	84.4	713
Loma Prieta	SF Pacific Heights	10-18-89	270	6.9	81.6	1250
Loma Prieta	SF Presidio	10-18-89	090	6.9	83.1	594
Loma Prieta	SF Rincon Hill	10-18-89	000	6.9	79.7	873
Loma Prieta	SF Sierra Point	10-18-89	115	6.9	68.2	-
Loma Prieta	Yerba Buena Island	10-18-89	090	6.9	80.6	660
Northridge	Burbank Howard Road	01-17-94	060	6.7	20.0	822
Northridge	LA Wonderland Av.	01-17-94	095	6.7	22.7	1223
Kobe	Kobe University	01-16-95	090	6.9	0.2	1043



Hazard curves & UHRS at soil sites





- Soil amplification functions are obtained from deterministic 1D wave propagation analysis using time histories of earthquake ground motions.

Random Vibration Theory (RVT) Methodology

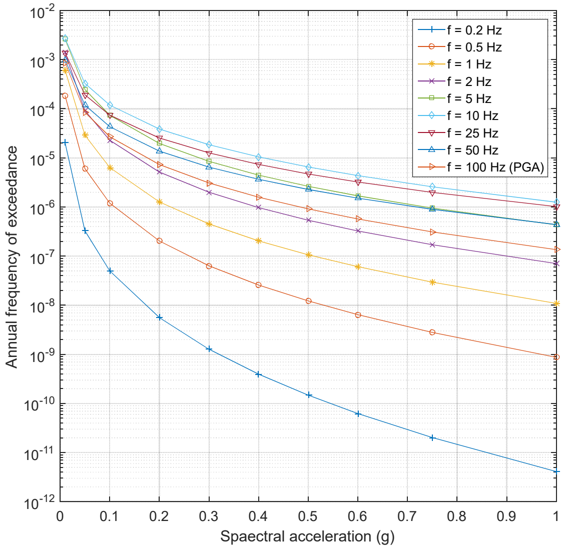
- ASCE/SEI 4-16 Standard
  - 2.3.2.2 Ground Response Computations

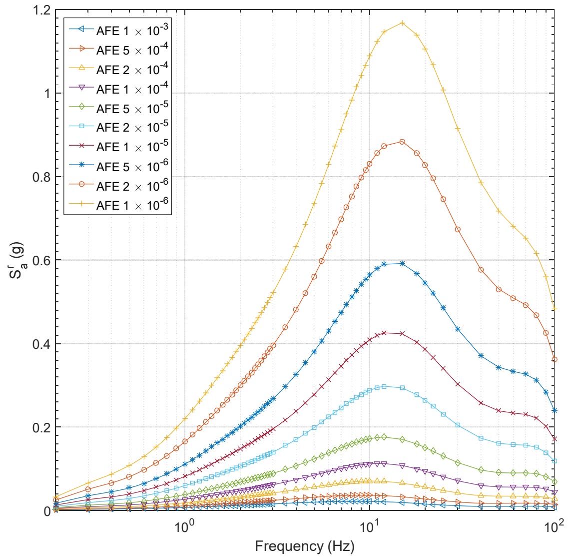
    Equivalent linear analyses shall implement either the response-history methodology or random vibration theory (RVT) methodology.
  - C2.3.2.2 Ground Response Computations

    Random vibration theory (RVT) is based on the same equivalent linear wave propagation problem as the response-history method. The main difference in terms of implementation is that the RVT method requires an acceleration response spectrum as input rather than an acceleration time series.

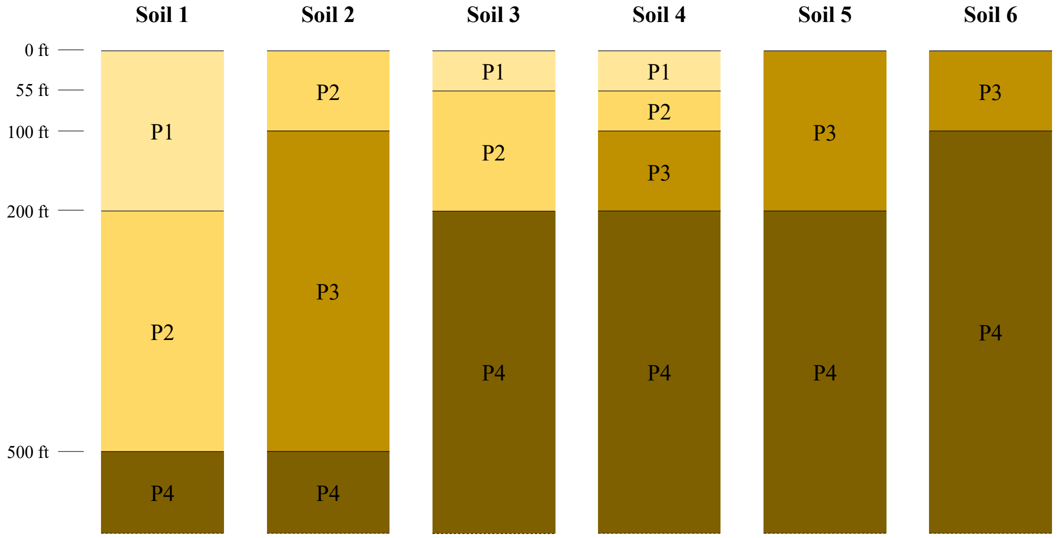
Random vibration theory (RVT) methodology

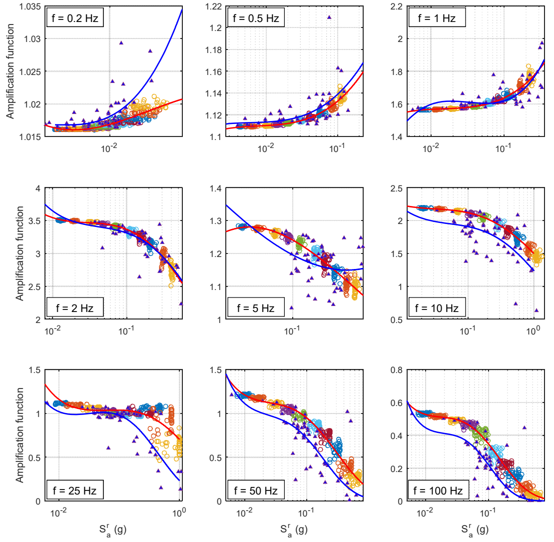
Hazard curves & UHRS at rock site



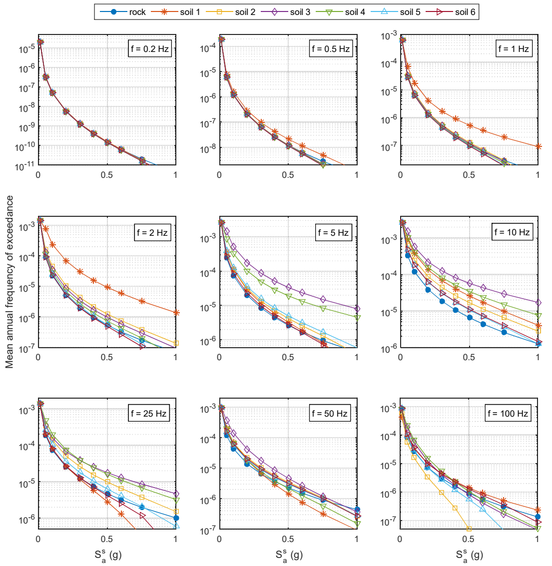


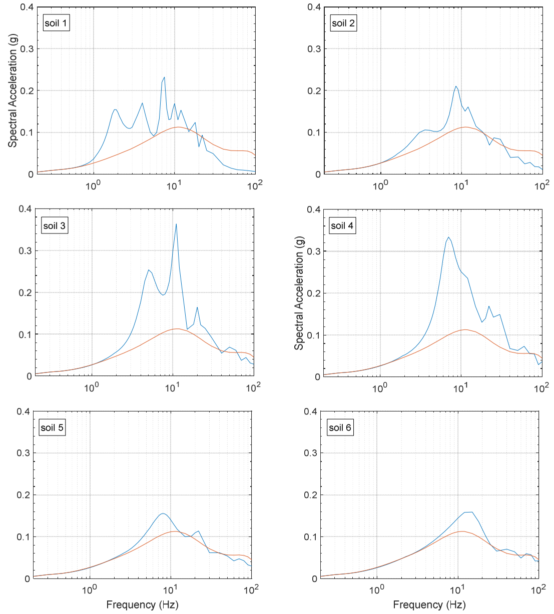
Soil sites and their amplification functions





Hazard curves & UHRS at soil sites





- **No time histories of earthquake ground motions are required.**

- **Soil amplification functions are obtained from stochastic 1D wave propagation analysis using random vibration theory.**

Probabilistic site response analysis

- **Site response analysis**

$$r(\omega) = H_r(\omega) a_{rock}(\omega)$$

- **Stochastic site response analysis**

$$G_r(\omega) = \left|H_r(\omega)\right|^2 G_{a_{rock}}(\omega)$$

- **For the stochastic site response analysis, a PSD function $G_{a_{rock}}(\omega)$, which is consistent with a target UHRS, must be determined.**

- **For equivalent nonlinear analysis, equivalent linear material properties for $H_r(\omega)$ must be determined. They depends on the peak strain and the corresponding effective strain.**

$$G_\varepsilon(\omega) = \left|H_\varepsilon(\omega)\right|^2 G_{a_{rock}}(\omega)$$

$$\varepsilon_{\max} = \rho\sqrt{\lambda_0}$$

$$\rho = \begin{cases} 1.253 + 0.259\nu_e\tau & \text{if } \ 0 < \nu_e\tau \le 2.1 \\ \sqrt{2\ln(\nu_e\tau)} + \dfrac{0.5772}{\sqrt{2\ln(\nu_e\tau)}} & \text{if } \ 2.1 < \nu_e\tau \end{cases}$$

$$\nu_e = \begin{cases} 2\delta\nu(0) & \text{if } \ 0 < \delta \le 0.1 \\ (1.63\delta^{0.45} - 0.38)\nu(0) & \text{if } \ 0.1 < \delta \le 0.69 \\ \nu(0) & \text{if } \ 0.69 < \delta \le 1 \end{cases}$$

$$\nu(0) = \frac{1}{\pi}\sqrt{\frac{\lambda_2}{\lambda_0}} \qquad \delta = \sqrt{1 - \frac{\lambda_1^2}{\lambda_0\lambda_2}} \qquad \lambda_n = \int_0^\infty \omega^n G_\varepsilon(\omega)\, d\omega$$

Response spectrum of a soil response

- **Acceleration response of a layered soil site**

$$G_a(\omega) = \left|H_a(\omega)\right|^2 G_{a_{rock}}(\omega)$$

- **Pseudo-acceleration of a single degree-of-freedom (SDF) system subjected to an outcropping bedrock motion or a motion in a layered soil site of which the PSD function is $\boldsymbol{G_a(\omega)}$**

$$G_{SDF}(\omega) = \left|H_{SDF}(\omega)\right|^2 G_a(\omega)$$

$$H_{SDF}(\omega) = -\frac{1}{1-\left(\omega/\omega_n\right)^2 + 2i\xi\left(\omega/\omega_n\right)}$$

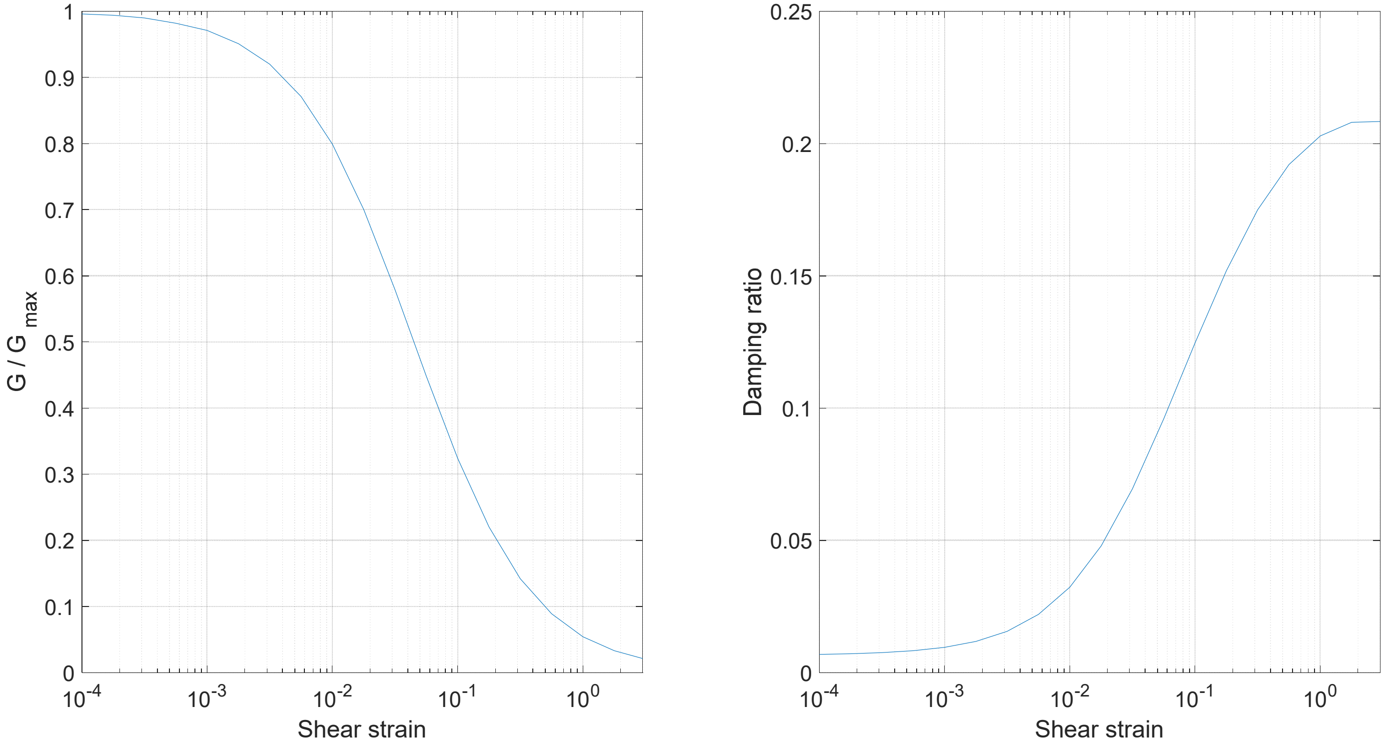
- **Mean value of a peak acceleration response or a spectral acceleration of a SDF system**

$$S_a = \rho\sqrt{\lambda_0}$$

Generic soil sites

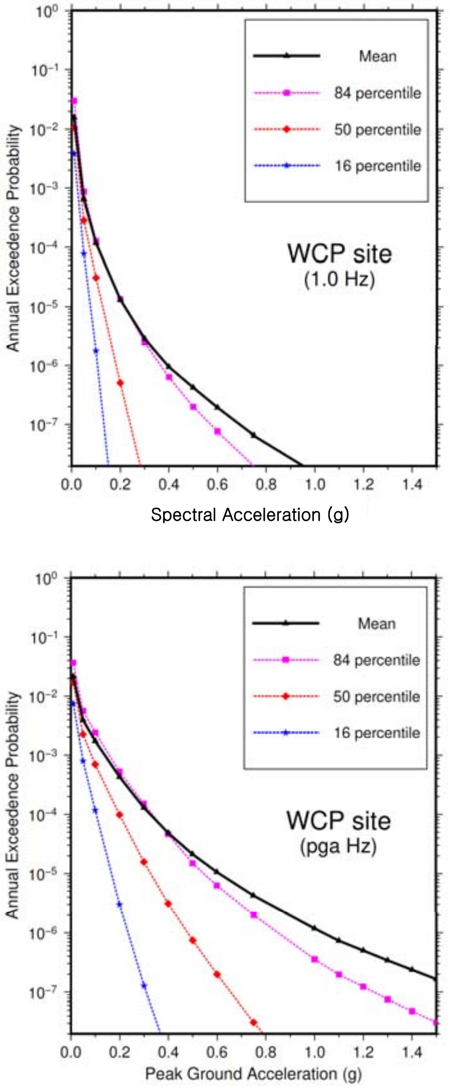
Soil depth (ft)	Soil site					
	1	2	3	4	5	6
0 ~ 55	P3	P2	P2	P4	P4	P1
55 ~ 100	P3	P3	P3	P4	P4	P2
100 ~ 200	P4	P3	P4	P4	P5	P3
200 ~ 500	P4	P5	P5	P5	P5	P4
500 ~ 1000	P5	P5	P5	P5	P5	P5
1000 ~	P5	P5	P5	P5	P5	P5

Soil layer	S-wave velocity (ft/sec)	Density (lb/ft^3)
P1	1200	125
P2	2000	130
P3	4000	135
P4	6000	145
P5	9200	155

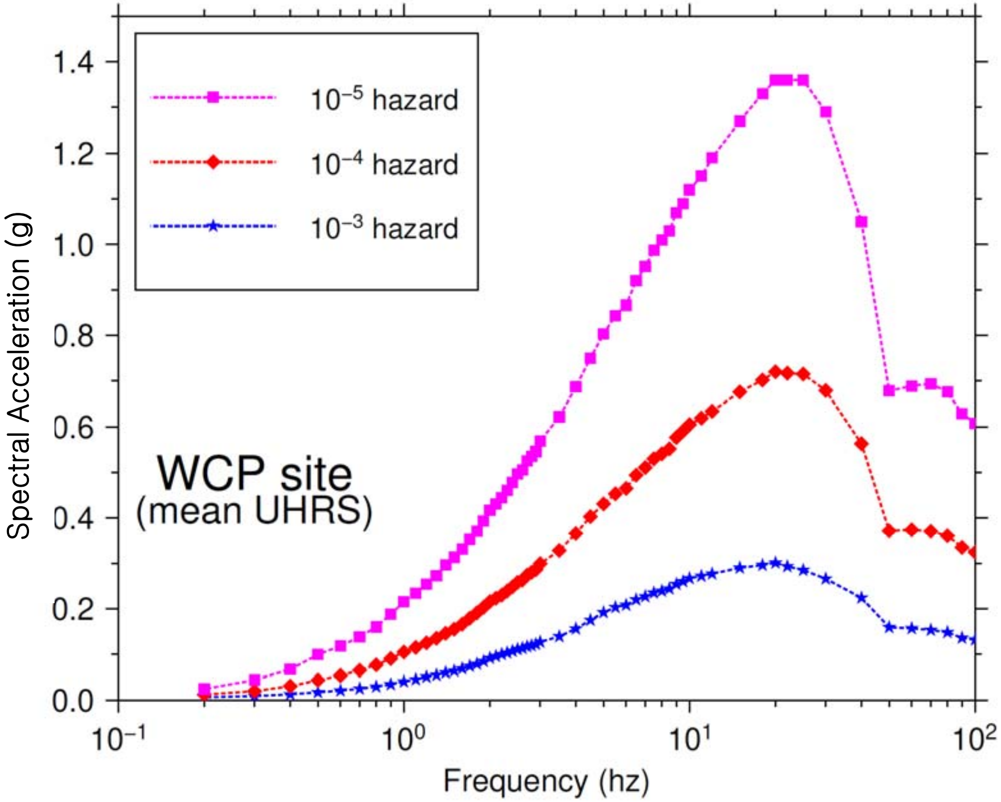


Hazard curves for a NPP site in Korea

- **Hazard curves**



- **Uniform hazard response spectra for outcropping bedrock motions**



Earthquake Ground Motions Records for RH Methodology

- **Nonlinear behavior in soil depends on considered earthquake ground motions.**
- **Ground motions from actual earthquakes are considered for nonlinear site response analysis.**

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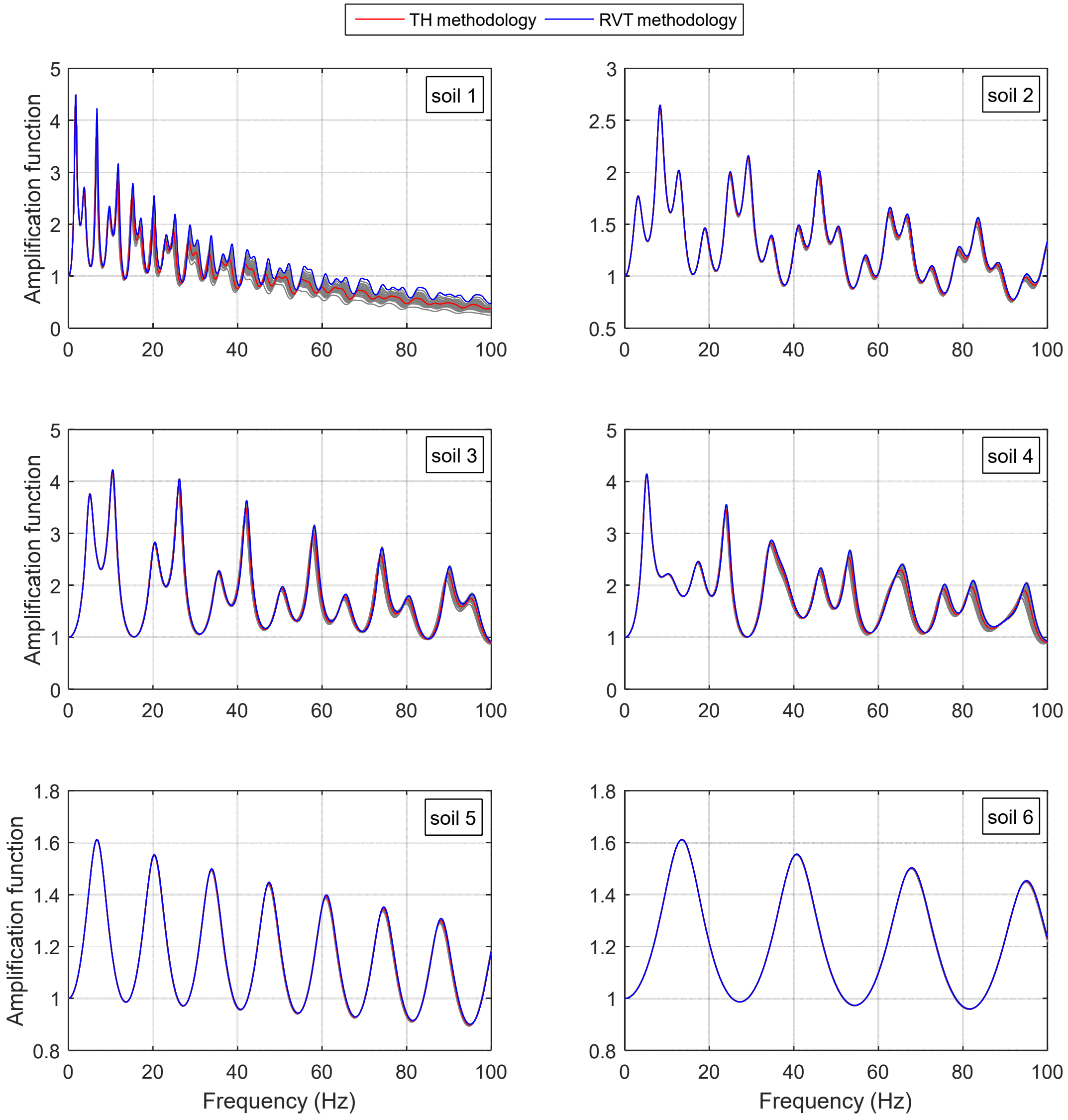
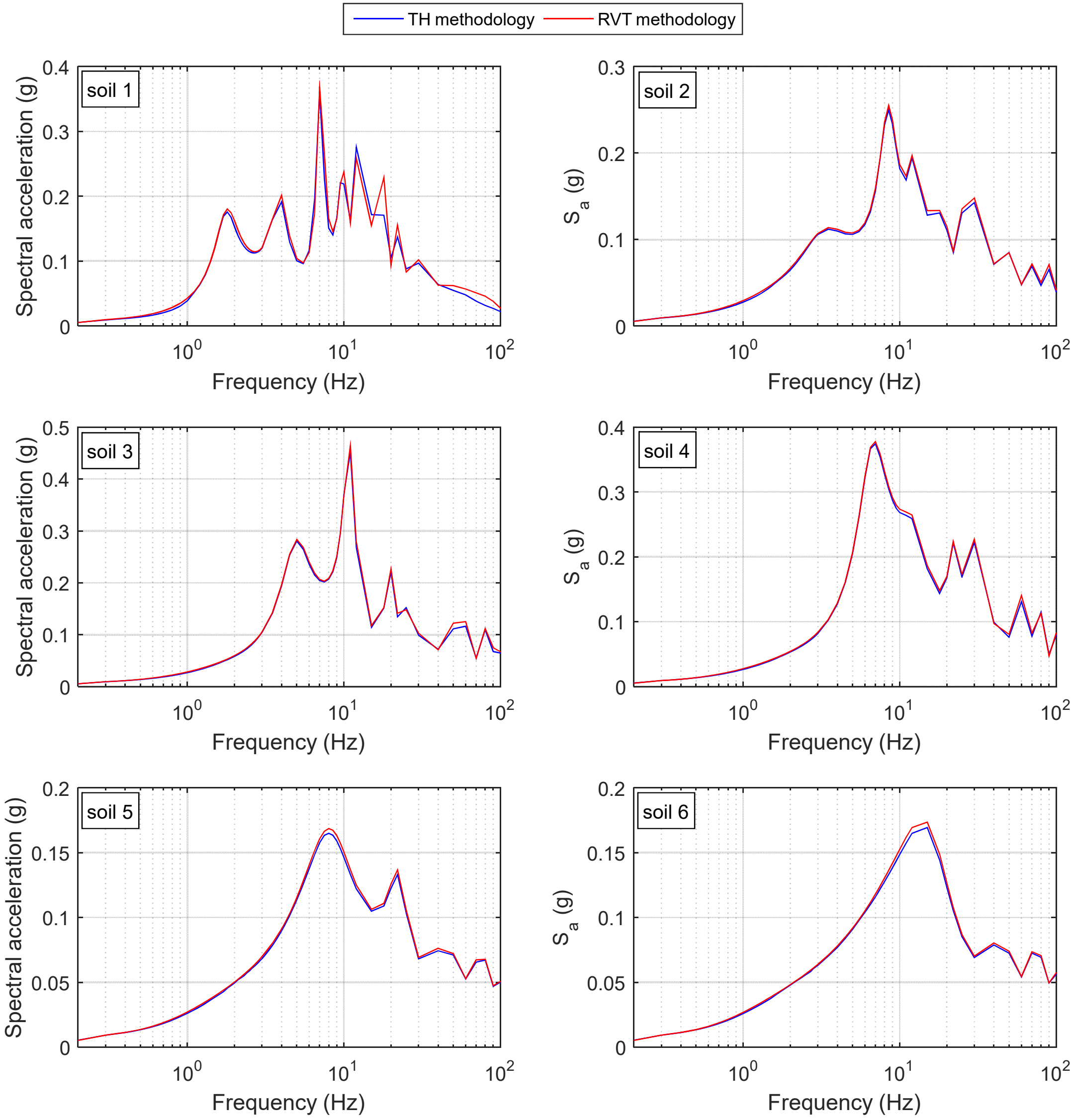
Kobe	Kobe University	01-16-95	090	6.9	0.2	1043

Verification of RVT methodology

- **Soil amplification functions**



- **UHRS at the soil surfaces**



Random Soil Profile

- ASCE/SEI 4-16 Standard
  - 2.3.1 Soil Profile Development

    A base case soil profile shall be developed for ground response analysis and shall be defined as horizontally bedded layers of soil with specified thickness, low strain shear wave velocity (V_s), unit weight (γ), and relationships of shear modulus (G) and hysteretic damping (β) reduction to shear strain levels defined from input sources of Section 2.2. The base case soil profile shall be defined in terms of the statistical variation of V_s, G, and β. The soil column profile shall be developed to ensure consistency with the geologic and geotechnical understanding of the site. Variability of layer thickness shall be considered if appropriate for the site being considered.

Random layer thickness

- In Toro's study, the layering is modeled as a Poisson process. The distance between layer boundaries or layer thickness has an exponential distribution.
    - Since an exponential distribution has a fixed coefficient of variation(COV) of 1, various values cannot be considered for the COV by Toro's model.
    - Besides, an exponential distribution has a mode of zero. It should be clarified that the zero-valued mode is proper for real soil sites because the observed normalized layer thickness has a non-zero mode.

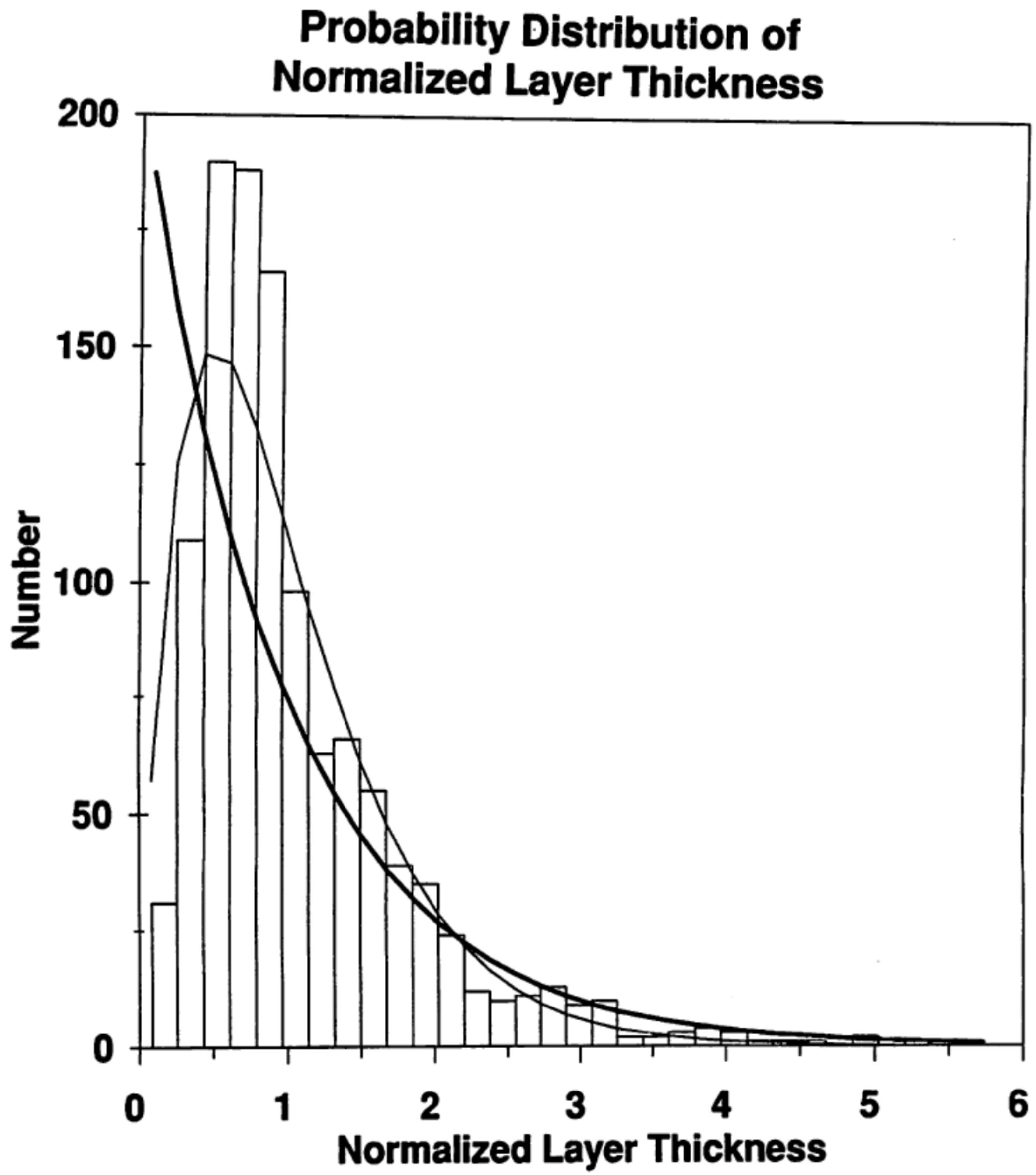


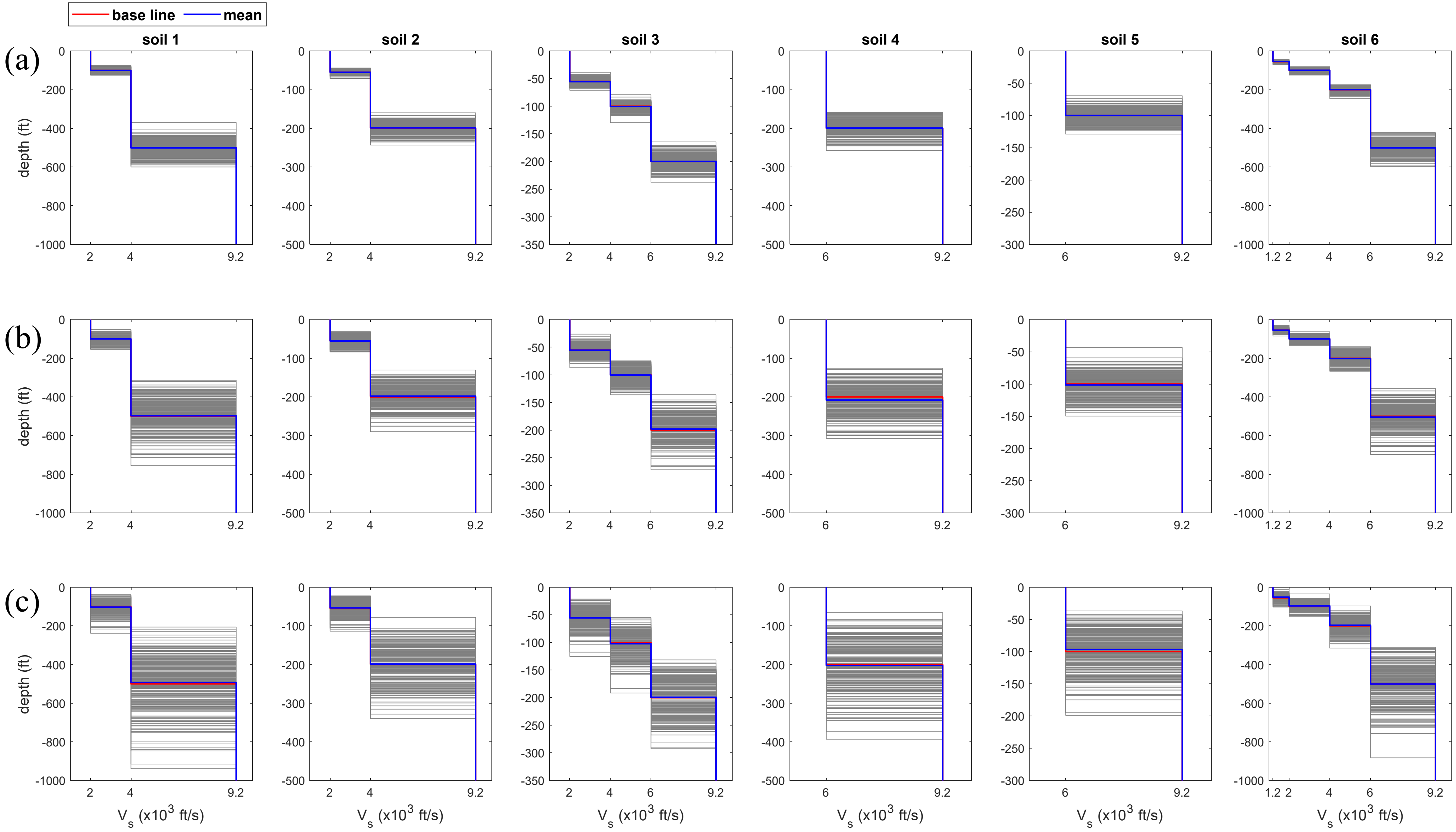
Figure 24. Observed distribution of normalized layer thickness τ (histogram). Thick line, exponential distribution; thin line, gamma distribution with COV of 0.71.

Proposed Model for Random Layer Thicknesses

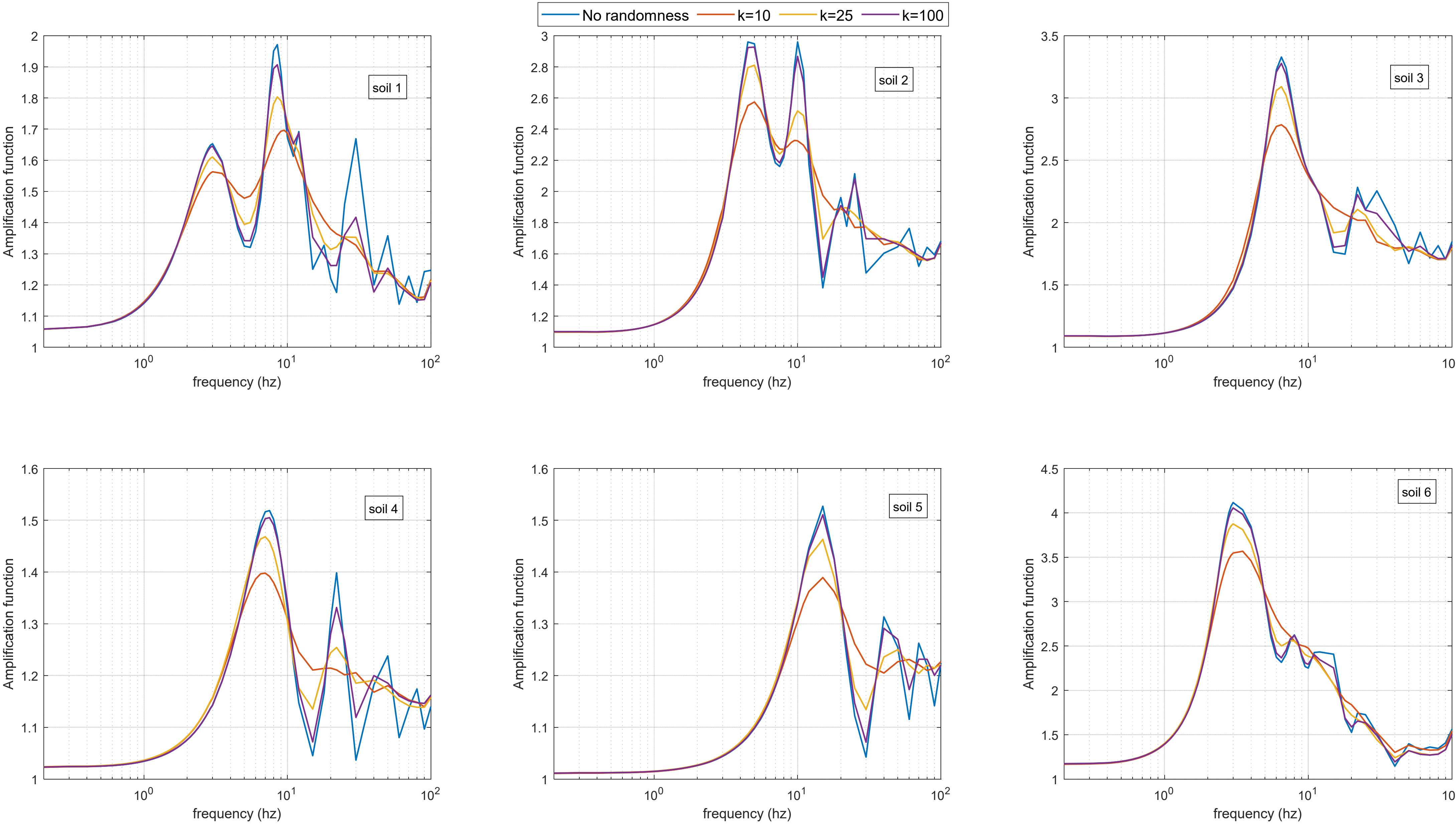
- **A layer with thickness h can be divided into k sub-layers. Based on Toro's study, the thickness of each sub-layer is assumed as an exponentially distributed random variable with a parameter $\lambda = k/h$. The total thickness of the layer can be obtained by summing those of the sub-layers. The sum of the variables is a random variable with an Erlang distribution of which the parameters are λ and k.**
  - **Its mean and COV are h and $1/\sqrt{k}$, respectively.**
  - **Its mode is $h\left(1-\frac{1}{k}\right)$.**
  - **The proposed probabilistic model for a random layer thickness can simulate the physical characteristics of real soil sites in a reasonable manner.**

Effects of random layer thicknesses

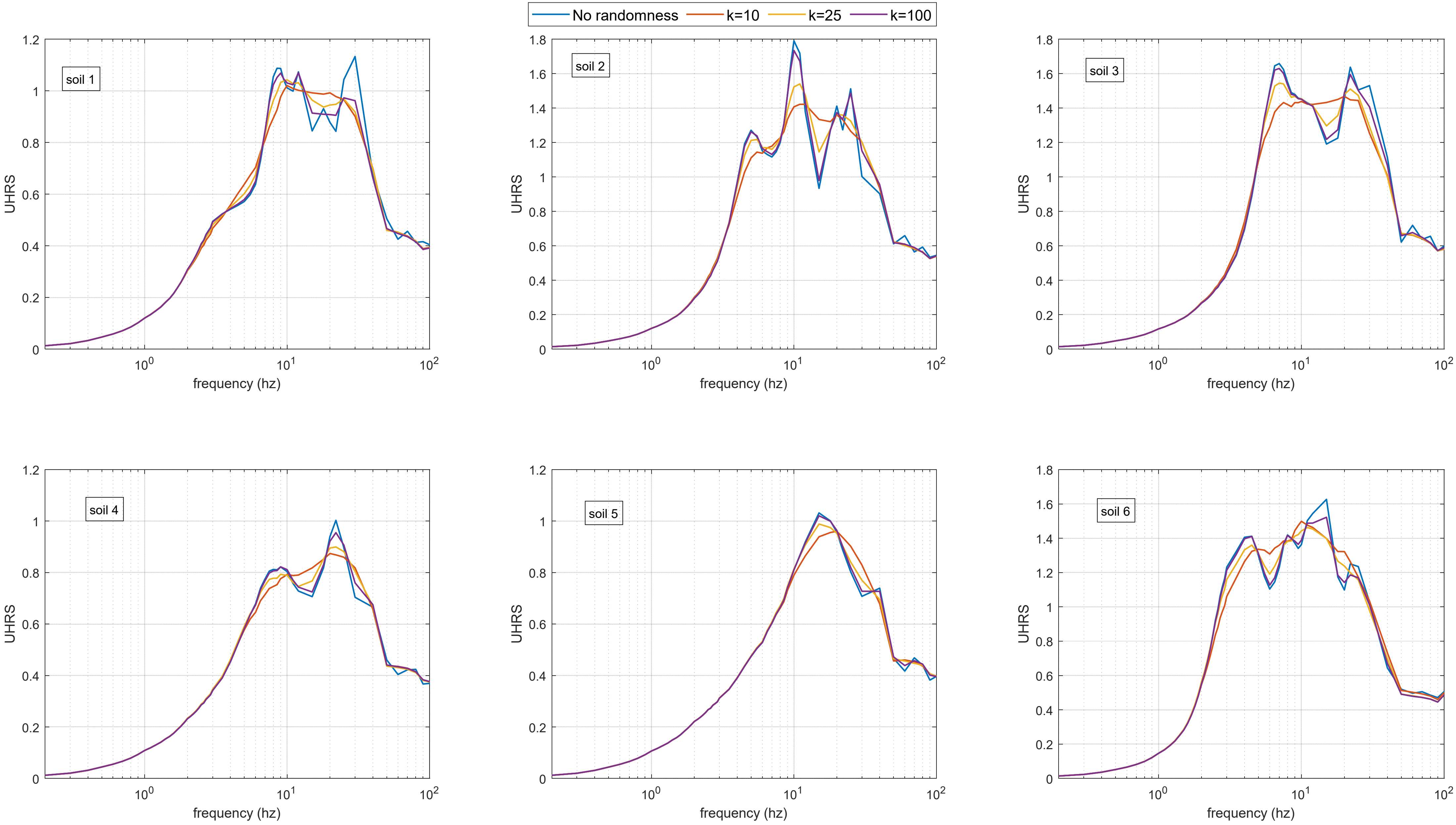
- **Realizations: (a) k = 100 or COV = 0.1, (b) k = 25 or COV = 0.2, (c) k = 10 or COV= 0.32**



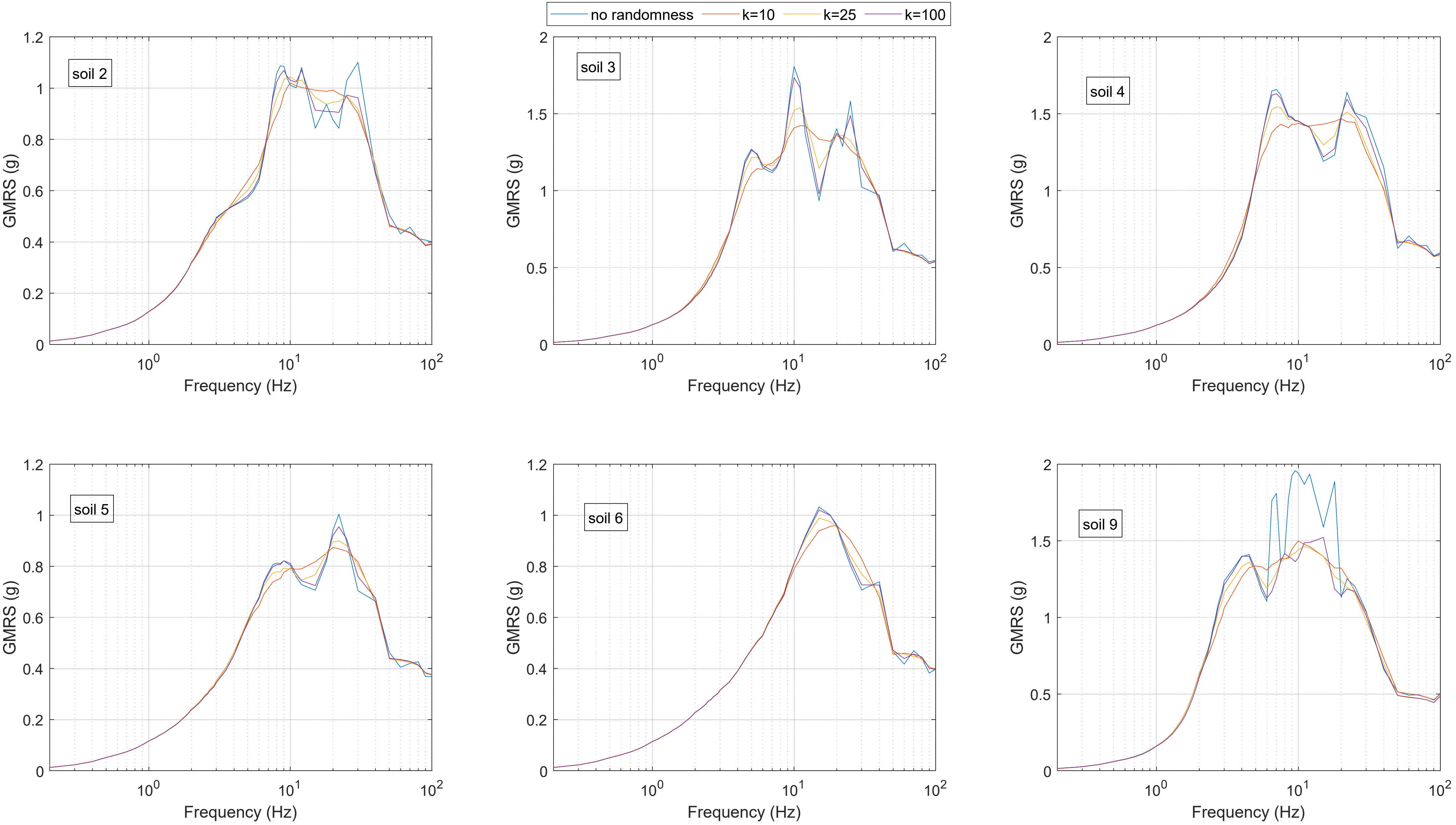
■ Soil amplification functions



- **UHRS at the soil surfaces**



GMRS at the soil surfaces



Random Low-strain Shear-wave Velocity

- **Low-strain shear-wave velocity**

$$V_{S,i} = \exp\left(\sigma_{\ln V_S} Z_i + \ln V_{S,i}^{\mathrm{med}}\right)$$

$$Z_i = \begin{cases} \varepsilon_1 & \text{for } i = 1 \\ \rho_{IL} Z_{i-1} + \varepsilon_i \sqrt{1-\rho_{IL}^2} & \text{for } i > 1 \end{cases}$$

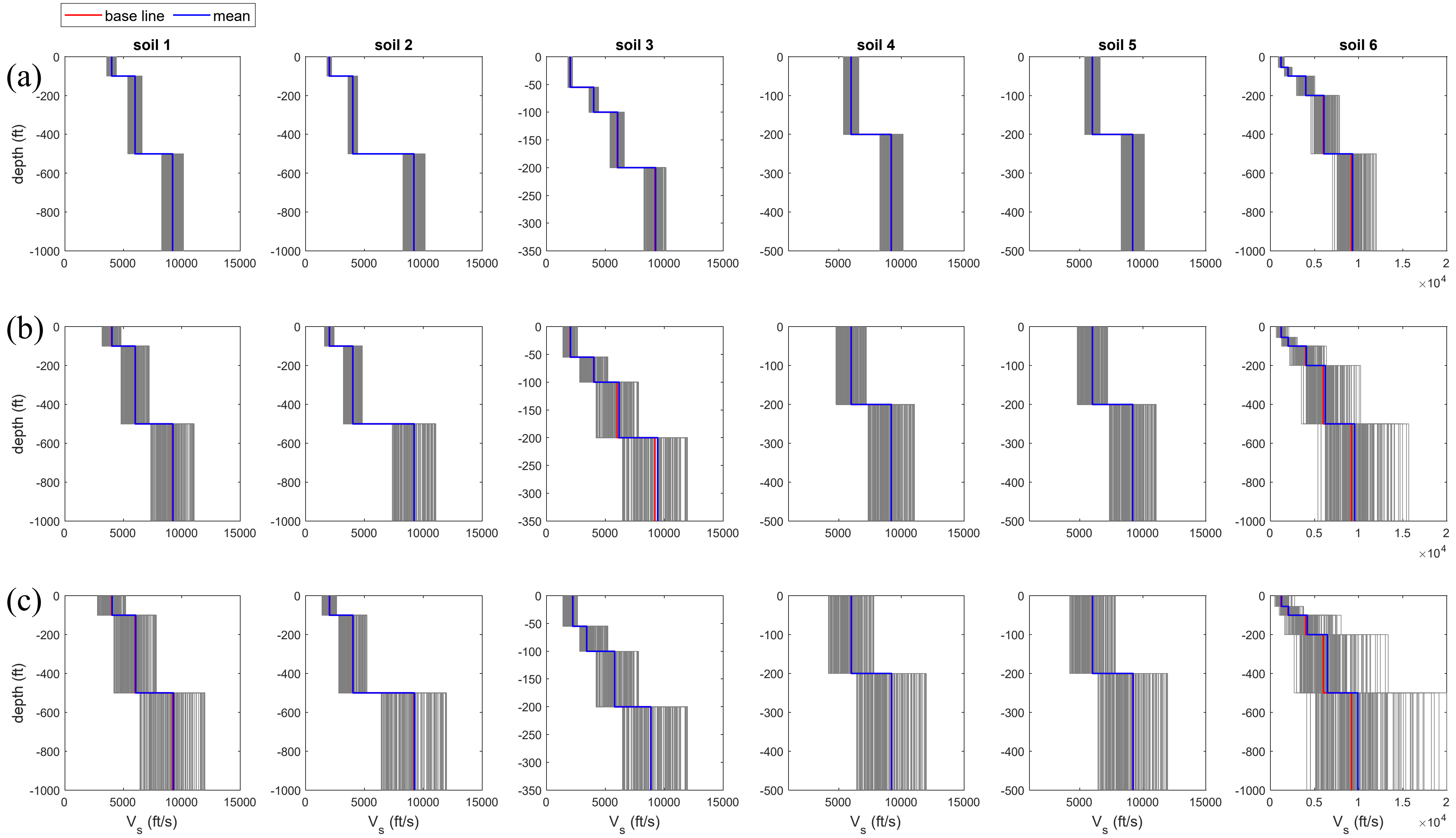
$$\rho_{IL}(d,t) = \left[1-\rho_d(d)\right]\rho_t(t) + \rho_d(d)$$

$$\rho_d(d) = \begin{cases} \rho_{200}\left[\dfrac{d+d_0}{200+d_0}\right]^b & d \le 200 \text{ m} \\ \rho_{200} & d > 200 \text{ m} \end{cases}$$

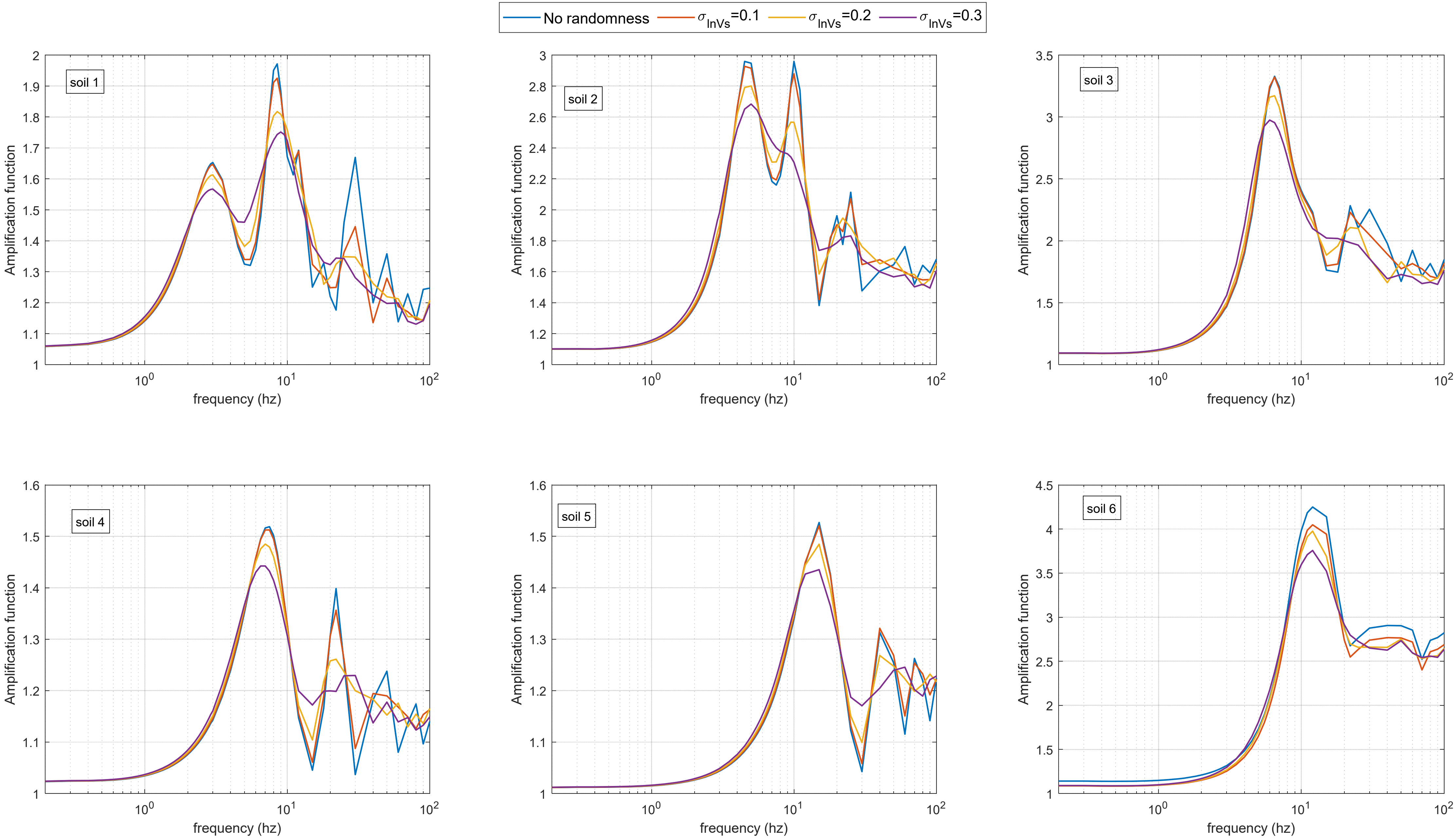
$$\rho_t(t) = \rho_0 \exp\left(-\frac{t}{\Delta}\right)$$

Effects of random low-strain shear-wave velocity

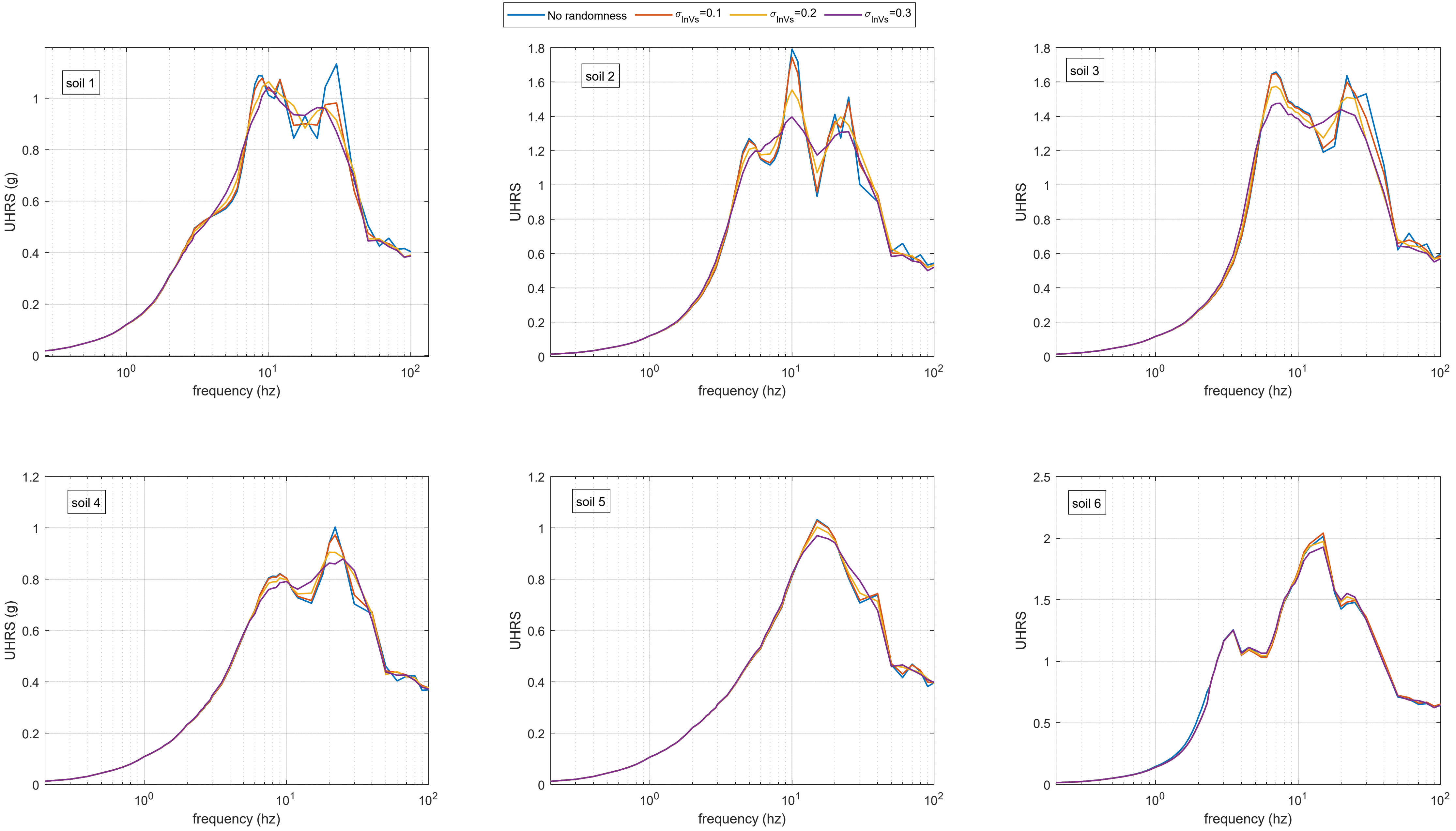
- **Realizations: (a) $\sigma_{\ln V_s} = 0.1$, (b) 0.2, (c) 0.3**



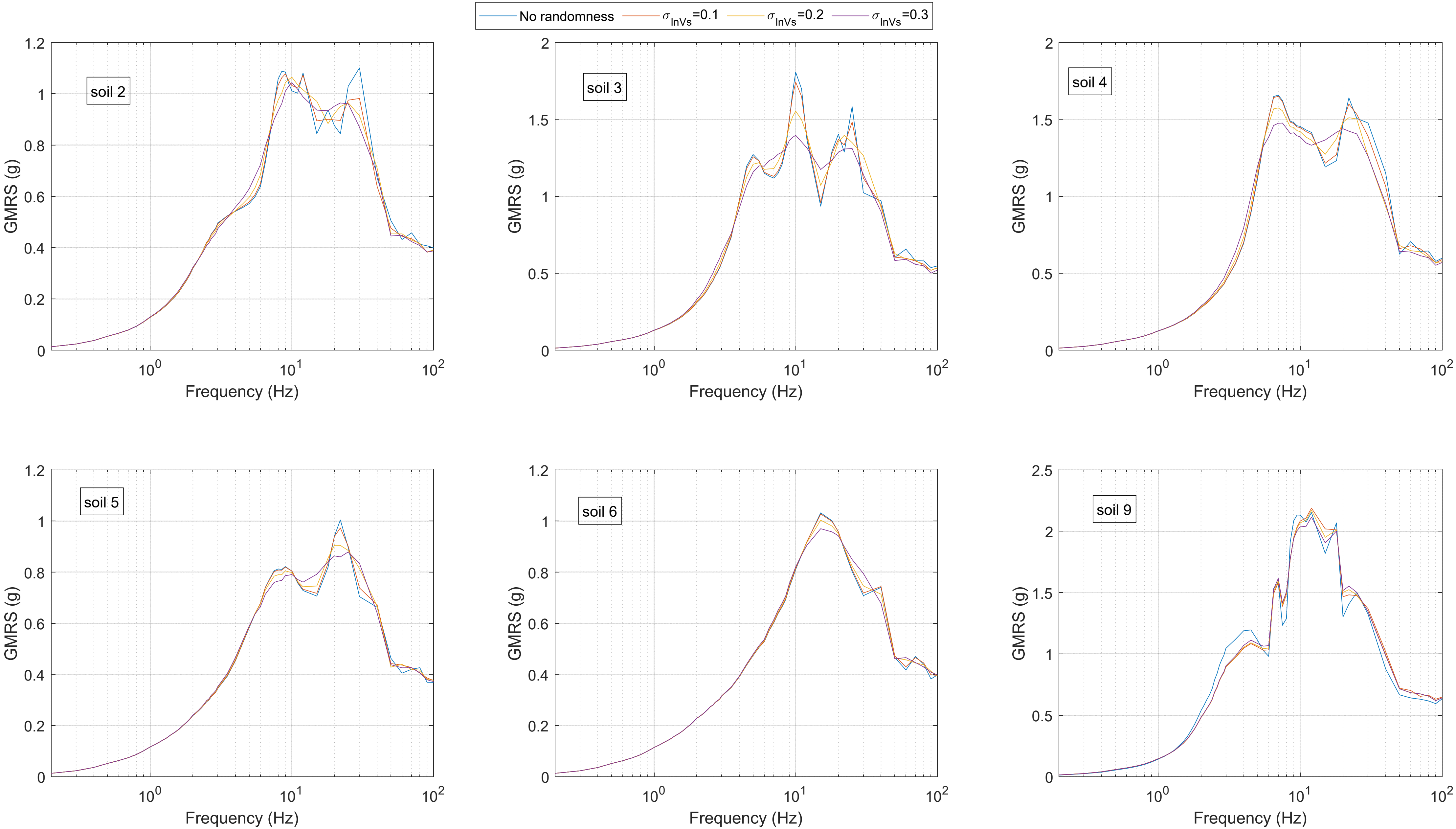
■ Soil amplification functions



■ UHRS at the soil surfaces



■ GMRS at the soil surfaces



Random Nonlinear Material Properties

- **Nonlinear dependences of material properties on shear strain levels**

$$G/G_{\max}(\gamma) = [G/G_{\max}(\gamma)]_{\text{mean}} + \varepsilon_1 \sigma_{NG}$$

$$\sigma_{NG} = \exp(-4.23) + \sqrt{\frac{0.25}{\exp(3.62)} - \frac{\left([G/G_{\max}]_{\text{mean}} - 0.5\right)^2}{\exp(3.62)}}$$

$$0.02 \le G/G_{\max}(\gamma) \le 1$$

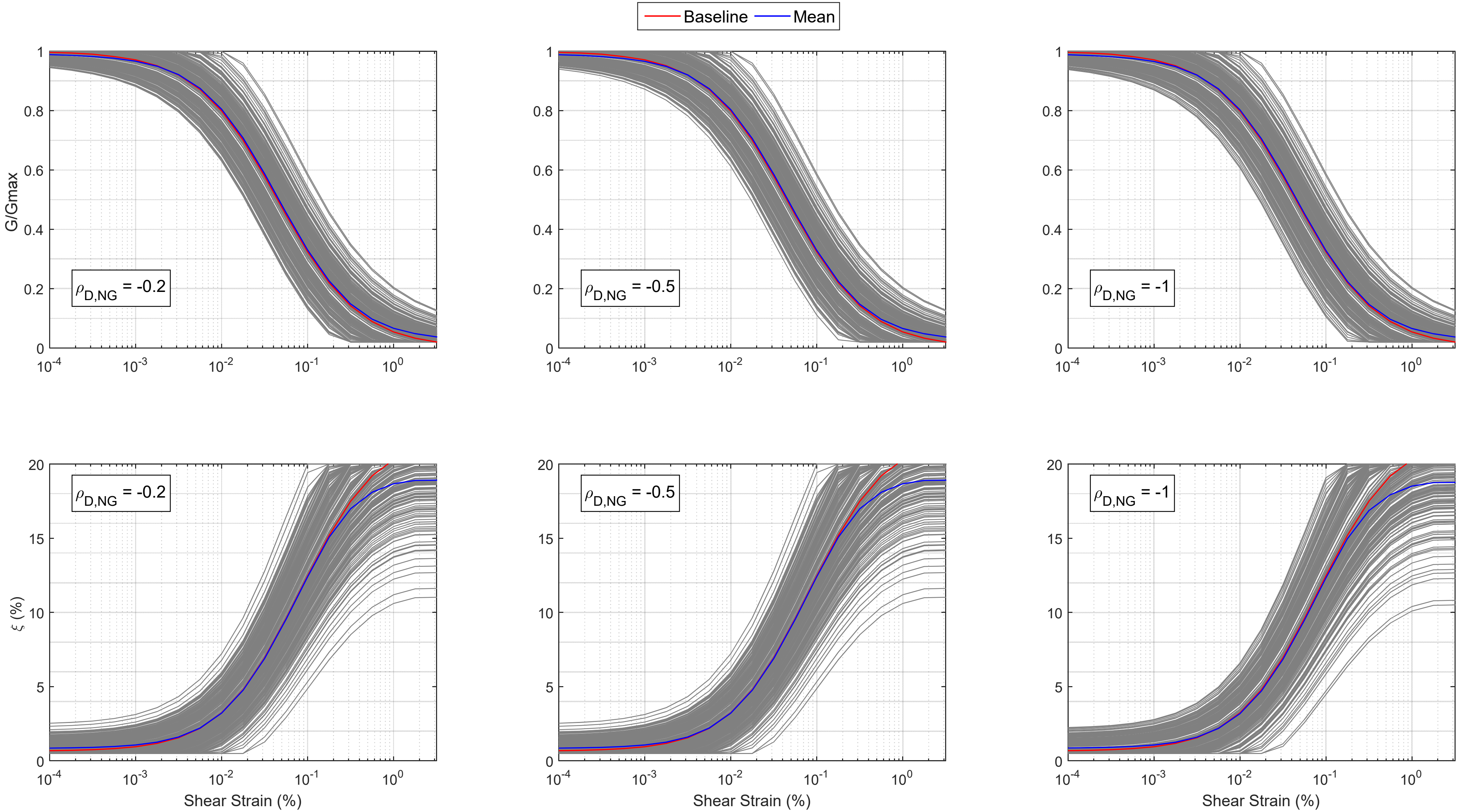
$$\xi(\gamma) = \xi_{\text{mean}}(\gamma) + \rho_{D,NG}\varepsilon_1\sigma_\xi + \sqrt{1-\rho_{D,NG}^2}\varepsilon_2\sigma_\xi$$

$$\sigma_\xi = \exp(-5.0) + \exp(-0.25)\sqrt{\xi_{\text{mean}}}$$

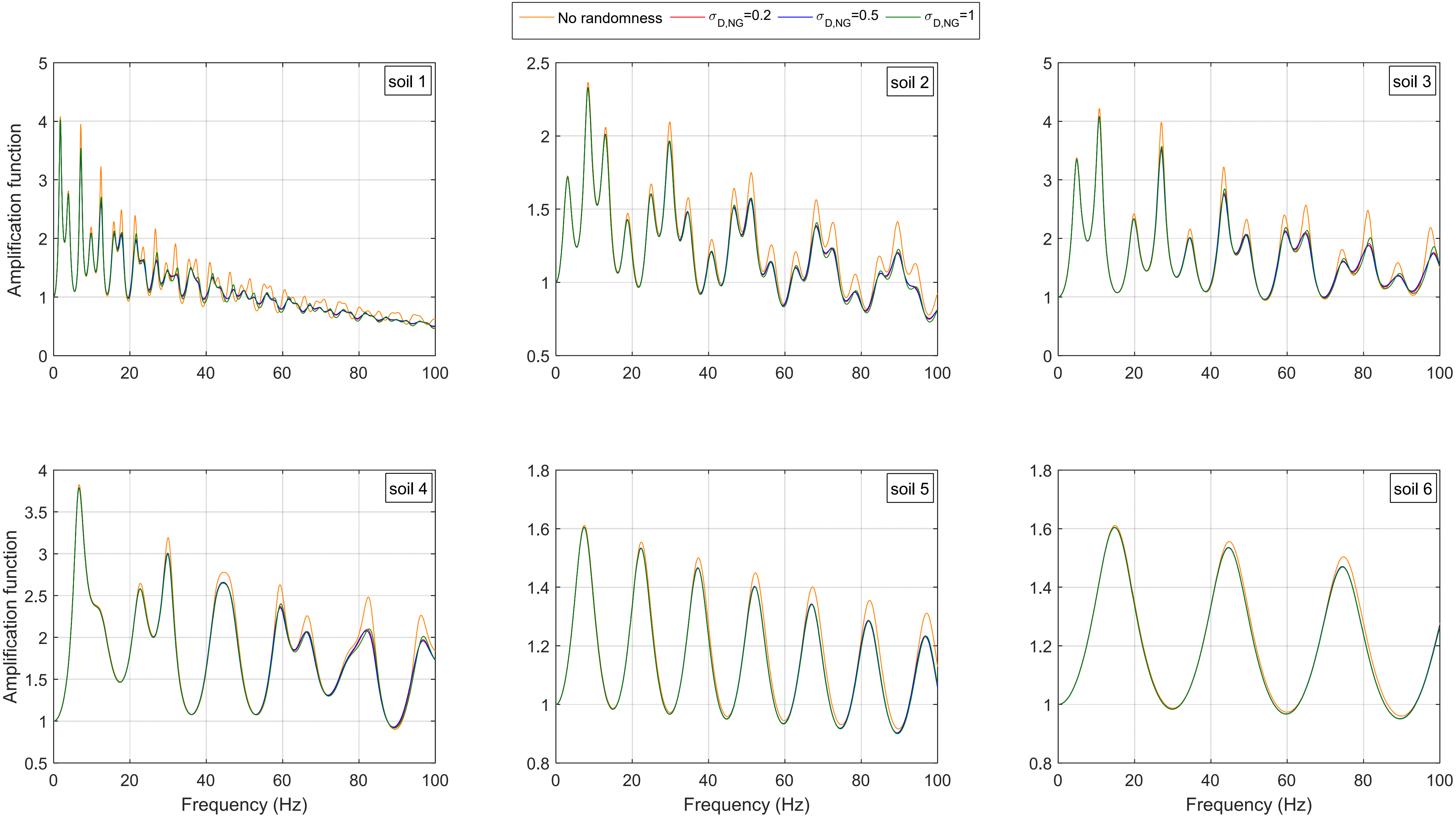
$$0.5\% \le \xi(\gamma) \le 20\%$$

Effects of nonlinear material properties

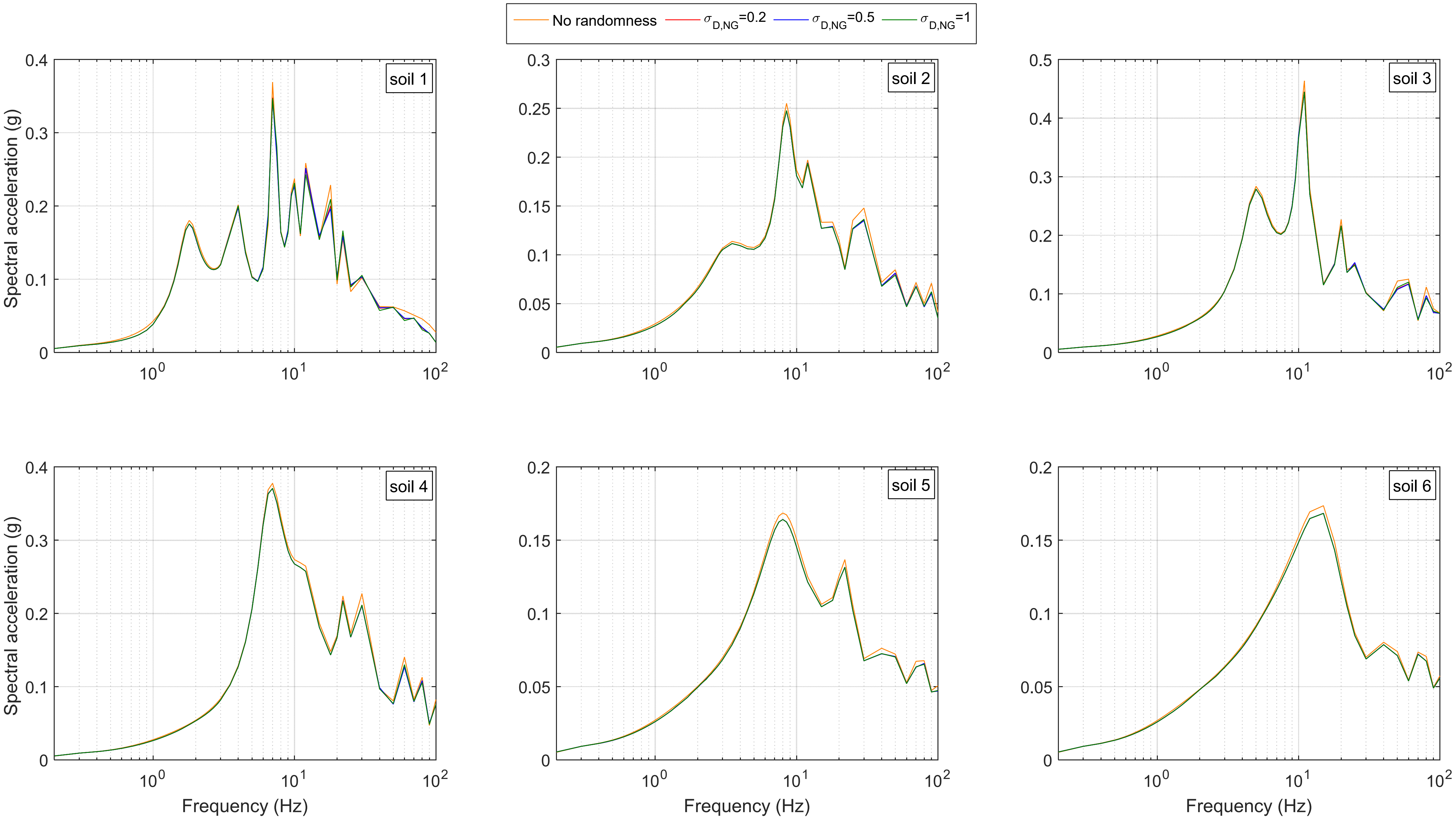
- **Realizations**



Soil amplification functions



- **UHRS at the soil surfaces**



Conclusion

- In this study, the effects of the randomness in bedrock outcrop motions and soil profiles on UHRS at soil sites were studied using the probabilistic site response analysis.
- The probabilistic site response analysis can be performed using equivalent linear ground response analysis of simulated soil profiles. The equivalent linear analysis can be implemented using the RVT methodology, which requires an acceleration response spectrum as input rather that an acceleration time history.
- Usually, it is required to define low-strain shear-wave velocity and relationships of shear modulus and hysteretic damping to shear strain levels in terms of their probability distributions and to consider variability of layer thickness if appropriate for the site being considered.
    - The random model for layer thickness with an Erlang distribution was proposed.
- It was demonstrated that the randomness of layer thickness and low-strain shear-wave velocity has significant effects on the soil amplification and UHRS/GMRS at the surfaces.

Thank you for your attention.

Any question?