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Conducting 1D site response analyses to capture 2D V_S spatial variability effects

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Abstract

One-dimensional site response analyses (1D SRAs) with shear-wave velocity (V_S) randomization are commonly performed to estimate median site-specific amplification factors (AFs) under the implicit assumption that this approach yields a realistic response. In this work, an investigation is conducted to determine the appropriate amount of V_S randomization ($\sigma_{\ln V_S}$) needed to capture a median response that accounts for 2D V_S spatial variability effects. Results from 2D SRAs and 1D SRAs with V_S randomization show that the median 2D seismic responses are generally higher than 1D responses at the site's fundamental frequency, and that higher V_S variability has a mild impact on the median 2D seismic response amplitude at the fundamental frequency, whereas it significantly reduces the median 1D response. Findings indicate that the 84th percentile AFs based on 1D SRAs conducted with V_S randomization using $\sigma_{\ln V_S}$ = 0.25, approximate well with the more realistic median 2D SRA-based AFs around the fundamental frequency, while the 70th to 60th percentiles might be more appropriate at higher frequencies. The benefit of using percentiles of the 1D SRA-based AFs higher than the median is shown for different site conditions and supported by comparisons against empirical data from four downhole sites.

Keywords

V_S randomization, 2D and 1D site response analyses, shear wave velocity, spatial variability, random fields

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Introduction

The estimation of the seismic response at the ground surface is a key component in the seismic design of structures. One-dimensional site response analyses (1D SRAs) are commonly used to assess the amplification or deamplification of seismic waves as they travel

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from a source at depth, through soil deposits, and reach the ground surface. This simplified analysis is widely used in engineering practice given that it requires a relatively simple site characterization, and it is computationally inexpensive. However, 1D SRAs condense the 3D nature of wave propagation to horizontally polarized vertically propagating shear (SH) waves traveling upward through a 1D soil column, which is representative of a soil deposit of horizontal layers that extend infinitely in the lateral directions. Given this simplification, observed discrepancies between empirical data and 1D SRA-based estimations are unsurprising (e.g. Afshari and Stewart, 2019; Baise et al., 2011; Kaklamanos et al., 2011, 2013; Kottke, 2010; Regnier, 2013; Regnier et al., 2018; Stewart et al., 2008; Tao and Rathje, 2019; Thompson et al., 2012; Zalachoris and Rathje, 2015). These discrepancies are generally attributed to (1) uncertainties associated with shear-wave velocity (V_S) and (2) conflicts between field reality and the 1D SRAs' underlying assumptions, such as laterally homogeneous V_S structure. In this work, 2D V_S spatial variability effects on the median seismic response are studied, and an approach for capturing these effects using 1D SRAs is investigated. In reality, there are no 2D sites, but rather 3D sites that unavoidably encompass a wide range of site conditions (e.g. variable V_S, inclined bedrock, inclined wave propagation) affecting the seismic response. However, herein, the expression "2D V_S spatial variability" is used to be explicit about the assumptions of this study, and the range of applicability of the conclusions drawn.

The effect of V_S spatial variability on the seismic response has been studied by regulators and researchers. For nuclear facilities, it is common to follow the guidelines by the Electric Power Research Institute (EPRI, 2013) to conduct 1D SRAs. These guidelines recommend using three base-case V_S profiles to account for the epistemic uncertainty on the V_S profile and to randomize each one of these base-case V_S profiles to account for aleatory variability. This approach, however, has been found to underestimate site response predictions (Teague and Cox, 2016). Previous research efforts have also studied spatial variability and other non-1D effects. Pehlivan (2013) performed 2D equivalent-linear SRAs on V_S random fields and 1D equivalent-linear SRAs on randomized V_S profiles and found that mean spectral accelerations from 2D SRAs are higher by 15%–40%. De Martin et al. (2013) performed 3D, 2D, and 1D SRAs using the spectral-element method and concluded that small deviations from 1D wave propagation theory strongly affect the period and amplitude of the system's resonant modes. Bielak et al. (1999) compared the estimations from 2D and 1D SRAs against observations from the 1988 Armenia Earthquake and concluded that results from 2D SRAs provide a better agreement.

In this article, 2D and 1D linear elastic SRAs are conducted to investigate a methodology for capturing 2D V_S spatial variability effects on the seismic response using 1D SRAs with V_S randomization. SRAs performed on 2D V_S correlated random fields and on 1D randomized V_S profiles are generated using the Toro model (1995). Various site conditions are considered to generate the 2D random fields, whereas the standard deviation of V_S ($\sigma_{\ln Vs}$) for 1D randomization is calculated from the 2D models and generic values are also used. Differences between the median 2D SRA- and 1D SRA-based seismic responses are discussed, and residuals are estimated. Two criteria for estimating a more realistic 2D seismic response using 1D SRAs are evaluated, and findings are contrasted against empirical data. Results from this study provide insights into the biases carried when estimating the seismic response using 1D SRAs with V_S randomization, and practical guidance is provided to conduct these analyses such that a more realistic seismic response that accounts for 2D V_S spatial variability effects is captured.

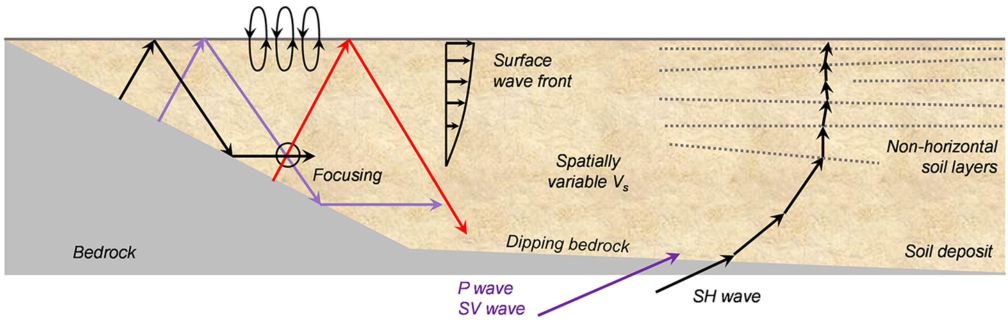

Figure 1. Schematic of various wave propagation phenomena in a natural environment.

Rationale for V_S randomization

One-dimensional SRAs are commonly conducted using randomized V_S profiles with two objectives: (1) to account for the spatial variability of natural soil deposits (e.g. Griffiths et al., 2016a; Kaklamanos et al., 2020; Tao and Rathje, 2019; Toro, 1995) and (2) to correct for overpredictions of the site amplification observed at the site's fundamental frequency when using 1D SRAs (e.g. Rodriguez-Marek et al., 2020; Zalachoris and Rathje, 2015). While these two aspects justify the use of randomized V_S profiles, there is limited guidance on how to conduct V_S randomization, and whether it yields a more realistic seismic response is unclear. Commonly, the amount of V_S randomization, that is, the deviation from the baseline or "seed" V_S profile, is controlled by $\sigma_{\ln V_s}$ and determined from V_{S30}-based site classes (e.g. EPRI, 2013). However, V_{S30} is an index that cannot capture site-specific features affecting seismic amplification and thus V_S randomization based on V_{S30} does not necessarily lead to a more realistic response.

A number of site-specific features and wave propagation mechanisms play a role in the site amplification (or deamplification), such as changes in soil's impedance, V_S spatial variability, constructive interference, wave reflections and focusing effects, surface waves, and so on (Figure 1). Out of all these, 1D SRAs that are most commonly used in practice can only explicitly model the changes in impedance and resonance effects. We hypothesize that each unmodeled site-specific feature can be uncoupled and implicitly captured in 1D SRAs using a selected amount of $\sigma_{\ln Vs}$. For instance, the seismic response for a site with spatially variable V_S and a dipping bedrock can be estimated from 1D SRAs with randomized V_S profiles generated using $\sigma_{\ln Vs} = \sigma_{\ln Vs,1} + \sigma_{\ln Vs,2}$, where $\sigma_{\ln Vs,1}$ is used to capture the V_S spatial variability effects on the seismic response, and $\sigma_{\ln Vs,2}$ is used to capture the dipping bedrock effects.

In this work, an approach for using V_S randomization and estimating an appropriate seismic response is investigated. The proposed approach for conducting 1D SRAs with V_S randomization has two parts: (1) using contributions to $\sigma_{\ln Vs}$ from each unmodeled site-specific feature and (2) estimating a realistic seismic response based on a calibrated or selected criterion (e.g. a percentile higher than the median or a scaled response). In this article, attention is placed on the amount of V_S randomization for capturing the V_S spatial variability effects on the median seismic response at ground surface, that is, $\sigma_{\ln Vs}$. V_S randomization is conducted using the model for V_S proposed by Toro (1995).

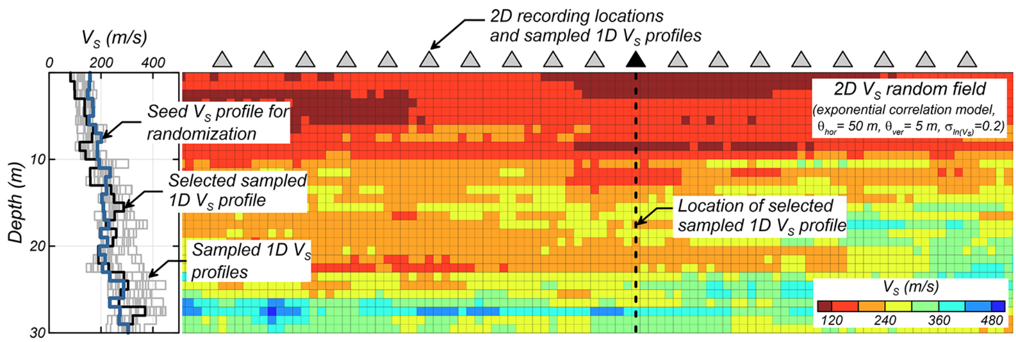

Figure 2. Sample window of a 2D correlated V_S random field and sampled 1D V_S profiles.

V_S randomization model by Toro

Toro (1995) proposed a V_S randomization model for the probabilistic characterization of V_S in SRAs with several sets of parameters for different V_{S30}-based site classes (Boore et al., 1994; Toro, 1995). The model's main parameters are $\sigma_{\ln Vs}$ and an auto-regressive functional form that determines the interlayer correlation. This model relies on the observation that V_S approximately varies with a log-normal distribution (e.g. Li and Assimaki, 2010), and it assumes a constant $\sigma_{\ln Vs}$ with depth. Toro also proposed models for randomizing layer thicknesses, and depth to bedrock, which are commonly used along with the model for randomizing V_S. In this work, only V_S is randomized.

Numerical investigation

Evaluation approach

Three sets of SRAs are conducted (Figure 2): (1) 2D SRAs on random fields constructed for several target $\sigma_{\ln Vs}$, (2) 1D SRAs with V_S randomization using several specified values of $\sigma_{\ln Vs}$, and (3) 1D SRAs on sampled V_S profiles extracted from the 2D random field models. The 2D ground-motion response is recorded at equally spaced locations along the ground surface. These results, which are herein assumed to represent a more realistic seismic response, are compared against 1D SRA-based estimates. The sampled V_S profiles consist of profiles numerically sampled from the 2D models at the recording locations (Figure 2). Results from this set of 1D SRAs provide insight into the ability of 1D SRAs to estimate an accurate seismic response when multiple flawlessly measured V_S profiles are available. Results from the three sets are compared in terms of transfer functions (TFs) for Fourier amplitudes and amplification factors (AFs) for response spectral values. All SRAs are linear elastic.

Numerical model

The 2D and 1D models consist of 1 m × 1 m square elements with different V_S values, which allow for an appropriate propagation of waves with frequencies lower than about 12.5 Hz (Kuhlemeyer and Lysmer, 1973). The 2D model's width is selected such that a seismic response along the middle zone, that is "recording zone," is unaffected by wave reflections from the edges of the model. Various model widths (or width-to-height W: H ratios) were tested for a 1D-type model (Figure 3a) until the estimated seismic response is

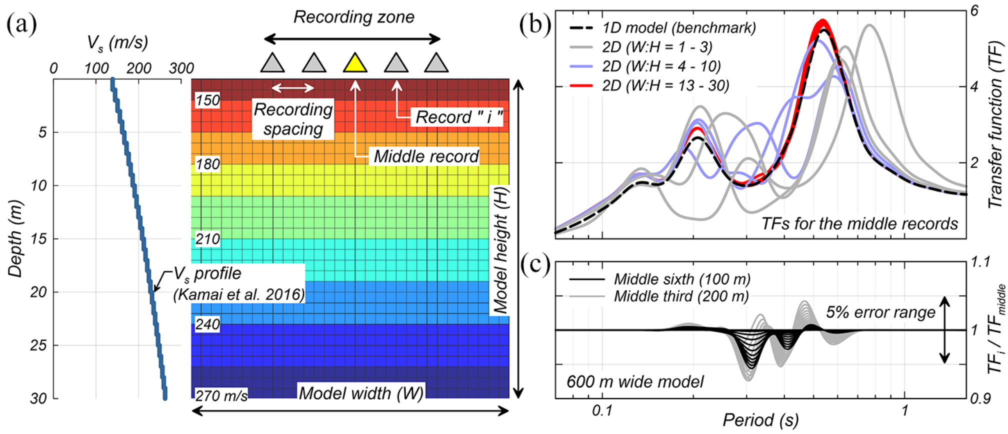

Figure 3. Selection of minimum model width. (a) Model setup for evaluation. (b) Evaluation in terms of TFs against the 1D benchmark. (c) Evaluation of allowable error in the 2D response.

comparable to the one obtained using 1D SRAs. A model width of 600 m (i.e. W: H = 20) is used to allow for a 100-m wide recording zone which results in errors in the TFs of less than 5% (Figure 3b and c). Each model has 21 recording locations equally spaced every 5 m along the surface. Preliminary analyses not presented herein for brevity indicated that shorter recording spacings do not provide additional benefit in the accuracy of the estimated seismic response.

A damping ratio of 10% is used for all soils in the numerical sections of this article. Note that damping is not used as a means to account for unmodeled natural phenomena such as wave scattering, instead, V_S randomization is used for that. The selection of a 10% damping ratio was led by a balance between the number of recorded responses along the model's surface, model size, and computational demand. Had a more realistic (lower) damping ratio been used, then a significantly larger 2D numerical model or more 2D models would have been required to obtain the same number of ground motion responses along the surface. Using this value of damping ratio does not affect the observed trends and conclusions drawn in this study, as indicated in a later section. The bedrock was modeled as a rigid base to isolate the effects of the soil–bedrock impedance ratio. The finite element software QUAD4MU (Hudson et al., 1994, 2003) is used to conduct 2D and 1D SRAs.

Baseline 2D random field models

The 2D sites consist of 30-m-deep correlated V_S random fields over a horizontally-oriented bedrock. The random fields are developed using the covariance matrix approach (Vanmarcke, 1983), based on a 1D seed V_S profile and a correlation function. The seed V_S profile is developed using the relations proposed by Kamai et al. (2016) for sites in California with a V_{S30} = 200 m/s, and the correlation function, ρ, is an exponential model with no nugget, given by:

$$\rho = \exp\left(-2\frac{\Delta_{\text{hor}}}{\theta_{\text{hor}}}\right)\exp\left(-2\frac{\Delta_{\text{ver}}}{\theta_{\text{ver}}}\right) \quad (1)$$

in which Δ_{hor} and Δ_{ver} are the lag distances along the horizontal and vertical directions, respectively, and θ_{hor} and θ_{ver} are the horizontal and vertical V_S correlation lengths,

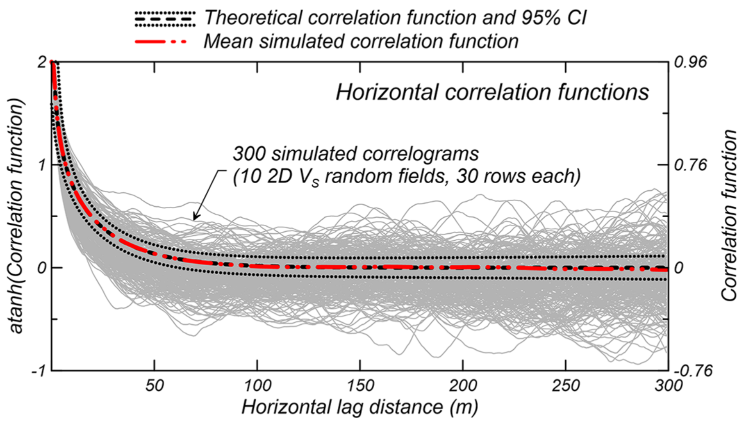

Figure 4. Theoretical and simulated horizontal correlation functions of ln(V_S) for the 2D random fields.

selected as 50 and 5 m, respectively. The selected correlation lengths yield a correlation anisotropy of 10, common in soil properties and geological environments (DeGroot, 1996; Phoon and Kulhawy, 1996, 1999). The 2D random field models are generated for target $\sigma_{\ln Vs}$ = 0.2, 0.3, 0.4, and 0.5, commonly observed in nature (e.g. Holzer et al., 2005; Wills and Clahan, 2006). Figure 2 shows a sample 2D random field model for a target $\sigma_{\ln Vs}$ = 0.2, and Figure 4 shows the correlation functions for ln(V_S) in the horizontal direction. The correlation values are presented in $\tanh^{-1}$ scale to produce an approximately normal distribution (Abrahamson et al., 1991) and are estimated for a maximum lag distance of half the model width to prevent biases induced by the number of available data pairs. The agreement between the theoretical and the mean simulated correlation functions confirms that the target correlation model is well captured by the generated profiles.

1D SRAs with V_S randomization

The seismic response is assessed through 1D SRAs on a suite of 50 randomized V_S profiles (Toro, 1995). The seed profile used for V_S randomization is calculated as the geometric mean of multiple profiles sampled from the recording zone, considered as the only portion of the 2D models affecting the seismic response, whereas $\sigma_{\ln Vs}$ is the standard deviation of the same profiles, used for V_S randomization. Hereafter, this standard deviation is referred to as "model-specific $\sigma_{\ln Vs}$." This approach is similar to practical applications where multiple V_S profiles are measured in the field and then used to estimate a representative V_S profile and $\sigma_{\ln Vs}$ (e.g. Griffiths et al., 2016b; Teague and Cox, 2016). Evaluations not included herein indicate that the ultimate seismic response is not sensitive to the location, or the number of the selected V_S profiles sampled within the zone of influence when more than 10 V_S profiles are used. In total, 50 V_S profile realizations are generated as it leads to stable results, with standard errors for the mean AF lower than 5% for most cases and lower than 8% for models with highly variable V_S. Using more realizations does not impact the results. Each set of results presented in this article are based on a different set of 50 V_S randomized profiles, such that conclusions are not based on a single one. The V_S randomization model was used with the interlayer correlation parameters recommended for sites with V_{S30} ranging from 180 to 360 m/s. These correlation parameters and those recommended for sites with V_{S30} ranging from 360 to 760 m/s are similar and using either set of parameters for a given seed V_S profile leads to practically the same seismic response.

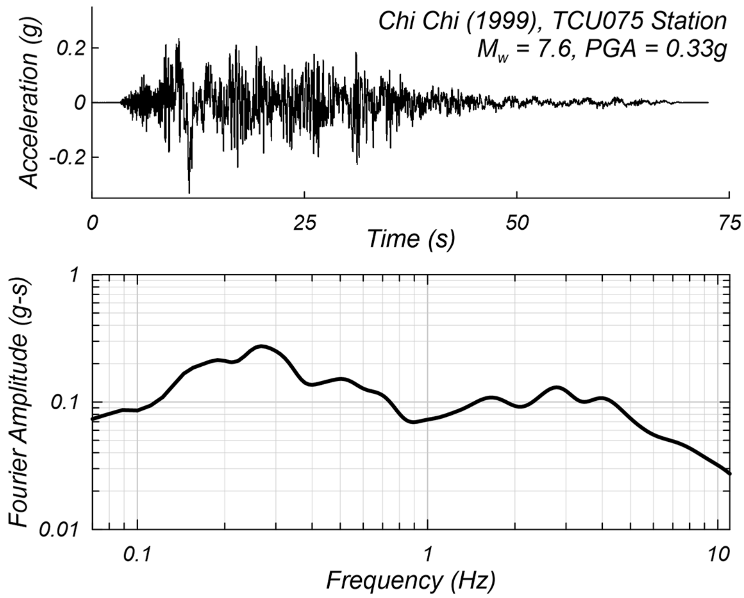

Figure 5. Input ground motion considered for the numerical evaluation of 2D versus 1D SRAs.

Input ground motions

The ground motion from the M7.6 Chi-Chi earthquake (1999) recorded at the TCU075 station (Figure 5) was downloaded from the Pacific Earthquake Engineering Research Center (PEER) Database (Ancheta et al., 2013) and is applied uniformly as vertically incident SH waves along the model base as acceleration. For linear elastic SRAs, a single input ground motion is sufficient for estimating the response in terms of TFs. In the case of AFs, we assume that any additional contribution to the variability that comes from multiple input ground motions is minimal compared to the variability already included using 2D V_S random fields and randomized 1D V_S profiles. This assumption is supported by additional analyses with different ground motions, not presented herein and a previous study by Bazzurro and Cornell (2004).

Baseline results

Results indicate discrepancies between 2D and 1D SRAs in terms of TFs and AFs. Figures 6 and 7 present TFs and AFs for four representative 2D models, each with different model-specific $\sigma_{\ln Vs}$, and the associated sampled and randomized 1D models. The discrepancies are consistently observed for different $\sigma_{\ln Vs}$ and are due to (1) amplification effects captured by 2D SRAs but missed by 1D SRAs, such as wave scattering and constructive interference, and (2) a stronger shifting of the 1D fundamental frequencies due to V_S randomization, which leads to the cancelation of peaks and troughs and thus lower median TFs and AFs, and overall highly variable responses across frequencies compared to the 2D results. This effect has also been pointed out by other researchers (e.g. Tao and Rathje, 2019; Teague and Cox, 2016). In all cases, the median 2D SRA-based TF is higher than the median 1D SRA-based TF from sampled V_S profiles around the fundamental frequency, and the latter is higher than the 1D SRA-based TF from randomized V_S profiles.

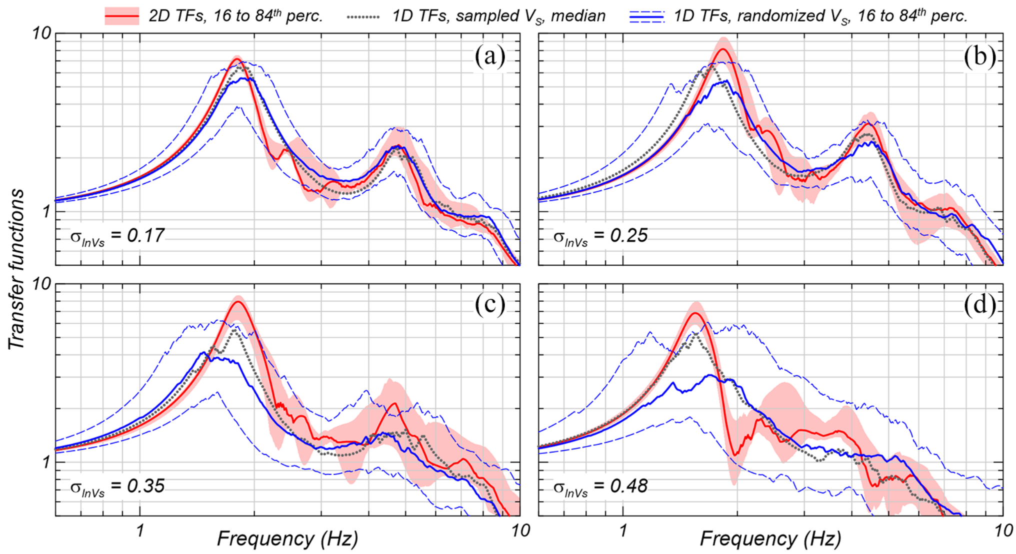

Figure 6. Transfer functions from 2D and 1D SRAs. Results from (a) to (d) correspond to four representative 2D V_S random field models, each with a different model-specific $\sigma_{\ln V_S}$, indicated in the bottom left corners, and the corresponding sampled 1D and randomized 1D V_S profiles. One-dimensional SRAs conducted with V_S randomization using the model-specific $\sigma_{\ln V_S}$.

The cancelation of peaks and troughs is less significant in the case of 1D SRAs on sampled profiles given the stronger correlation of the 1D columns compared to the randomized V_S profiles. These results also suggest that highly variable sites present a weaker second mode TF when estimated based on 2D SRAs, which is due to wave scattering caused by soil heterogeneities (De la Torre et al., 2019). Similar trends are observed in the median 2D SRA- and 1D SRA-based AFs (Figure 7), although with milder differences given that AFs have contributions from a range of Fourier spectrum frequencies at a single oscillator frequency (Bora et al., 2016). These observations are consistent with previous similar studies (e.g. Bielak et al., 1999; Nour et al., 2003; Pehlivan, 2013).

Importantly, this numerical evaluation indicates that the site's V_S variability, captured through $\sigma_{\ln V_S}$, has a different impact on the 2D and 1D seismic responses. In other words, using model-specific $\sigma_{\ln V_S}$ values for 1D SRAs with V_S randomization does not necessarily lead to a more realistic seismic response. It is worth noting that 2D SRA-based TFs generally show higher amplitudes than 1D SRA-based TFs. Various researchers have observed that 1D SRAs overpredict the responses at the site's fundamental frequency (e.g. Rodriguez-Marek et al., 2020; Zalachoris and Rathje, 2015). It is therefore likely that 2D SRAs suffer from a similar issue. Assuming that the degree of overprediction is similar in 2D as in 1D SRAs, results from this work are not affected, as the relative differences between 2D and 1D SRAs are studied rather than absolute amplitudes. An immediate approach to test the validity of conclusions drawn from this numerical evaluation can rely on empirical data, as presented later in this article.

V_S randomization to account for 2D V_S spatial variability

The previous section shows that randomizing V_S with model-specific $\sigma_{\ln V_S}$ values does not necessarily lead to an appropriate median seismic response. Here, an evaluation of the ability of V_S randomization with a generic $\sigma_{\ln V_S} = 0.25$ to capture 2D V_S spatial variability

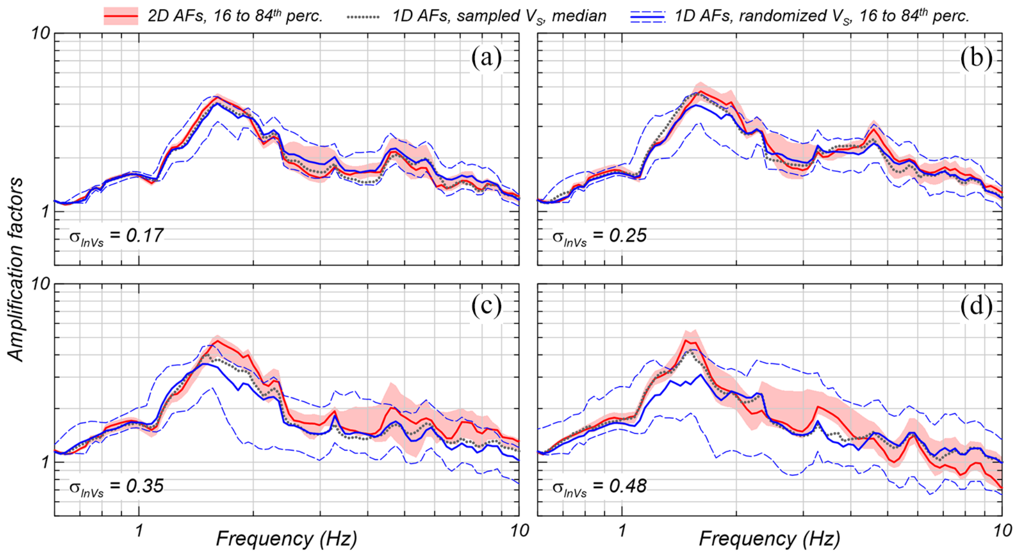

Figure 7. Amplification factors from 2D and 1D SRAs. Results from (a) to (d) correspond to four representative 2D V_S random field models, each with a different model-specific $\sigma_{\ln Vs}$, indicated in the bottom left corners, and the corresponding sampled 1D and randomized 1D V_S profiles. One-dimensional SRAs conducted with V_S randomization using the model-specific $\sigma_{\ln Vs}$.

effects is conducted, and the performance of a generic $\sigma_{\ln Vs}$ is compared against model-specific $\sigma_{\ln Vs}$ values.

The results in terms of TFs and AFs are, respectively, presented in Figures 8 and 9 for the same representative sites selected for Figures 6 and 7. In all cases investigated, that is, $\sigma_{\ln Vs}$ = 0.16 to 0.48, the 84$^{\text{th}}$ percentile TFs and AFs at the fundamental frequency estimated using a generic $\sigma_{\ln Vs}$ = 0.25 are similar to those estimated using model-specific $\sigma_{\ln Vs}$ values. Using $\sigma_{\ln Vs}$ = 0.25 leads to TFs slightly broader compared to the ones from model-specific $\sigma_{\ln Vs}$ for sites with low V_S variability, and narrower TFs in the case of highly variable sites. These results suggest that $\sigma_{\ln Vs}$ = 0.25 could be used to capture 2D V_S spatial variability effects on the seismic response.

Criteria for estimating a representative seismic response

Results indicate that median 1D SRA-based TFs and AFs (with or without V_S randomization) are lower than the median 2D SRA-based TFs and AFs, around the fundamental frequency. This suggests that the median 2D response cannot be captured by the median 1D response. As such, two criteria to approximate the median 2D response using 1D SRAs with V_S randomization are investigated: (1) 1D seismic response percentiles higher than the median, and (2) scaling factors to adjust the median 1D seismic response. Results in this section are presented in terms of AFs only, but similar trends are observed for TFs.

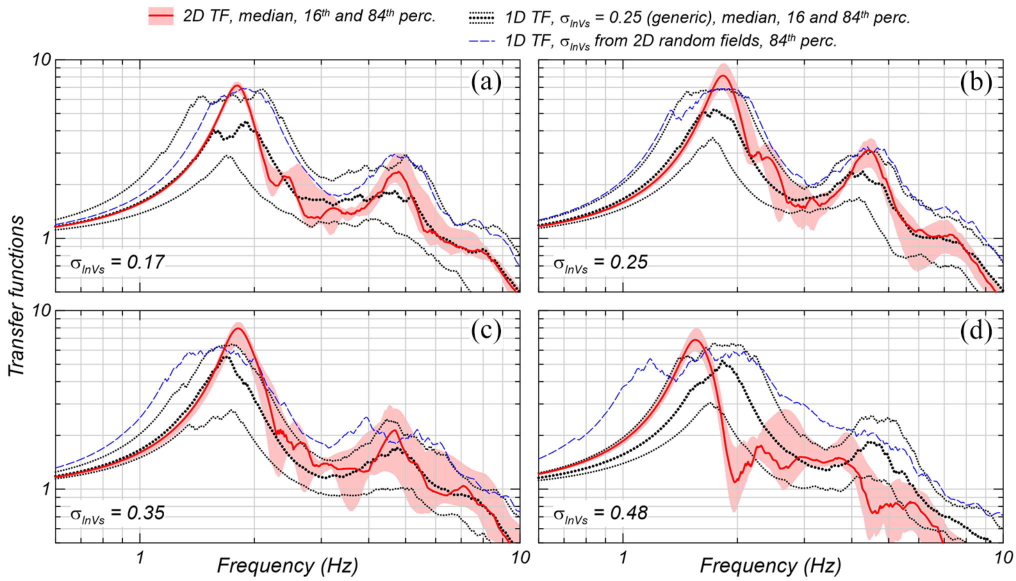

Figure 8. Transfer functions from 2D and 1D SRAs. Results from (a) to (d) correspond to four representative 2D V_S random fields, each with different $\sigma_{\ln V_S}$, indicated in the bottom left corners, the corresponding randomized 1D V_S profiles using model-specific $\sigma_{\ln V_S}$, and 1D V_S profiles using a generic $\sigma_{\ln V_S}$ = 0.25.

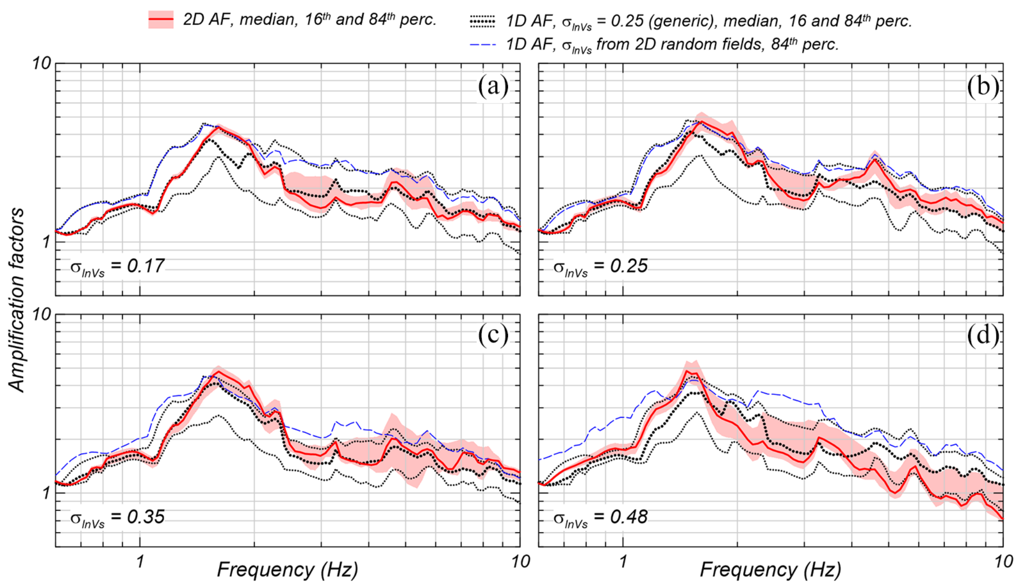

Figure 9. Amplification factors from 2D and 1D SRAs. Results from (a) to (d) correspond to four representative 2D V_S random fields, each with different $\sigma_{\ln V_S}$, indicated in the bottom left corners, the corresponding randomized 1D V_S profiles using model-specific $\sigma_{\ln V_S}$, and 1D V_S profiles using a generic $\sigma_{\ln V_S}$ = 0.25.

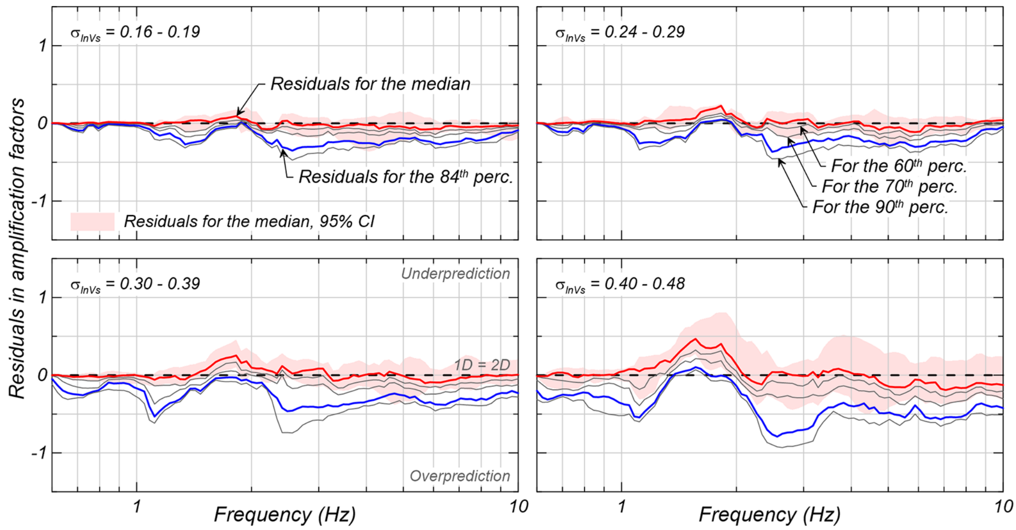

Figure 10. Median residuals for various percentiles of 1D SRA-based amplification factors compared to 2D SRA-based median amplification factors. V_S randomization conducted using model-specific $\sigma_{\ln V_S}$, indicated in top left corners.

Potential criterion 1: percentiles higher than the median 1D SRA-based seismic response

This approach aims at capturing a median response that accounts for 2D V_S spatial variability effects using a percentile higher than the median 1D SRA-based response. To evaluate the benefit from this approach, residuals are estimated for the nth percentile of the 1D SRA-based AFs as:

$$Residual = \ln(AF_{2D,\,median}) - \ln\left(AF_{1D,\,n^{th}percentile}\right) \quad (2)$$

where n^{th} can be the median, 60th, 70th, 84th, or the 90th percentile. Positive and negative residuals indicate underprediction and overprediction, respectively. Figures 10 and 11 present residuals for AFs estimated using 10 2D random fields, and the corresponding randomized 1D V_S profiles generated using model-specific $\sigma_{\ln V_S}$, indicated in the top left corners, and a generic $\sigma_{\ln V_S}$ = 0.25. In both figures, solid lines represent the median residuals estimated from all the 10 2D random fields, each one with a different model-specific $\sigma_{\ln V_S}$ affecting the seismic response, hence the range of $\sigma_{\ln V_S}$ values. In Figure 10 (model-specific $\sigma_{\ln V_S}$), residuals for median 1D SRA-based AFs (95% CI) vary from −0.5 to 0.75, with scatter increasing with $\sigma_{\ln V_S}$. Logically, these residuals decrease, that is, they transition from underprediction to overprediction, as higher percentiles of the 1D SRA-based AFs are considered. The 84th–90th percentile AFs have residuals near zero at the fundamental frequency (i.e. around 1.8 Hz), whereas the 60th–70th percentile AFs reach near-zero residuals at higher frequencies. In Figure 11 (generic $\sigma_{\ln V_S}$ = 0.25), the differences between 2D and 1D SRA-based AFs at the fundamental frequency are similar to those obtained when using model-specific $\sigma_{\ln V_S}$ values. However, at higher frequencies, the overprediction is slightly higher for sites with low V_S variability ($\sigma_{\ln V_S}$ from 0.16 to 0.19), and lower for sites with high V_S variability ($\sigma_{\ln V_S}$ from 0.3 to 0.48). For highly variable sites, the 60th

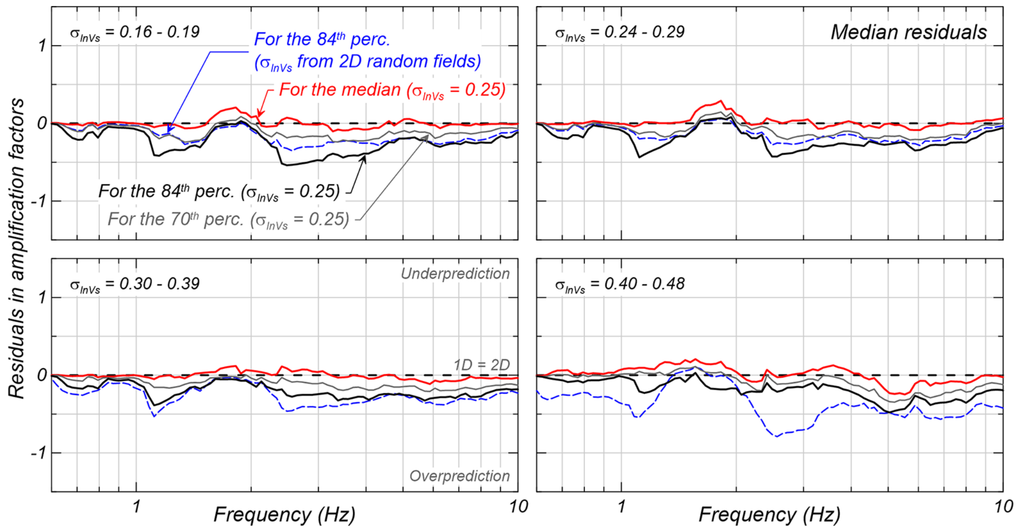

Figure 11. Median residuals for the 50th, 70th, and 84th percentiles of 1D SRA-based amplification factors compared to 2D SRA-based median amplification factors. V_S randomization conducted using model-specific $\sigma_{\ln Vs}$, indicated in the top left corners, and a generic $\sigma_{\ln Vs}$ = 0.25. Residuals for the 84th percentile 1D SRA-based amplification factors from V_S randomization with model-specific $\sigma_{\ln Vs}$ (Figure 10) included for reference.

percentile AF appears to be high enough to capture the median 2D SRA-based response at frequencies other than the fundamental.

Potential criterion 2: scaling factors to adjust the median 1D SRA-based seismic response

This approach aims at capturing a median response that accounts for 2D V_S spatial variability effects by scaling the median 1D SRA-based response. This approach is similar to using correction factors to account for 2D or 3D effects (e.g. Chávez-García and Faccioli, 2000). The scaling factors are estimated as:

$$Scaling\ Factor = \frac{AF_{2\mathrm{D,\,median}}}{AF_{1\mathrm{D,\,median}}} \tag{3}$$

in which $AF_{2D,\,median}$ is the median 2D SRA-based AF estimated for a site, and $AF_{1D,\,median}$ is the median 1D SRA-based AF for a set of 50 randomized V_S profiles used to assess the seismic response of the same site. Generally, scaling factors vary from 0.5 to 2.3 (Figure 12). Higher factors are estimated for more variable sites. For instance, a median factor of 1.5 could be applied to a 1D SRA-based AF to estimate the median 2D AF at the fundamental frequency for sites with $\sigma_{\ln Vs}$ from 0.4 to 0.48.

Using scaling factors presents two limitations: (1) they depend on the site's frequency modes, the site's $\sigma_{\ln Vs}$, and vary across frequencies, which makes them challenging to know and calibrate for a wide range of site conditions, and (2) they are highly variable even at a single frequency, often with factors lower and higher than 1 and a median near 1 that do not properly correct neither overprediction nor underprediction. This approach

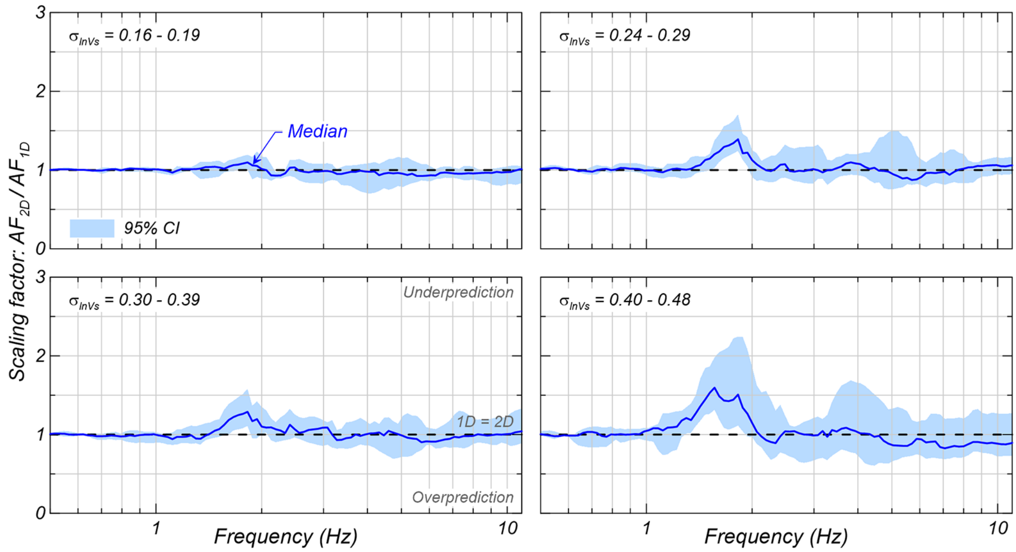

Figure 12. Scaling factors to estimate median 2D amplification factors accounting for V_S spatial variability based on 1D SRAs with V_S randomization using model-specific σ_{lnVs}, indicated in top left corners.

Table 1. Summary of parameters for all the evaluated site conditions

Parameter	Baseline case	Parametric evaluation
Input ground-motion boundary condition	Rigid	Elastic (V_S = 500, 760, 1500 m/s)
Correlation model	Exponential	Spherical, polynomial decaying, squared exponential
Horizontal correlation length, θ_{hor} (m)	50	5, 25, 500
Vertical correlation length, θ_{ver} (m)	5	10, 15, 25
Site depth (m)	30	50, 100, 200
Site's V_{S30} (m/s)	200	300, 400, 500
Soil's damping ratio (%)	10	2, 5, 15

V_S: shear-wave velocity.

might be appropriate for site-specific projects, where a few 2D SRAs can be conducted to calibrate scaling factors (e.g. Anderson et al., 2018), but appears unsuitable for a generalized recommendation.

Parametric evaluation

A parametric evaluation is conducted to study the consistency of the observed trends of the residuals in AFs for different site conditions. This evaluation is conducted for 2D random fields developed for a target $\sigma_{\text{lnVs}} = 0.2$ and varying other baseline conditions one at the time. These conditions are the underlying bedrock, the V_S heterogeneity (correlation model, σ_{lnVs}, and correlation lengths), the site's stiffness and fundamental frequency (V_{S30} and depth), and the soils' damping ratio. All the investigated parameters and values are listed in Table 1. TFs and AFs are estimated with model-specific $\sigma_{\ln Vs}$, and the residuals for the median and 84th percentile AFs are calculated and compared against results for the baseline case. In this case, residuals are shown against the normalized frequency, f/f_0, where f_0 is the site's fundamental frequency, to remove the effect of differences in f_0 of different sites. Herein, attention is placed on the consistency of the improved performance of the 84th percentile over the median 1D SRA-based AFs, at the fundamental frequency ($f/f_0 = 1$). A study of the effects of the site conditions on the 2D SRA-based TFs and AFs and the sampled 1D SRA-based TFs and AFs is presented by Pretell et al. (2022).

Effect of underlying bedrock conditions

The baseline site was modeled using a rigid base to isolate the influence of the soil–bedrock impedance ratio. A rigid base does not allow for the dissipation of energy when seismic waves bounce back down to the model base. Here, the effect of this assumption is studied. An elastic base allows for some energy dissipation, which is a more common field condition. The elastic base is modeled for three $V_{S,\ \mathrm{bedrock}} = 500$, 760, and 1500 m/s. The results indicate that the presence of an elastic base leads to a mild reduction of residuals, with lower V_S values leading to lower residuals (Figure 13a). At the fundamental frequency, the 1D SRA-based median AF underpredicts the response, while 84th percentile AFs are relatively stable and lead to near zero residuals. At higher frequencies, the median and 84th percentile 1D SRA-based AFs generally overpredict the response. The relative difference between the residuals corresponding to a rigid and an elastic base is minor and follows the same trends as observed for the baseline site. Thus, a rigid base is used for further parametric analyses.

Effect of correlation model

The correlation model controls how fast the V_S correlation decays with distance. The baseline site was developed using V_S random fields that follow an exponential correlation model. The effect of the selected correlation is evaluated using the spherical, the polynomial decaying, and the squared exponential correlation models (e.g. Lloret-Cabot et al., 2014). The results do not show a significant variation of the residuals for different correlation models compared to the baseline site (Figure 13b). Overall, all residuals for the median and 84th percentile AFs cluster closely and vary within a narrow range of 0.1 ln units.

Effect of horizontal correlation length

The horizontal correlation length, θ_{hor}, determines the span within which V_S is highly correlated in the horizontal direction. Sites with longer θ_{hor} have a more similar V_S in the lateral direction and thus are more compliant to the 1D SRA assumption of lateral continuity. Another interpretation for longer θ_{hor} is for sites with low V_S variability relative to the size of the structure of interest. The baseline site's θ_{hor} of 50 m is decreased and increased ($\theta_{hor} = 5$, 25, and 500 m) to evaluate the effect of shorter and longer horizontal correlation lengths. The results indicate that sites with longer θ_{hor} lead to smaller residuals, that is, the 2D and 1D seismic responses are more similar (Figure 13c), whereas sites with shorter θ_{hor}, that is, more variable in the lateral direction, lead to further underpredictions of the 2D SRA-based median AFs at the fundamental frequencies.

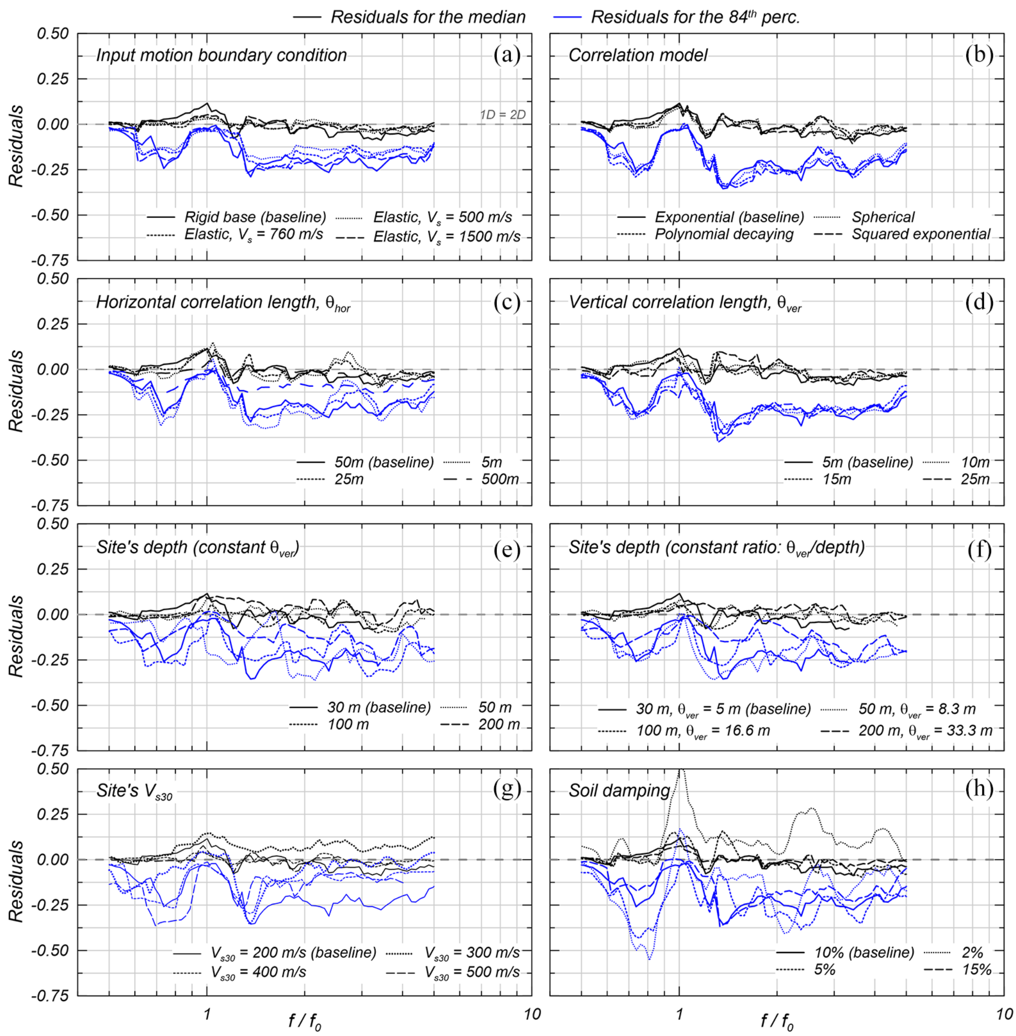

Figure 13. Residuals for the median and 84th percentile 1D SRA-based amplification factors relative to the median 2D SRA-based amplification factors for various site parameters related to (a): the underlying bedrock condition, (b) to (d): the V_S heterogeneity, (e) to (g): the site's stiffness and fundamental frequency, and (h): damping. One-dimensional SRAs conducted with V_S randomization using the model-specific $\sigma_{\ln V_S}$.

Effect of vertical correlation length

The vertical correlation length, θ_{ver}, determines the span within which V_S is correlated in the vertical direction. Sites with longer θ_{ver} are representative of soil deposits with thicker layers of approximately uniform V_S. The baseline site's θ_{ver} of 5 m is increased (θ_{ver} = 10, 25, 50 m) to evaluate the effect of longer vertical correlation lengths. The results indicate that longer θ_{ver} values lead to higher overpredictions of the seismic response at the fundamental frequency (Figure 13d). The residuals for the 1D SRA-based median and 84th percentile AFs are not significantly affected by θ_{ver} and vary within 0.2 ln units across frequencies.

Effect of site's depth

The baseline site had a depth of 30 m and a θ_{ver} of 5 m. The effect of the site depth on the estimated residuals is evaluated for the depths of 50, 100, and 200 m through two scenarios: (1) deeper sites with constant θ_{ver} and (2) deeper sites with constant θ_{ver}/depth. When necessary, the 2D baseline model geometry and element dimensions are changed to accommodate the larger (deeper and wider) models while balancing the number of recordings and the computational demand. The results indicate that the AFs for deeper sites with θ_{ver} = 5 m are generally underpredicted by the median 1D SRA-based AFs at the fundamental and some high-frequency modes, and that 1D SRA-based 84th percentile AFs are more representative of median 2D SRA-based AFs at f/f_0 (Figure 13e). Similar trends are observed in the case of deeper sites with constant θ_{ver}/depth (Figure 13f).

Effect of site's V_{S30}

The baseline site was generated to have an overall V_{S30} of 200 m/s following the relations by Kamai et al. (2016). The effect of V_{S30} is evaluated for the values of 300, 400, and 500 m/s. In all cases, the parameters used to generate 1D V_S profiles are the same and correspond to sites with V_{S30} from 180 to 360 m/s (Toro, 1995). The results indicate that median 1D SRA-based AFs underpredict the median 2D SRA-based AFs at the site's fundamental frequency and they might under- or overpredict AFs at higher frequencies (Figure 13g). The 84th percentile 1D SRA-based AFs lead to near zero residuals at the fundamental frequency and higher overprediction at higher frequencies.

Effect of soil damping

The dissipation of energy during wave propagation is controlled by the damping ratio. The baseline site's materials are modeled with a damping ratio of 10%. The effect of using different critical damping ratios is evaluated for damping ratio values of 2%, 5%, and 15%. The results indicate a significant impact of damping on the residuals, with lower damping leading to higher and a more erratic variability of residuals (Figure 13h). The effect of damping on the absolute seismic responses is important. However, the effect of damping on the relative difference between the seismic responses estimated using 2D and 1D SRAs is relatively minor. Given a selected damping ratio, the difference between the residuals corresponding to the 1D SRA-based median and 84th percentile 1D SRA-based AFs is similar to the previous scenarios in variability across frequencies and magnitude.

Conclusion: The parametric evaluation indicates some variability in the magnitude of residuals for different site conditions but consistent trends in the differences between the residuals from the median and 84th percentile 1D SRA-based AFs. Therefore, it is concluded that the applicability of the potential criteria for estimating a more realistic median seismic response is not limited to the baseline case.

Empirical consistency

The ability of 1D SRAs with V_S randomization using $\sigma_{\ln Vs}$ = 0.25 combined with the selection of a percentile higher than the median seismic response to be approximate a more realistic response that captures V_S spatial variability effects is evaluated against ground-motion data. Toward this end, data from four downhole sites are used: (1) Delaney Park (Alaska), (2) Garner Valley (California), (3) HYGH10 (Japan), and (4) IBRH13 (Japan). These stations are selected as they are identified as sites unlikely to be exposed to non-1D

Table 2. Key features of the downhole sites selected for the evaluation of empirical consistency

Downhole site	Depth (m)	V_{S30} (m/s)	Site type		No. of events[a]	Database
			TR20[b]	Tea12[c]		
Delaney Park	61	270	A	LG	15	NEES
Garner Valley	150	285	A	LG	89	NEES
HYGH10	100	225	A	LP	23	KiK-net
IBRH13	100	335	A	LG	120	KiK-net

V_S: shear-wave velocity; NEES: Network for Earthquake Engineering Simulations.
[a]Both components of each event are used.
[b]Tao and Rathje (2020): A: 1D sites dominated by true resonances.
[c]Thompson et al. (2012): L: Low variability, G: Good fit, P: Poor fit.

effects and their seismic response to be dominated by true resonances (Tao and Rathje, 2020). Nevertheless, 1D SRAs might still lead to underestimation of the median empirical TF amplitudes, except at the fundamental frequency where overprediction is well known to occur. We argue that while these sites do not present complex geological structures, observed discrepancies between theoretical and empirical responses are mainly due to the V_S spatial variability inherent to natural deposits. Therefore, these sites offer an opportunity to examine the trends and findings obtained from the numerical work discussed earlier. Key features of the downhole sites, including the taxonomy by Tao and Rathje (2020) and Thompson et al. (2012), are presented in Table 2. A description of the sites' geology is presented by Combellick (1999) for Delaney Park, Bonilla et al. (2002) for Garner Valley, and borehole logs for HYGH10 and IBRH13 are available on the Kiban Kyoshin Network (KiK-net) website (National Research Institute for Earth Science and Disaster Resilience (NIED), 2019).

Ground-motion recordings

Ground-motion recordings are collected from the Network for Earthquake Engineering Simulations (NEES) database for Delaney Park and Garner Valley and from the KiK-net database for the HYGH10 and IBRH13 sites. In the case of Delaney Park and Garner Valley, which have sensors at multiple depths, ground-motion recordings from the deepest sensor are used to work with the widest possible ground-motion frequency band. The ground motions are used as recorded, without any rotation. The recordings are processed, baseline corrected, and filtered with a Butterworth band-pass filter (0.5–25 Hz) using the software PRISM (Jones et al., 2017). The recordings are then selected for the site response evaluation based on the following two criteria: (1) an average signal-to-noise ratio (SNR) higher than 5 within the frequency range of interest (Ktenidou et al., 2011) and (2) peak accelerations lower than 0.01 g in the sensor at depth such that SRAs remain within the linear elastic range (e.g. Kaklamanos et al., 2013). A summary of the number of records that meet these criteria is presented in Table 2.

Evaluation and results

The baseline V_S profiles for each site, reported by Tao (2018), are randomized using the model proposed by Toro (1995) to generate 50 V_S profiles. For these sites, the previously investigated generic $\sigma_{\ln V_S} = 0.25$ is used alongside with correlation parameters for sites

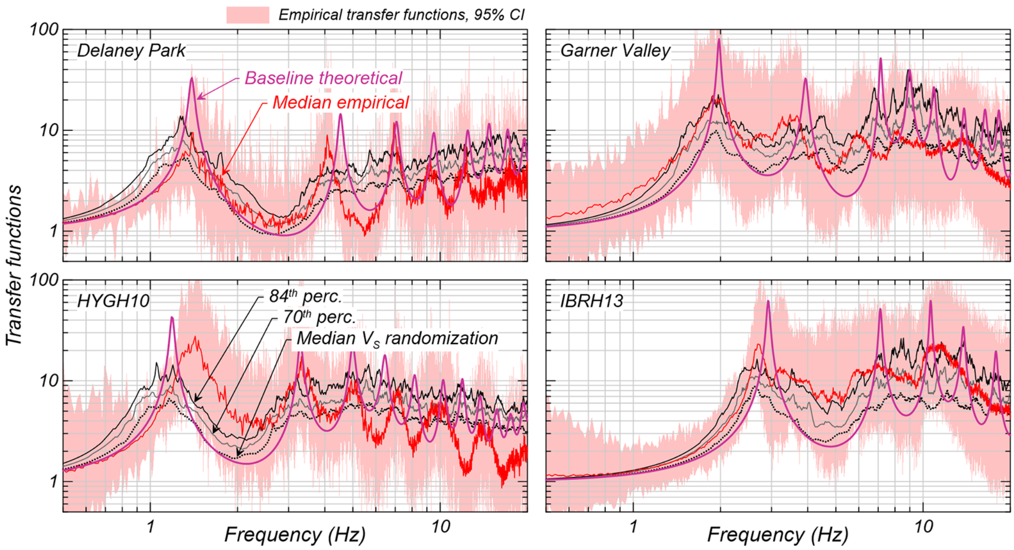

Figure 14. Theoretical and empirical transfer functions for four sites classified as A based on the site taxonomy by Tao and Rathje (2020). Theoretical transfer functions based on 1D SRAs with V_S randomization using a generic $\sigma_{\ln V_S}$ = 0.25 to capture 2D V_S spatial variability effects.

with V_{S30} from 180 to 360 m/s. Previous studies have suggested that $\sigma_{\ln V_S}$ for V_S randomization should decrease with depth and its selection should be guided by geological information (Tao and Rathje, 2019). However, given that enough data are not commonly available, a constant value of $\sigma_{\ln V_S}$ is used in this study. The evaluation does not account for epistemic uncertainty on the baseline V_S profile. Theoretical TFs are computed using the code NRATTLE, written by C. Mueller, modified by R. Herrmann, and included in the strong-motion programs by Boore (2005). NRATTLE uses the Thomson–Haskell solution to compute the 1D SH-wave TF (Haskell, 1953; Thomson, 1950) based on a V_S profile, density, and the inverse of the quality factors (Q_s^{-1}). Values for Q_s are estimated as one-tenth of V_S (Olsen et al., 2003), and damping as half the inverse of the Q_s (Joyner and Boore, 1988). For this, the baseline V_S profiles are considered, regardless of V_S randomization, which leads to damping values ranging from 0.5% to 3.2% (Delaney Park), 0.15% to 2.6% (Garner Valley), 0.35% to 3.7% (HYGH10), and 0.15% to 3% (IBRH13). Alternative relations for quality factors as a function of damping have been proposed for California (Campbell, 2009) and KiK-net sites (Cabas et al., 2017). These relations generally lead to higher damping values and thus ultimate lower theoretical TFs and AFs are also possible. Vertical incident waves are assumed in all cases.

Theoretical and empirical TFs and AFs are compared in Figures 14 and 15, and residuals for AFs presented in Figure 16. For each site, 50 theoretical TFs are calculated along with 50 theoretical AFs per ground-motion recording. Unsurprisingly, given the sites' classification as A (Tao and Rathje, 2020), the fundamental frequency mode is well captured by the theoretical TFs, except at HYGH10 where some discrepancy is observed. This discrepancy is attributed to errors in the baseline V_S profile and can be addressed in practice using multiple baseline profiles (e.g. EPRI, 2013).

Results in terms of TFs show that amplitudes of the first mode empirical median TFs are better approximated by the 84$^{\text{th}}$ percentile than by the median theoretical TFs. At higher frequencies, the median to the 84$^{\text{th}}$ percentile theoretical TFs fluctuate from

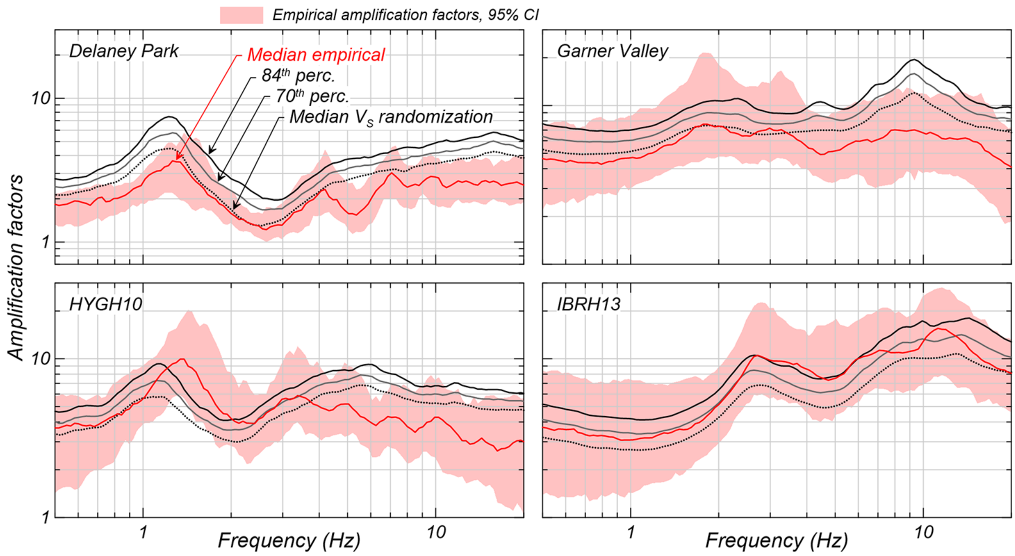

Figure 15. Theoretical and empirical amplification factors for four sites classified as A based on the site taxonomy by Tao and Rathje (2020). Theoretical amplification factors based on 1D SRAs with V_S randomization using a generic $\sigma_{\ln V_S}$ = 0.25 to capture 2D V_S spatial variability effects.

overprediction to underprediction at different frequency ranges. Basically, the higher modes are smoothed out by V_S randomization as previously pointed out by Tao and Rathje (2019). Results in terms of AFs, generally used in engineering design, present three different behaviors: (1) at Delaney Park and Garner Valley, the median theoretical AF is near or higher than the empirical median AF, and thus higher percentiles overpredict the AF consistently across frequencies; (2) at IBRH13, the median and 70th percentile theoretical AFs are generally lower than the empirical median AF, and the 84th percentile captures well the empirical median AF across frequencies; and (3) at HYGH10, results fluctuate between ranges of under- and overprediction for the median and higher percentile AFs. The overprediction of the seismic response at Delaney Park might be due to the high V_S variability inferred from geological conditions at this site (Tao and Rathje, 2019). It is therefore always recommended to estimate site-specific $\sigma_{\ln V_S}$ based on measured V_S profiles to guide the selection of a more appropriate percentile (60th or 70th AFs) at frequencies other than the fundamental.

The seismic response estimated using empirical data from downhole vertical arrays shows consistency with results and trends obtained from the numerical investigation. To evaluate the overall benefit of using a higher percentile, mean residuals for the median, the 70th, and the 84th percentile 1D AFs are estimated for the numerical investigation considering all the baseline sites for a generic $\sigma_{\ln V_S} = 0.25$ (Figure 11) and for the empirical data (Figure 15). This preliminary statistical evaluation indicates consistency between the numerical and empirical trends (Figure 17). Using percentiles higher than the median seismic response reduces the underpredictions to residuals near zero at the fundamental frequency observed for HYGH10 and IBRH13 in Figure 16, although with site-specific differences as observed in Figures 14 and 15.

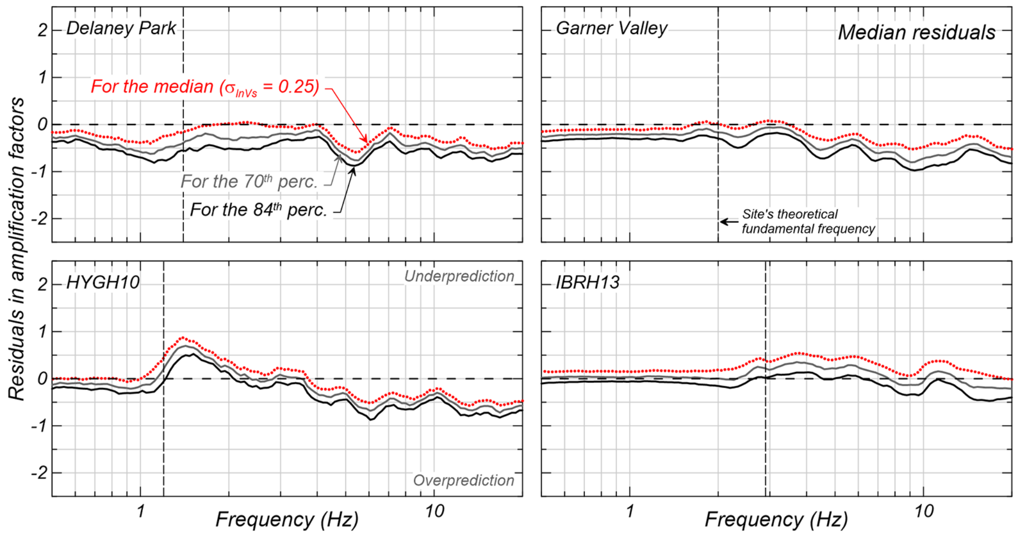

Figure 16. Residuals for various 1D SRA-based amplification factor percentiles. 1D SRAs conducted with V_S randomization using a generic σ_{lnVs} = 0.25. *Note: Site's theoretical fundamental frequency corresponding to the first mode observed in the theoretical transfer function.*

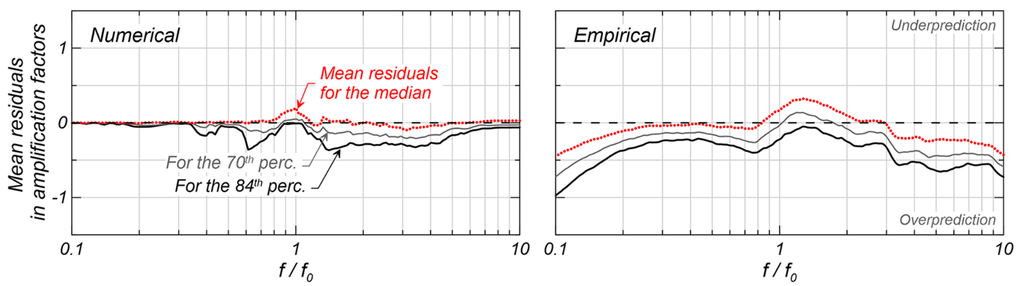

Figure 17. Mean of median residuals in amplification factors for the investigated numerical baseline sites (Figure 11) and the four downhole sites (Figure 16).

Conclusions

One-dimensional site response analyses (1D SRAs) with shear-wave velocity (V_S) randomization are commonly conducted to estimate the median site-specific seismic amplification (or deamplification) under the implicit assumption that this approach leads to a realistic response. The results from the numerical evaluation using 2D SRAs and 1D SRAs with V_S randomization indicate that the latter leads to TFs lower by 30%–50% and AFs lower by 10%–40%, around the sites' fundamental frequency. Meanwhile, the observed underpredictions are either lower or overpredictions at higher frequencies. The inability of 1D SRAs with V_S randomization to capture a more realistic 2D response is mainly due to the combined effects of (1) the shifting of the individual 1D responses' fundamental modes that lead to the coincidence of peaks and troughs at common frequencies that cancel each other out when the median seismic response is estimated, and (2) the intrinsic limitations of 1D SRAs to capture the amplification effects other than those caused by impedance changes and resonance (e.g. constructive interference). Results from this numerical evaluation do not support the use of median AFs from 1D SRAs with V_S randomization for the design of structures.

AFs estimated using 1D SRAs with V_S randomization ($\sigma_{\ln Vs} = 0.25$) and percentiles higher than the median capture well the median 2D AFs that account for the effect of V_S spatial variability, at the fundamental frequency. Results from the numerical evaluation suggest that in most cases, $\sigma_{\ln Vs} = 0.25$ for V_S randomization has a similar or superior performance in preventing underpredictions using model-specific $\sigma_{\ln Vs}$ computed from the 2D random fields for capturing 2D V_S spatial variability effects. The percentile 84th AF is an appropriate estimate at the fundamental frequency, the 70th percentile AF is a better alternative at higher frequencies for sites with slightly to moderately variable V_S ($\sigma_{\ln Vs}$ lower than 0.3), and the 60th percentile AF for highly variable sites ($\sigma_{\ln Vs}$ higher than 0.3). These findings are supported by a numerical evaluation using linear elastic 2D and 1D SRAs on sites with spatially variable V_S across multiple site conditions, and an initial analysis using empirical data from four downhole vertical arrays. The trends are consistent in numerical results across different site conditions, but three behaviors are observed for the performance of higher percentiles from 1D SRAs in the empirical evaluation, ranging from consistent overprediction of AFs to consistent underprediction, or a mixture of both. It is expected that avoiding overpredictions from the 84th percentile AFs would require conducting 2D or 3D SRAs with appropriate V_S models.

Results from this study also show that $\sigma_{\ln Vs}$, used for V_S randomization, has a different impact on 2D and 1D SRAs. In 2D SRAs, a higher $\sigma_{\ln Vs}$ leads to mild variations of the median seismic response (TFs and AFs) amplitudes and a moderate increase in the response variability. In 1D SRAs with V_S randomization, a higher $\sigma_{\ln Vs}$ leads to a significant decrease in the median seismic response amplitudes and a significant increase in the response variability across frequencies. At the same time, $\sigma_{\ln Vs}$ has a strong impact on TFs than it has on AFs. Due to these effects, conducting V_S randomization with site-specific $\sigma_{\ln Vs}$ does not necessarily lead to a more appropriate median seismic response, particularly for sites with highly variable V_S ($\sigma_{\ln Vs}$ higher than 0.3). Nevertheless, using measured V_S profiles in site-specific SRAs is critical, and knowing the site-specific $\sigma_{\ln Vs}$ can guide the selection of a representative seismic response percentile at frequencies other than the fundamental. The measurement of site-specific V_S profiles is encouraged.

This study focused on the estimation of a median seismic response that captures 2D V_S spatial variability effects. Linear elastic 2D SRAs were conducted on correlated V_S random fields with $\sigma_{\ln Vs}$ values from 0.16 to 0.48, and 1D SRAs on randomized V_S profiles developed using the model proposed by Toro (1995) for V_S randomization only. Empirical data from sites classified as A using the taxonomy proposed by Tao and Rathje (2020) were compared against the results from SRAs conducted using damping ratios estimated based on quality factors and V_S values (Joyner and Boore, 1988; Olsen et al., 2003). Findings from this work are subject to the above considerations and have not been tested against other conditions, such as sites inferred to be exposed to non-1D effects and complex geology. Further investigations are deemed necessary to investigate the effects of additional 2D features affecting the seismic response, the soil's nonlinearity, among others. Similarly, a comprehensive statistical evaluation of the residuals associated with the seismic response estimated as a percentile higher than the median from 1D SRAs with V_S randomization should be conducted.

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