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Microtremor Full-Wavefield Modeling of Effective Phase Velocity and Horizontal-to-Vertical Spectral Ratio at Kyoto Reference Borehole Site: Comparison with Surface-Wavefield Modeling Based on a Velocity Structure with a Cap Layer --Manuscript Draft--

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Abstract:	Two types of data commonly used for microtremor exploration are phase-velocity dispersion curves obtained through an array measurement and horizontal-to-vertical spectral ratios (HVSRS) obtainable by a single-station measurement. Phase-velocity dispersion curves obtained by applying the spatial autocorrelation (SPAC) method to the array waveforms have a characteristic peaked shape in some cases. This dispersion curve shape has traditionally been explained as a consequence of the predominance of higher modes over fundamental mode in the Rayleigh waves. In this study, the effects of body waves on phase velocities and HVSRSs were investigated based on both field measurements and theoretical calculations of microtremors. We used vertical-component array waveforms and single-station three-component waveforms of microtremors, obtained at and around a site where combined P-wave-S-wave (PS) and density loggings were conducted in the Kyoto Basin, Japan (site KD-1), to identify phase velocities and HVSRSs at frequencies in the range 0.2–2 Hz. The corresponding theoretical phase velocities and HVSRSs were identified using full-wavefield synthetic data, which were generated assuming excitation points randomly distributed over the surface of a horizontally-stratified velocity structure model created based on the logging data. The following key results were obtained. The measured phase-velocity dispersion curve exhibits a peaked shape with the value exceeding the S-wave velocity of the Tamba(Tb)-Group, which is the bedrock (half-space) of the velocity structure model. Theoretical calculations based on the surface-wavefield theory were unable to reproduce this peaked shape; however, theoretical calculations based on the full-wavefield theory reproduced it with extraordinary accuracy. To reproduce the peaked shape based on the surface-wavefield theory, it was necessary to construct a model containing a cap (i.e., high-velocity layer) connected under the Tb-Group. The theoretical calculation based on the full-wavefield also accurately reproduced the peak value and peak frequency of the measured HVSRSs.
Author Comments:	
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	Dr. Tokimatsu is a pioneer in finding a method to evaluate the apparent (effective) phase velocity and HVSR in the wavefield including all modes of surface waves, and has published many related papers. One of the co-authors of our paper used to work with Dr. Tokimatsu, but he has had no conflicts of interest with Dr. Tokimatsu in the last 20 years, and we believe he will be able to review our paper objectively. Dr. Tokimatsu is currently a Chief Technology Adviser of Tokyo Soil Research Co., Ltd..
	Sheri Molnar University of British Columbia semolnar@mail.ubc.ca Dr Molnar showed good agreement between the S-wave velocity structure estimated from borehole surveys and microtremor observations at the surface. In our study, the validity of the velocity structure model based on PS logging data from borehole surveys is also important for the evaluation of phase velocities and HVSRs of microtremors. For these reasons, Dr Molnar is an appropriate reviewer.
	Hitoshi Morikawa, Dr. Eng. Professor, Tokyo Institute of Technology morikawa.h.aa@m.titech.ac.jp Dr Morikawa has a deep understanding not only of the observations and evaluation of subsurface structures in microtremor surveys, but also of the theoretical and probabilistic aspects of the underlying microtremor wavefields. The present study is unique in that it is a theoretical evaluation of the influence of body waves on the microtremor wavefield, rather than a processing of observational data or an evaluation of velocity structures. For these reasons, Dr Morikawa is an appropriate reviewer.
	Sebastiano Foti Politecnico di Torino sebastiano.foti@polito.it
Opposed Reviewers:	
Response to Reviewers:	
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Question	Response
Key Point #1: Three key points will be printed at the front of your manuscript so readers can get a quick overview. Please provide three COMPLETE sentences addressing the following: 1) state the problem you are addressing in a FULL sentence; 2) state your main conclusion(s) in a FULL sentence; and 3) state the broader implications of your findings in a FULL sentence. Each point must be 110 characters or less (including spaces).	We investigated the effects of body waves on the peaks of phase velocity and HVSR of microtremor records.
Key Point #2:	Full wavefield modeling can be used to reproduce phase velocity exceeding bedrock S-wave velocity and HVSR.
Key Point #3:	The proposed method for calculating phase velocity and HVSR is useful for velocity structure modeling.

1 Microtremor Full-Wavefield Modeling of Effective Phase Velocity and Horizontal-to-Vertical
2 Spectral Ratio at Kyoto Reference Borehole Site: Comparison with Surface-Wavefield Modeling
3 Based on a Velocity Structure with a Cap Layer

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Abstract

Two types of data commonly used for microtremor exploration are phase-velocity dispersion curves obtained through an array measurement and horizontal-to-vertical spectral ratios (HVSRs) obtainable by a single-station measurement. Phase-velocity dispersion curves obtained by applying the spatial autocorrelation (SPAC) method to the array waveforms have a characteristic peaked shape in some cases. This dispersion curve shape has traditionally been explained as a consequence of the predominance of higher modes over fundamental mode in the Rayleigh waves. In this study, the effects of body waves on phase velocities and HVSRs were investigated based on both field measurements and theoretical calculations of microtremors. We used vertical-component array waveforms and single-station three-component waveforms of microtremors, obtained at and around a site where combined P-wave–S-wave (PS) and density loggings were conducted in the Kyoto Basin, Japan (site KD-1), to identify phase velocities and HVSRs at frequencies in the range 0.2–2 Hz. The corresponding theoretical phase velocities and HVSRs were identified using full-wavefield synthetic data, which were generated assuming excitation points randomly distributed over the surface of a horizontally-stratified velocity structure model created based on the logging data. The following key results were obtained. The measured phase-velocity dispersion curve exhibits a peaked shape with the value exceeding the S-wave velocity of the Tamba(Tb)-Group, which is the bedrock (half-space) of the velocity structure model.

31 Theoretical calculations based on the surface-wavefield theory were unable to reproduce this
32 peaked shape; however, theoretical calculations based on the full-wavefield theory reproduced it
33 with extraordinary accuracy. To reproduce the peaked shape based on the surface-wavefield theory,
34 it was necessary to construct a model containing a cap (i.e., high-velocity layer) connected under
35 the Tb-Group. The theoretical calculation based on the full-wavefield also accurately reproduced
36 the peak value and peak frequency of the measured HVSRs.

37

38 INTRODUCTION

39 The microtremor survey method is used to estimate the subsurface structure with a wide range of
40 S-wave velocity (about 100-3000 m/s) distributed at various depths from a few meters to a few
41 kilometers, based on the phase velocity dispersion curves and/or the horizontal-to-vertical spectral
42 ratios (HVSRS) of surface waves identified from microtremor measurement data (Okada, 2003;
43 Cornou et al., 2006; Foti et al., 2018). In addition, this method is widely used in earthquake
44 engineering because of its advantages such as low cost, the rapidity of field operations, and the
45 simplicity of data analysis.

46 The spatial autocorrelation (SPAC) and frequency wavenumber (FK) methods proposed by Aki
47 (1957) and Capon (1969), respectively, are the most popular methods for identifying the phase-
48 velocity dispersion curve of microtremors. In particular, the practical utility of the SPAC method
49 has been demonstrated by many studies (Tokimatsu, 1997; Bettig et al., 2001; Ohori et al., 2002;
50 Okada, 2003; Morikawa et al., 2004; Arai and Tokimatsu, 2005; Cornou et al., 2006; Molnar et al.,
51 2015; Garofalo et al., 2016; Asten and Hayashi, 2018). In recent work, the phase velocities of Love
52 waves were successfully determined by applying the SPAC method (Yoshida and Uebayashi,
53 2020), and the capability of the analysis method of Yoshida and Uebayashi (2020) to extract Love
54 waves in the general wavefield of microtremors was examined theoretically based on a random
55 process model (Cho et al., 2022). As these examples demonstrate, the SPAC method is an

extremely powerful analytical technique that can determine the phase velocities of not only Rayleigh waves, but also Love waves.

Phase-velocity dispersion curves obtained by applying the SPAC method to microtremor array data may have a characteristic peaked shape (i.e., the phase velocity is greater at a certain frequency than at a lower frequency) due to a subsurface structure. This dispersion curve shape has traditionally been explained as a consequence of the predominance of higher modes over the fundamental mode in Rayleigh waves (Tokimatsu et al., 1992; Cho et al., 2006). This interpretation is premised on the assumption that the primary contribution to microtremor wavefields comes from surface waves. However, when subsurface velocity structure has a high S-wave velocity contrast, body waves can contribute more than surface waves to vertical components, even at distances of several tens of wavelengths from the vibration sources (Tokimatsu and Tamura, 1995; Tamura, 1996; Ohori et al., 2010). Also, it has been pointed out that in a simple two-layer subsurface structure, where a soft layer overlies a hard half-space, the body waves dominate at a frequency lower than the S-wave resonance frequency (Pileggi et al., 2011). This implicitly testifies to the need to consider body waves when identifying phase velocities in a frequency range lower than the resonant frequency.

Uebayashi et al. (2020) adopted a horizontally stratified velocity structure model and the full-wavefield theory, which considers both surface and body waves to calculate synthetic data with

the assumption that excitation points are randomly distributed over the ground surface, to which they applied the SPAC method to obtain phase velocities. This procedure yielded a phase-velocity dispersion curve with a peaked shape. They called the peak value the peak phase velocity. The observation of such phenomena in synthetic data calculations raised some questions: Can the peak phase velocity observed in the real world be reproduced by the full-wavefield theory? Furthermore, can it be reproduced by the surface-wavefield theory?

Meanwhile, the interpretation of the peak frequency of HVSRs as that of the ellipticity of the fundamental mode of Rayleigh waves began with Nogoshi and Igarashi (1971) and persisted until the early 2000s (e.g., Konno and Ohmachi, 1998; Fäh et al., 2001; Scherbaum et al., 2003). Thereafter, Arai and Tokimatsu (2004) succeeded in fitting not only the peak frequency of HVSRs but also the spectral shape over wide frequency ranges, taking into account not only the Rayleigh waves but also the Love waves, using a novel computational technique that accounts for higher modes. Furthermore, techniques for computing HVSRs based on the full-wavefield theory, with body waves taken into account, have been discussed in the literature (e.g., Lunedei and Albarello, 2010; Lontsi et al., 2015; García-Jerez et al., 2016; Wu et al., 2017), and body waves have been shown to have a relatively large impact on HVSRs below the peak frequency of HVSRs (Lunedei and Albarello, 2010; Pileggi et al., 2011). With these results in mind, a question is also raised for HVSRs: Can the theories used to reproduce the peak phase velocity observed in the real world also

reproduce the peak value and the spectral shape of an HVSR?

The objective of this paper is to answer these questions about the phase velocity and HVSR. To achieve this objective, we first use vertical-component array waveforms and single-station 3-component waveforms of microtremors, obtained at and around a site where combined P-wave–S-wave (PS) and density loggings were conducted in the Kyoto Basin, Japan (site KD-1), to identify phase velocities and HVSRs at frequencies in the range 0.2–2 Hz. Next, we show that measured phase-velocity dispersion curves exhibit clear peaks. We also show that such dispersion curve shapes can be reproduced by theoretical calculations based on a full-wavefield approach applied to a velocity structure model based on the logging data at the KD-1 site. In addition, we explore the causes of peak formation in a phase-velocity dispersion curve, which allows us to perform a theoretical evaluation using a variety of velocity-structure models, considering full- and surface-wavefield perspectives. Finally, we show that the HVSR peak identified from the measurement data can be reproduced by the full-wavefield approach used in the phase velocity evaluation. To explore the cause of the formation of the HVSR peak, we also perform a theoretical evaluation using the same procedure as the phase velocity evaluation described above.

PHASE VELOCITY AND HORIZONTAL-TO-VERTICAL SPECTRAL RATIO (HVSR) AT

KYOTO REFERENCE BOREHOLE SITE (KD-1)

PS logging and microtremor measurement

The Kyoto Basin is a long north-south basin surrounded by mountains on three sides (east, west, and north), as shown in Figure 1. Figures 2(a)-(c) show the results of PS and density loggings conducted using a combination of downhole and suspension methods at three sites in the Kyoto Basin (KD-0, KD-1, and KD-2 in Fig. 1) having different sediment-bedrock interface depths (The Committee of Investigation for Kyoto Basin Subsurface Structure, 1999, 2000, 2002). The logs show a clear velocity contrast at the interface between the Tamba Group (Tb-Group), which is the bedrock in this region, formed during the Jurassic to Triassic, and the Osaka Group (Os-Group), an unconsolidated sedimentary layer formed during the late Pliocene to early Pleistocene. The bedrock depth increases gradually from north to south.

Microtremor array measurements were conducted during limited nighttime hours on each day of March 12 to 17, 2000, to minimize noise from human activity. Synchronous measurements were made at seven points to constitute a two-fold triangular array. These measurements were made for each of the L-, M-, and S-arrays (Fig. 1 and Table 1). Microtremor measurements were made using seven identical pairs of instruments, each pair consisting of a vertical-component velocity seismometer (Shindo Giken Corp. UPS-SPAC, natural period 7 s) and a data logger with 16-bit A/D converter (Hakusan Corp. LS-8000SH). Referring to a single 60-min measurement as one set,

for each array radius we gathered three or four sets of data for use in our analysis described in the next section. L-array measurements were made twice on different days. Single-station three-component microtremor measurements were conducted at the KD-1 site during the daytime on March 15, 2021. These measurements lasted 30 min and were made using a three-component velocity-type seismometer (Lennartz Electronic LE-3D/5SMK3, natural period 5 s) and a 24-bit data logger (Hakusan Corp. LS-8800). As examples, Figure 3 shows the power spectra at seven points consisting of the largest L-array. These are intermediary quantities to obtain phase velocities by the SPAC method, where the data processing procedure and the parameters are fully described in the next section. Because the difference in the spectra between these measurement points is slight, we infer that the microtremor field is spatially stationary within the range of our measurements.

Identification of phase velocities

Both the SPAC and FK methods were used to determine phase velocities. For the SPAC method, our data-processing procedure consisted of the following four steps. **(1)** The Hanning (cosine) window (e.g., Carter et al., 1973) with a taper ratio of 0.5 was applied to the waveform to extract data segments with a duration of 81.92 s, which were transformed to the frequency domain by a fast Fourier transform (FFT). The FFT spectra were amplitude-squared or multiplied, depending

146 on whether the estimation target was power- or cross-spectral density, respectively. **(2)** To smooth
 147 each spectrum thus obtained, the moving average (arithmetic mean) was applied in the band from
 148 0.1 to 2.0 Hz (Bendat and Piersol, 2010). The bandwidth of the averaging was set to 0.043 Hz at
 149 0.1 Hz and 0.079 Hz at 2.0 Hz, and it progressively increased with increasing frequency in the
 150 range 0.1–2.0 Hz (e.g., Konno and Omachi, 1998; Bendat and Piersol, 2010). **(3)** Steps 1 and 2
 151 were applied to all the data segments, which were extracted from the waveforms with 50%
 152 overlapping (e.g., Carter et al., 1973). The frequency distribution of the rms value of the amplitudes
 153 in data segments was investigated prior to tapering, and the data segments with abnormal values
 154 were considered to have nonstationary portions and were eliminated. The data segments selected
 155 automatically in this manner were used to estimate the spectra. As a result, the total numbers of
 156 data segments ranged from 139 to 353 depending on the array size. Finally, these smoothed spectra
 157 were used to obtain ensemble averages. That is, in this paper, the spectral density is estimated by
 158 a combination of spectral domain smoothing and ensemble averaging (Bendat and Piersol, 2010),
 159 and the SPAC coefficients are obtained on this basis. Figure 4 shows the SPAC coefficients thus
 160 obtained for the 11 different array sizes listed in Table 1. **(4)** Considering that the SPAC coefficient
 161 ρ for a certain array radius r satisfies $\rho = J_0(r\omega/c)$ (Tokimatsu, 1997), the phase velocity c
 162 was obtained by inverse analysis of this equation. The phase velocities were obtained from the
 163 SPAC coefficients for each array radius corresponding to the range of wavelengths from $2.5r$ to

5r. The number of array radii for each frequency that satisfies this condition is shown in Figure 5(a). The mean value and standard deviation for each frequency were calculated for this number of obtained phase velocities, and a phase velocity dispersion curve was identified by connecting the means for each array radius [Fig. 5(b)]. Note that the phase velocity thus obtained is called the effective phase velocity when multiple modes dominate in the microtremor wavefield (we do not assume dominance of the fundamental mode at all frequencies). The standard deviations of the phase velocity are relatively large at frequencies below about 0.4 Hz. The reliability of the phase velocities identified in this low frequency range is discussed in Appendix A.

For the FK method, we used the same data-segment lengths and overlaps as for the SPAC method but fixed the smoothing bandwidth at 0.05 Hz. We estimated frequency-wavenumber spectra from the waveforms at seven points each for the L-, M-, and S-arrays, and then determined phase velocities from the peaks of these spectra at each frequency [Fig. 5(c)]. Note that the FK method generally identifies less accurate phase velocities in the long wavelength band than does the SPAC method (Cho, 2023); therefore, phase velocities below 0.5 Hz could not be identified.

The phase-velocity dispersion curves determined via the SPAC and FK methods are in good agreement, with both indicating phase velocities above 3 km/s in the frequency range from 0.4 to 0.5 Hz. This phase velocity exceeds the S-wave velocity of the underlying Tb-Group and attains its peak value at about 0.45 Hz for the SPAC method. This confirms that the peak phase velocity

predicted by the synthetic data of microtremors described in the introduction can be seen in the real world.

Identification of the HVSR

We used the following procedure to determine HVSRs from the observational data. From the 30-min three-component data obtained as described previously, we excluded by visual inspection noise portions corresponding to vibrations induced by traffic passing near the measurement point. For the remaining data, 20 non-overlapping data segments with a duration of 81.92 s were extracted. The FFT was applied to each data segment for each component to determine the Fourier spectra, and then the absolute squared power spectra of the FFT spectra were ensemble averaged (i.e., arithmetic means were taken at each frequency). From the resulting averaged power spectra of each component, the root sum of the two orthogonal horizontal components was divided by the root of the vertical component to obtain the HVSR. The identified HVSRs are discussed in detail in the section “Comparison of HVSRs between theoretical calculation and measurement” below.

EFFECTIVE PHASE VELOCITY IN FULL-WAVEFIELD

Velocity structure model

Using the logging data, we created eight models of the velocity structure at KD-1. We first created seven models [Figs. 6(a)-(c)] as follows. To model the Os-Group, which exists to a depth of 0.223 km based on the PS logging data at KD-1, we subdivided this group into eight layers by visual inspection (layer Nos. 1–8 in Table 2), and then took averages of each physical property in each layer to be the representative values of the model. For the Tb-Group, which exists at depths below 0.223 km, we subdivided the depth portion into two layers, or an upper and lower layer, at the depth Z indicated in Figure 6 as the boundary between these layers (layer Nos. 9 and 10 in Table 2). Note that the upper layer has PS logging data, whereas the lower layer does not. In constructing this model, we considered three uncertainties (cf. the physical properties listed in Table 3):

- (1) The fluctuations in the physical properties of the upper layer, which can be identified based on PS logging data;
- (2) The arbitrariness in setting the physical properties of the lower layer that characterize the velocity contrast at depth Z ; and
- (3) The arbitrariness in setting the value of depth Z .

For item (1), because the Tb-Group exhibits large variations in S- and P-wave velocities, we defined a primary model (model 111) by averaging the physical properties in the relevant segment, and then added and subtracted the standard deviation to define two additional models (models 112 and 113) [Fig. 6(a), Table 3].

For item **(2)**, we noted that Tb-Group S- and P-wave velocities were smaller overall at KD-1 [Fig. 2(b)] than at KD-0 [Fig. 2(a)] or KD-2 [Fig. 2(c)]. Because the fundamental physical properties of the Tb-Group, the basement layer in this area, are considered to be common, KD-1, located between KD-0 and KD-2, is expected to have a layer with physical properties equivalent to the Tb-Group in KD-0 and KD-2 at a depth beyond the bottom of the PS logging (i.e., 0.35 km). To represent this layer, we added a new layer with physical properties equal to the average values (2.6 km/s) of Tb-Group physical properties at sites KD-0 and KD-2 beneath the layers of the existing model. We took the modified model constructed in this way to be our new model 111. Then we constructed two additional models: a model in which there is no velocity contrast (V_{s10}/V_{s9}) within the Tb-Group (model 121) and a model in which this velocity contrast is larger (model 131) [Fig.6(b), Table 3]. Tb-Group velocity contrasts for models 111, 121, and 131 are 1.58, 1.00, and 1.94, respectively. Here, the physical properties of layer No. 10 of model 131 were set based on those (3.2 km/s for the S-wave velocity) of the bedrock of the Osaka and Nara basins adjacent to the southwest and south sides of the Kyoto Basin, respectively (Kagawa et al., 2004).

Finally, for item **(3)**, we created three models (models 111, 211, and 311) with different values for the interface depth Z with the velocity contrast of **(2)** above [Fig.6(c), Table 3].

In addition to these seven models, for use in computing phase velocities and HVSRS solely based on the surface-wavefield theory, we defined an eighth model [model 111A, Fig.6(d), Table

4] by adding four new layers to the primary model 111 at depths of 4 km and greater. It should be noted that this corresponds to the cap layer of Harvey (1981). Wu et al. (2017) obtained the HVSRs by applying the full-wavefield theory to a velocity structure model without a cap layer. Their work suggests that the same HVSRs can be reproduced by applying the surface-wavefield theory to a velocity structure model with a cap layer added to that model. To put it another way about one of the objectives of our study, it was to investigate whether the above suggestion of Wu et al. for HVSRs also applies to the reproducibility of the peak phase velocity. Note that the cap layer by Wu et al. (2017) was introduced for convenience to evaluate the contribution of body waves by the surface-wavefield theory. However, the added layers (layer Nos. 11-14 in Table 4) in model 111A above corresponds to the subsurface structure up to the mantle (olivine) distributed beneath the Mohorovičić discontinuity that is thought to exist beneath the Kyoto Basin.

Calculation method

Our proposed calculation of the effective phase velocity based on the full-wavefield consists of two main steps: modeling of the full-wavefield using the discrete wavenumber method (Bouchon, 1979) to numerically simulate the actual microtremor field, and theoretically incorporating the wavenumber spectra obtained by this modeling into the calculation process of the SPAC method. The details of this formulation are given in Uebayashi et al. (2020), and only the main points are

254 explained here.

255 Effective phase velocities in the SPAC method were traditionally interpreted in terms of surface
256 waves (e.g., Cho, 2019). To allow interpretation on the basis of full-wavefields, Uebayashi et al.
257 (2020) related the SPAC coefficient $\bar{\rho}_v$ obtained from vertical microtremor components to the
258 wavenumber k according to

$$259 \quad \bar{\rho}_v(f, r) = \int_0^{\infty} J_0(rk) P_v(f, k) dk, \quad (1)$$

260 where $J_0(\cdot)$ is the zeroth-order Bessel function of the first kind, r is the radius, and P_e is a
261 quantity that normalizes the one-dimensional frequency (f)-wavenumber spectrum, called the
262 Hankel spectrum $H_v(f, k)$ (Haubrich and Macamy, 1969), by the power $S_v(f)$ [eq. (3)] for all
263 wavenumbers, as expressed in equation (2).

$$264 \quad P_v(f, k) = \frac{H_v(f, k)}{S_v(f)}, \quad (2)$$

265 where

$$266 \quad S_v(f) = \int_0^{\infty} H_v(f, k) dk. \quad (3)$$

267 Based on the SPAC method, H_v is obtained from the azimuthal integral of the power F_v of waves
268 arriving from each azimuth ϕ at a certain point, and is expressed as

$$269 \quad H_v(f, k) = \frac{1}{2\pi} \int_{-\pi}^{\pi} F_v(f, \phi, k) d\phi. \quad (4)$$

270 We compute FK power spectra by converting a frequency response $G_v(f, a, \theta)$ of an arbitrary

point (a, θ) in the cylindrical coordinate system for excitation points randomly distributed over the ground surface (Lachet and Bard, 1994) to the frequency-wavenumber domain using the following equation:

$$F_v(f, k, \phi) = \left| \int_0^{\bar{R}} \int_0^{2\pi} G_v(f, a, \theta) \exp\{iak \cos(\theta - \phi)\} a \cdot da d\theta \right|^2, \quad (5)$$

where $G_v(f, a, \theta)$ is a frequency response of the vertical motion and was obtained by the discrete wavenumber method (Bouchon, 1979) using the Cartesian coordinate system. (x, y) to (a, θ) is transformed by $(x, y) = (a \cos\theta, a \sin\theta)$. i is the imaginary unit. The frequency responses due to each excitation point were summed for all excitation points to obtain G_v in equation (5).

Substituting the left side of equation (1) obtained in the process described above into the following equation based on the relationship between the effective phase velocity and the SPAC coefficient (e.g., Cho, 2018) yields the effective phase velocities c^e for the full-wavefield:

$$c^e(f) = \frac{2\pi r f}{J_0^{-1}(\bar{\rho}_v(f, r))}. \quad (6)$$

In this study, aside from the use of the realistic velocity structure model, the computational procedures described above, together with the parameter values for the theoretical calculations, are identical to those of Uebayashi et al. (2020).

Theoretical calculation results and comparison with measurement results

Concerning the first question posed in the introduction regarding phase velocity, in this section we compare the phase velocities based on the full-wavefield theory with those identified from the measurement record. Before going into the main topic of this section, we investigate how the phase velocities from the primary model (model 111) are affected by each of the three aforementioned uncertainties described in the section “Velocity structure model.” The investigation found the following three results. **(1)** For larger values of the P- and S-wave velocities in the upper layer of the Tb-Group [Fig. 6(a)], the peak phase velocity decreases slightly and the frequency at which it peaks shifts upward [Fig. 7(a): models 112 < 111 < 113 for P- and S-wave velocities]. **(2)** The peak phase velocity is almost proportional to the velocity contrast at the boundary between the upper and lower layers of the Tb-Group [Fig. 6(b)], [Fig. 7(b): models 121 < 111 < 131 for velocity contrast]. **(3)** As the boundary between the upper and lower layers of the Tb-Group deepens [Fig. 6(c)], the frequency at which the phase velocity peaks shifts slightly downward, but the peak value remains unchanged [Fig. 7(c): models 211 < 111 < 311 for boundary depth]. In summary, we find that the value of the peak phase velocity is strongly affected by the velocity contrast at the boundary between the upper and lower layers of the Tb-Group, but is seldom affected by the boundary depth.

To answer the question (i.e., “Can the peak phase velocity observed in the real world be reproduced by the full-wavefield theory?”), the phase velocities of the primary model among the seven models shown in Figure 7 best reproduced those identified from the measurements not only

in terms of peak value and peak frequency, but also in terms of the spectral shape near the peak. From this result, we can say at this stage that in modeling the P- and S-wave velocities for each layer of the Tb-Group consisting of two layers at KD-1, we best reproduced the measured phase velocities by using the average value of the PS logging data in the Tb-Group at KD-1 for the upper layer and the average value of the PS logging data in the Tb-Group at KD-0 and KD-2 for the lower layer.

PEAK PHASE VELOCITY FROM SURFACE-WAVEFIELD VIEWPOINT

Reproducibility by surface-wave modeling of peak phase velocity generated by full-wavefield modeling

Concerning the second question (i.e., “Can the peak phase velocity be reproduced by the surface-wavefield theory?”) regarding the phase velocity, in this section, we evaluate the reproducibility of the peak phase velocity by the surface-wavefield theory. The thick gray solid and dashed curves shown in Figure 8 are the calculation results of the effective phase velocities obtained by superposition of all Rayleigh wave modes based on the surface-wavefield theory (Tokimatsu et al., 1992) for models 111A and 111, respectively. For reference, the phase velocities of each order mode of Rayleigh waves for each model are also shown as thin gray solid and dashed curves. The

phase-velocity dispersion curves based on the full-wavefield theory (circles in Fig.7) and the measurements (solid and dashed lines in Fig.7) are also shown for comparison with those based on the surface-wavefield theory. In this figure, the phase velocity dispersion curve based on the surface-wavefield theory (gray dashed curve) for model 111 (i.e., the primary model used for our full-wavefield calculations) does not exhibit the peaked shape and is quite different from those of the full-wavefield theory and the measurements below 0.55 Hz. In contrast, the phase velocity dispersion curve (thick grey solid line) based on the surface-wavefield theory for model 111A, which includes a cap layer, does show a peaked shape, which approximately matches that based on the full-wavefield theory (circles). Above 0.45 Hz, except for around 2 Hz, the surface-wavefield of Model 111A and the full-wavefield of Model 111 agree extremely well. This can be interpreted as the full-wavefield having no body-wave component and the surface-wave component making up the entire composition of the full-wavefield.

Similarity of peak phase velocity generation mechanism between full- and surface-wavefields

To investigate how the peaked shape generated by the body-wave component in the full-wavefield for model 111 is formed in the surface-wavefield phase-velocity curves for model 111A, we evaluated the medium response for each mode of Rayleigh waves. The results, shown in Figure 9,

indicate that the medium response for the fundamental mode exhibits the minimum value near the peak frequency, while the medium response for each of the higher-order modes exhibits a local maximum at a slightly shifted frequency. In particular, in the range 0.4–0.55 Hz, which corresponds to the width of the peak, the higher-order modes make greater contributions to peak formation. This signifies that the peaked shape of phase-velocity curves is due to the influence of multiple higher-order modes excited by the addition of the cap layer in model 111A. In other words, the peak phase velocity due to body waves may be reproduced by applying the surface-wavefield theory to a model with an additional layer of higher elastic-wave velocities below the velocity structure model used to calculate them.

To investigate the displacement field at depth of both the full- and surface-wavefields described above, the distributions, in the depth direction, of the amplitudes of vertical motions corresponding to five distinct frequencies were calculated based on the surface-wavefield theory for models 111 and 111A and based on the full-wavefield theory for model 111 (Fig. 10). The amplitude distributions based on the surface-wavefield theory [Figs. 10(a) and 10(b)] were obtained based on Arai and Tokimatsu (2004). That is, the power spectra of all modes of the Rayleigh waves were summed and square-rooted. In contrast, the amplitude distributions based on the full-wavefield theory [Fig. 10(c)] were obtained from the square root of the power spectrum of equation (3) calculated at each depth. These distributions were normalized by the corresponding surface

amplitudes. Looking at the curves corresponding to the peak frequency (0.45 Hz) near a depth of 0.6 km (indicated by an arrow in each figure), we can find a local maximum in the surface-wave result for model 111 [Fig. 10(a)], but not in the surface-wave result for model 111A [Fig. 10(b)] nor in the full-wave result for model 111 [Fig. 10(c)]. Thus, the results of Figure 10 demonstrate that full-wave calculations including body-wave effects may yield results similar to those of surface-wave calculations based on a velocity-structure model with a cap layer.

The above depth distributions can be used to interpret the difference in the values of the phase velocities at 0.45 Hz as calculated based on the surface-wavefield theory for models with and without the cap layer (thick grey curve vs. dashed grey curve in Fig. 8). In the model without the cap layer [Fig. 10(a)], there is an accumulation of surface-wave energy (inferred from the amplitude) near a depth of 0.6 km, and almost no energy at depths below 10 km; in contrast, for the model with the cap layer [Fig. 10(b)] we can see surface-wave energy penetrating to depths below 10 km. This finding implies that, in the model with the cap layer, S-wave velocities in layers at depths of 10 km or greater contribute to the formation of peak phase-velocity dispersion curves.

We next examine the contribution of each mode to the frequency-specific amplitude distributions for model 111A, which is shown in Figure 10(b). Figure 11 plots the amplitude distributions for the first five modes. The higher-order modes, which generate the peaked shape of a phase-velocity dispersion curve, have relatively large amplitudes at depths of 10 km and deeper.

In summary, with respect to the previous statement that when the cap layer is present, the spatial distribution of the surface-wave energy extends to depths of approximately 10 km and below, it is found that this depth extension is made by the higher-order modes.

As described in the section "Velocity structure model", the cap layer is not a fictitious layer introduced for the sake of convenience to reproduce the peak phase velocity by surface-wavefield theory; rather, it corresponds to the deep subsurface structure up to the mantle. The results in this section raise the question of whether the measured peak phase velocity is caused by the body waves generated in the model (model 111) with the lower Tb-Group which is the half-space or by the higher-mode surface waves generated in the model (model 111A) with the mantle. However, it is difficult to answer this question clearly within the scope of the present study.

HVSR IN FULL-WAVEFIELD

To investigate the question posed in the introduction regarding the HVSR, in this section, the HVSRs based on the full-wavefield theory used to evaluate phase velocities are compared with those of measurements. In addition, the reproducibility of HVSRs based on the surface-wavefield theory is discussed.

396 Calculation method

397 The HVSR for the full-wavefield theory is given by

398
$$HVSR = \left\{ \frac{S_r(f) + S_t(f)}{S_v(f)} \right\}^{1/2}, \quad (7)$$

399 where S_r , S_t , and S_v are the power spectra corresponding to the radial r , tangential t , and
400 vertical v components, respectively, of the cylindrical coordinate system. Of these, S_v is the
401 same as the left-hand side of equation (3) used to obtain the theoretical phase velocity. Moreover,
402 S_r and S_t are obtained from the same equation, in which the subscript v in equation (3) for the
403 vertical motions is rewritten as r and t . Here, the frequency responses G_r and G_t in the radial
404 and tangential motions are needed to replace G_v in equation (5). However, it is not necessary to
405 calculate them anew in the process of deriving the HVSR. This is because G_r and G_t in addition
406 to G_v can be obtained as a three-dimensional response simultaneously in the process of obtaining
407 the full-wavefield phase velocity.

408 The HVSR based on the surface-wavefield theory, not limited to the full-wavefield theory,
409 depends on parameter α , that is, the ratio of horizontal to vertical vibration force. This is because
410 the HVSR in the surface-wavefield depends on the Rayleigh-to-Love-waves amplitude ratio (RLR)
411 that changes with the value of α . The relationship between HVSR and α based on the surface-
412 wavefield theory has been theoretically investigated in an explicit form (Tokimatsu and Arai, 1998).
413 However, there is arbitrariness in setting the value of α in the HVSR evaluation. It has been

empirically shown that the range of variation of α is about 0.35–0.6 in the frequency band (0.2–2 Hz) we focused on (Arai, 1999). With this as a reference, we used the median value (about 0.5) to obtain the HVSR of the full-wavefield. Note that we have verified in Appendix B that the value of α set here is reasonable.

Comparison of HVSRs between theoretical calculation and measurement

Figure 12 shows HVSRs calculated for each of the seven models in Table 3. The measured HVSRs are also shown in the figure for comparison. It can be seen that the peak frequencies of these HVSRs lie close to the frequencies at which peak phase velocities occur. With the exceptions of model 112, model 113 [Fig. 12(a)], and model 311 [Fig. 12(c)], theoretical HVSRs for different velocity-structure models differ only slightly. Comparison of the theoretical and measurement results shows that the theoretical HVSRs largely reproduce the shape of the measured HVSRs. For model 121, we can see no clear velocity contrast except at the Os-Group/Tb-Group boundary (at 0.223 km deep), indicating that HVSR peaks are formed under strong effects of this velocity contrast and the thickness of the Os-Group layers. This result also follows from the observation that models 111, 112, and 113, which have different degrees of velocity contrast, yield different values for the magnitude of the HVSR peak near 0.45 Hz. In model 112, there is no velocity contrast at a depth of 0.223 km, but there is a large velocity contrast at $Z=0.35$ km, causing the

peak frequency to shift downward. In contrast, the magnitude and depth of the velocity contrast between the upper and lower layers in the Tb-Group layers, which generate peaked shapes in the phase-velocity dispersion curves, have essentially no impact on the formation of HVSR peaks for the frequency band presented. This conclusion also follows from the observation that models 121, 131, and 211 yield nearly identical HVSR spectra.

Comparison with surface-wavefield

Figure 13 shows HVSRs determined from the surface-wavefield theory (Tokimatsu and Arai, 1998), which considers Rayleigh and Love waves simultaneously, for models 111 and 111A, together with the full-wavefield theory and measurement results for comparison. In the calculation of the surface-wavefield, the value of α was set to 0.5, as was the case for the full-wavefield. Comparing the surface-wavefield results for model 111A, in which the cap layer is present, to the full-wavefield results for model 111, we find that the peak frequencies at 0.48 Hz and shapes of the spectra are in general agreement. This result confirms previous studies (Lunedei and Albarello, 2010; Wu et al., 2017), which found that the higher-order modes of the surface waves generated by considering the cap layer reproduced the HVSRs formed by the body waves, even in the low-frequency range below 1 Hz for the real site. Although not shown in the figure, the peak values of HVSRs for the surface-wavefield for model 111 lie far beyond the vertical-axis extents of the plots

because the cutoff frequency for the first-order higher mode is 0.58 Hz for model 111 and only the fundamental mode exists near our frequencies of interest. That is, as is evident from the results of Arai and Tokimatsu (2004, 2005), such high-velocity layers (i.e., the cap layer) prevent HVSRs from attaining unobservable large peak values.

DISCUSSION

The peak frequencies of both the phase-velocity dispersion curves and the HVSRs were very close at 0.45 Hz and 0.48 Hz, respectively. We also note that these frequencies lie near an S-wave resonant frequency, as the following calculation shows: Based on the velocity structure in Table 2, for layer Nos. 1 to 8, the Os-Group is 0.223 km thick and has an average S-wave velocity of 0.46 km/s, from which we can calculate a resonant frequency of 0.52 Hz by the quarter-wavelength method of S waves. The mechanism from the point of view of wave type that produces the peak phase velocity of vertical motions is interpreted in Uebayashi et al. (2020) as follows: the peak phase velocity is formed under strong contributions of the P waves to the vertical components, which are generated at the surface and the subsurface boundary by conversion from the SV waves; SV waves propagate over large distances within the surface layer while being reflected multiple times at the S-wave resonance frequency. This interpretation also applies to the vertical motion, which is a component of the HVSR peak, because the two peak frequencies are proximate. In

contrast, it was inferred that the other component of the HVSR peak, the horizontal motion, has a greater contribution from Love waves than from SH waves as body waves (see Appendix C).

Early studies of microtremor phase velocities and HVSRs assumed that wavefields were dominated by the fundamental mode of Rayleigh waves. Later studies incorporated the effects of higher-order modes in addition to the fundamental mode, and have been extending the consideration to include the effect of Love waves as described in the introduction. In this study, we showed that full-wavefield calculations, or the incorporation of body waves, can accurately reproduce the observational results obtained at experimental site KD-1 in the Kyoto Basin, not only for HVSRs but also for phase velocities. This finding demonstrates that, for the purpose of accurately reproducing peak phase velocities, full-wavefield modeling is a viable alternative to surface-wave modeling with cap layers.

Comparing the panels with the same labels [(a), (b), and (c)] in Figure 7 (for phase velocity) and Figure 12 (for HVSR) showing the effect of the uncertainty in velocity structure, shows that Figure 7 reveals a larger change near each peak frequency due to model differences than does Figure 12. This may indicate that the phase velocity is more sensitive to differences in velocity structure than is the HVSR. In other words, it may be effective in improving accuracy to use the phase velocity in addition to HVSR for velocity structure estimation using the full-wavefield theory.

The goal of this study, to see if the peak phase velocities observed in reality can be reproduced by full and surface wavefield theories, and if these theories are also effective in reproducing HVSRs, has been achieved. We hope to address interesting questions like "Which is the microtremor wavefield in the real world?"

CONCLUSIONS

In this work, the effects of body waves on the phase velocities and HVSRs of microtremors were investigated based on a comparison of measurements and theoretical calculations to confirm whether the measured peak phase velocity can be reproduced by the full-wavefield theory and/or the surface-wavefield theory, and whether these theories are also effective in reproducing HVSRs. Specifically, the methods of investigation were as follows:

- (1) We used vertical-component array waveforms and single-station three-component waveforms of microtremor records, obtained at and around a site in the Kyoto Basin (KD-1) where PS logging was conducted. To reproduce the measured microtremor wavefield by theory, we first performed theoretical calculations of microtremor wavefields based on the full-wavefield and the surface-wavefield theories using a velocity-structure model in which the Tb-Group, which is the shallowest consolidated layer (i.e., bedrock) in this region, is treated as the bottom layer

of a half-space.

- (2) To investigate the velocity structure at depths beyond the bottom of the PS logging at KD-1, we used PS-logging data at two additional sites, located south and north of KD-1, to construct several velocity-structure models, taking into account three sources of uncertainty. Among these, two layers with different physical properties were assumed for the Tb-Group. Comparisons were made between the calculation results using these models for the phase velocities and HVSRs.
- (3) To reproduce the measured peaks of phase velocities and HVSRs based on the full-wavefield theory and also on the surface-wavefield theory, we constructed a model containing a cap (i.e., high-velocity) connected to and underlying the Tb-Group and calculated microtremor fields on the basis of the surface-wavefield theory.

The following conclusions were reached for each of the above methods:

- (1) The measured phase-velocity dispersion curve exhibited a peaked shape, with the peak value (i.e., peak phase velocity) exceeding the assumed bedrock (half-space) S-wave velocity. Theoretical calculations based on the surface-wavefield theory were unable to reproduce this peaked shape; however, theoretical calculations based on the full-wavefield theory reproduced it with extraordinary accuracy. Furthermore, the theoretical calculation based on the full-wavefield accurately reproduced the peak value and peak frequency of the measured HVSRs.

On the other hand, the one based on the surface-wavefield reproduced the peak frequency, but not the peak value.

(2) Larger values of the velocity contrast between the two Tb-Group layers correspond to higher values of the peak phase velocity, but did not affect the frequency at which the peak occurred. Both the value and frequency of the peak phase velocity were seldom affected by variations in the depth of the inter-layer boundary. The peak of the HVSRs was generated due to the velocity contrast between the Tb-Group (i.e., bedrock comprising consolidated sedimentary layers) and the Os-Group (i.e., unconsolidated sedimentary layers) and was largely independent of the velocity contrast within the Tb-Group layers. In other words, the above results show that the reproducibility of the peak frequencies of the phase velocities and HVSRs was robust to uncertainties in the velocity structure caused by the variability and the inadequate borehole depth of the PS logging data used in this study.

(3) The peaks of the phase velocities and HVSRs obtained from the surface-wavefield considering the cap layer good agreed with those from the full-wavefield. It was revealed that, in the surface-wave-based calculations, the peaked shapes of phase-velocity dispersion curves are formed by the contributions from multiple higher-order modes.

540 Data and resources

541 Microtremor array observation data and PS- and density logging data used in this work were
542 obtained by the Committee of investigation for Kyoto basin subsurface structure established by
543 Kyoto City Office and provided by Kyoto City Disaster Prevention and Crisis Management Office.
544 Plots of the logging data used in this paper are published on the website listed in the references.

545

546 Declaration of competing interests

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

548

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Figure Captions

Figure 1. Location of the microtremor arrays and three boreholes for the PS and density loggings plotted on the Kyoto Basin topographic map (Geol. Surv. Japan, AIST, 2022).

Figure 2. PS and density loggings at the three sites plotted in Fig. 1. The high velocity contrasts at depths 0.7 km at site KD-0, 0.22 km at site KD-1, and 0.2 km at site KD-2 correspond to the boundary between the Tamba and Osaka Groups, respectively [(a)-(c)].

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Figure 5. Number of different array radii used to estimate the phase velocity for SPAC method (a) and phase velocities identified by SPAC (b) and FK (c) methods.

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Figure 7. Comparison among theoretical phase velocities for the velocity-structure models shown in Table 3 and phase velocities of SPAC and FK methods shown in Figs. 5(b) and 5(c). Panels (a), (b), and (c) correspond respectively to varying the medium parameters of layer Nos. 9 and 10, and the depth Z , as summarized in Tables 2 and 3.

Figure 8. Comparison of theoretical phase velocities between the surface-wave and the full-wave modelings. Black solid and dashed lines are redrawn from Figs. 5(b) and 5(c).

Figure 9. Rayleigh-wave medium responses of model 111A. The lower panel shows an enlargement of the frequency range from 0.40 to 0.60 Hz.

Figure 10. The normalized amplitudes of vertical component in the depth direction at five frequencies. Panels (a) and (b) represent the mode-composed surface- (Rayleigh-) wavefield for model 111 and model 111A, respectively. Panel (c) represents the full-wavefield for model 111. Arrows are shown to illustrate the difference in features of the amplitude at 0.45 Hz between panels (a), (b), and (c).

Figure 11. The normalized amplitudes of the Rayleigh-wave 0th-5th modes that make up the depth-dependent shape of Fig. 10(b). The amplitude distributions, excluding the second mode, at 0.5 Hz, so far beyond the horizontal axis of the plots, have little effect on the amplitude at the same frequency shown in Fig. 10(b), because the second mode is dominant in the medium response shown in Fig. 9.

Figure 12. Comparison between theoretical HVSRs for the velocity-structure models in Table 3 and measured HVSRs. Panels (a), (b), and (c) correspond respectively to varying the medium parameters of layer Nos. 9 and 10, and the depth Z , as summarized in Tables 2 and 3.

Figure 13. Comparison of HVSRs between the surface-wave and the full-wave modelings. Gray solid line represents measured HVSRs redrawn from gray solid line in Fig. 12.

Figure A1. (a) Comparison of the number of different array radii between two different ranges of wavelengths used to evaluate phase velocities below 0.5 Hz. r is the array radius. (b) The same as Fig. A1(a), but for comparison of phase velocities. Phase velocities corresponding to wavelength range from $2.5r$ to $10r$ were evaluated from array radii greater than 1 km.

Figure B1. Comparison of HVSRs between measurement, full-wave modeling calculated as $\alpha=0.5$, and the upper and lower bounds derived from surface-wave modeling. α is the ratio of horizontal-to-vertical vibration force.

Figure B2. Comparison between the horizontal amplitude ratios of P-SV to SH-waves for full-wave modeling and those of the Rayleigh wave to the Love wave for surface-wave modeling.

Figure C1. Relative power spectra as a function of phase velocity at the peak frequency 0.48 Hz

769 in full-wavefield HVSR.

770 **Figure C2.** Fundamental-mode phase velocities of Love wave and Rayleigh wave calculated from

771 model 111.

772

Appendices

Appendix A: Reliability of peaked shape of phase velocity dispersion curve identified by the SPAC method

The phase velocities determined by applying the SPAC method to the measured microtremor records showed relatively large variations below approximately 0.4 Hz, as shown in Figure 5(b).

In this appendix, we discuss the reliability of the phase velocities identified as the average value of the variation at each frequency. As mentioned in the main text, the phase velocities were obtained from the SPAC coefficients for each array radius corresponding to the range of wavelengths from $2.5r$ to $5r$. In the SPAC method, the standard range of wavelengths based on the empirical relationship between wavelength and phase velocity for detection accuracy is generally said to be $2r$ to $7r$. Because the range we used is narrower than this, the identified phase velocities are a conservative evaluation. However, at approximately 0.4 Hz and below, the number of array radii available for phase velocity evaluation is no more than two, as shown in Figure 5(a). As a result, the standard deviation in the low-frequency range in Figure 5(b) became larger. Therefore, in an attempt to re-evaluate the phase velocity, we added data for each array radius corresponding to the upper wavelength limit of $7r$ to $10r$ for frequencies below 0.5 Hz.

The expanded range of wavelengths used in the phase velocity evaluation increased the number of array radii used in the analysis to a range of 4–6 [Fig. A1(a)]. As a result, the re-evaluation was

smaller than the initial evaluation in the standard deviation limited to ≤ 0.4 Hz. However, there was little difference in the average value of the re-evaluated phase velocities from the initial evaluation [Fig. A1(b)]. To evaluate phase velocity, one must make a trade-off between the amount of data (number of array radii) and the width of the wavelength band (conservative setting) to ensure reliability, so the best upper wavelength is difficult to determine. However, in the present case, as shown in Figure A1(b), because there is little difference in the average phase velocity between the initial evaluation and the re-evaluation, the shape of the phase velocity dispersion curve at frequencies lower than the initially evaluated peak frequency, which is based on the average values of the phase velocity, can be considered reliable to some extent.

Appendix B: Verification of the horizontal-to-vertical ratio of vibration force used to calculate full-wavefields

Single-force point sources randomly distributed on the ground surface are often used in the modeling of microtremor wavefields (e.g., Lachet and Bard, 1994; Uebayashi et al., 2020). The HVSRs in the surface-wavefield vary with the horizontal-to-vertical amplitude ratio α of the steady-state vibration force (Tokimatsu and Arai, 1998), and this is also true for the full-wavefield. In this section, we verify that 0.5 is a reasonable value for α based on surface-wavefield theory and empirical HVSRs. The reason for using the surface-wavefield theory is that there is a formula

809 that relates the HVSR to a value of α (Tokimatsu and Arai, 1998). In this formula, the HVSRs take
 810 their upper bound [eq. (B1)] when α is infinity (no vertical component in the vibration force) and
 811 their lower bound [eq. (B2)] when α is zero (no horizontal component in the vibration force) (Saito,
 812 2017).

$$813 \quad \begin{cases} HVSR_{upper} = \left[\frac{\sum_j (u/w)_j^4 (A_{Rj}/k_{Rj})^2 + \sum_j (A_{Lj}/k_{Lj})^2}{\sum_j (u/w)_j^2 (A_{Rj}/k_{Rj})^2} \right]^{1/2} \\ HVSR_{lower} = \left[\frac{\sum_j (u/w)_j^2 (A_{Rj}/k_{Rj})^2}{\sum_j (A_{Rj}/k_{Rj})^2} \right]^{1/2} \end{cases}, \quad (B1), (B2)$$

814 where the subscript j is the order of the mode; u/w is the Rayleigh-wave ellipticity; A_R and
 815 A_L are the medium responses for Rayleigh and Love waves, respectively; and k_R and k_L are the
 816 wavenumbers of Rayleigh and Love waves, respectively. As shown in Figure B1, the measured
 817 HVSRs, as well as the HVSRs obtained from the full-wavefield theory, lie between the upper and
 818 lower bounds of the HVSRs (thin solid curves) obtained using equations (B1) and (B2). This
 819 confirms that our set of α values is consistent.

820 The value of α changes not only the Rayleigh-to-Love-waves amplitude ratio (RLR) in the
 821 surface-wavefield (Tokimatsu and Arai, 1998), but also P-SV-to-SH-waves amplitude ratio (PSV-
 822 SHR) in the full-wavefield. Next, we evaluate α in terms of these amplitude ratios. The three-
 823 dimensional frequency responses (G_r, G_t, G_v) of the full-wavefield described in the main text were
 824 obtained by combining the frequency responses of each wave type, such as P, SV, and SH waves

(Bouchon, 1979). In other words, the full-wavefield responses can be expressed by the following forms: $G_r = G_r^P + G_r^{SV} + G_r^{SH}$, $G_t = G_t^P + G_t^{SV} + G_t^{SH}$, and $G_v = G_v^P + G_v^{SV}$. By substituting each term on the right-hand side of these equations in place of G_v in equation (5), the power spectrum for each wave type can be obtained in the same way that the power spectrum S_v is calculated from equations (3), (4), and (5). Therefore, from the power spectra in the P-SV-wavefield $(S_r^{P-SV}, S_t^{P-SV}, S_v^{P-SV})$ and in the SH-wavefield $(S_r^{SH}, S_t^{SH}, 0)$, the PSV-SHR in a full-wavefield is expressed as follows:

$$PSV - SHR = \left\{ \frac{S_r^{P-SV}(f) + S_t^{P-SV}(f)}{S_r^{SH}(f) + S_t^{SH}(f)} \right\}^{\frac{1}{2}}. \quad (B3)$$

As shown in Figure B2, which focuses on the frequency band below about 1 Hz that forms the peak of the HVSR, the PSV-SHRs are consistent with the RLRs and are not smaller than the RLRs corresponding to the upper bound ($\alpha=\infty$) of the HVSR. Note that the RLRs corresponding to the lower bound ($\alpha=0$) of the HVSR are infinity.

Furthermore, the PSV-SHR are less than 1.0 with RLR. This is consistent with the view that Love waves contribute more to the horizontal amplitude of microtremors than do Rayleigh waves (e.g., Arai and Tokimatsu, 2000; Bonnefoy-Claudet et al., 2008). This suggestion implies that our value of α (0.5) is consistent.

Appendix C: Contributions of body and surface waves at the HVSR peak determined by full-wavefield modeling

In this appendix, we evaluate the contribution of body and surface waves to the peak formation of HVSRs in the full-wavefield. As can be seen from equations (3) and (7), the power spectra of the horizontal and vertical components of the HVSRs are derived by integrating the Hankel spectra with respect to wavenumber. By observing the Hankel spectrum at the peak frequency of the HVSR, the power for each wavenumber can be found. If the phase velocity is used as the independent variable instead of the wavenumber, the power for each phase velocity can be determined. Figure C1 shows the power spectra of horizontal (black solid curve) and vertical (gray solid curve) motions in the full-wavefield with respect to the phase velocity at the peak frequency of HVSR of 0.48 Hz. The horizontal motion is a vector composite of the radial and tangential motions. The horizontal power spectrum is a composite of the SH and P-SV wavefields, as described in Appendix B, so the figure also shows the power spectra of SH and P-SV waves. Note that the vertical axis is normalized by the peak value of the horizontal component in the full-wavefield.

Examination of the horizontal component shows that the power spectrum of the full-wavefield is generally dominated by that of the SH-wavefield, with a phase velocity of 1.9 km/s, as indicated by the circle in Figure C1. This phase velocity corresponds to the Love-wave phase velocity at 0.48 Hz, as shown by the circle in Figure C2. In contrast, examination of the vertical component

860 shows that the phase velocity of Rayleigh waves at the same frequency is 2.2 km/s, as shown by
861 the triangle in Figure C2. However, as shown in Figure C1, the power of the vertical component
862 (triangle) is not large at this phase velocity, with a peak at about 3.8 km/s (arrow). These results
863 confirm that surface waves (Love waves) contribute to horizontal motions, whereas body waves
864 contribute to vertical motions at the peak frequency of the HVSR.
865

866 Tables

867 **Table 1.** Eleven different array sizes used to calculate SPAC coefficients.

point	L-array		M-array		S-array	
	L1, L2, L3	L4, L5, L6	M1, M2, M3	M4, M5, M6	S1, S2, S3	S4, S5, S6
radius (m)	1250	625	750	375	500	188
side length (m)	2167	1083	1300	650	—	325

868

869 **Table 2.** Velocity-structure model at the KD-1. The values of the variables V_{S9} , V_{P9} , ρ_9 , V_{S10} , V_{P10} ,

870 ρ_{10} , and Z are listed in Table 3.

layer No.	group	top depth (km)	thickness (km)	S-wave velocity (km/s)	P-wave velocity (km/s)	density (g/cm ³)
1	Os- Group	0	0.023	0.320	1.600	1.75
2		0.023	0.021	0.458	1.865	1.93
3		0.044	0.027	0.404	1.665	1.88
4		0.070	0.049	0.470	1.785	2.00
5		0.120	0.034	0.456	1.726	1.91
6		0.154	0.016	0.623	1.945	2.11
7		0.170	0.023	0.547	1.889	2.04
8		0.193	0.030	0.478	1.793	1.93
9	Tb- Group	0.223	$Z-0.223$	V_{S9}	V_{P9}	ρ_9
10		Z	∞	V_{S10}	V_{P10}	ρ_{10}

871

Table 3. Seven subsurface structure models. Model 111 is the primary model, and the other six models are modified versions of model 111.

model No.	Z	V _{S9}	V _{p9}	ρ_9	V _{S10}	V _{p10}	ρ_{10}
111	0.50	1.65	4.13	2.54	2.60	5.10	2.65
112		1.06	3.43	2.42			
113		2.24	4.83	2.65			
121		1.65	4.13	2.54	1.65	4.13	2.54
131	3.20				5.80	2.70	
211	2.60				5.10	2.65	
311							0.80

Table 4. Model 111A with the cap layer (Harvey, 1981) consisting of four layers connected below model 111 for use in the calculation of surface-wavefields.

layer No.	top depth (km)	thickness (km)	S-wave velocity (km/s)	P-wave velocity (km/s)	density (g/cm ³)
1-9	same as model 111				
10	0.5	3.5	2.6	5.1	2.65
11	4.0	8.0	3.2	5.8	2.7
12	12.0	10.0	3.4	6.0	2.8
13	22.0	12.0	3.8	6.6	2.9
14	34.0	∞	4.6	8.0	3.2

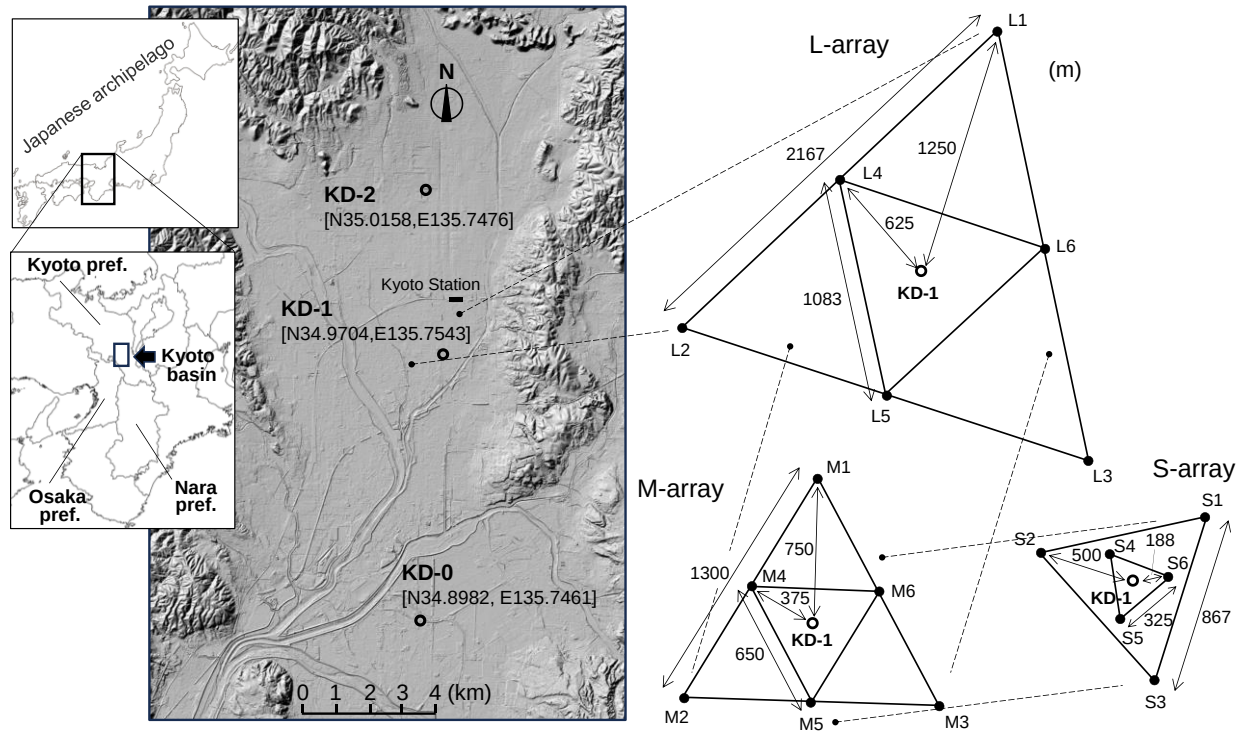


Figure 1. Location of the microtremor arrays and three boreholes for the PS and density loggings plotted on the Kyoto Basin topographic map (Geol. Surv. Japan, AIST, 2022)..

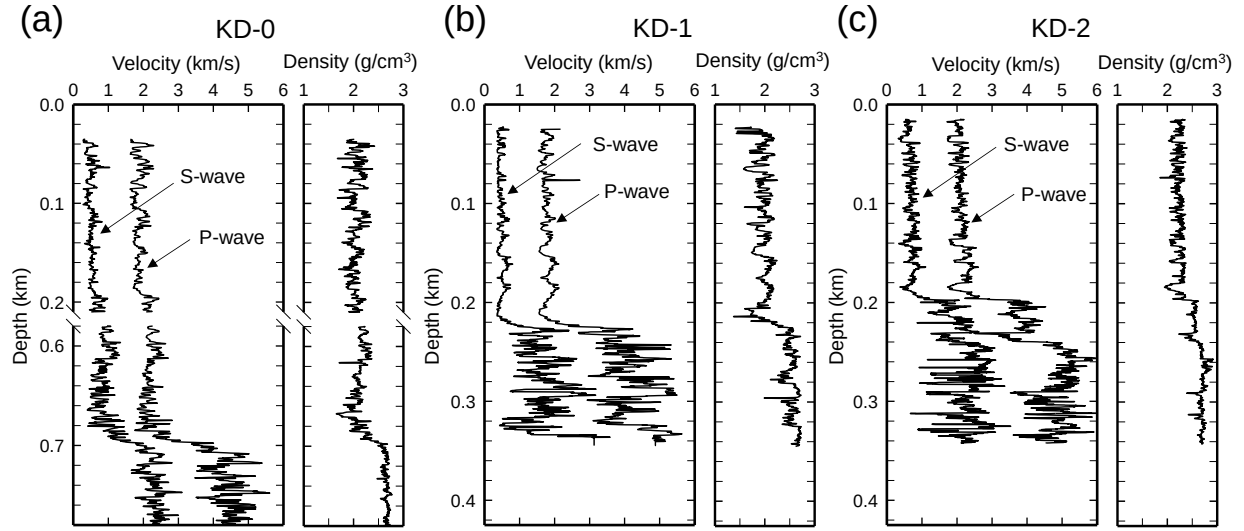
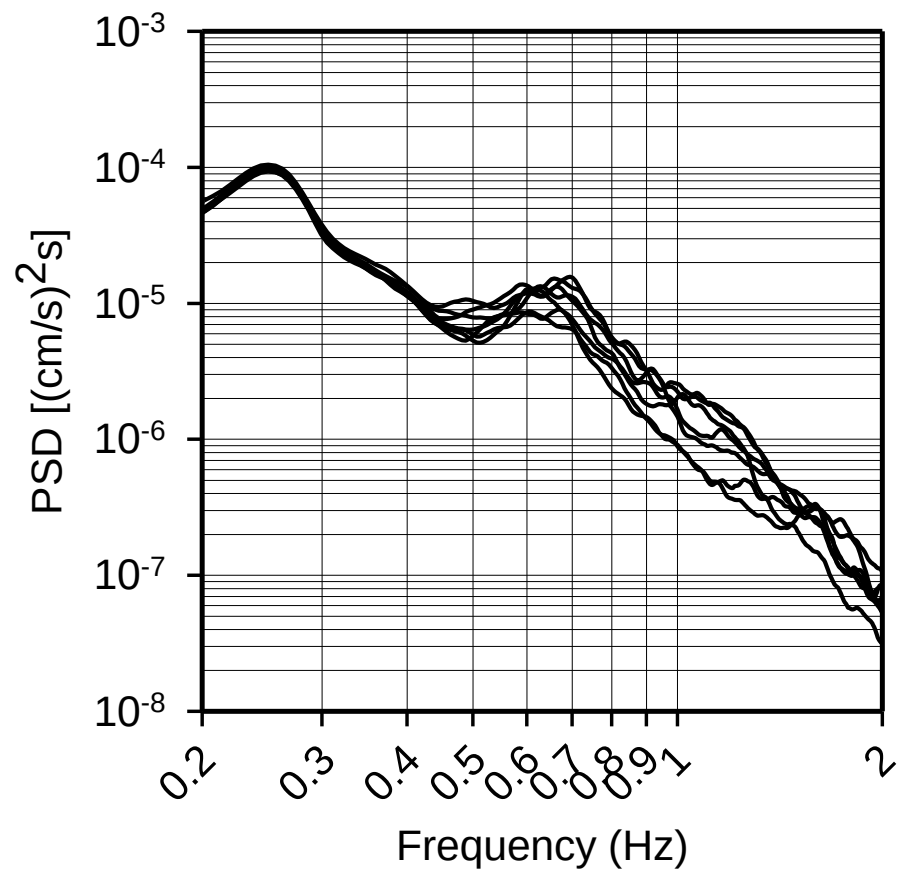


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888

889 **Figure 3.** Example of power spectral density (PSD) of the waveforms measured at seven points

890 for the L-array.

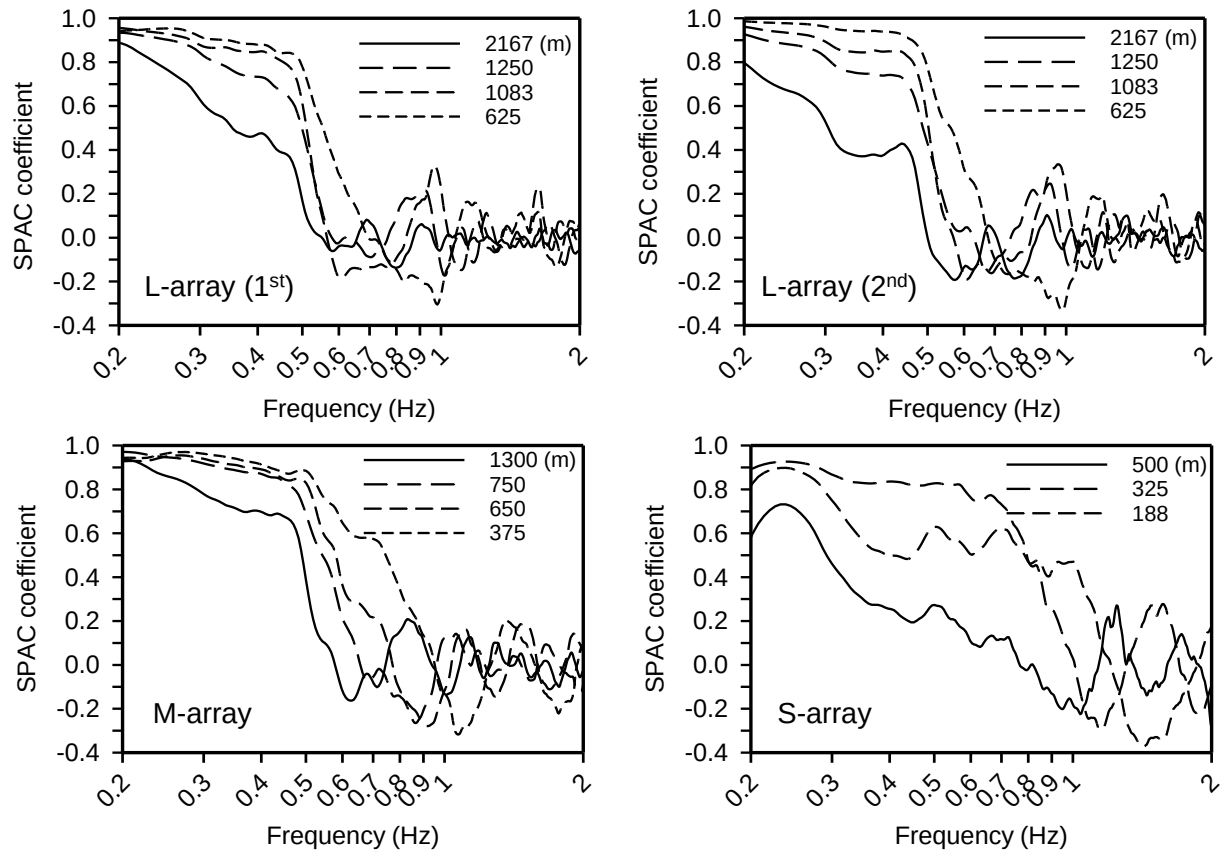


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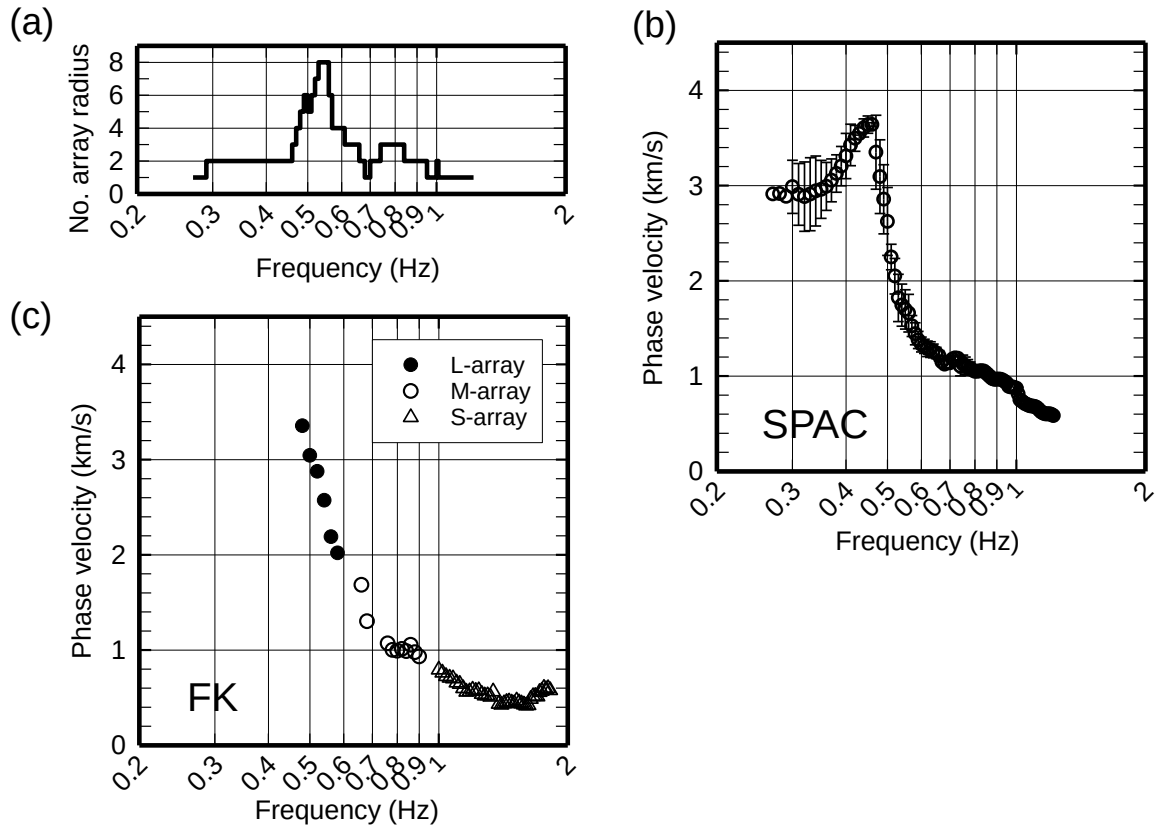


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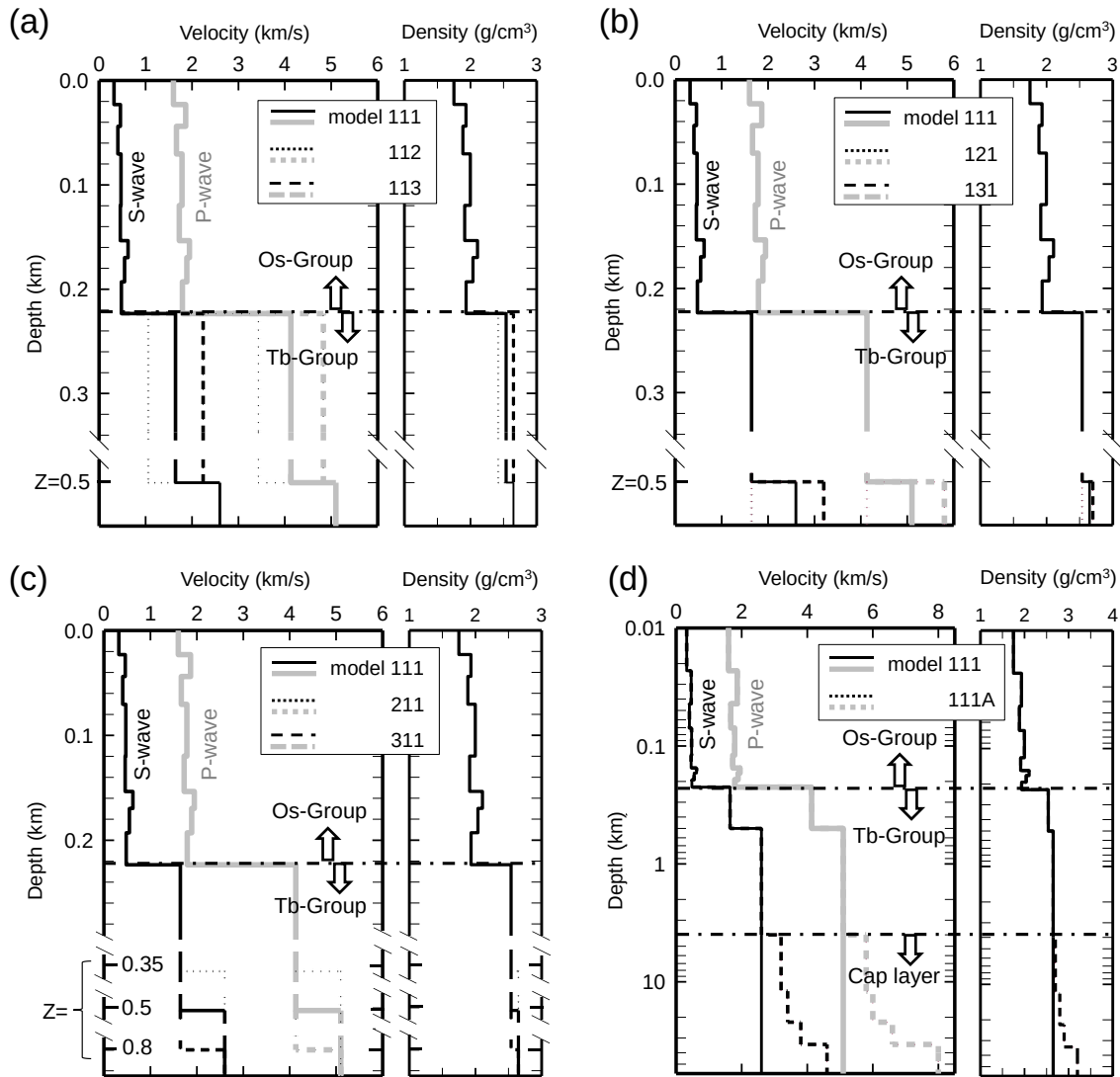


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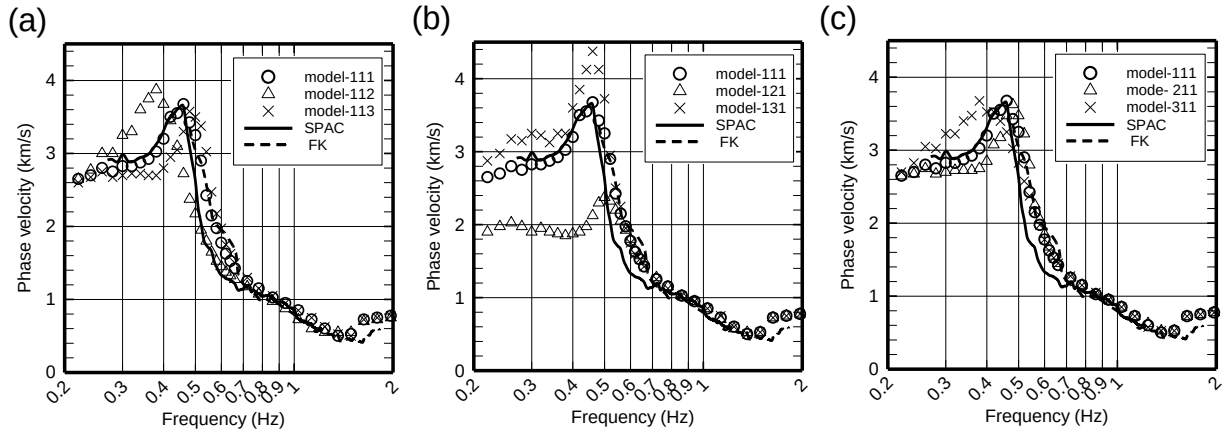


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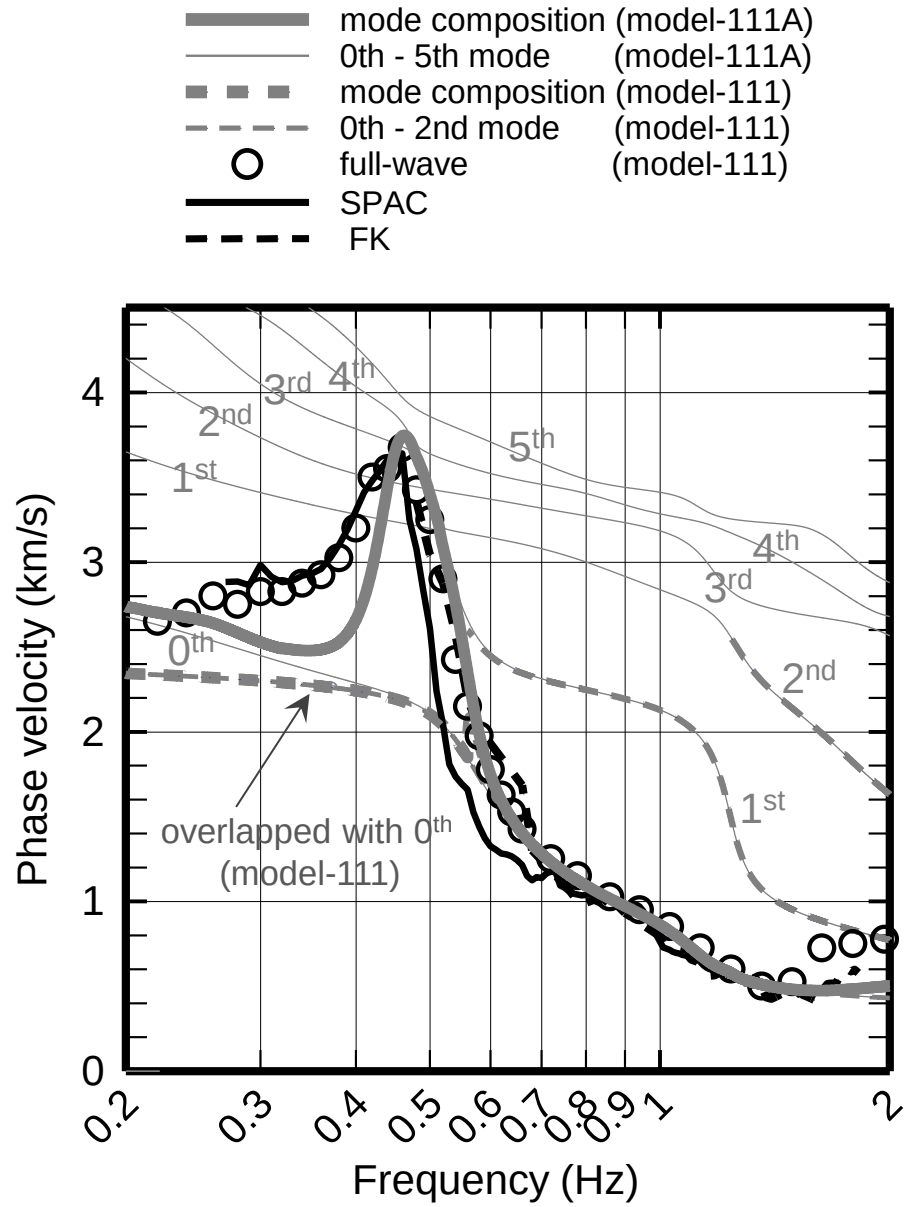


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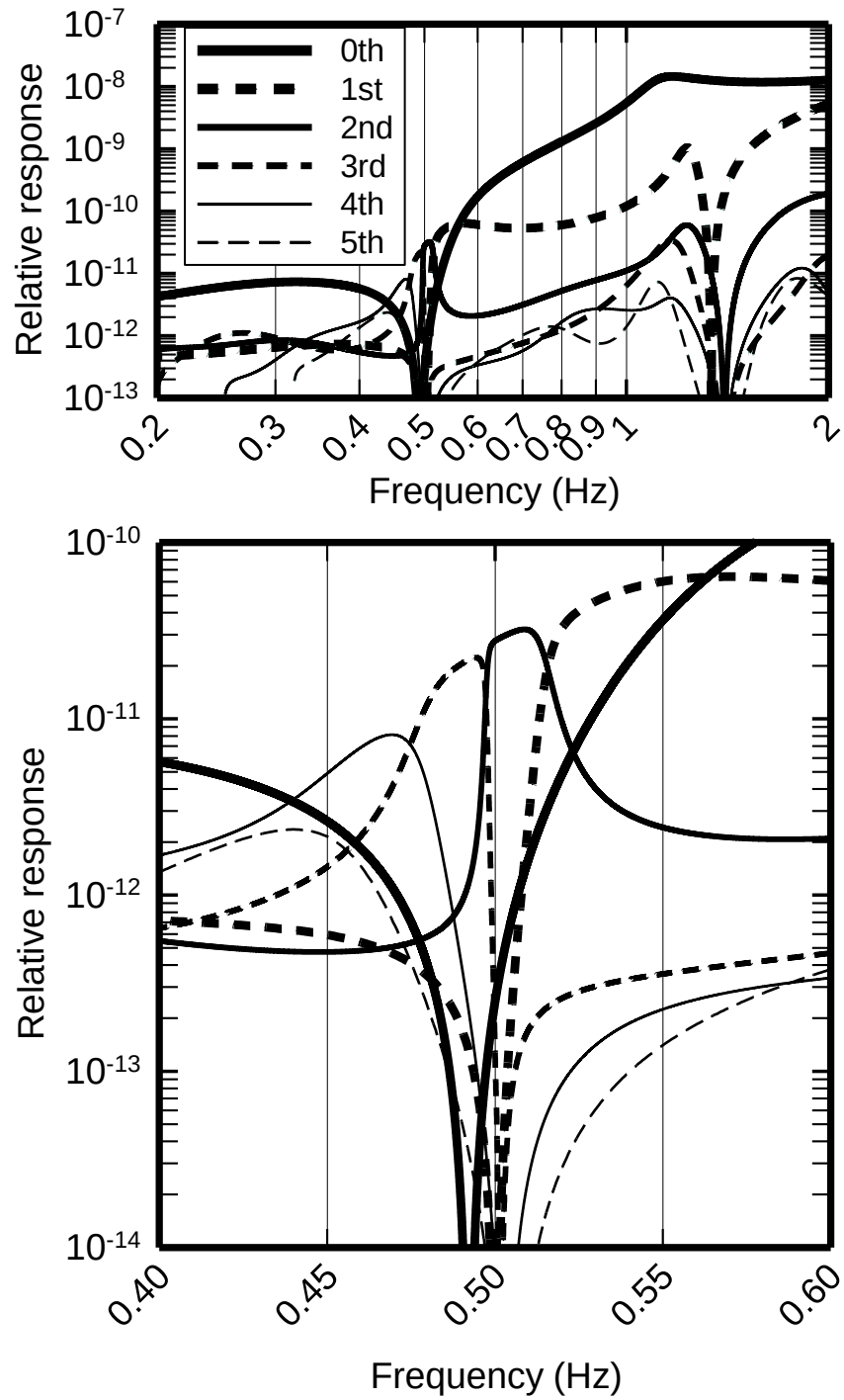


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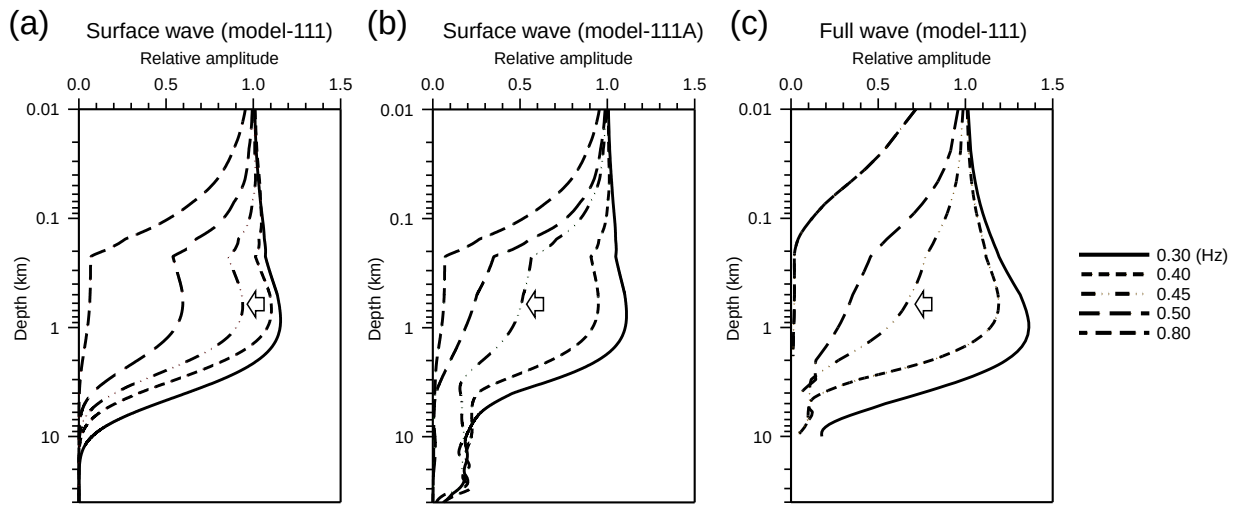


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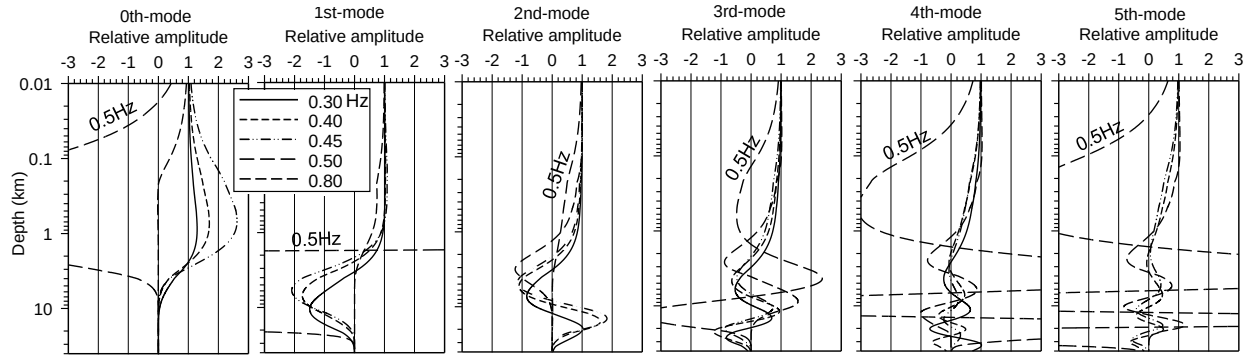


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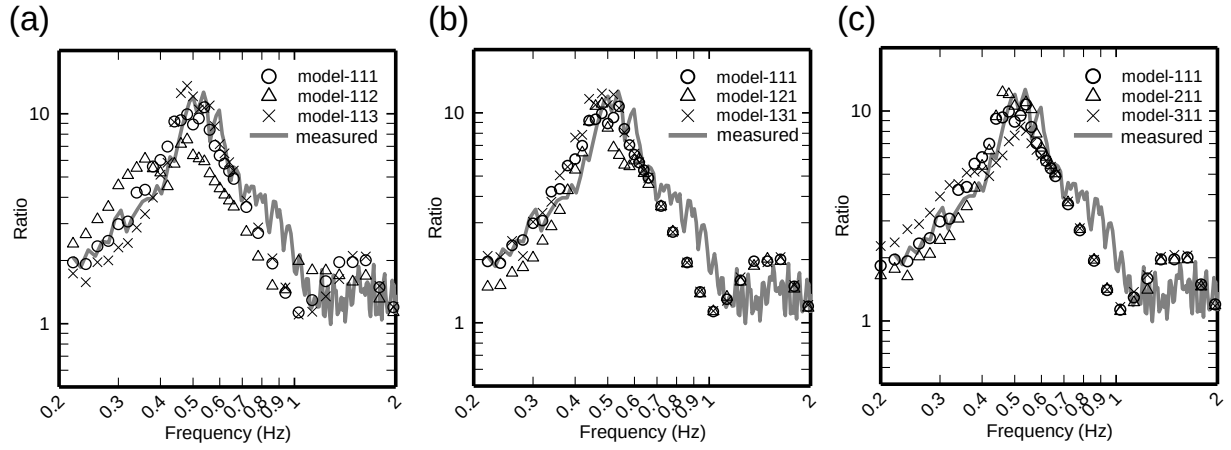
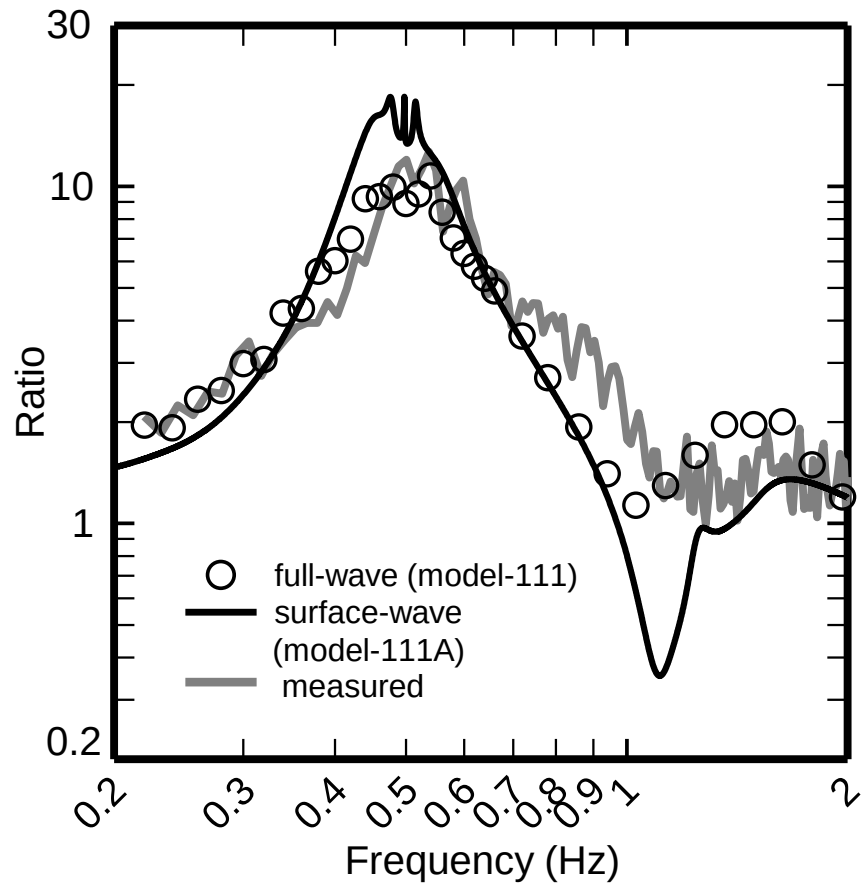


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935

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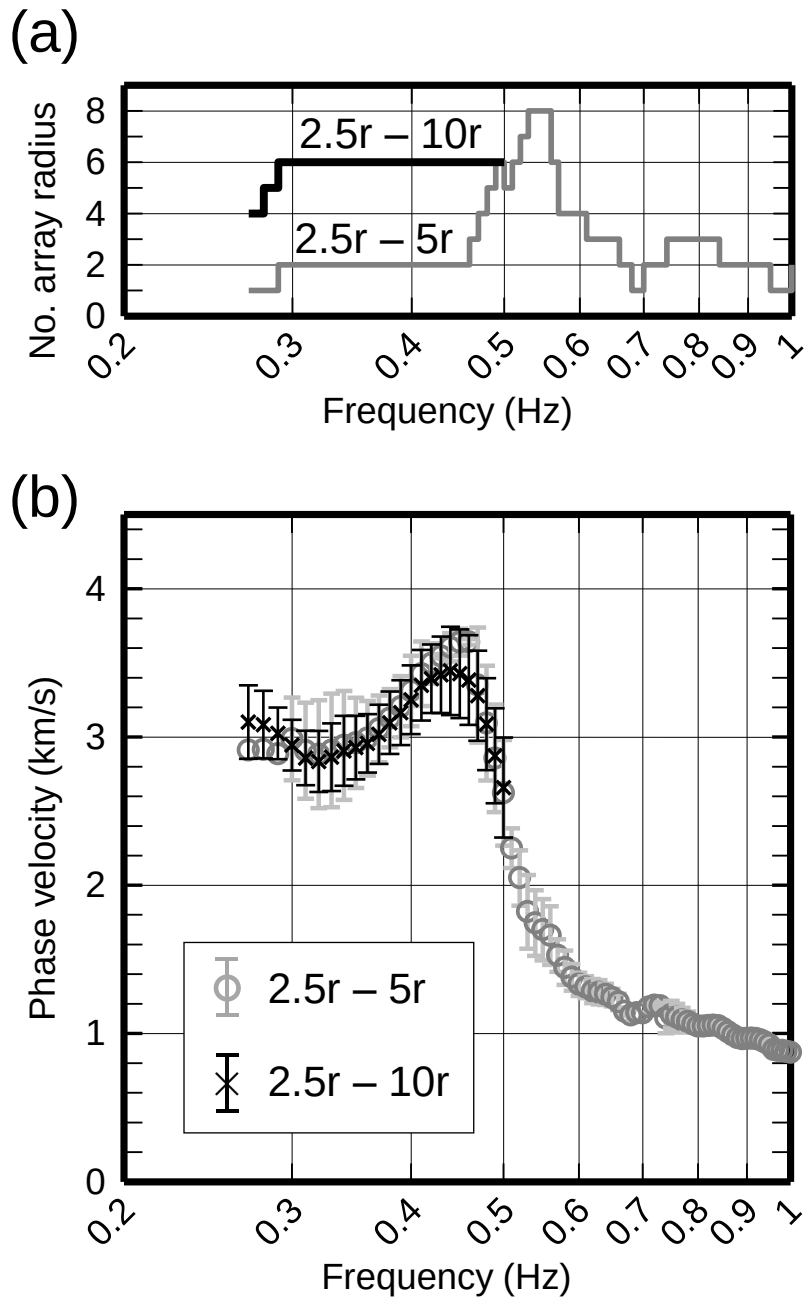


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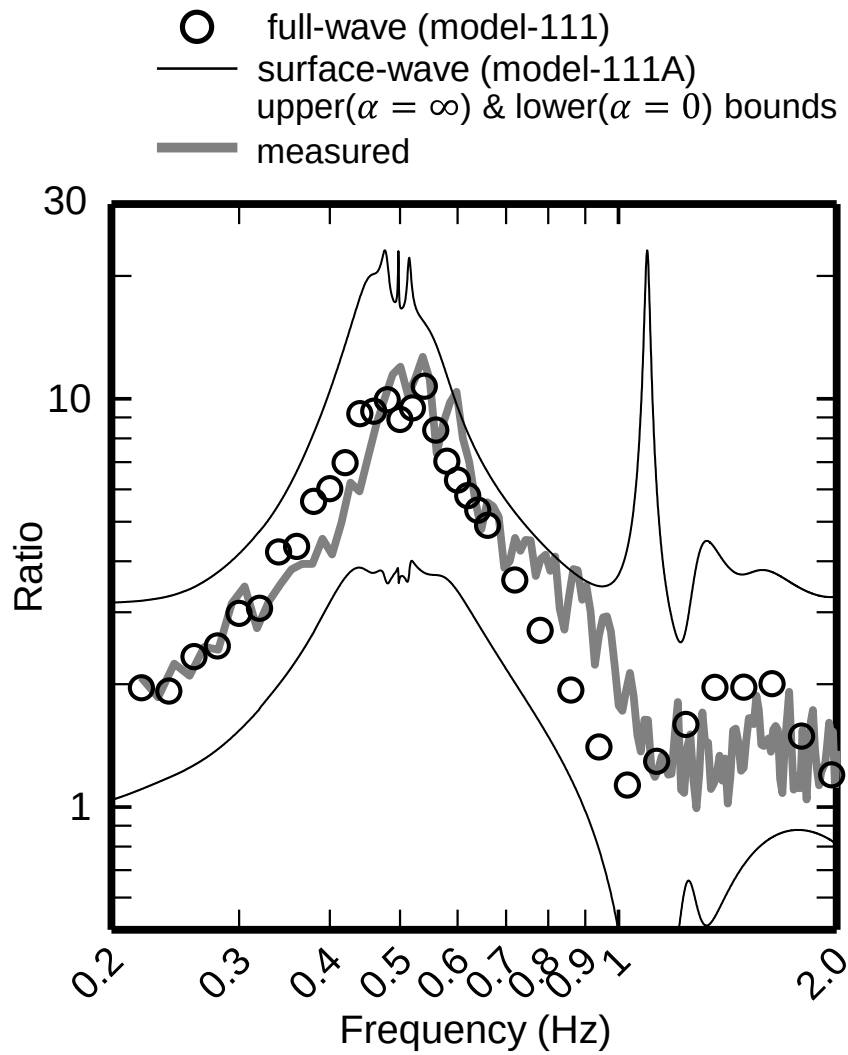


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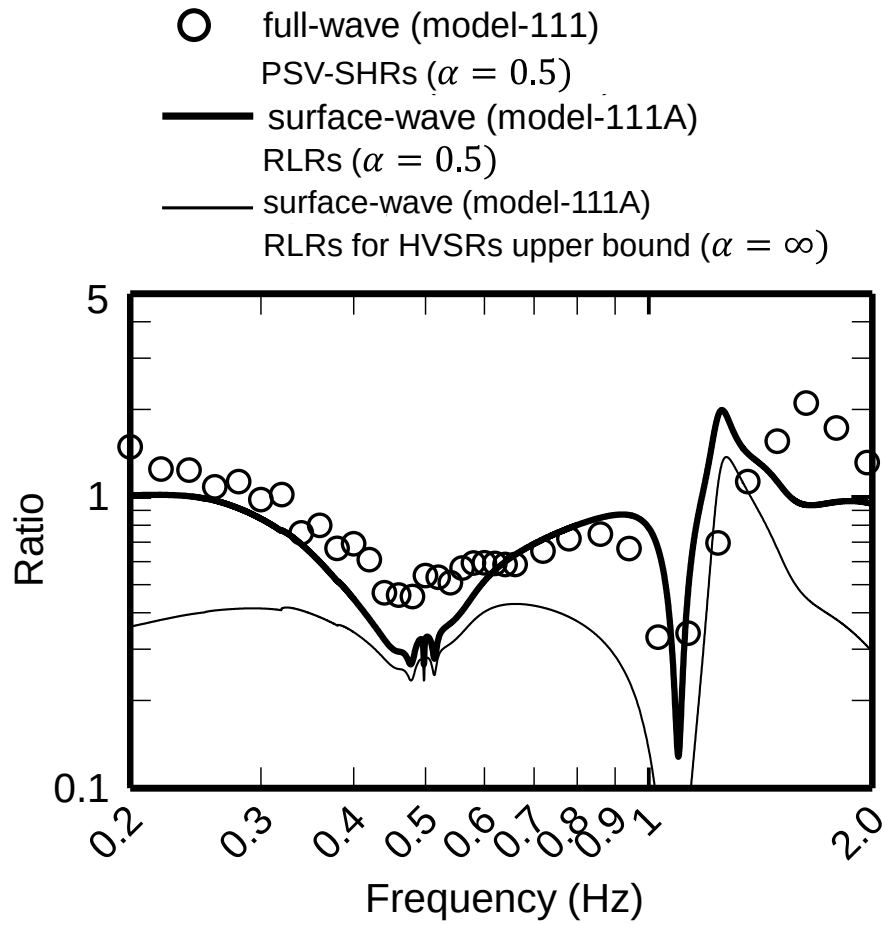


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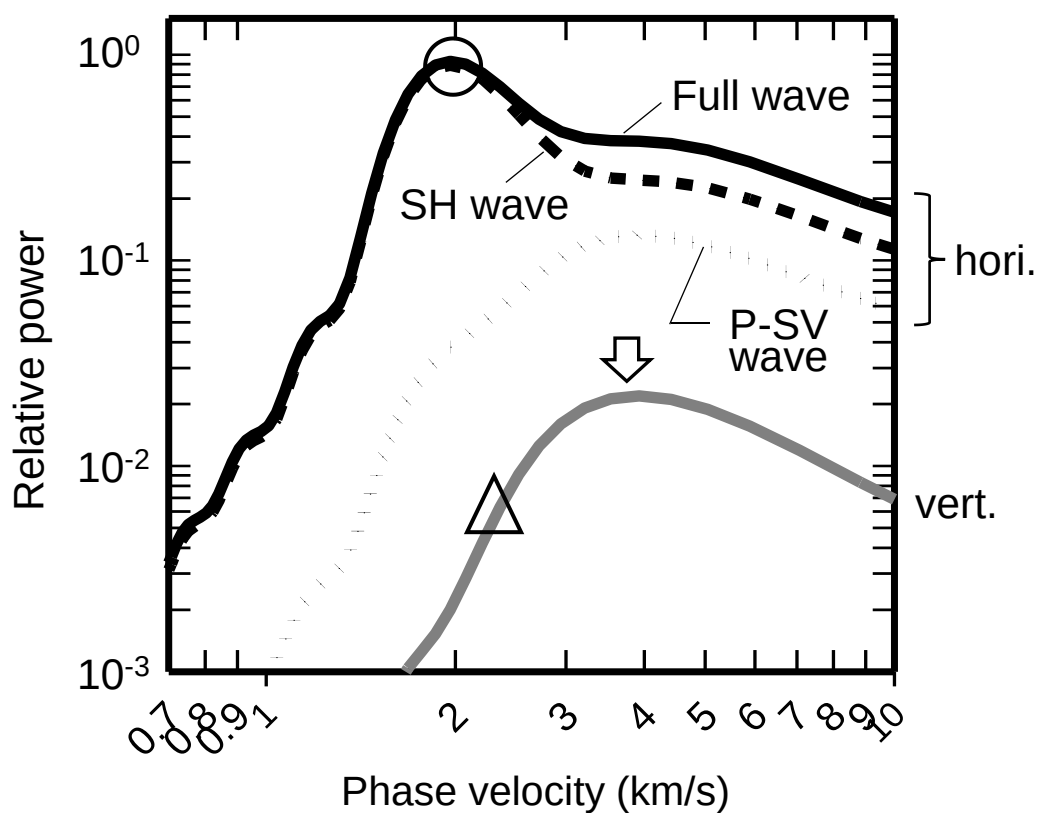
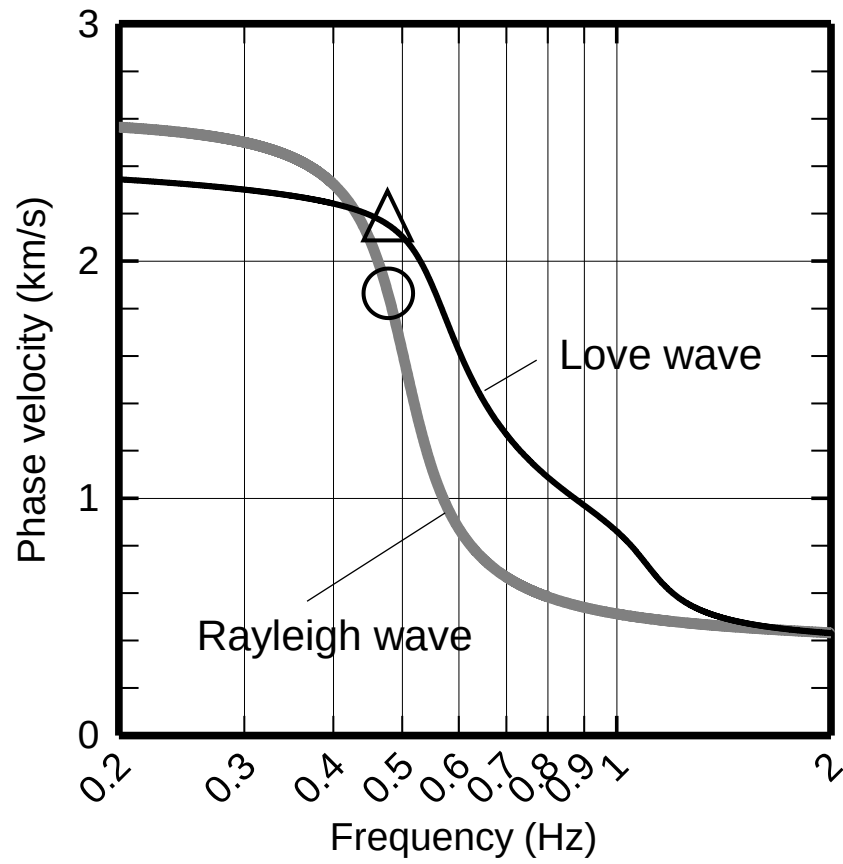


Figure C1. Relative power spectra as a function of phase velocity at the peak frequency 0.48 Hz in full-wavefield HVSR.



957

958 **Figure C2.** Fundamental-mode phase velocities of Love wave and Rayleigh wave obtained from

959 model 111.

Figure1

