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Authors

Pinilla-Ramos, Camilo I

Dreger, Douglas S

Pitarka, Arben

et al.

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Analysis of the Azimuthal Dependency of HVSR in Complex 3D Velocity Structures Using Numerical Modeling

Camilo I. Pinilla-Ramos^{*1}, Douglas S. Dreger², Arben Pitarka³, Norman A. Abrahamson⁴, Robert E. Kayen⁴, and Pablo Castellanos-Nash⁵

ABSTRACT

Using a numerical modeling scheme, we evaluate the azimuthal source-to-site dependence of the horizontal-to-vertical spectral ratio (HVSR) by comparing wavefields propagated through a horizontally layered velocity structure and more complex velocity structures. We choose the best combination of the radial, tangential, and vertical source components to model the ambient noise's seismic source that better explains the observations on a test site. We adopt this derived source configuration to generate simulated wavefields propagated in a horizontally layered velocity model (1D) and a canonical 3D velocity structure and then compute their HVSR spectra. Our simulations use four distinct source locations, each providing a different source–receiver azimuth, to evaluate how variations in wave propagation from these configurations influence HVSR spectra. We extend the analysis to two additional velocity models by introducing stochastic perturbations to the deterministic 1D and 3D velocity structures. We find that the source configuration strongly affects the HVSR amplitude across all analyzed velocity structures. The results suggest that the spectral shape of HVSR tends to be stable along all azimuths in sites placed over velocity structures in which a horizontally layered velocity model can be assumed. Conversely, sites located over 3D velocity structures may exhibit strong azimuth-dependent spectral shapes in HVSR if the wavefield is governed by unidirectional wave fronts, even in some cases making the predominant frequency dependent on the source-to-site azimuth. We propose a methodology based on 2D seismic array analysis and wavenumber-domain filtering to identify HVSR spectral-shape fluctuations as a function of azimuth. We discuss our findings and implications in constraining site terms in ground-motion modeling.

KEY POINTS

- Three-dimensional velocity structures can induce strong spectral shape changes of horizontal-to-vertical spectral ratio (HVSR) depending on the source-site azimuth.
- HVSR spectral shape tends to be azimuthally independent on sites where the 1D velocity model assumption is valid.
- Two-dimensional seismic arrays are foundational to understand a complete description of the HVSR spectrum of ambient noise.

Supplemental Material

INTRODUCTION

Ambient noise analysis can provide insights into fundamental questions regarding Earth's structure, its impulsive response, and how Earth's crust interacts with wavefields induced by earthquakes (Aki, 1957; Frankel *et al.*, 2001; Dolenc and Dreger, 2005; Nayak *et al.*, 2017; Perron *et al.*, 2018;

Vantassel *et al.*, 2024). This has motivated the exploration of the Earth using ambient noise, leading to several advances in recent decades. Of particular importance to this study is the use of the horizontal-to-vertical spectral ratio (HVSR) from ambient noise as a site amplification predictor (Nakamura, 2019), popularized at the end of the 1980s (Nakamura, 1989). HVSR has been adopted for seismic site classification

1. GFZ, Helmholtz-Zentrum für Geoforschung, Potsdam, Germany, <https://orcid.org/0000-0002-4034-6618> (CIP); 2. Department of Earth and Planetary Science, Berkeley, California, U.S.A., <https://orcid.org/0000-0002-6590-3089> (DSD); 3. Lawrence Livermore National Laboratory, Livermore, California, U.S.A., <https://orcid.org/0000-0001-6026-8859> (AP); 4. Department of Civil Engineering, University of California, Berkeley, California, U.S.A., <https://orcid.org/0000-0001-7900-6023> (NAA); <https://orcid.org/0000-0002-0356-072X> (REK); 5. Alten NL, Capelle aan den IJssel, Netherlands, <https://orcid.org/0000-0002-8585-8035> (PC)

*Corresponding author: camilo.pinilla@berkeley.edu

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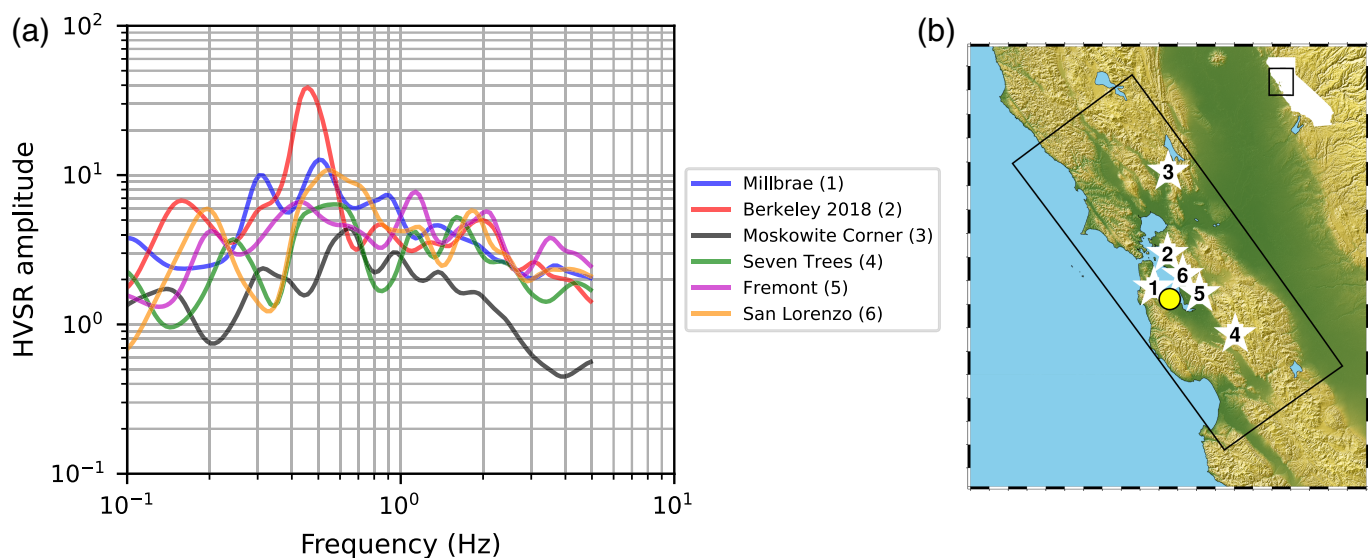
and site-effect evaluations worldwide (Lachet *et al.*, 1996; Standards New Zealand, 2004; Bonnefoy-Claudet *et al.*, 2006; Haghshenas *et al.*, 2008; Pitilakis *et al.*, 2018) and for estimating the site amplification for the horizontal component and the shear-wave (S wave) velocity profile (Arai and Tokimatsu, 2004; Kawase *et al.*, 2011, 2018; Teague *et al.*, 2018; Hallal *et al.*, 2022). Molnar *et al.* (2022) provided a state-of-the-art summary of the use of HVSR for site classification and characterization of site effects. In particular, HVSR has widely been used to identify the predominant frequency (i.e., the frequency with the largest amplitude) of sites with strong resonances (Satoh *et al.*, 2001; Rodriguez and Midorikawa, 2003; Cultrera *et al.*, 2014; Hassani *et al.*, 2019; Kawase *et al.*, 2019). Using the HVSR amplitude as a site amplification predictor is another alternative implementation (Senna *et al.*, 2008; Ghofrani *et al.*, 2013; Kawase *et al.*, 2018). For instance, HVSR amplitude has been used to model site terms in ground-motion models (GMMs) in California (Pinilla-Ramos *et al.*, 2022) and South America (Pinilla-Ramos *et al.*, 2024), adopting ergodic GMMs as backbones (Abrahamson *et al.*, 2014; Abrahamson and Gulerce, 2022). The HVSR amplitude from ambient noise was shown to explain up to 54% of the systematic site-amplification patterns at low frequencies in California using the Next Generation Attenuation-West2 Project dataset (Pinilla-Ramos *et al.*, 2022). This 54% prediction power is comparable with the maximum variance explained by V_{S30} for site terms in California, a region where V_{S30} is among the best predictors of local amplification globally (Pinilla-Ramos *et al.*, 2024). Using the amplitude has the advantage that it does not require identification of the predominant frequency, which can be difficult to determine for sites without clear peaks in their HVSR spectrum.

The wavefield observed by a seismometer contains the impulsive response of a full 3D velocity structure. Whereas some sites can be modeled reasonably well with a horizontally layered velocity model (1D), others require accurate complex velocity models (3D) to avoid misrepresenting the effects of the actual geologic structures (Thompson *et al.*, 2009, 2012; Pilz and Cotton, 2019; Pilz *et al.*, 2022). The fundamentals of HVSR can be directly explained by Green's functions between the source and the site, making the dependence on the 3D structure evident. Previous works have pointed to the impact of lateral heterogeneities (i.e., 3D geologic structures) in the velocity model in the HVSR spectrum (Matsushima *et al.*, 2014, 2017; Sánchez-Sesma, 2017; Sgatonni and Castellaro, 2020; Sánchez-Sesma *et al.*, 2023); however, the current state of 3D community velocity models is not detailed enough for this purpose, especially for modeling vertical components of waveforms at relatively high frequencies (Pinilla-Ramos *et al.*, 2025), hindering the effort of properly modeling HVSR. Consequently, with the current state of the art, HVSR from ambient noise can be used as a proxy to understand site-amplification patterns and the Earth's structure, given that HVSR

provides implicit information about the crust's local and regional impulsive response.

Sánchez-Sesma *et al.* (2011), assuming a diffuse field (Weaver, 1982, 1985; Lobkis and Weaver, 2001; Sánchez-Sesma and Campillo, 2006), developed a comprehensive approach to model HVSR, deriving an analytic solution to the elastodynamic wave equation, allowing for the computation of HVSR. A diffuse field assumes that the wavefield is in a steady-state regime, losing all information about the source location and depending only on the propagation medium, leading to an equipartition of energy (Weaver, 1982, 1985). This implies that the seismic energy arrives at the site from all azimuths with equal likelihood, without directional bias. Some studies have pointed out that the ambient noise wavefield exhibits directional propagation (Frankel *et al.*, 2001; Schulte-Pelkum *et al.*, 2004; Dolenc and Dreger, 2005; Nayak *et al.*, 2017), as evidenced by azimuthal dependencies in its amplitude. This can be interpreted in terms of how different geologic structures have different resonant modes, which can be excited differently, depending on the directionality of the wavefield entering the basin or the source location within the basin (Castellaro and Musinu, 2022). Thus, if the ambient noise wavefield exhibits directionalities with higher energy, it can illuminate local geologic structures with an azimuthal bias, thereby breaking the assumption of energy equipartition across the different phases of the wavefield. This may imply that, depending on the analyzed site, its underlying geologic structure and frequency band, ambient noise may exhibit a mix of diffuse-like and azimuthally dependent features that govern spectral amplitudes.

To illustrate the impact of azimuthal dependence on the HVSR spectrum, we present an example. We select a seismic station located over a complex geologic structure within the San Francisco Bay Area, California. We analyzed HVSR from the coda of six small local earthquakes recorded at a seismic station in Northern California, each from a different azimuth. The coda is usually assumed to represent the wavefield after a whole process of scattering that tends toward a diffuse regime, losing any signature of the source nature and depending more on the velocity structure. We window 30 s after 98.5% of the total accumulated energy, following a similar methodology to estimate duration from acceleration waveforms, such as the parameter D_{5-95} (e.g., Pinilla-Ramos *et al.*, 2023). We compute the HVSR spectrum for this coda window of 30 s length from six earthquakes using the procedure explained later, the waveforms of which are shown in Figure S1, available in the supplemental material to this article, and the HVSR in Figure 1. The wide azimuthal sampling and location of each earthquake with respect to the test site are displayed in the map of Figure 1. Cross sections showing the complexities of the velocity structures in the San Francisco Bay Area are shown in Figure S2. By comparing the station location with respect to the cross-section C–C, we can state that this station is a case of a site placed over a complex geologic structure, and the coda wavefield exhibits a



clear azimuthal dependency. This example illustrates how the azimuthal dependency of the incoming waves can significantly impact HVSR. This may be evidence that, in complex velocity structures, if the amplitude of the ambient noise wavefield is governed by clear propagation patterns from given sources and azimuths, this directionality may condition the observed HVSR spectrum.

Acknowledging that multiple sources generate the ambient noise, this study assesses cases in which wavefronts from specific azimuths govern the wavefield. Because of wave attenuation, the contribution to the wavefield from a given source will depend not only on its amplitude but also on its relative location to the receivers, as the wave amplitude decays according to power laws (with theoretical exponents in half-spaces of -1 for body waves and -0.5 for surface waves for geometrical attenuation). These instances can lead to frequency bands in which the Fourier amplitudes are dominated by a few sources (or azimuths) rather than a fully diffuse field. Therefore, we investigate how a single source, or a specific propagation direction, interacts with complex geological structures, and assess the effects on HVSR spectra. We first develop a realistic source model to simulate HVSR spectra consistent with those observed in ambient noise recorded at a test site in the San Francisco Bay Area, California, using a horizontally layered (1D) velocity model for the inversion. We numerically compute Green's functions using a finite-difference scheme. The source model is constructed by combining these Green's functions as the source's Cartesian components, and then extracting the displacement field that best reproduces the observed HVSR spectrum test site. This source model is then applied to the 1D velocity model and a more complex velocity structure (3D velocity model) by including a canonical basin in the 1D velocity model. We compute HVSR spectra from waveforms simulated in both velocity models, and evaluate the impact of 3D wave-propagation regimes on HVSR spectra

Figure 1. (a) Example of the azimuthal dependency on horizontal-to-vertical spectral ratio (HVSR) spectra extracted from the coda of six small earthquakes that occurred in the San Francisco Bay Area. The station adopted, J037, is placed over a complex geologic structure. (b) The map shows the epicenter locations (stars), and the station is the yellow circle. The legend in the middle indicates the names of the earthquakes shown on the map with a corresponding number. The rectangle shows the limits of the cross-sections shown in Figure S2. The color version of this figure is available only in the electronic edition.

by examining their azimuthal stability. We include two additional velocity models in our analysis by adding stochastic fluctuations to the 1D and 3D deterministic velocity models. Finally, we propose a wavenumber-domain filtering method to assess the azimuthal stability of the HVSR spectra. This methodology enables the identification of sites for which observed HVSR spectral shapes are azimuth independent, and instances in which HVSR spectra exhibit strong azimuthal dependencies, aiming for a better interpretation of HVSR.

DEVELOPMENT OF A SOURCE MODEL

In this section, we developed a suitable source model consistent with the observations at a test site in the San Francisco Bay Area, California, assuming a 1D isotropic, horizontally layered medium.

Framework for source modeling

Let us consider a source characterized by a force with Cartesian components f_1, f_2 , and f_3 . We can express the displacement field induced by that source located at $\vec{x}_s$ in the receiver located at $\vec{x}_r$ as

$$u_i(\vec{x}_r) = \sum_p^{n=3} G_{ip}(\vec{x}_s, \vec{x}_r) f_p(\vec{x}_s), \quad (1)$$

in which $G_{ip}(\vec{x}_s, \vec{x}_r)$ is the Green's function tensor defined as the impulsive response of the velocity structure at receiver

component “ i ” from a source with a unit force applied in the “ p ” direction. If θ is the azimuth between a source–receiver pair, we can express the displacement as

$$\begin{aligned} u_r(\vec{x}_r) &= (f_1 \cos(\theta) + f_2 \sin(\theta)) \cdot G_{RH}(\vec{x}_s, \vec{x}_r) + f_3 \cdot G_{RV}(\vec{x}_s, \vec{x}_r), \\ u_\phi(\vec{x}_r) &= (f_1 \sin(\theta) - f_2 \cos(\theta)) \cdot G_{TH}(\vec{x}_s, \vec{x}_r), \\ u_z(\vec{x}_r) &= (f_1 \cos(\theta) + f_2 \sin(\theta)) \cdot G_{ZH}(\vec{x}_s, \vec{x}_r) + f_3 \cdot G_{ZV}(\vec{x}_s, \vec{x}_r), \end{aligned} \quad (2)$$

in which u_r , u_ϕ , and u_z are the receiver’s radial, tangential, and vertical displacement components; $G_{RH}(\vec{x}_s, \vec{x}_r)$, $G_{RV}(\vec{x}_s, \vec{x}_r)$, $G_{TH}(\vec{x}_s, \vec{x}_r)$, $G_{ZH}(\vec{x}_s, \vec{x}_r)$, and $G_{ZV}(\vec{x}_s, \vec{x}_r)$ are the Green’s tensor components; R, T, and Z refer to the receiver’s radial, tangential, and vertical components, and H and V are the source horizontal and vertical components, respectively. u_ϕ does not depend on f_3 because there is no energy transfer and conversion between SH waves and SV waves or P waves in an isotropically and horizontally layered medium.

The HVSr spectrum can be expressed as

$$\text{HVSr}(\vec{x}_r, f) = \frac{\sqrt{u_r(\vec{x}_r, f)^2 + u_\phi(\vec{x}_r, f)^2}}{u_z(\vec{x}_r, f)}, \quad (3)$$

in which “ f ” is the angular frequency. Conceptually, if we knew the sources’ locations, their source time function, times, Cartesian decompositions, and the impulse responses between the sources and the receiver, the HVSr could be computed directly. However, due to the practical complexities of estimating these source and wave-propagation features, the ambient noise wavefield is modeled as a random variable to reflect the current state of knowledge.

Modeling HVSr at a test site

We apply this framework to the seismic station located at Richmond Field Station (RFS) in California to compute Green’s functions and the HVSr spectrum. For the geophysical characterization, we adopt a velocity model based on a down-hole test performed by Johnson and Silva (1981) at RFS, who evaluated the dynamic properties in depth through a borehole of 35 m. We adopt the Gil7 velocity model (Dreger and Romanowicz, 1994) up to a depth of 6.5 km to complement the borehole data. Figure 2 presents the wave propagation velocity profile adopted for the analysis.

To validate our velocity model, we deployed a triangular-shaped seismic array consisting of seven 20 s period Trillium Compact triaxial seismometers with a maximum aperture of 100 m. Ambient noise was recorded for one hour. We compute the experimental dispersion curve of the fundamental mode of Rayleigh waves using the code Geopsy (Wathelet et al., 2020). The comparison between the experimental curve obtained from the array analysis and the theoretical result from the adopted 1D velocity model is shown in Figure 3 (black and red lines,

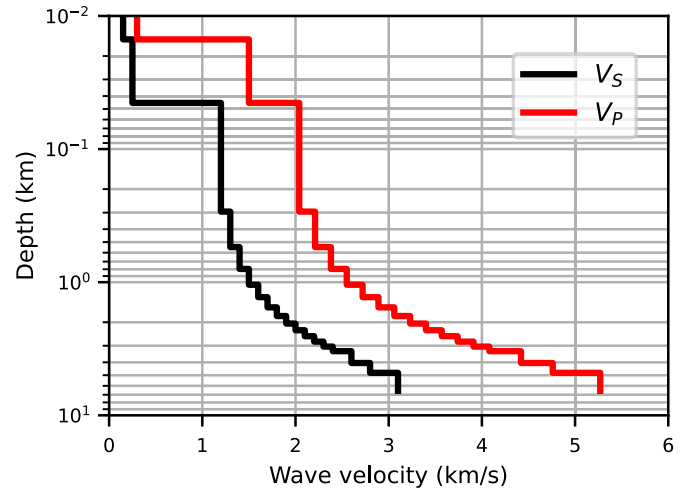


Figure 2. Velocity model adopted to estimate the source configuration. The color version of this figure is available only in the electronic edition.

respectively). The high-frequency range of the Rayleigh dispersion curve was obtained from a multichannel analysis of surface waves test in a linear array with 3 m separation deployed to characterize the soft sediments near the surface at RFS, and its dispersion curve is shown in the supplemental material (Fig. S3). By comparing the experimental and theoretical dispersion curves, we conclude that our adopted velocity model is consistent with the actual velocity structure, at least up to 2 Hz. Below this frequency, we adopt the Gil7 velocity model, the near-surface materials for which are consistent with the borehole’s deepest materials, thereby producing a smooth transition between the two velocity models.

We compute the Green’s functions from equation (2) numerically, using the program Seismic Wave 4 (SW4), which solves the elastodynamic wave equation with an anelastic linear constitutive model through a finite-difference scheme with fourth-order accuracy in time and space (Petersson and Sjögreen, 2012; Petersson and Sjögreen, 2012, 2015). We perform the simulations in a volume with dimensions of 29 km in length, 15 km in width, and 6.5 km in depth. We keep 3 km at each edge as absorbing boundary elements, except at the free surface. We use hexahedral cubic elements with a size of 100 m at the bottom of the model, applying three mesh refinements toward the surface, where the elements have a size of 12.5 m. Given that 30 absorbing boundary elements of 100 m occupy the bottom of our domain, the effective usable depth is reduced to 3.5 km.

We adopt for this numerical scheme a linear array of 40 receivers at the surface and one source aligned with the array, as shown in Figure S4 (the other sources [red stars] are used in the next section). Under this formulation, HVSr amplitude depends on the Cartesian components of the source (equation 1). To generate different source realizations, we combine the three Cartesian components of the source by making a grid

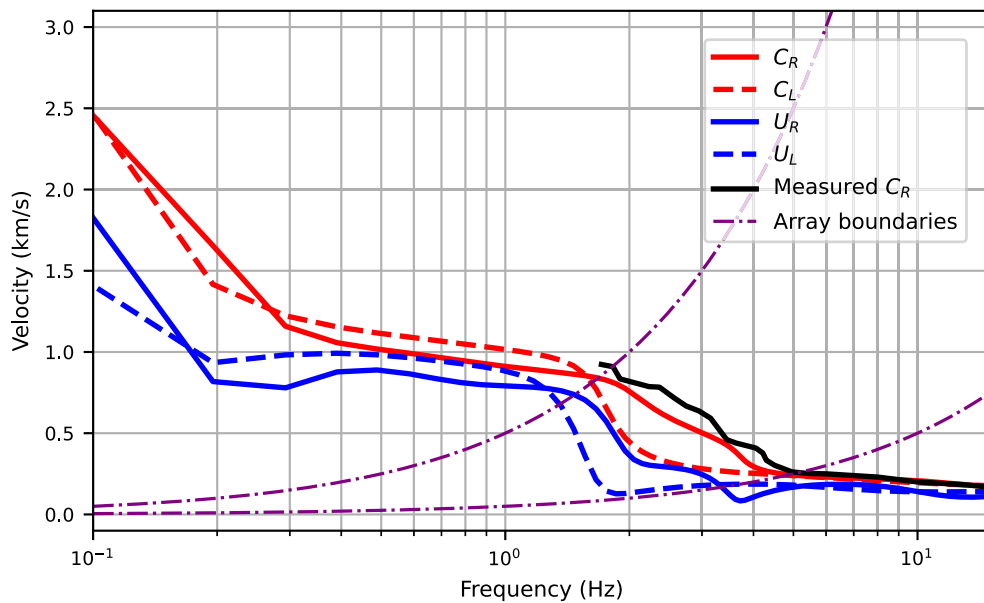


Figure 3. Dispersion curves for the phase and group velocity for the fundamental mode of Love and Rayleigh waves using our 1D velocity model (see Fig. 2). The black line shows the observed dispersion curve for the fundamental mode of the Rayleigh wave, extended beyond the high-frequency boundary using information from a linear array analysis. The purple dashed lines represent the array visibility constrained by its dimensions. C_R and C_L are the phase velocities for the fundamental mode of the Rayleigh and Love waves, respectively, and U_R and U_L are their group velocities. The color version of this figure is available only in the electronic edition.

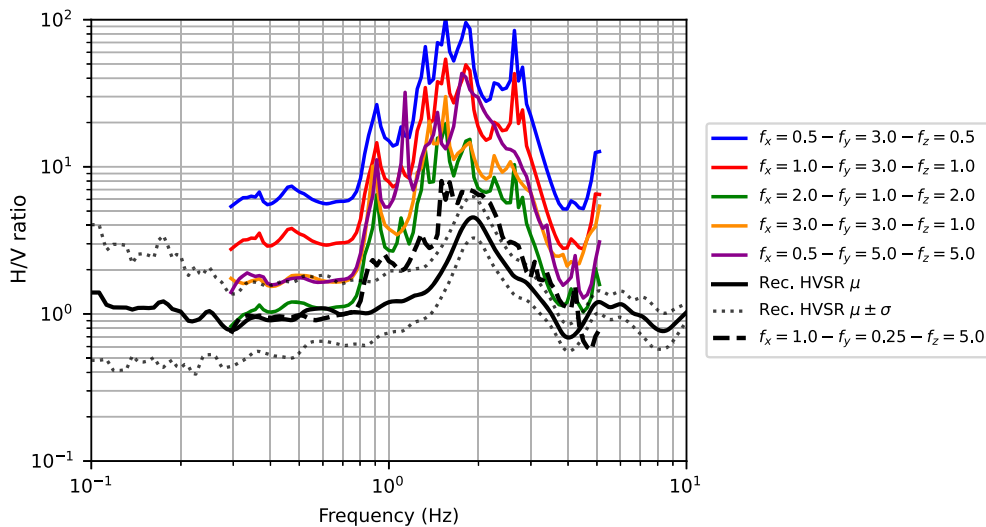


Figure 4. HVSR amplitude as a function of several combinations of radial, tangential, and vertical force components. The radial component is fixed at an amplitude of 1, and the other two components are varied between 0.25 and 5. The black lines represent the recorded HVSR spectrum median plus and minus one standard deviation. The black dashed line shows the HVSR spectrum that more closely matches the observed predominant frequency. The color version of this figure is available only in the electronic edition.

search of f_r , f_θ , and f_z . As the receivers are aligned with the point source, the cylindrical coordinates of the source components are also aligned with our Cartesian system f_x , f_y , and f_z , respectively. The Cartesian components are sampled from

amplitudes from 0.25 to 5. We adopt a methodology similar to that of Bonnefoy-Claudet *et al.* (2006) to evaluate HVSR for the 1D velocity model by computing the mean HVSR spectrum across 40 receivers. Examples of the resulting HVSR spectra obtained by averaging the 40 HVSR from each source configuration are displayed in Figure 4, showing a strong sensitivity to the components of the source. We retain only frequencies above 0.3 Hz, corresponding to wavelengths that our mesh can properly resolve. The waveform processing methodology is described in the next section. When the vertical component governs the source illumination, the HVSR spectra reach smaller amplitudes, and the opposite occurs when the tangential (f_t or f_y) component governs the source radiation. The coupling of the P -SV phases in layered media implies that increases in the radial component (X component) contribute to both the vertical and horizontal components, making the analysis of its contribution to the HVSR spectra more complex. By minimizing the squared error residuals between the observed HVSR spectrum and the different realizations, the source configuration that best explains the observations is the following: $f_r = 1$, $f_\phi = 0.25$, $f_z = 5$ ($f_x = 1$, $f_y = 0.25$, $f_z = 5$), which is shown with dashed lines in Figure 4. The predominant frequency in the numerically computed and observed HVSR spectra is similar, at approximately 1.8 Hz, and there

are differences in HVSR amplitudes at the spectral peak, which is close to one standard deviation from the observations. The shape of the numerically computed HVSR matches the observed HVSR.

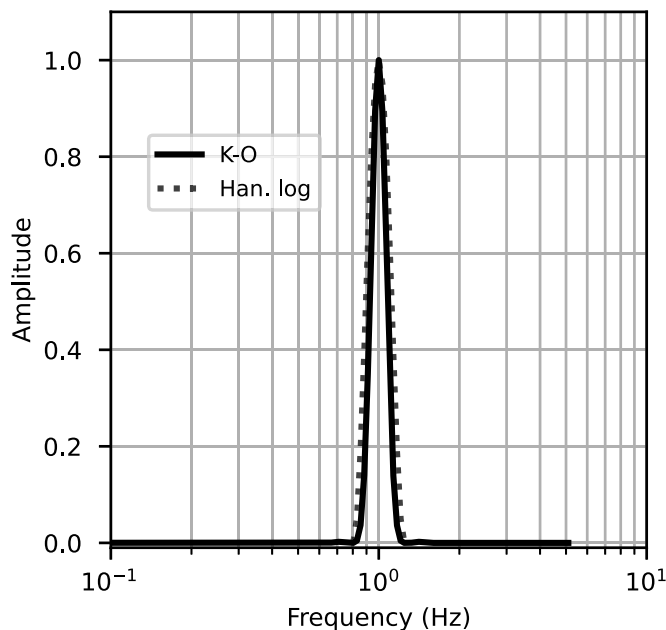


Figure 5. Comparison between the well-known Konno–Ohmachi (K–O) smoothing window (solid line) and our smoothing procedure using a Hanning window sampled on a log scale (Han. log; dotted line).

Waveform processing methodology

An established practice in computing HVSR is to smooth the Fourier amplitudes using a Konno–Ohmachi window (Konno and Ohmachi, 1998). This window provides even smoothing with the same weight across all central frequencies on the log scale. The Konno–Ohmachi filtering requires convolving this window at each analyzed central frequency, which exponentially increases the computational resources required for large datasets. In this study, we adopted a different smoothing scheme consistent with the Konno–Ohmachi filter, which is computationally more efficient. After applying a 2% taper in the time domain, we resample the Fourier amplitude on a log scale, using a frequency vector of 200 samples between 0.01 and 5.1 Hz with a step incremental size of 1.032. We then convolve the resampled Fourier amplitudes with a 15-point Hanning window. The comparison of this smoothing window with the Konno–Ohmachi smoothing window with a “ b ” value of 30 is displayed in Figure 5, which shows very good agreement between them. The advantage of our smoothing methodology is that it preserves smoothing on a logarithmic scale while requiring only resampling of the Fourier amplitude in the logarithmic space and a single convolution. This eliminates the need for repeated convolutions at each central frequency, yielding a significant reduction in computational cost.

NUMERICAL MODELING OF HVSR IN COMPLEX VELOCITY STRUCTURES

In this section, we evaluate the impact of 3D wave propagation on HVSR by comparing HVSR from simulated wavefields

propagated through a 1D and a 3D canonical velocity structure. All velocity models adopted use a volume for the simulations and mesh discretization consistent with the description in the last section: 29 km in length, 15 km in width, and 6.5 km in depth.

Velocity model and simulation setup

The first velocity model represents a horizontally layered structure (1D velocity model), using the same velocity profile as that used to develop the source model (Fig. 2; Fig. S4). The second velocity model represents a 3D canonical velocity structure, with the inclusion of a trapezoidal basin in the Gil7 velocity structure similar to Miah *et al.* (2024). This basin dips at an angle of 30°, reaching a maximum depth of 600 m, beyond which the basin becomes flat. Because SW4’s mesh elements are hexahedral, the slope representation follows a stair-step pattern with a spacing of 12.5 m. The element size in the slope is significantly smaller than the wavelengths associated with the frequencies we are solving. In addition, we do not condition any geometrical features on our analysis. Therefore, we expect that the impact of this geometry will not be significant. The shear-wave velocities for the sediments in the basin follow a strengthening power law with an exponent of 0.25 with $V_S = 200$ m/s at the surface and $V_S = 550$ m/s at 600 m depth. The velocity structure below the basin follows the Gil7 velocity model. The 3D velocity model is presented in Figure 6.

We adopt a Poisson solid relationship (a V_P/V_S ratio of 1.73) for the materials of the GIL7 velocity model and a V_P/V_S ratio of 2.0 for the sedimentary materials, representing a classic granular material relationship. For the anelastic attenuation (Q) model, we adopt a frequency-independent Q using the relations between Q and the shear-wave and compression-wave velocities derived from Kennett (1983): $Q_S = V_S/10$ and $Q_P = 2Q_S$, in which Q_S and Q_P are the attenuation factors for shear waves and compression waves, respectively, and V_S is in meters per second.

To sample the simulated wavefield, we include a line of 40 receivers perpendicular to the basin strike (aligned with the X axis). We select four locations as sources at a distance of about 15 km from the array’s center. We fix the Cartesian source component amplitudes as $f_x = 1.0$, $f_y = 0.25$, and $f_z = 5.0$, with the Y axis oriented toward the strike direction of the basin (as shown in Fig. 6). Two sources are aligned with the receivers, with one source outside the basin and the other in the basin, where the basin’s bottom is flat (see Fig. 6). Another source is chosen perpendicular to the array, based on a projection from the array’s center, to evaluate the interaction of predominantly SH and Love waves with the velocity structures. The fourth source is located obliquely to the array, with an azimuth from the center of the array of approximately 315°, where we expect complex interactions between the SH and SV components of the wavefield and the basin. The Green’s functions for the 3D velocity structure were computed numerically using the

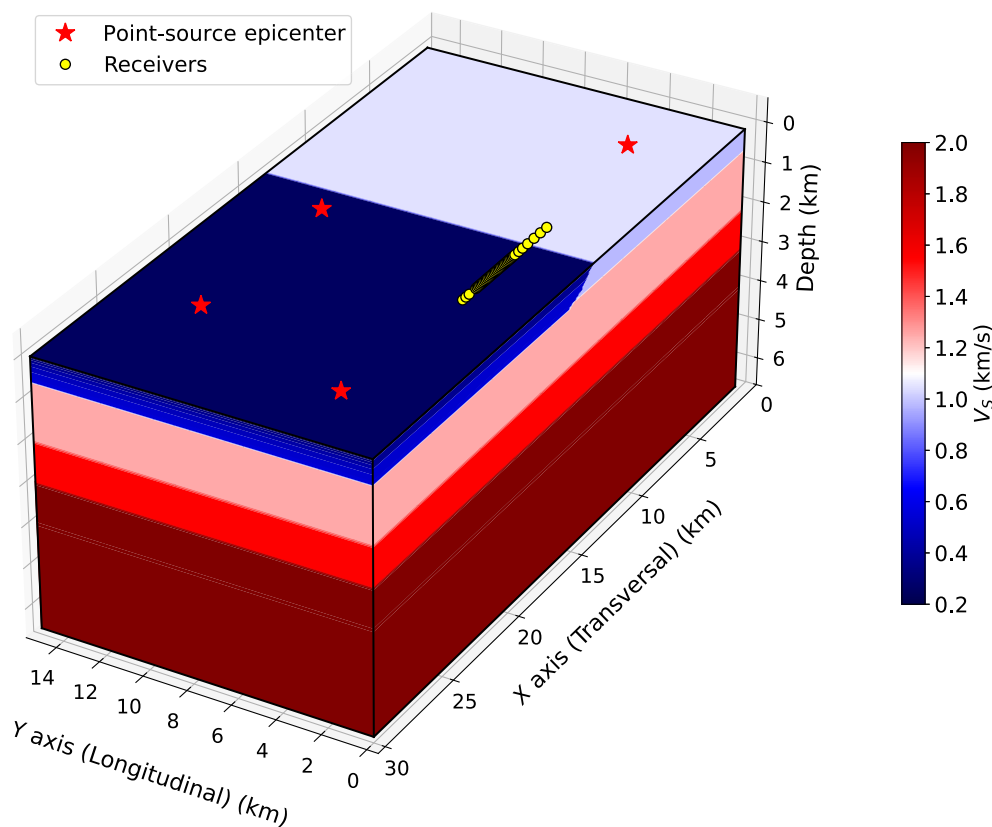


Figure 6. Three-dimensional velocity model adopted for the numerical modeling. The stars represent the source locations, and the circles represent the receivers. The scale of the vertical axis is amplified by a factor of 2. The color version of this figure is available only in the electronic edition.

scheme described earlier and the source parameterization developed in the previous section. As we model Green's functions, we adopt delta functions for the source time function, which provide a flat illumination of the source spectrum across the entire frequency range (see Fig. S5). Then, we multiply each component by the factors found in the previous section, with the resulting wavefield being a linear combination of these components, following equation (1). We decide to use a linear array of receivers to focus the analysis on how differences in receiver locations relative to the basin edge affect HVSr spectra, while maintaining a similar average distance between the receivers and the sources.

In the finite-difference formulation, the numerical solution accumulates discretization errors as it propagates through the computational grid (Petersson and Sjögreen, 2023). By numerically solving Lamb's problem with SW4 and analytically using Mooney's formula (Mooney, 1974), Petersson and Sjögreen (2023) showed how the numerical error increases by decreasing the number of elements per wavelength adopted in the simulation. They recommend adopting several grid points per wavelength (PPWs) ranging from 6 to 10. We adopt six PPWs to achieve sufficient numerical accuracy while maintaining a minimum resolution for all materials within the volume, based on the

number of grid PPWs. In general, most of the elements in our domain satisfy PPWs larger than eight, and our threshold of six PPWs applies to the elements near the surface and inside the basin, characterized by the lowest shear-wave velocities in our volume. Considering this numerical constraint, we can achieve a maximum frequency of at least 3.3 Hz across the entire domain.

HVSr in the 1D velocity structure

As a first step, we analyze the case of the 1D velocity structure. The resulting waveforms at six locations are shown in Figure 7 for the four source locations. The sources aligned with the seismic array produce a similar wave train, dominated by SV and P phases. Because $f_x = 1$ and $f_y = 0.25$, sources perpendicular and oblique to the array excite more SH phases, resulting in wavetrains dominated by a different polari-

zation, making the energy more spread in time. HVSr at the six locations is shown in Figure 8. The HVSr amplitude varies with source location, source-to-receiver distance, and the Cartesian components of the source, indicating that HVSr spectra can be sensitive to source characteristics. In this case, the effect is particularly strong above 0.75 Hz. On average, the spectral shape tends to stabilize into a consistent HVSr pattern, although certain features may vary depending on the source configuration and the distance between the source and the receiver. In some instances, a second predominant frequency manifests at approximately 0.8 Hz. We note that the velocity profile shown in Figure 8a of these figures is limited to the top 1 km, whereas the velocity model used in the simulations extends to 6.5 km.

HVSr in the 3D velocity structure

We numerically computed the Green's functions for the 3D velocity model at the receivers and sources shown in Figure 6. As with the 1D velocity model, the source set used in this model excites different wave types. Longitudinal sources for the linear receiver array mostly induce Rayleigh waves, whereas perpendicular ones tend to produce more Love waves, with the oblique source inducing a mix of both. The normalized waveforms for the four sources at six different stations shown in

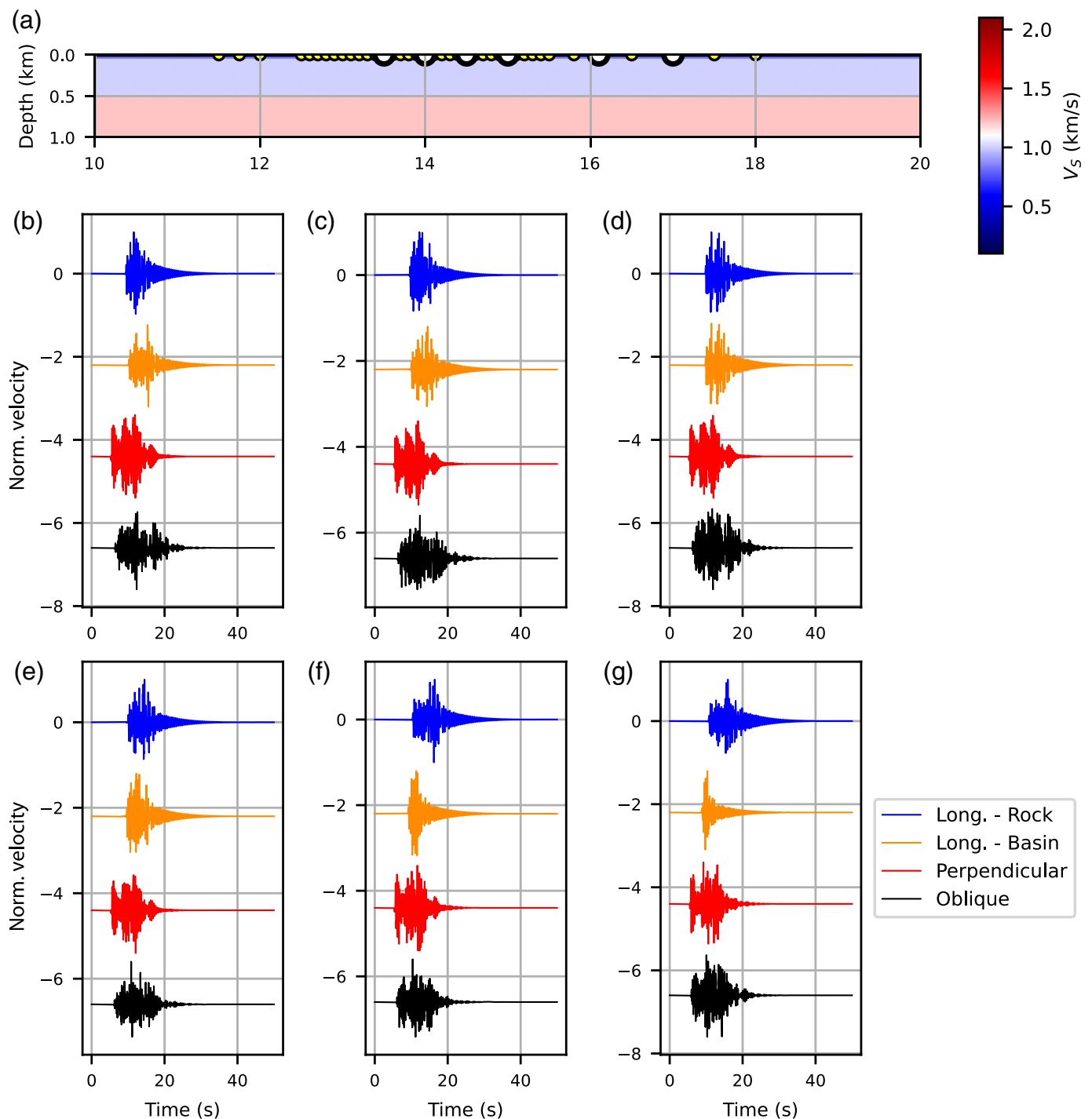
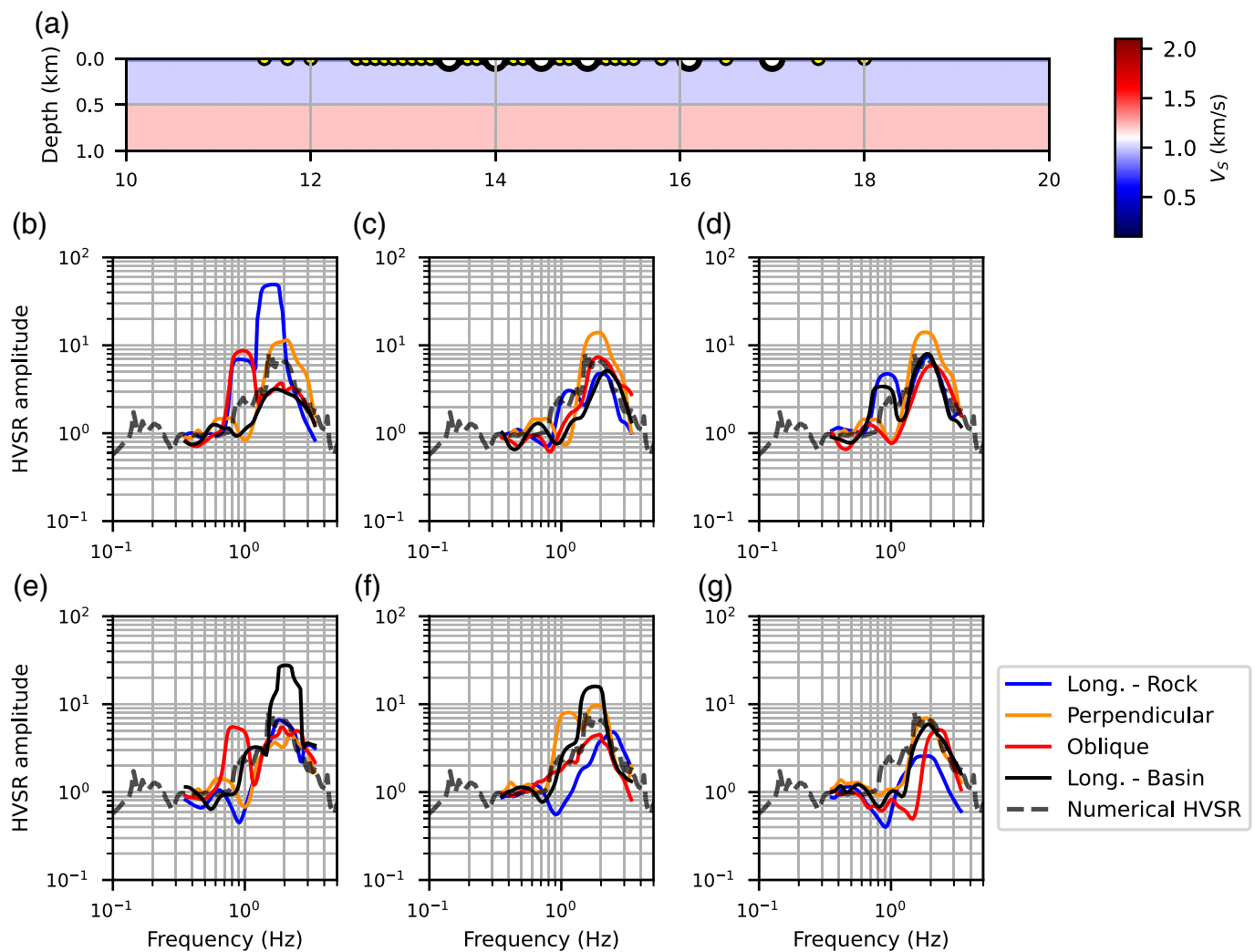


Figure 9 demonstrate how complex the wavefield becomes by including a 3D velocity structure. There are significant differences in impulsive responses across source locations and relative source components, indicating that their variations induce complex phases in the wavefield within this 3D velocity structure. The wavefield from a source located outside the basin propagates mostly through a 1D horizontal and isotropic layered medium before transferring energy to the basin. It generates the simplest waveforms within the basin. In contrast, sources located within the basin transfer energy directly to the basin, thereby enriching the wavefield with more complex phases.

Figure 7. Waveforms obtained from the numerical modeling using the 1D velocity model. (a) The 1D velocity model in the first 1 km depth. The black circles are the locations of the six selected receivers. (b–g) Waveforms at the six stations for the four source locations. The white circles in (a) represent the location of the receivers in (b–g). Panels (b) to (g) show waveforms at different coordinates: 13.5, 14, 14.5, 15, 16.1 and 17 km, respectively. Long. - Rock, source located longitudinal to the receivers' array on the direction outside the basin; Long. - Basin, source located longitudinal to the receivers' array over the direction inside the basin; Perpendicular, source located perpendicular to the linear array; Oblique, source located oblique to the linear array. The yellow dots are the other array's receivers. The color version of this figure is available only in the electronic edition.



These complexities in the wavefield also manifest in HVSR, as shown in Figure 10. The HVSR amplitude and even the predominant frequency, f_p , vary significantly across sources. The changes in HVSR amplitude were also observed in the 1D velocity model; however, in contrast to the 1D model analysis, 3D wave propagation yields HVSR with different spectral shapes for the four source-to-site azimuths considered. In this more complex velocity structure, there is no stable spectral shape at a given station; the spectral shape is strongly azimuthally dependent. Moreover, HVSR in this 3D velocity structure shows similar fluctuations to those obtained from the coda recordings shown in Figure 1, without repeating spectral shapes and exhibiting different predominant frequencies, depending on the source location.

HVSR in a velocity model with stochastic variability

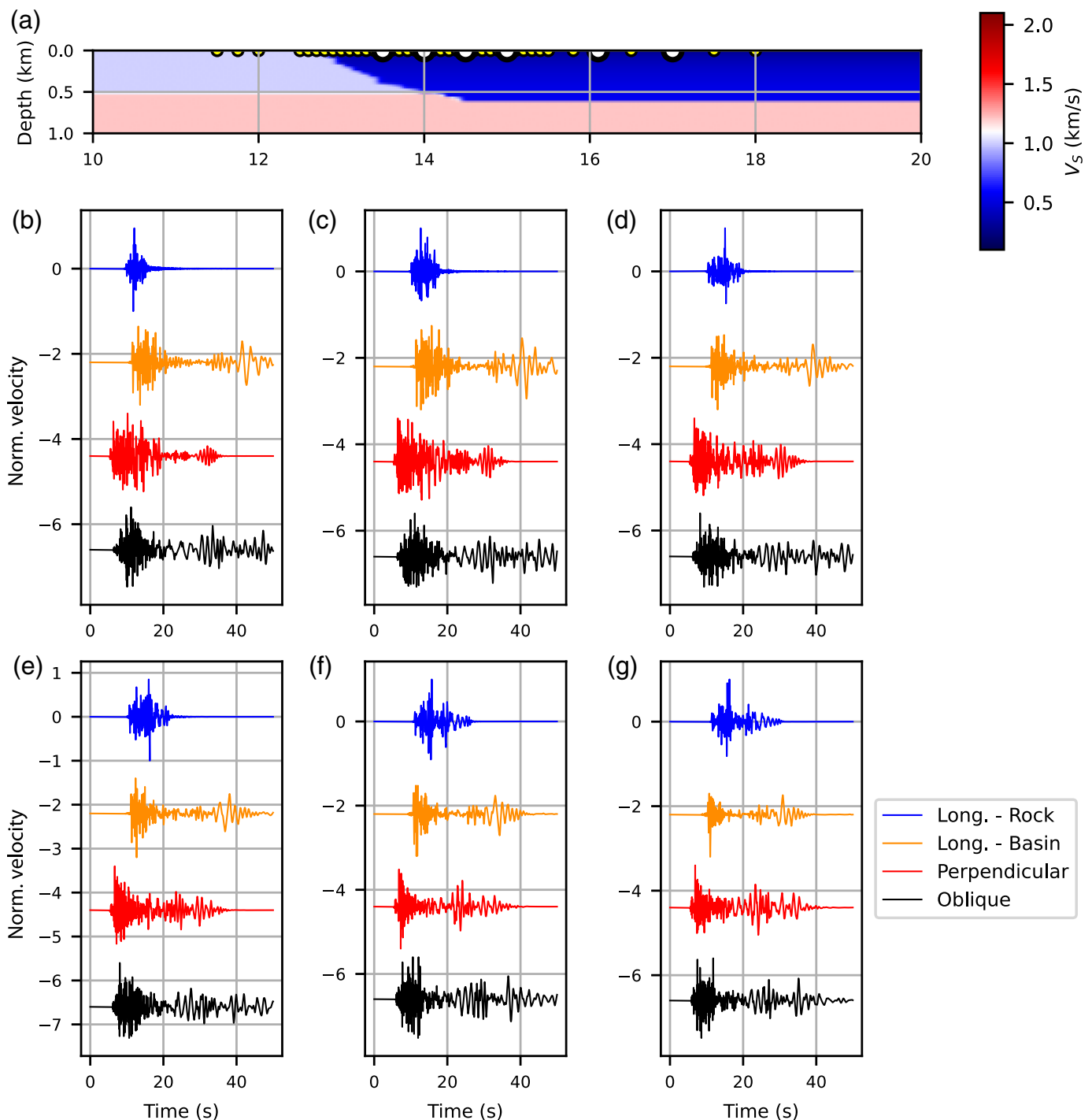
The Earth's crust exhibits spatial fluctuations across scales, reflected in inclusions of small-scale structures that give rise to spatial heterogeneities in material properties. This motivates us to perform the same set of numerical simulations on two additional velocity models that incorporate stochastic variability in the velocity structure. We adopt a correlation structure for stochastic fluctuations based on a Von Kármán spectral

Figure 8. HVSR spectra obtained from the numerical modeling using the 1D velocity model. (a) The 1D velocity model in the first 1 km depth. The black circles are the locations of the six selected receivers. (b–g) HVSR spectra at each station for the four sources. The white circles in (a) represent the location of the receivers in (b–g). Panels (b) to (g) show waveforms at different coordinates: 13.5, 14, 14.5, 15, 16.1 and 17 km, respectively. The dashed lines are the HVSR spectra that more closely match the observed predominant frequency. The yellow dots are the other array's receivers. The color version of this figure is available only in the electronic edition.

distribution (Wilcox, 1962), as this autocorrelation function is a suitable alternative to model spatial fluctuations of the Earth's crust properties (Frankel and Clayton, 1986). The probability density function of a Von Kármán distribution for a 3D distribution is proportional to

$$P(k) \propto \sigma^2 \left(\frac{1}{1 + a^2 k^2} \right)^{3/2 + H}, \quad (4)$$

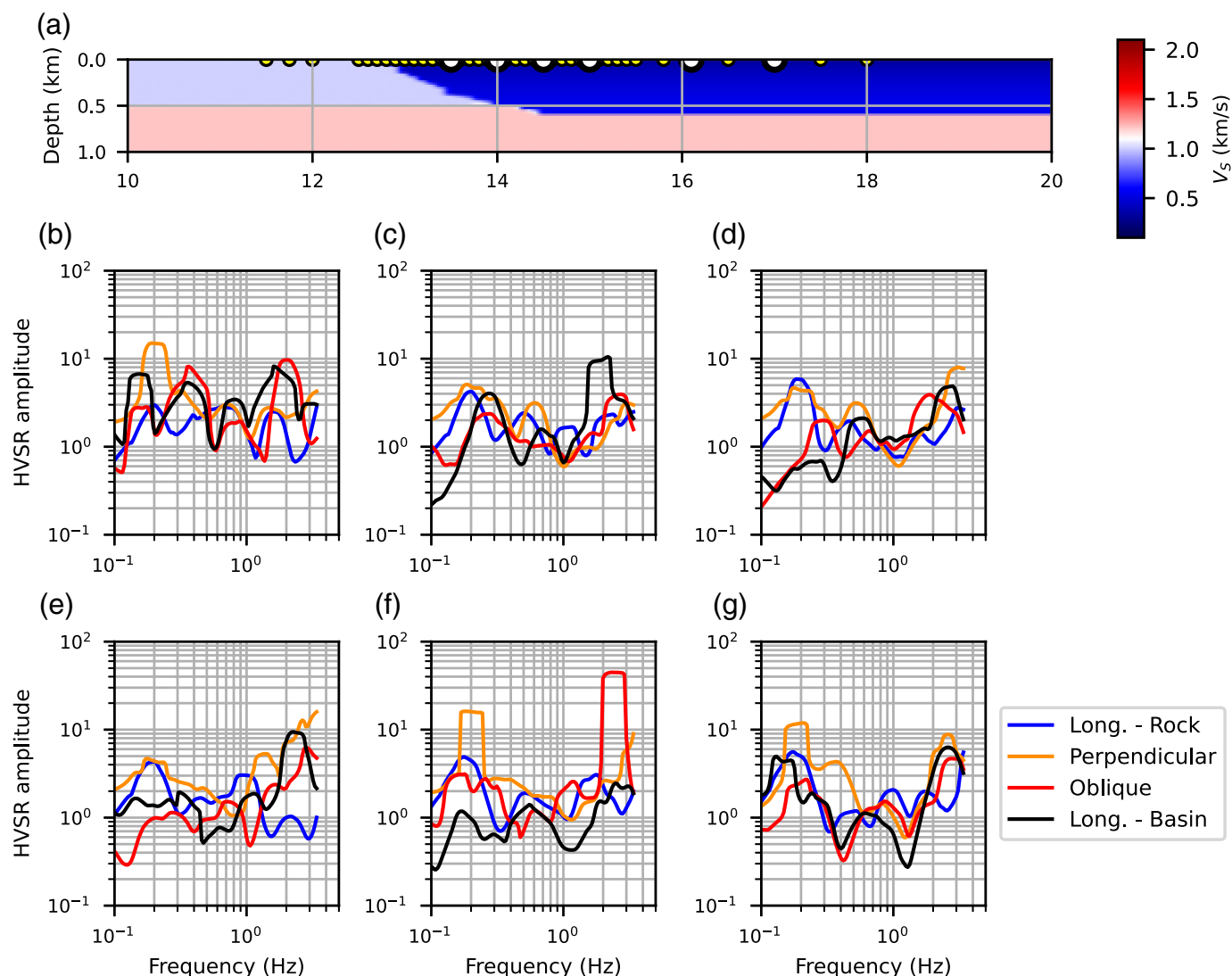
in which H is the Hurst exponent, σ is the standard deviation, and a is the correlation length. The standard deviation modulates the magnitude of the fluctuations, whereas the correlation



length controls the extent of their spatial influence. In seismological applications at wavelengths of several kilometers, some studies have reported that the σ values between 0.05 and 0.1 and correlation lengths of 1000 m fit the spatial coherence decay in recorded data (Savran and Olsen, 2019; Pitarka and Mellors, 2021). At a smaller scale, Abrahamson *et al.* (2022) modeled the spatial coherence decay of the vertical component of waveforms using seismological simulations with stochastic fluctuations and compared with data from seismic arrays of a few hundred meters. Using their data, an ergodic approximation of the fluctuations at this scale can be parameterized with a standard

Figure 9. Waveforms obtained from the numerical modeling using the 3D velocity model. (a) Cross-section of the deterministic 3D velocity model in the first 1 km depth. (b–g) Waveforms at the six stations for the four source locations. The white circles in (a) represent the location of the receivers in (b–g). Panels (b) to (g) show waveforms at different coordinates: 13.5, 14, 14.5, 15, 16.1 and 17 km, respectively. The yellow dots are the other array's receivers. The color version of this figure is available only in the electronic edition.

deviation of 0.1–0.2 and a correlation length ranging from 50 to 200 m. These two approaches are based on different scales. We seek a random perturbation field that spans a range of

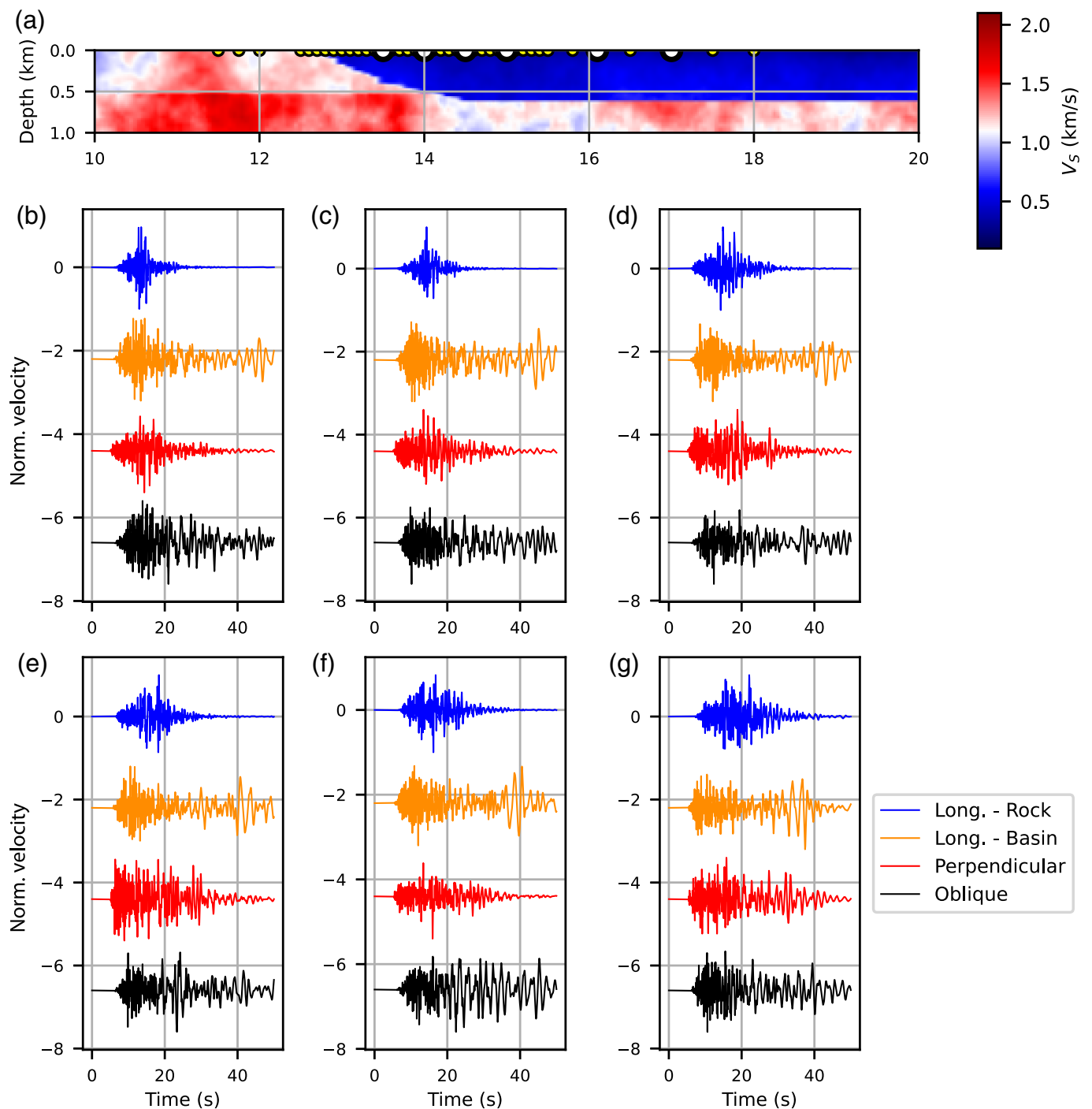


wavelengths to emulate the inclusion of substructures and local perturbations. We adopted a σ of 0.15, representing small-scale fluctuations, and vertical- and horizontal-correlation lengths of 1000 m. The Hurst exponent was set to 0.5, corresponding to an exponential distribution, which is within the range reported by other researchers (Savran and Olsen, 2019; Pitarka and Mellors, 2021). Because of the velocity contrast between the basin and the basement materials, these stochastic perturbations primarily influence the velocity properties of the basement.

We perform numerical simulations that account for stochastic fluctuations in the velocity structure. We keep the random number seed generator constant throughout the computation of the components of the Green's functions. The impact of stochastic fluctuations in the wavefield is shown in Figure 11 for the 3D velocity model. Including stochastic fluctuations disperses the energy over a longer time window, introducing new phases and reducing the dominance of a few high-amplitude phases in the waveforms. For receivers at 15, 16.1, and 17 km, some waveforms even exhibit large amplitudes up to 30 s after the arrival of the first S waves.

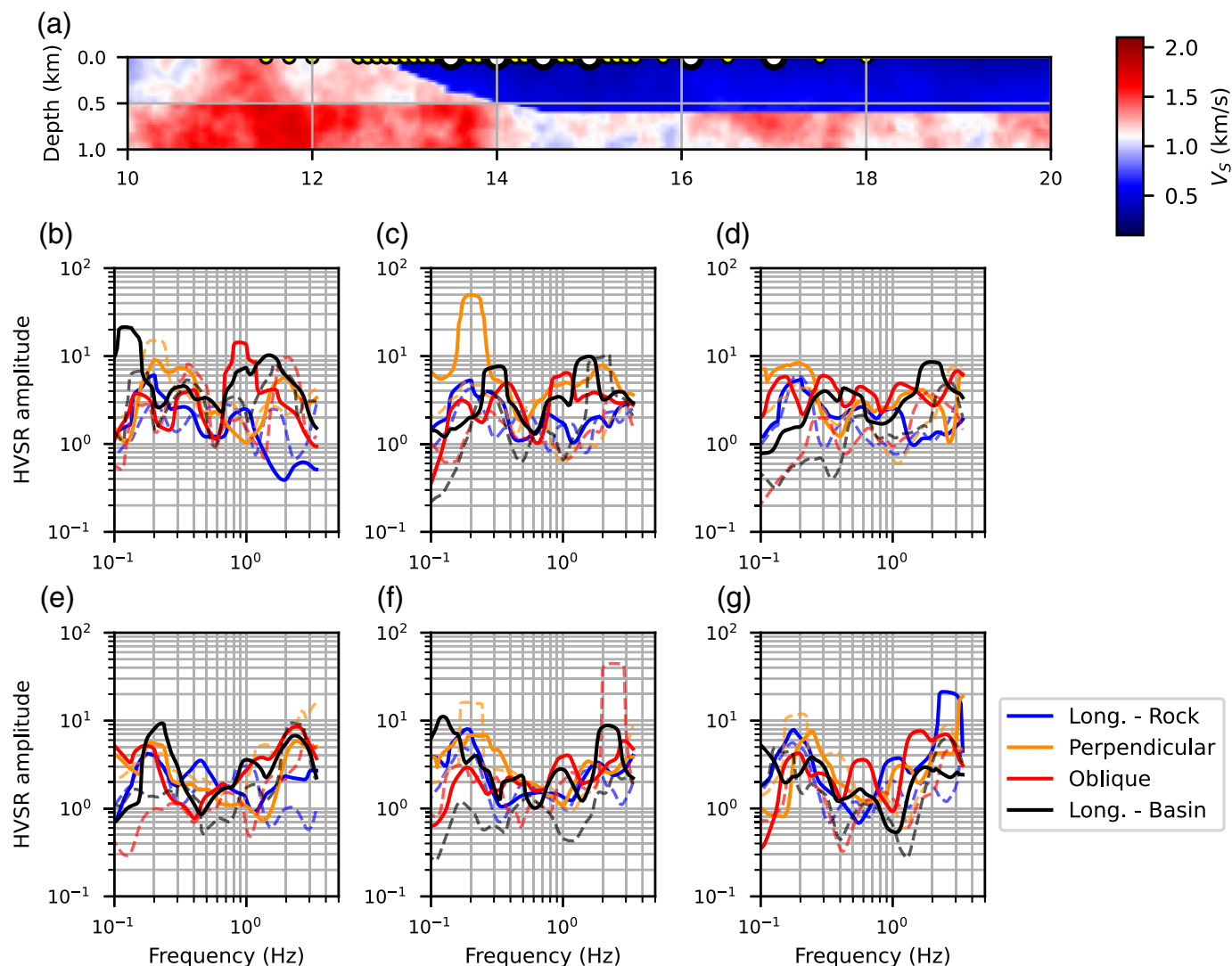
Figure 10. HVSR spectra obtained from the numerical modeling using the 3D velocity model. (a) Cross section of the 3D velocity model in the first 1 km depth. (b–g) HVSR spectra at each station for the four sources. The white circles in (a) represent the location of the receivers in (b–g). Panels (b) to (g) show waveforms at different coordinates: 13.5, 14, 14.5, 15, 16.1 and 17 km, respectively. The yellow dots are the other array's receivers. The color version of this figure is available only in the electronic edition.

The HVSR spectra from this 3D velocity model with stochastic spatial variations are shown in Figure 12. Including stochastic fluctuations in the velocity model produces significant differences in HVSR relative to the deterministic 3D velocity model. For instance, some peaks in the spectra manifested in the deterministic 3D velocity model disappear in the stochastic velocity model, and vice versa. When the receivers are in the flat region of the basin, the spectral differences between the two velocity models are smaller. Nevertheless, this more complex wavefield exhibits distinct HVSR spectral shapes compared with the deterministic velocity structure.



Waveforms when including stochastic perturbations in the 1D velocity model are shown in Figures S6 and S7. The waveforms in the time domain, compared with the deterministic 1D velocity model, exhibit longer durations and more complex phases, yet remain simpler than those of the 3D velocity structure. The 1D velocity model with inclusion of stochastic perturbations tends to yield HVSr similar to those of the 1D deterministic velocity model. However, the inclusion of local stochastic structures introduces additional fluctuations into the spectral shape, increasing the variability of HVSr amplitude.

Figure 11. Waveforms obtained from the numerical modeling using the 3D velocity model with inclusion of stochastic fluctuations. (a) Cross section of the 3D velocity model in the first 1 km depth. (b–g) Waveforms at the six stations for the four source locations. The white circles in (a) represent the location of the receivers in (b–g). Panels (b) to (g) show waveforms at different coordinates: 13.5, 14, 14.5, 15, 16.1 and 17 km, respectively. The yellow dots are the other array's receivers. The color version of this figure is available only in the electronic edition.



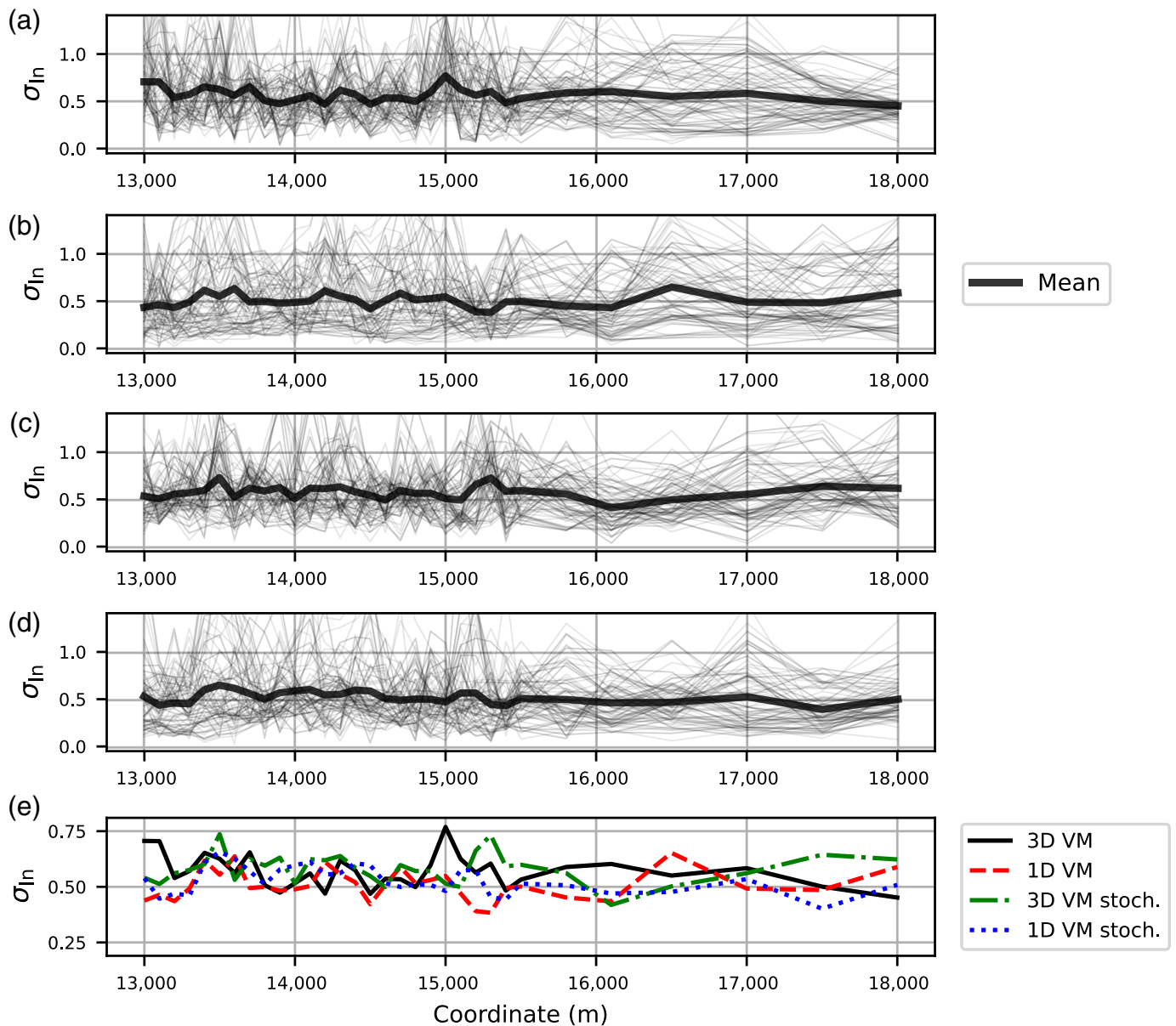
ANALYSIS OF THE STABILITY OF HVSR AMPLITUDE

The numerical simulations conducted demonstrate how different velocity models affect the variability and stability of HVSR. As a next step, we statistically analyze the fluctuations in HVSR amplitude and f_p . We first compare the standard deviation of HVSR amplitude between the four source locations at different frequencies and for different velocity models (Fig. 13). Each gray line in this figure represents the standard deviation of HVSR for the four different sources at a different frequency (log-sampled between 0.31 and 3.1 Hz), and the thick black line is the mean along all the frequencies for a given velocity model. Figure 13e compares the standard deviation between the four models. The mean of these frequency-dependent standard deviations, computed over the receivers, is presented in Table 1 for the four velocity models. We exclude from this analysis stations outside the basin (coordinates less than 13,000) to ensure that wavelengths are computed properly within the adopted volume for all velocity models, yielding 31 receivers. The 1D velocity model without perturbations (deterministic 1D velocity model) has the smallest standard

Figure 12. HVSR spectra obtained from the numerical modeling using the 3D velocity model with inclusion of stochastic fluctuations. The dashed lines are the HVSR spectra from the 3D deterministic velocity model at the same location. (a) Cross section of the 3D velocity model in the first 1 km depth. The black circles are the locations of the six selected receivers. (b–g) HVSR spectra at each station for the four sources. The white circles in (a) represent the location of the receivers in (b–g). Panels (b) to (g) show waveforms at different coordinates: 13.5, 14, 14.5, 15, 16.1 and 17 km, respectively. The yellow dots are the other array's receivers. The color version of this figure is available only in the electronic edition.

deviation (0.508 log-natural [LN] units). As the velocity structure becomes more complex, the variability of the HVSR amplitude increases. Nevertheless, despite HVSR changes for different source locations and velocity models, the standard deviation of the HVSR amplitude for the four cases varies within a small range for the four velocity models: 0.508–0.581 LN units. This suggests that, in addition to the velocity model, the source components play a key role in modulating HVSR amplitude variability.

Figure 14 shows how the predominant frequency f_p changes at different coordinates and at different source locations for the



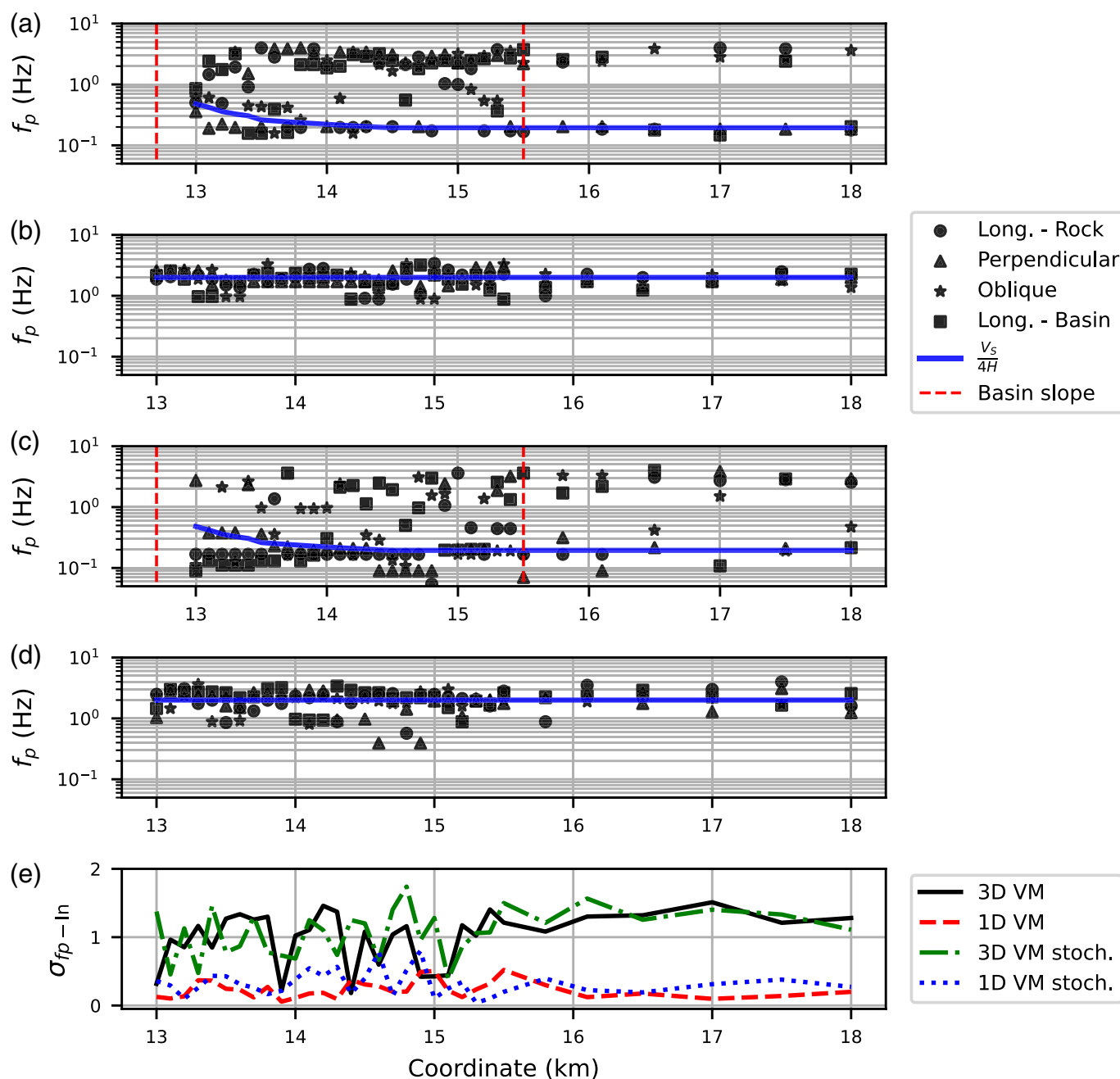
four velocity models. f_p was computed following the recommendations from the SESAME project (SESAME, 2004). Whereas the HVSR amplitude is affected by the source location and the velocity model, f_p depends weakly on the source location in the 1D velocity model, being rather stable within the deterministic and stochastic structures. In contrast, f_p in the 3D velocity models is highly sensitive to the source location and its components, producing substantial changes in the spectral shape.

The values of the fundamental frequency of a vertically propagating S wave in an isotropically and horizontally layered medium (using the classical equation $f_0 = \frac{V_p}{4H}$) are also shown in Figure 14. For both 1D velocity models, f_p is around the value consistent with 1D vertically propagating S waves f_0 . Conversely, for the 3D velocity models, f_p does not necessarily converge to the theoretical f_0 value; f_p depends on how the source location and its azimuth relative to the receiver illuminate the velocity

Figure 13. Standard deviation of HVSR amplitude in natural logarithmic units across the four sources as a function of receiver coordinates. Each light black line represents the standard deviation of the HVSR amplitude for the four sources at a given frequency. The thick black line is the mean standard deviation over all frequencies. (a) Deterministic 3D velocity model (3D VM). (b) Deterministic 1D velocity model (1D VM). (c) Stochastic 3D velocity model (3D VM stochastic). (d) Stochastic 1D velocity model (1D VM stochastic). (e) Comparison of the mean standard deviation between the four VMs at different locations. The color version of this figure is available only in the electronic edition.

structure. Including stochastic variability in the 3D velocity model increases the variability of f_p . Moreover, there are some source–receiver azimuths for which there is a smooth transition of the predominant frequency as the sediments thicken, following the f_0 value, but this pattern is not stable in space.

Another notable feature manifests at the basin edge in the 3D velocity structures, in which f_p lacks a clear pattern and is



highly variable. Within this region, f_p varies between 3 and 0.2 Hz, exhibiting even larger fluctuations for the stochastic 3D velocity structure. This highlights the well-known complexities induced in the waveform by its interaction with major geologic structures, particularly basin edges.

METHODOLOGY TO ASSESS HVSR AZIMUTHAL DEPENDENCE

At this point, a key question is how to determine whether wave propagation on a site can be assumed to be governed by 1D or 3D geologic structure. In simple velocity structures, the HVSR spectral shape tends to be stable, whereas in complex geologic structures, it can exhibit strong azimuthal dependence. From a taxonomic perspective, variations in HVSR between horizontal

Figure 14. Predominant frequency f_p as a function of receiver coordinates for the four source locations. (a) Deterministic 3D VM. (b) Deterministic 1D VM. (c) Stoch. 3D VM. (d) Stoch. 1D VM. (e) Comparison of the standard deviation in natural logarithmic units of f_p across the four VMs. The color version of this figure is available only in the electronic edition.

TABLE 1

Overall Standard Deviation ($\bar{\sigma}_{\ln}$) of the HVSR Amplitude for the Four Different Velocity Models

Velocity Model	$\bar{\sigma}_{\ln}$
1D—deterministic	0.508
1D—stochastic	0.530
3D—deterministic	0.570
3D—stochastic	0.581

components may offer an alternative criterion for distinguishing sites located over complex geologic structures (Sgattoni and Castellaro, 2020). However, to move beyond classification criteria, a wavefield filter in the wavenumber domain can be used to quantitatively assess the azimuthal variation of the HVSR spectrum and identify these directional dependencies. For example, several approaches have been used to filter in the space domain wavefronts arriving from a given azimuth in geophysics (Capon, 1969; Davies *et al.*, 1971; Douglas, 1998; Rost and Thomas, 2002), and applied in particular to ambient noise (Wapenaar *et al.*, 2013; Zhang *et al.*, 2024). Moreover, Zhang *et al.* (2024) and Wapenaar *et al.* (2013) applied azimuthal filtering to ambient-noise interferograms to mitigate illumination bias, demonstrating that the method is effective for stationary broadband noise fields. This analysis would require a seismic array equipped with triaxial seismometers and a sufficiently large dimension to provide adequate coverage of the wavelengths of interest. In addition, azimuthal resolution is fundamentally linked to interseismometer spacing and the array's azimuthal distribution, which determine the array's visibility at a given azimuth and frequency.

Considering a wavefield sampled at location $\vec{X}$ and time t , $\vec{u}(\vec{X}, t)$, its Fourier transform over frequency f , and wavenumber $\vec{k}$ is given by (Capon, 1969)

$$\vec{u}(\vec{k}, f) = \iiint \vec{u}(\vec{X}, t) e^{-2\pi i(\vec{k} \cdot \vec{X} - ft)} d\vec{x} dy dt. \quad (5)$$

A filter in the wavenumber domain can be applied using an azimuth-dependent kernel that keeps wavenumbers within a bin defined by two angles, removing the spectral amplitudes outside the selected azimuth range,

$$\vec{u}(\vec{k}, f | \theta_0 < \theta < \theta_1) = \vec{u}(\vec{k}, f) g(\theta | \theta_0, \theta_1), \quad (6)$$

in which $g(\theta | \theta_0, \theta_1)$ is the kernel filter function and $\vec{u}(\vec{k}, f | \theta_0 < \theta < \theta_1)$ is the filtered wavefield between azimuths θ_0 and θ_1 . The k -filtered wavefield in the space domain is obtained by inverting the Fourier transform, as

$$\vec{u}(\vec{X}, f | \theta_0 < \theta < \theta_1) = \iint \vec{u}(\vec{k}, f | \theta_0 < \theta < \theta_1) e^{2\pi i \vec{X} \cdot \vec{k}} d\vec{k}_x d\vec{k}_y. \quad (7)$$

Following this approach, we can filter each one of the three components of the wavefield and then compute the HVSR spectrum over a range of azimuths to assess potential azimuthal dependencies.

Subsequently, we describe the procedure for implementing this method using a seismic array of triaxial seismometers.

1. Converting the waveforms to the frequency domain: After recording ambient noise for a long enough time, we window the waveforms and preprocess them following a classical method in the Fourier domain for HVSR applications

(e.g., SESAME, 2004), except that we need to keep the phases (not calculate the norm of the spectra yet) and avoid any smoothing at this stage. Windows outside the ranges of the short- and long-term noise variance are neglected.

- 2. Converting the waveforms to the wavenumber domain:** First, a 2D mesh of wavenumbers is stored in a matrix, representing all the $\vec{k}$ considered for the analysis. Within each subwindow used to compute the HVSR spectra, we solve for the integral in equation (5) at each (k_x, k_y) pair and each frequency.
- 3. Applying azimuthal filtering in the wavenumber domain:** $\vec{u}(\vec{k}, f)$ is multiplied by a filtering kernel (as in equation 7). This will keep just the azimuths within the filtering kernel. For example, a kernel based on trigonometric functions, similar to the one used by Zhang *et al.* (2024), can be formulated as

$$g(\theta(\vec{k}) | \theta_0, \theta_1, \Delta\theta) = \begin{cases} 0 & \theta < \theta_0 \\ \sin\left(\frac{\pi(\theta - \theta_0)}{\Delta\theta}\right) & \theta_0 < \theta < \theta_0 + \Delta\theta \\ 1 & \theta_0 + \Delta\theta < \theta < \theta_1 - \Delta\theta \\ \sin\left(\frac{\pi(\theta_1 - \theta)}{\Delta\theta}\right) & \theta_1 - \Delta\theta < \theta < \theta_1 \\ 0 & \theta > \theta_1 \end{cases} \quad (8)$$

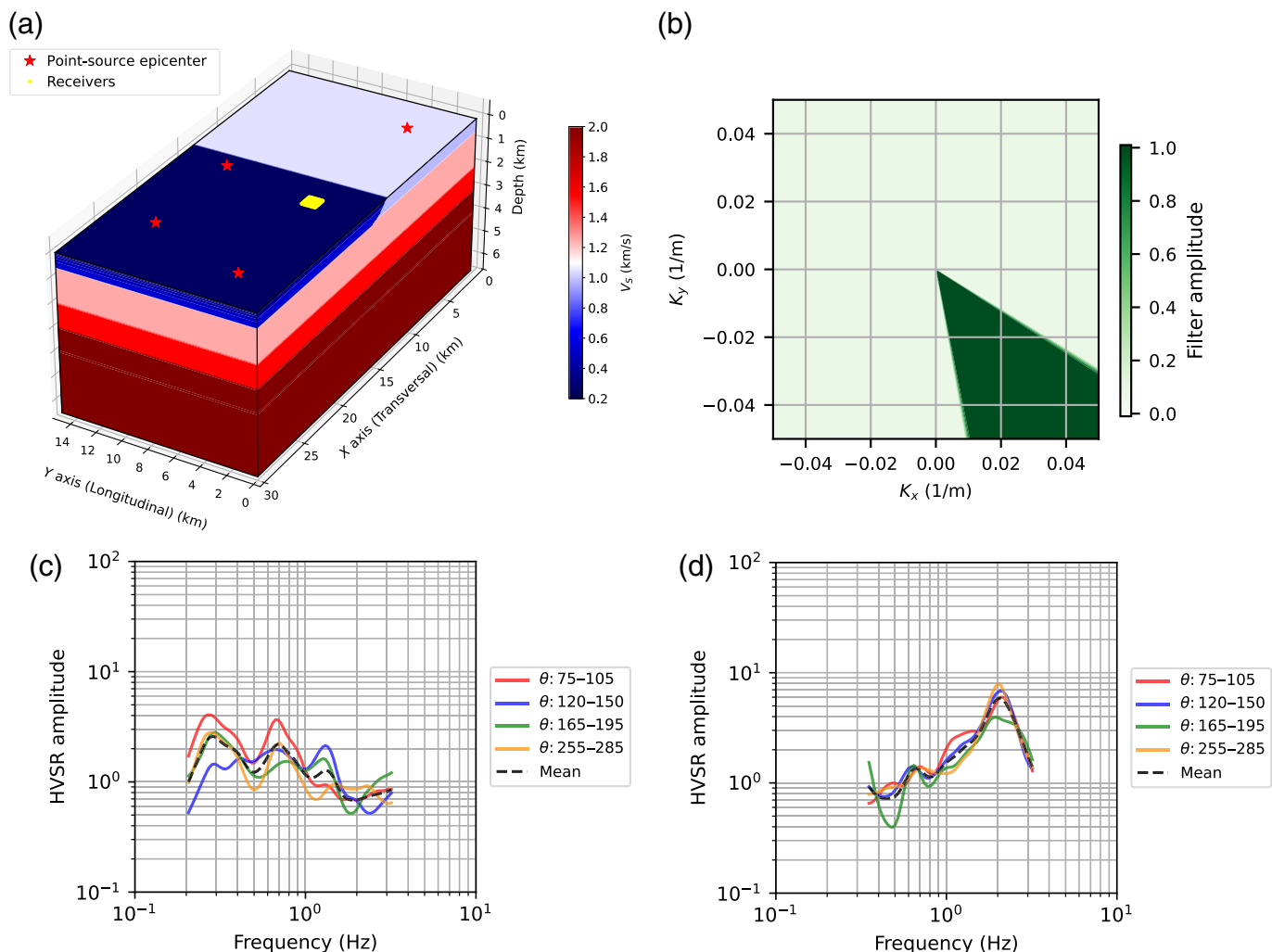
in which an example of its realization is shown in Figure 15b for an azimuth range of 50°, using $\theta_0 = 120^\circ$, $\theta_1 = 170^\circ$, and $\Delta\theta = 2.5^\circ$.

- 4. Transforming the filtered wavefield to the spatial domain:** Using the inverse transform of the wavenumber domain, we can retrieve the filtered Fourier spectra for each component at location $\vec{X}$, $\vec{u}(\vec{X}, f | \theta_0 < \theta < \theta_1)$, similar to step 2.
- 5. Compute the HVSR spectra at each window at location $\vec{X}$:** Finally, at each window, we compute the norm at each frequency, smooth the spatially filtered Fourier amplitudes in the frequency domain, and compute the HVSR using equation (3).

Implementation example using seismic array data from simulations

We implement spatial filtering in the wavenumber domain to assess whether the HVSR exhibits azimuthal dependence using simulated wavefields. We adopt the deterministic 1D and 3D velocity models and a square array of receivers with a spacing of 100 m over 1 km, resulting in 121 receivers (see yellow square in Fig. 15a). The center of the array is located at (14,000, 3500), near the basin edge in the 3D velocity model. These coordinates enable us to sample the azimuths from the four source locations, corresponding to relatively wide azimuth bins. We generate one wavefield by summing at each receiver located at $\vec{x}_r$ the contribution of all the source realizations,

$$u_i(\vec{x}_r, t) = \sum_{j=1}^{n=4} \sum_{p=1}^{n=3} G_{ip}(\vec{x}_r, \vec{x}_{s-j}, t) f_p, \quad (9)$$



in which $G_{ip}(\vec{x}_r, \vec{x}_{s-j}, t)$ is the Green's tensor that provides the impulsive response of the velocity model from a source located at $\vec{x}_{s-j}$ in a receiver at $\vec{x}_r$ when the “ p ” component has a unit force. $f_p = \vec{f}$ is the set of coefficients adopted previously for modeling the Cartesian components of the source.

We applied a wavenumber-filtering scheme in four bins to retain energy from azimuths associated with the given sources. The resulting HVSR varying as a function of azimuths are shown in Figure 15c,d for four different azimuth bins when using the 3D and 1D velocity models, respectively. The HVSR from the 1D velocity model exhibits no strong azimuthal dependence, with spectral shapes consistent with one another and minor fluctuations. In contrast, for the wavefield propagated through the complex velocity structure, HVSR differ substantially across the selected azimuth bins. Even an f_p around 0.7 Hz is observed in HVSR when the source comes from azimuths ranging from 75° to 105° , which is not manifested in the other spectra. Similarly, the peak observed at around 0.3 Hz disappears when keeping azimuths traveling within the directions from 120° to 150° .

Figure 15. (a) Location of the seismic array used to test the wavenumber-filtering methodology in a complex velocity structure using simulations (yellow square). The seismic array has a network of 11-by-11 receivers within a 1 km by 1 km square. The scale of the vertical axis is amplified by a factor of 2. (b) Example of the wavenumber-filtering kernel adopted for the methodology. This kernel retains only wavenumbers with azimuths between 120° and 170° and a $\Delta\theta = 2.5^\circ$. (c) HVSR obtained after filtering the wavefield in four bins of azimuth in the 3D velocity structure. (d) HVSR obtained after filtering the wavefield in four bins of azimuth in the 1D velocity structure. The color version of this figure is available only in the electronic edition.

Implementation example using observations from array data

In this section, we present an example of wavenumber filtering on real data to highlight the challenges we may encounter when applying this methodology to seismic arrays. We use the seismic array used for estimating the dispersion curves when validating the 1D velocity model, the geometry for which is displayed in Figure 16a. The impulsive response of the array, computed using equation (5) when adopting $\vec{u}(\vec{X}, t) = 1$, represents the range of $\vec{k}$ vectors for which the array has visibility,

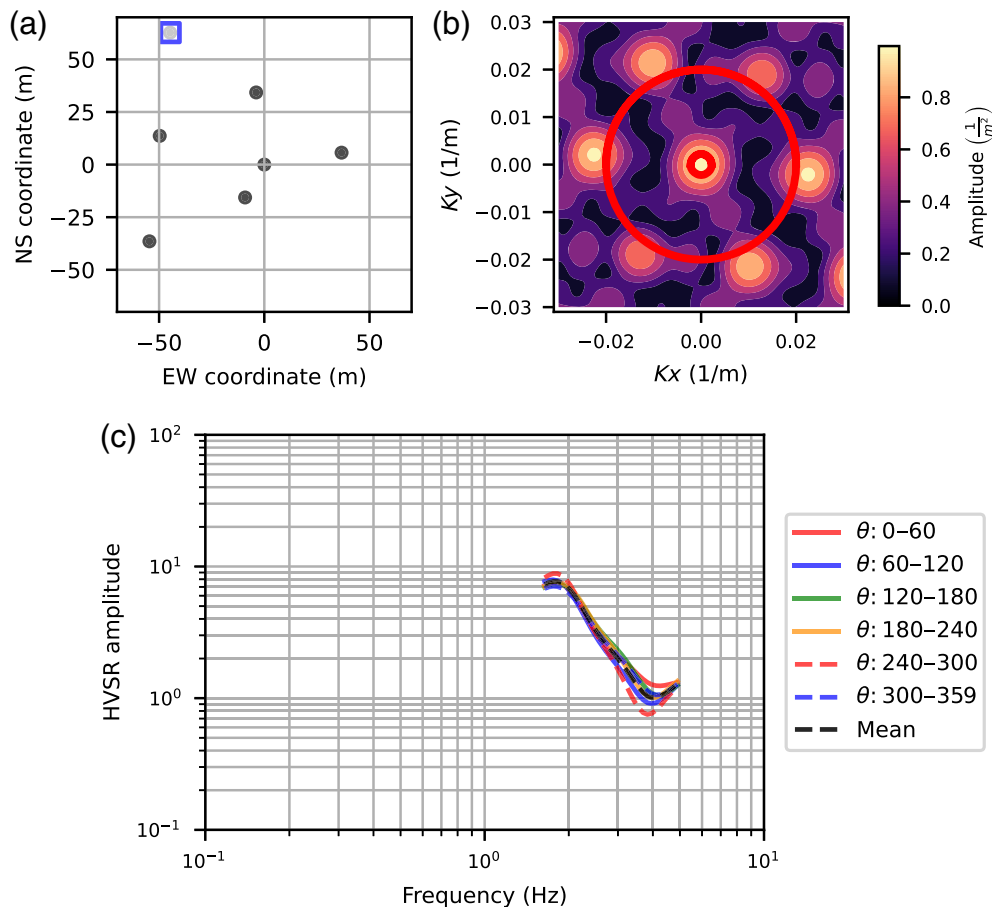


Figure 16. (a) Seismic array geometry. The blue square represents the receiver to which the wavenumber-filtering methodology is applied when conducting the inverse spatial Fourier transform. (b) Impulsive response of the array. The two red circles in the k -spectrum denote the maximum and minimum wavenumbers that this seismic array can resolve, given its maximum and minimum aperture. (c) HVSR obtained after filtering the wavefield in six bins of azimuth following the methodology described in [Methodology to Assess HVSR Azimuthal Dependence](#) section. EW, east-west; NS, north-south. K_x and K_y are the wavenumber in the x and y direction. The color version of this figure is available only in the electronic edition.

and is displayed in Figure 16b. We implement filtering in the wavenumber domain on this array and assess HVSR binned by azimuths in the receiver marked with a blue square in Figure 16a. The filtered HVSR for each azimuth bin is shown in Figure 16c. HVSR for all azimuth bins shares a similar shape, suggesting that this site can be modeled using a 1D velocity model within the frequency range this seismic array has visibility (1.8–5 Hz). Indeed, this is consistent with the HVSR obtained from the coda, similarly to Figure 1, as shown in Figure 17, but this time for this site (RFS). Compared with the HVSR from the introduction, the HVSR curves at the RFS station exhibit a more consistent spectral shape across all six earthquake events between 1.8 and 5 Hz.

This geophysical experiment also highlights the challenges in defining and designing the seismic array's dimensions, particularly the maximum and minimum apertures. In this case, the velocity structure and array geometry permit visibility only in the frequency range from 1.8 to 5 Hz. To achieve visibility at

lower frequencies, the array aperture should be larger, underscoring the importance of integrating the frequency range of interest with the array geometry in the design of these geophysical experiments.

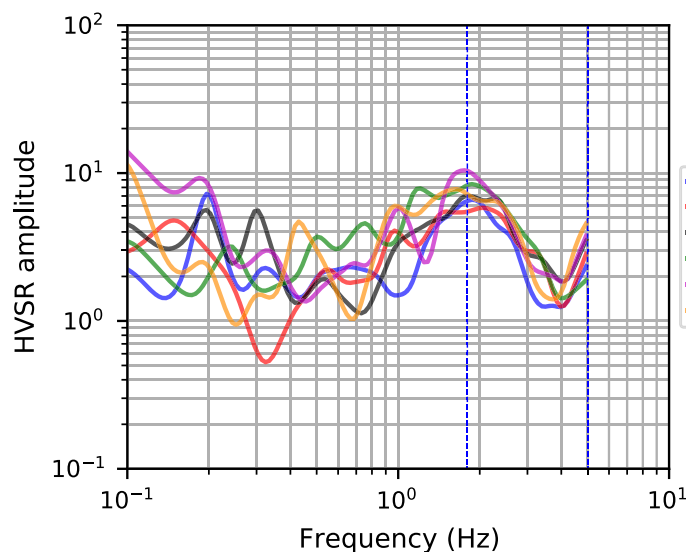
DISCUSSION

Impact of 3D velocity structures on the HVSR spectrum

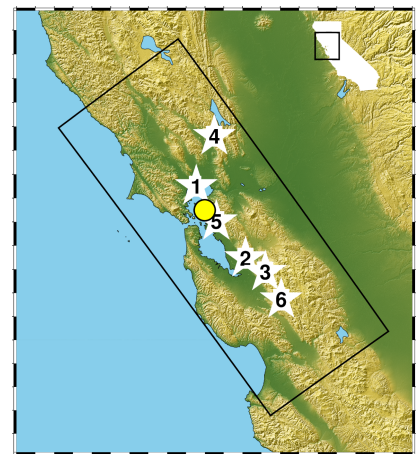
This study shows that complex velocity and geological structures can induce significant azimuth-dependent variations in the wavefield and, consequently, in its HVSR. This leads us to wonder whether the spectral shape from a single observation is stable along the entire polar circle, whether complex geologic structures induce a strong bias in the predominant phases observed, and whether unidirectional phases govern the ambient noise wavefield. Even the azimuths of those wavefronts that govern the amplitude of given frequency ranges can differ from those governing the seismic hazard associated with the spatial distribution of the local fault system. This is a key point, as treating an HVSR spectrum as azimuthally

isotropic can lead to misinterpretation of the mean site term or local surface amplification factors from earthquakes at azimuths different from the sources that generate the ambient noise observations, if these azimuth-dependent effects are significant.

Because of wave attenuation, the ambient noise's wavefield observed at the surface may result from a limited azimuth range, reflecting the results of the impulsive response of the velocity structure with a bias due to the orientation for these azimuths (Frankel *et al.*, 2001; Schulte-Pelkum *et al.*, 2004; Dolenc and Dreger, 2005; Nayak *et al.*, 2017). For instance, using a seismic array deployed at Santa Clara in the San Francisco Bay Area, California, Dolenc and Dreger (2005) demonstrated that the wavefield of ambient noise exhibits different orientations of propagation, depending on the location of the main sources of ambient noise. They noted that the wavefield is primarily governed by waves from Half-Moon Bay, located 15 km northwest. They reported fluctuations in the ambient noise wavefield over time, with particularly



Black Point (1)
Fremont (2)
Milpitas (3)
Moskowitz Corner (4)
Piedmont (5)
Seven Trees (6)



pronounced effects during storms at Half-Moon Bay. Such fluctuations have also been documented in valleys across Central and Western Europe (Lattanzi *et al.*, 2023). These results are consistent with Nayak *et al.* (2017), who highlighted the impact of adopting 3D velocity structures when retrieving empirical Green's functions from ambient noise, compared with 1D velocity models.

Because of the potential azimuthal dependence of the ambient noise wavefield and, consequently, its HVSR, we should define two site classes based on the behavior of their HVSR-spectral azimuthal response: 1D and 3D sites. A useful framework for 1D site taxonomy involves assessing the ratio of lateral to vertical heterogeneity length scales, in which sites behave as 1D systems when lateral fluctuations are much smaller compared with vertical variations (Castellaro and Musinu, 2022). Under these conditions, the HVSR spectral shape is relatively stable. Conversely, in 3D sites, the HVSR spectral shape can exhibit large changes depending on the source-site azimuth, even making the predominant frequency unrelated to the standard, vertically propagating *S* wave in a 1D medium, if the manifestation of basin-induced surface waves dominates the wavefield, as shown in Figure 14. Additionally, there is likely a continuous transition from stable 1D conditions toward wave propagation in complex structures, inducing azimuthal dependencies in HVSR spectra. The usual procedure for recording ambient noise relies on a single seismometer (a single-station approach). Spatially filtering observations from 2D arrays may be a key step in broadening our understanding of ambient noise, its HVSR, and its relationship with earthquake ground motions.

Implications for using HVSR to estimate site terms in GMMs

The discussion in the previous section has statistical implications for capturing systematic amplification patterns using HVSR. For instance, based on GMMs, an observation can be decoupled into the following:

Figure 17. Similar to Figure 1, this figure displays the HVSR from six different earthquakes at the Richmond Field Station. Within the frequency range of our seismic array's visibility, 1.8–5 Hz (vertical dashed lines), HVSR is more stable in terms of spectral shapes for this station than in the case illustrated in the Introduction. The rectangle shows the limits of the cross-sections shown in Figure S2. The color version of this figure is available only in the electronic edition.

$$\ln(Y_{es}) = \ln(Y_{\text{erg}}(M, R_{\text{RUP}}, V_{S30}, \dots)) + \delta B_e + \delta S2S_s + \delta WS_{es}, \quad (10)$$

in which Y_{es} is the observed ground motion from earthquake “*e*” at site “*s*,” $Y_{\text{erg}}(M, R_{\text{RUP}}, V_{S30}, \dots)$ is the median ground motion from an ergodic GMM, δB_e is the between-event residual, $\delta S2S_s$ is the site term, and δWS_{es} is the within-site residual (Al-Atik *et al.*, 2010). For this study, $\delta S2S_s$ is of key importance, as it represents the systematic deviation in ground-motion amplitude that the site “*s*” exhibits compared with the average site scaling in the GMM. If the reference amplification is modified to be a rock condition rather than the median amplification from the GMM, $\delta S2S_s$ would represent the total site amplification, which, for practical purposes, implies adding a constant to this equation (e.g., Pinilla-Ramos *et al.*, 2022). $\delta S2S_s$ can be estimated using empirical models (e.g., Senna *et al.*, 2008; Kawase *et al.*, 2019; Pinilla-Ramos *et al.*, 2022; Pinilla-Ramos *et al.*, 2024). However, a key question arises: if the analyzed site is placed upon a complex geologic structure, and given azimuths govern the ambient noise wavefield, will the $\delta S2S$ model include strong biases by not accounting for the connection between the azimuths from the ambient noise behind the estimated HVSR spectrum and the earthquake-site azimuth? For instance, Lacour *et al.* (2025) developed an azimuthal-dependent site-term model for Southern California using data from the CyberShake platform (Graves *et al.*, 2011). They showed a strong variation of up to one LN unit (a factor of almost 3 on a linear scale) in the median site terms, depending on the source-site azimuth. This question regarding

the azimuthal stability of HVSR spectra should be addressed to improve our local amplification prediction capabilities. Currently, our proposed methodology can aid us in identifying sites where the HVSR can be interpreted as azimuthally stable. Moreover, if azimuthal dependence is observed in HVSR spectra, this information can be incorporated into ground-motion modeling to map azimuthal variations in the site terms $\delta S2S$.

CONCLUSIONS

Using numerical simulations, we show that at sites located over complex velocity structures, the spectral shape of HVSR depends strongly on the velocity model. Our results show that the predominant frequency f_p tends to be stable at sites over simple velocity structures, wherein horizontally layered media can be reasonably assumed. In contrast, at sites on complex velocity structures, f_p strongly varies as a function of the wavefront directionality and its interaction with local geologic structures.

The HVSR amplitude is less stable than f_p and strongly depends on source features, consistent with the conclusions of Molnar *et al.* (2022). HVSR amplitude can provide important insights into constraining site amplification, as it has the great advantage of being a continuous frequency-dependent predictor of site amplification. An alternative is to normalize HVSR spectra, which helps stabilize HVSR amplitude fluctuations when constraining site amplification, improving its predictive capabilities (Pinilla-Ramos *et al.*, 2022). Further research is needed to better understand these fluctuations, thereby improving the variance reduction of models based on HVSR amplitude.

Finally, it is important to acknowledge the interaction between the ambient noise wavefield and local geologic structures. The directionality of ambient noise may not reflect the source-site azimuths of the faults controlling the seismic hazard. Wavenumber filtering of the wavefield can be used to identify the HVSR spectrum associated with the controlling faults for a given azimuth. Evaluating ambient noise using 2D seismic arrays is a key step in widening our understanding of observed HVSR and its relationship to the site amplification from earthquakes at different locations.

DATA AND RESOURCES

For the simulations, we used the program Seismic Wave 4 (SW4, v. 3.0, Petersson and Sjögreen, 2012, 2015; Sjögreen and Petersson, 2012; <https://geodynamics.org/resources/sw4>, last accessed August 2026). The seismic array data can be found in Zenodo (doi: [10.5281/zenodo.12614743](https://doi.org/10.5281/zenodo.12614743)) in mseed format. The data analysis was performed in Python. The supplemental material provides seven figures that provide insight into the details of the analysis.

DECLARATION OF COMPETING INTERESTS

The authors acknowledge that there are no conflicts of interest recorded.

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