Originally published as:

Zhu, C., Cotton, F., Pilz, M. (2020): Detecting Site Resonant Frequency Using HVSR: Fourier versus Response Spectrum and the First versus the Highest Peak Frequency. - Bulletin of the Seismological Society of America, 110, 2, 427-440.

<https://doi.org/10.1785/0120190186>

Detecting Site Resonant Frequency Using *HVSR*: Fourier versus Response Spectrum and the First versus the Highest Peak Frequency

Chuanbin Zhu^{*1}, Fabrice Cotton^{1, 2} and Marco Pilz¹

Abstract

In this investigation, we examine the uncertainties using the horizontal-to-vertical spectral ratio (*HVSR*) technique on earthquake recordings to detect site resonant frequencies at 207 KiK-net sites. Our results show that the scenario-dependence of response (*PSA*) spectral ratio could bias the estimates of resonant frequencies for sites having multiple significant peaks with comparable amplitudes. Thus, the Fourier spectrum (*FAS*) should be preferred in computing *HVSR*. For more than 80% of the investigated sites, the first peak (in the frequency domain) on the average *HVSR* curve over multiple sites coincides with the highest peak. However, for sites with multiple peaks, the highest peak frequency (f_p) is less susceptible to the selection criteria of significant peaks and the extent of smoothing to spectrum than the first peak frequency (f_0). Meanwhile, in comparison to the surface-to-borehole spectral ratio (*SBSR*), f_0 tends to underestimate the predominant frequency (at which the largest amplification occurs) more than f_p . In addition, in terms of characterizing linear site response, f_p shows a better overall performance than f_0 . Based on these findings, we thus recommend seismic network operators to provide f_p on the average *HVSR*_{*FAS*} curve as a priority, ideally together with the average *HVSR*_{*FAS*} curve in site characterization.

Introduction

Many previous investigations (e.g., Pitilakis *et al.*, 2018; Derras *et al.*, 2017; Stambouli *et al.*, 2017; Zhao and Xu, 2013; Luzi *et al.*, 2011; Zhu *et al.*, 2019a) have shown that site resonant frequency (or period) has a better overall performance than the conventional 30 m time-averaged shear-wave velocity (V_{S30}) in depicting site response. Hence Zhu *et al.*, (2019a) recommended using the resonant frequency as the primary predictor variable in site-effects models. Also, resonant frequency tops the list of mandatory site proxies recommended by the “Seismology and Earthquake Engineering Research Infrastructure Alliance for Europe: Networking databases of site and station characterization” (SERA-NA5) project to characterize recording stations.

One approach to obtain site resonant frequency is the horizontal-to-vertical spectral ratio (*HVSR*) approach. This technique gained momentum after a series of articles by Nakamura (1989) who very recently clarified a few misunderstandings about the so-called “Nakamura method” (Nakamura, 2019). Since then, innumerable investigations on implementing the *HVSR* method on either ambient noises or earthquake ground-motions sprung up, as reviewed by Bard (1995), Kudo *et al.* (2004) and many others. Regarding the theoretical aspects of the *HVSR*, we refer interested readers to reviews by, for instance, Bonnefoy-Claudet *et al.* (2006) and Lunedei and Malischewsky (2015), as well as works by Kawase *et al.* (2011) and many others.

Though exceptions can be found in literature, there is a general consensus that *HVSR* approach can reveal the fundamental resonant frequency of most sites but tends to underestimate the level of ground-motion amplification compared with the classic standard spectral ratio (*SSR*, Borchardt, 1970; Lachet *et al.*, 1996; Riepl *et al.*, 1998, Duval *et al.*, 2001; Haghshenas *et al.*, 2008; Rong *et al.*, 2017; and others). *SSR* requires a reference rock site (Steidl *et al.*, 1996) which is often difficult

to find in practice, thus, the single-station *HVSR* technique is appealing, at least, in detecting site resonant frequency.

Alternatively, Tokeshi *et al.* (1996) proposed to use the phase of the one-sided autocorrelogram of the horizontal components (Fourier Phase Spectral Method, *FPSM*) to derive site resonant frequency. However, Parolai *et al.* (2001) later demonstrated that the *FPSM* technique had no advantage over the *HVSR* approach. Thus, we will focus this study on the *HVSR* method and its uncertainties in quantifying resonant frequency. In a preceding study (Zhu *et al.*, 2019b), we compiled four sets of resonant frequency data derived by different teams using spectral ratio techniques at KiK-net stations and compared the resonant frequency measurements at the same site. We have found different levels of discrepancies in these data, which has motivated the present investigation.

In this paper, we first present this comparison of resonant frequencies from different teams and postulate the factors explaining these inconsistencies, followed by a description of the procedure of obtaining resonant frequency using the *HVSR* approach. Then we utilize the KiK-net recording network and investigate how different factors in the process affect the determination of resonant frequency, including using Fourier (*FAS*) spectral ratio or (5% damped) pseudo-spectral acceleration (*PSA*) ratio, the degree of smoothing to spectrum, the definition of significant peaks, and the choice of the first or the highest peak frequency when there are multiple peaks. Then we evaluate the efficacies of various resonant frequencies derived under different schemes in modelling liner site effects. Based on their performance, we finally determine the optimal scheme to derive site resonant frequency using *HVSR*.

Potential Factors Explaining Inconsistencies in Resonant Frequency Measurements

To determine the resonant frequency of a given site using spectral ratio methods (e.g., *HVSR*) on earthquake data, one may utilize either the complete (from P-arrival to the end of S-coda) or partial (typically S-wave window) waveform with a signal-to-noise ratio above a certain level. Then one needs to compute the spectral ratios on either smoothed *PSA* or *FAS* of each recording and then obtain the spectral ratios averaged over all recordings at the site.

Next, from the average spectral ratio curve, one can pinpoint all significant peaks (f_s) which are often defined as local maxima points fulfilling certain clarity (e.g., larger than 2.0) and/or stability criteria (SESAME, 2004). Then, from these significant peaks, one can pick up either the first-peak frequency (f_0) or the highest-peak frequency (f_p) as site resonant frequency. However, since there is a lack of a uniform procedure, measurements of resonant frequency are not without uncertainties as can be seen from four sets of empirically-derived resonant frequency data at KiK-net sites compiled by Zhu *et al.*, (2019b) (Fig. 1).

These data sets were published by Wang *et al.* (2018) using *HVSR*, by Wang (2017) and Pousse (2005) using surface-to-borehole spectral ratio (*SBSR*), and by Fujiwara *et al.* (2009) using radial-to-vertical spectral ratio (*RVSR*) approaches, respectively (Table 1). Complete waveforms of earthquake recordings were utilized except for Fujiwara *et al.*, (2009) who used only S-coda waves (20 s after S-wave arrival). More details pertaining to the determination of resonant frequency are tabulated in Table 1. There are substantial inconsistencies among their results (Fig. 1), especially between those obtained by Pousse (2005) and Fujiwara *et al.* (2009).

The choice of *PSA* (Wang *et al.*, 2018) or *FAS* (Pousse, 2005; Fujiwara *et al.*, 2009; Wang, 2017) may contribute to the inconsistencies in these data (Fig. 1). As pointed out by Bora *et al.*

(2016), the response spectral ordinate at a high oscillator-frequency is not controlled by the Fourier spectral ordinate at the corresponding frequency but is determined by Fourier amplitudes in a rather broad frequency range. In addition to this peculiar property, response spectral ratios are scenario-dependent (Stafford *et al.*, 2017), and this scenario-dependency is strong at high frequencies and is particularly evident for small earthquakes. Thus, frequency- and scenario-dependent differences exist between *PSA*- and *FAS*-based spectral ratios. However, many researchers used the *PSA* and *FAS* interchangeably (e.g., Molnar *et al.*, 2015), which may be one source of discrepancy in resonant frequencies (Fig. 1).

Damping used in calculating a response spectrum (e.g., 5%) has an incidental smoothing effect. However, if *FAS* is utilized to compute spectral ratios, additional smoothing to *FAS* is required prior to dividing the horizontal component by its vertical counterpart (Table 1). Choice of smoothing techniques (e.g., the type of smoothing operator and the degree of smoothing) will affect the value of the spectral ratio and subsequently the qualification of significant peaks. Hence, inhomogeneous smoothing can also cause a mismatch in resonant frequency (Fig. 1).

Besides, in all these above studies, site resonant frequency is identified from significant peaks, but what qualifies a significant peak is defined rather subjectively. As can be seen from Table 1, the definition of significant peaks varies from study to study. This discretionary exercise contributes to the disparities among these resonant frequency data (Fig. 1). Also, after detecting all significant peaks on an average spectral ratio curve, either the first (f_0) or the highest (f_p) peak frequency is treated as site resonant frequency. Some studies (e.g., Hassani and Atkinson, 2018) utilized f_p whereas others (e.g., Ghofrani *et al.*, 2013 and 2014) opted for f_0 (Table 1). There is often a lack of an evidence-based justification to their choice of one instead of the other, which is also responsible for the inconsistency in site resonant frequency. Nevertheless, it is worth noting

that there are other factors that contribute to the deviations observed in Figure 1. For instance, resonant frequency based on *SBSR* can differ from that based on *HVSR* if an abrupt impedance contrast exists below the borehole sensor.

Identification of Resonant Frequency using *HVSR* at KiK-net stations

In a preceding investigation (Zhu *et al.*, 2019a), we studied the linear site effects at 207 KiK-net sites (Table S1). Site amplification at each site was derived using the *SBSR* approach on earthquake recordings. Site data is displayed in Figure 2a. $Z_{0.8}$ is the depth (in meters) to the isosurface having $V_S = 800$ m/s and is obtained from KiK-net velocity profiles. Downhole stations of these 207 sites are all installed in layers at least 100 m deep from the ground surface and having shear-wave velocity larger than 800 m/s. Thus, downhole recordings are not expected to be significantly contaminated by downgoing waves (Bonilla *et al.*, 2002).

Zhu *et al.* (2019a) selected a total number of 1840 ground motions recorded by these stations between October 1997 and December 2011 from the KiK-net database processed by Dawood *et al.* (2016). The complete waveform from P-arrival was utilized (e.g., Thompson *et al.*, 2012). The rupture distance (R_{rup}) of these selected ground motions was up to 400 km, and the moment magnitude (M_w) was in the range between 3.5 and 8.0 (Fig. 2b). All the selected records had a low-cut frequency of 0.24 Hz or lower and had a signal-to-noise ratio of no less than 3.0 in the usable frequency range. Selected seismograms were considered not being significantly affected by soil nonlinearity according to the threshold proposed by Fujimoto and Midorikawa (2006). Each of these 207 stations had recorded at least three such events. In the present investigation, we utilize the same dataset (Zhu *et al.*, 2019a) to derive resonant frequencies. We refer readers to Zhu *et al.*

(2019a) for more details on data selection. The main steps of site frequency determination using HVSR technique are as follows:

- i) Computing FAS and PSA of each time-series (complete waveform);
- ii) Smoothing FAS and PSA using Konno-Ohmachi window (Konno and Ohmachi, 1998) with a smoothing coefficient $b=20$ (default), 30 and 40, respectively;
- iii) Obtaining $HVSR(f)$ by dividing the geometrical mean of the two horizontal components (NS and EW) of a certain recording by its vertical component (V):

$$\log_{10}HVSR_{ij}(f) = 0.5[\log_{10}(H_{NS})_{ij}(f) + \log_{10}(H_{EW})_{ij}(f)] - \log_{10}(V)_{ij}(f) \quad (1)$$

where $HVSR_{ij}$ is the horizontal-to-vertical Fourier or response spectral ratio of the ground motion recorded at station j from event i ; and $(H_{NS})_{ij}$, $(H_{EW})_{ij}$ and $(V)_{ij}$ are the Fourier or response spectrum of the NS , EW and V components, respectively;

- iv) Deriving $\overline{HVSR}(f)$ by averaging $HVSR(f)$ s over all recordings (≥ 3) at a certain site;

$$\log_{10}\overline{HVSR}_j(f) = \frac{\sum_{i=1}^{n_j} \log_{10}HVSR_{ij}(f)}{n_j} \quad (2)$$

$$std_j(f) = \sqrt{\frac{\sum_{i=1}^{n_j} (\log_{10}HVSR_{ij}(f) - \log_{10}\overline{HVSR}_j(f))^2}{n_j}} \quad (3)$$

where $\overline{HVSR}_j(f)$ and $std_j(f)$ are the mean H/V spectral ratio and its standard deviation at station j , respectively; and n_j is the number of recordings at station j ;

- v) Identifying all significant peaks (f_s) on $\overline{HVSR}_j(f)$;
- vi) Picking up both the first (f_0) and the highest (f_p) peak frequencies from significant peaks (© Table S1, see Data and Resources).

Not every extremum point on a $\overline{HVSR}_j(f)$ curve qualifies as a significant peak (f_s). Following

the SESAME (2004) guideline, in step (v), a local extremum point is only regarded as f_s if it passes one or more of the following criteria:

$$C1 \quad \log_{10} \overline{HVS R_j}(f_s) > 0.3;$$

$$C2 \quad f \text{ can be found within both } [f_s/4, f_s] \text{ and } [f_s, 4f_s] \text{ with } \log_{10} \left[\frac{\overline{HVS R_j}(f_s)}{\overline{HVS R_j}(f)} \right] > 0.3;$$

$C3$ Standard deviation of $\log_{10} \overline{HVS R_{ij}}(f_s)$ s ($i = 1, 2, \dots, n_j$) lower than a frequency dependent threshold $\theta(f_s)$, where $\theta(f_s) = 0.48$ for $f_s < 0.2$ Hz; $\theta(f_s) = 0.40$ for $0.2 \leq f_s < 0.5$ Hz; $\theta(f_s) = 0.30$ for $0.5 \leq f_s < 1.0$ Hz; $\theta(f_s) = 0.25$ for $1.0 \leq f_s < 2.0$ Hz; and $\theta(f_s) = 0.20$ for $f_s \geq 2.0$ Hz.

According to the criterion/criteria applied in qualifying a significant peak, we define the following notation to differentiate the resonant frequencies or periods identified subsequently:

f_{p1}, f_{p2} and f_{p3} – highest significant-peak frequencies under criterion/criteria $C1$, $C1\&2$, and $C1\sim3$, respectively;

T_{p1}, T_{p2} and T_{p3} – resonant periods, reciprocals of f_{p1}, f_{p2} and f_{p3} , respectively;

f_{01}, f_{02} and f_{03} – first significant-peak frequencies under criterion/criteria $C1$, $C1\&2$, and $C1\sim3$, respectively;

T_{01}, T_{02} and T_{03} – resonant periods, reciprocals of f_{01}, f_{02} and f_{03} , respectively.

Response or Fourier Spectral Ratio?

Response spectral ratios show scenario-dependency (Stafford *et al.*, 2017) and thus could give a different resonant frequency from Fourier spectral ratios. Figure 3a compares the highest peak

frequencies derived from Fourier (f_{p1_FAS}) and response (f_{p1_PSA}) spectral ratios when only criterion $C1$ is applied to select significant peaks. There are 201 sites having both f_{p1_FAS} and f_{p1_PSA} . At 11 out of 201 sites (or 5%), the two highest peak frequencies deviate significantly $|\log_{10}(f_{p1_FAS}/f_{p1_PSA})| > 0.3$. Outliers in Figure 3a often correspond to sites at which there are multiple significant peaks with comparable peak values. When the screening criterion $C2$ is also applied (results are not shown here for brevity), the number of sites having both f_{p2_FAS} and f_{p2_PSA} reduces to 97. However, the deviation between these two resonant frequencies lessens slightly. Significant deviation only occurs at 4 out of 97 (or 4%) sites.

Figure 3b displays the ratios of $\overline{HVS\overline{R}}_{PSA}(f)$ to $\overline{HVS\overline{R}}_{FAS}(f)$ at the 207 KiK-net sites in log10 units. It confirms that the response spectral ratios are close to Fourier spectral ratios at low frequencies whereas the former are apparently larger than the latter at high frequencies (Bora et al., 2016). Thus, for sites with multiple significant peaks, especially those with one of the significant frequencies in a relatively high-frequency range, using the response and Fourier spectral ratios could lead to different estimates of resonant frequency. To elaborate on this issue, we choose a KiK-net site IWTH16 (Fig. 4a) as an example. To obtain its resonant frequency, a total number of 144 seismograms recorded at this station is selected with a PGA in the range between 0.05 and 0.2 m/s^2 . Magnitude-distance distribution is displayed in Figure 4b.

Figure 5a and b depict the $HVS\overline{R}(f)$ s of these 144 recordings at IWTH16, as well as their average ($\overline{HVS\overline{R}}(f)$, bold solid line) and average $\pm$ one standard deviation (dashed lines) using Fourier and response spectra, respectively. Dots correspond to the highest peak frequencies (f_{p1}) of each individual curve under the screening criterion $C1$. The true value of f_{p1} of this site is defined from $\overline{HVS\overline{R}}(f)$. There is more than one significant peak on $\overline{HVS\overline{R}}(f)$, but the one at 0.38 Hz is dominant in both Figure 5a and b. The highest peaks of each individual Fourier spectral ratio curve

cluster in frequency bands [0.2, 0.6] and [0.6, 2.0]. In contrast, for response spectral ratio curves, there are also the highest peaks in ranges [2.0, 8.0] and [8.0, 20].

However, resonant frequency is defined as the peak frequency of the average *HVSR* curve instead of the average of peak frequencies of each individual curve (Ghofrani and Atkinson, 2014). Meanwhile, the average *HVSR* curve is often based on a number (at least three) of randomly selected ground-motion recordings. To mimic this process, we select N ($N \geq 3$) spectral ratio curves randomly from Figure 5 and then determine f_{p1} from their average. For each N , we repeat the identification process for 100 times. The distributions of the identified f_{p1} using Fourier and response spectra are shown in Figure 6a and b, respectively.

For the minimum number $N=3$, using *FAS*, the true site resonant frequency (0.38 Hz) is correctly identified 88 out of 100 times (Fig. 6a) whereas using *PSA*, f_{p1} is only correctly identified 62 out of 100 times (Fig. 6b). Averaging *HVSRs* over more records can further curtail the randomness. Nine records are needed to have a 100% correct identification of f_{p1} for IWTH16 when *FAS* is used (Fig. 6a). In comparison, *PSA* requires 59 recordings to achieve the same level of certainty (Fig. 6b). Thus, for sites having multiple significant peaks with comparable peak values, utilizing response spectrum is more likely to have biased estimates of resonant frequency than using Fourier spectrum. This can be attributed to the scenario-dependence of response spectral ratios, especially at high frequencies (Stafford *et al.*, 2017). In contrast, Fourier spectral ratios show little such dependency (Zandieh and Pezeshk, 2011). The nonlinear feature of response spectral ratios also explains the larger scatter at relatively high frequencies (> 2.5 Hz) in Figure 5b than that in Figure 5a.

Therefore, for sites with multiple comparable peaks, the Fourier spectral ratio should be preferred over the response spectral ratio in the determination of site resonant frequency. We thus

use *FAS* to compute spectral ratios hereafter. However, for other sites, i.e. those with a single clear peak or with more than one peak having distinct amplitudes, utilizing either Fourier or response spectrum makes little difference.

The First or the Highest Peak Frequency?

Susceptibilities of the First and the Highest Peak Frequencies

Significant peaks were defined differently in previous researches (Table 1). To investigate the influence of peak definition, we thus compare the site resonant frequencies derived using only the screening criterion *C1* with these obtained using *C1*, *C2* and *C3* in Figure 7. Figure 7a suggests that the definition of significant peaks has a remarkable impact on the first peak frequency (f_0). 56 out of 169 (or 33%) sites have f_0 significantly affected. When more screening criteria are applied, many significant peaks identified under a less strict condition will be disqualified, resulting in more no-peak sites but less multiple-peaks sites, as shown in Table 2. Under a more robust peak definition, f_{01} initially identified could be rejected, in which case the significant peak at a higher frequency would be picked up as the first peak frequency (f_{03}), as shown in Figure 7a with $f_{03} > f_{01}$ at many sites.

In comparison, Figure 7b indicates that, at 158 out of 169 (or 93%) sites, the highest peak frequencies (f_p) remain the same regardless of the change in peak-definition. This is exemplified in Figure 7c, which illustrates the *HVSR(f)*s at site FKSH10. When a stricter peak definition is applied, the highest peak frequency, i.e., 6.19 Hz, remains unchanged. However, the first peak frequency changes from 0.42 to 6.19 Hz. Thus, Figure 7 implies that the f_p is less susceptible to the defining criteria of significant peaks than f_0 .

Unsmoothed *FAS* is spiky, and often smoothing is required. Konno-Ohmachi weighting function (Eq. 4, Konno and Ohmachi, 1998) is one of the most widely applied smoothing functions with a constant window width and symmetric shape around central frequency (on logarithmic scales):

$$W_B(f, f_c) = \left(\frac{\sin(\log_{10} \frac{f}{f_c})^b}{(\log_{10} \frac{f}{f_c})^b} \right)^4 \quad (4)$$

where f_c is the central frequency at which the smoothing is performed, and b is a coefficient inversely proportional to bandwidth. A smaller b value results in a stronger smoothing. The degree of smoothing affects the amplitudes of *HVSR* and subsequently the qualification of significant peaks (e.g., Konno and Ohmachi, 1998; Bard, 1995).

Figure 8 compares the site resonant frequencies identified using different (Konno-Ohmachi smoothing) b values. At 25% of the sites (or 42 out of 169 sites), the first peak frequency f_{03} (Fig. 8a) identified using $b=20$ deviates significantly from that determined using $b=40$, namely $|\log_{10}[f_{03}(b=20)/f_{03}(b=40)]| > 0.3$. In contrast, the highest peak frequency f_{p3} (Fig. 8b) does not vary much with the smoothing coefficient; only 5 out of 169 (or 3%) sites are outside the range $|\log_{10}[f_{p3}(b=20)/f_{p3}(b=40)]| \leq 0.3$. This comparison implies that f_0 is more sensitive to the smoothing coefficient than f_p .

When a stronger smoothing (a lower b value) is applied, the amplitudes of all peaks will decrease and, as a consequence, some significant peaks identified under a weaker smoothing may fail the same selection criteria of significant peaks. With the increase in b value, there are more sites with multiple significant peaks and fewer sites having no or a single peak (Table 2). Thus, for a site with multiple significant peaks, a stronger smoothing could result in a significant peak at

a higher frequency being identified as f_0 (Fig. 8a). However, f_p (Fig. 8b) corresponds to the highest peak and thus is less sensitive to the degree of smoothing than f_0 .

It is worth noting that, for KiK-net sites with both f_0 and f_p assigned, f_0 equals f_p for the majority of sites. The percentage of sites with $f_0=f_p$ is contingent on the peak screening criteria. For instance, there are 82% of sites where f_{02} coincides with f_{p2} , and the percentage is 85% for $f_{03}=f_{p3}$. For those with different f_0 and f_p , the former is smaller than the latter, so are their amplitudes, hence, f_p is associated with a larger velocity contrast at a shallower depth than f_0 .

Comparison with Resonant Frequencies from *SBSR*

In a preceding study (Zhu *et al.*, 2019a), we computed *SBSRs* at the 207 KiK-net stations, as exemplified in Figure 9. Also shown are surface-to-borehole cross-spectral ratios of horizontal components (*c-SBSR*), horizontal-to-vertical spectral ratios at borehole station (*HVSR_b*) and surface-to-borehole spectral ratios of vertical components (*SBSR_v*). All spectral ratios presented in this section, “Comparison with Resonant Frequencies from *SBSR*”, are calculated on smoothed *FAS* using a Konno-Ohmachi window ($b=20$) and are provided as an electronic supplement to this article (® File [Spectral Ratios](#), see [Data and Resources](#)). Criterion *C1* and *C2* are used to select significant peaks. Following the same procedure, we obtain the first (f_{02_SB}) and the highest (f_{p2_SB}) peak frequencies from each $\overline{SBSR}(f)$ curve and compare them with those determined from $\overline{HVSR}(f)$, i.e., f_{02_HV} and f_{p2_HV} .

There are 20 sites for which $\overline{HVSR}(f)$ exhibits a significant peak in a rather low-frequency band ($< \sim 1.0$ Hz), but a peak is completely absent in this frequency range on its corresponding $\overline{SBSR}(f)$ curve (Fig. 9a). This clearly indicates the existence of an abrupt velocity contrast below the borehole, even though all these 207 KiK-net stations have downhole sensors installed in layers

at least 100 m below the ground surface and with shear-wave velocity larger than 800 m/s. For the remaining 187 sites, we take the $\overline{SBSR}(f)$ of each site as its empirical transfer function. Among them, there are 11 sites with resonant frequencies being identified from neither $\overline{HVS\overline{R}}(f)$ nor $\overline{SBSR}(f)$ (Fig. 9b), 29 sites with resonant frequencies from either $\overline{HVS\overline{R}}(f)$ or $\overline{SBSR}(f)$ (Fig. 9c), and 147 sites with resonant frequencies from both $\overline{HVS\overline{R}}(f)$ and $\overline{SBSR}(f)$ (Fig. 9d).

We only utilize the 147 sites at which resonant frequencies can be identified from both $\overline{SBSR}(f)$ and $\overline{HVS\overline{R}}(f)$. Though the effects of downgoing waves on $\overline{SBSR}(f)$ could be mitigated due to our careful data selection, we could not completely rule out the possibility of pseudo resonances, which could affect the determination of f_{02_SB} and f_{p2_SB} using $\overline{SBSR}(f)$ through our fully automatic procedure. Thus we carefully check the presence of pseudo resonances on $\overline{SBSR}(f)$ by comparing the theoretical transfer functions using within and outcrop boundary conditions. Wherever pseudo resonant frequencies are found to be mistakenly picked up from $\overline{SBSR}(f)$ by our automatic procedure, we modify the resonant frequencies to true resonant frequencies (only 13.6% of the sites need such modification). Then f_{02_SB} and f_{p2_SB} can be confidently taken as site fundamental and predominant frequencies and be used to gauge the resonant frequencies from $\overline{HVS\overline{R}}(f)$ in Figure 10.

To quantify the comparison, we adopt different measures of goodness-of-fit (GoF), including the Nash-Sutcliffe model Efficiency coefficient E (Nash and Sutcliffe, 1970), index of agreement d (Willmott, 1981), Pearson correlation coefficient r and mean absolute error MAE as listed in Table 3. E can range from $-\infty$ to 1 whereas both d and r vary between 0 and 1. For all these three GoF measures, the higher the value, the better the match. For instance, a value of 1 indicates a perfect match. Also listed in Table 3 is the number of sites with f_{HV}/f_{SB} out of a certain range.

In terms of approximating the fundamental frequency f_{02_SB} , Table 3 demonstrates that there are a slightly less number of sites out of the range $|\log_{10}(f_{02_SB}/f_{02_HV})| < 0.1$ in Figure 10b than in Figure 10a, which is also true for the range $|\log_{10}(f_{02_SB}/f_{02_HV})| < 0.3$. GoF indicators in Table 3 also, in general, suggest that f_{p2_HV} is better than f_{02_HV} in approximating f_{02_SB} . The success rates of the *HVSR* method in detecting site fundamental frequency are approximately 70% for the benchmark $0.8 \leq f_{SB}/f_{HV} \leq 1.25$ and more than 90% for $0.5 \leq f_{SB}/f_{HV} \leq 2.0$.

When it comes to matching the predominant frequency f_{p2_SB} (Fig. 10c and d), all metrics in Table 3 consistently suggests that f_{p2_HV} is favourable compared to f_{02_HV} . In addition, Figure 10c and d also illustrate that, at most sites, f_{02_HV} and f_{p2_HV} are either close to or lower than f_{p2_SB} , implying that the *HVSR* technique tends to underestimate the predominant frequency obtained using the *SBSR* method at some sites. This is consistent with previous findings based on the comparison of peak frequencies derived using *HVSR* and *SSR* approaches (e.g., Duval *et al.*, 2001).

The underestimation of the *HVSR* approach to predominant frequency at some sites is mainly due to site amplification in the vertical component. For a pair of surface and downhole stations with no major velocity contrast below the borehole, we have

$$HVSR(f) = \frac{H(f)}{H_b(f)} \cdot \frac{H_b(f)}{V_b(f)} \cdot \frac{V_b(f)}{V(f)} = \frac{HVSR_b(f)}{SBSR_v(f)} \cdot SBSR(f) \quad (5)$$

where $H(f)$ and $V(f)$ - Fourier spectra of horizontal and vertical components, respectively, of a surface recording; $H_b(f)$ and $V_b(f)$ - Fourier spectra of horizontal and vertical components, respectively, of a downhole recording. For the 187 sites with no major velocity contrast below borehole, $\overline{HVSR_b(f)}$ s and $\overline{SBSR_v(f)}$ s are depicted in Figure 11.

For earthquake recordings, $\overline{HVSR_b(f)}$ (Fig. 11a) is close to 1.0 and is rather stable over the whole frequency band, namely a constant around unity, as also reported by Rong *et al.*, (2017).

The vertical amplification $\overline{SBSR}_v(f)$ (Fig. 11b) is near 1.0 only at low frequencies ($< \sim 1.0$ Hz), followed by significant amplifications at higher frequencies. Thus, according to Eq. 5, *HVSR* amplitudes approximate site amplifications at low frequencies but underestimates them at relatively high frequencies mainly due to vertical site response (e.g., Lachet *et al.*, 1996; Duval *et al.*, 2001; Bindi *et al.*, 2011). This underestimation could lead to the significant peak on $\overline{HVSR}(f)$ at a lower frequency being picked up as the highest peak, underestimating the site predominant frequency at some sites (Fig. 10c and d).

Efficacy in Modelling Linear Site Effects

The comparisons of peak frequencies from *HVSR* and *SBSR* (Fig. 10 and Table 3) do not directly reveal which peak frequency, the first or the highest *HVSR* peak frequency, should be utilized as a site indicator. To provide a direct answer to this question, the performance of a site proxy in depicting site effects should serve as a benchmark since one of the primary usages of site parameters is to characterize site amplification. To this end, we take the $\overline{SBSR}(f)$ as the empirical amplification function of each site. Though this amplification is not identical to that derived from $\overline{SSR}(f)$, the difference does not affect us gauging the efficacies of site proxies.

Konno-Ohmachi smoothing function with $b=20$ is utilized in this section. To increase the population size of resonant frequencies, we only apply a less restrictive criterion (*CI*) to determine peak frequencies from $\overline{HVSR}(f)$. Besides f_{p1_FAS} and f_{01_FAS} , f_{p1_PSA} is also considered as a comparison, as well as the conventional site proxy V_{S30} . To compare with our previous study (Zhu *et al.*, 2019a), we utilize resonant periods T_{p1_FAS} , T_{01_FAS} and T_{p1_PSA} which are reciprocals of

corresponding resonant frequencies. Amplification factors (AF) at an oscillator period $T=0.4$ s against T_{p1_FAS} and V_{S30} are exemplified in Figure 12a and b, respectively.

Based on visual inspection, the relationship between AF and site period (Fig. 12a) can be described by a polynomial function. The function with fewest terms that are statistically significant is a quadratic function. Higher-order polynomials were also tested but only resulted in an insignificant increase in the coefficient of determination (R^2). Thus, a second-order polynomial (Eq. 6) is adopted to depict the variation of AF with site resonant period. Site amplification is modelled as a linear function of V_{S30} (Eq. 7). We calculate the amplification residual (Res) of observation about the regression line and the standard deviation of residuals (σ_{Res}) according to Eq. 8 and 9, respectively. The performance of each site indicator is evaluated based on σ_{Res} . A lower σ_{Res} suggests a better modelling performance. The comparison is presented in Figure 13a for amplification models using a single proxy. Figure 13b depicts the relative change in σ_{Res} compared with that of model $AF(T_{p1_FAS})$.

$$\ln[AF(Y)] = b_0 + b_1 \ln(Y) + b_2 [\ln(Y)]^2 \quad (6)$$

$$\ln[AF(V_{S30})] = a_0 + a_1 \ln(V_{S30}) \quad (7)$$

$$Res = \ln(AF_{obs}) - \ln(AF_{pre}) \quad (8)$$

$$\sigma_{Res} = \sqrt{\frac{\sum_1^N [\ln(AF_{obs}) - \ln(AF_{pre})]^2}{N}} \quad (9)$$

where

AF_{obs} - Observed site amplification at a certain period using $SBSR_{FAS}$;

AF_{pre} - Predicted site amplification, including $AF(V_{S30})$ and $AF(Y)$;

$AF(V_{S30})$ and $AF(Y)$ - Site amplifications predicted using V_{S30} and Y , respectively;

Y - Various site resonant periods, e.g., T_{pI_FAS} , T_{0I_FAS} or T_{pI_PSA} ;

Res - Amplification residual;

σ_{Res} - Standard deviation of amplification residuals;

N - Number of sites.

Figure 13a and b indicate that T_{pI_FAS} performs slightly better than T_{pI_PSA} in the investigated period range in characterizing linear site response. This is in good agreement with our preceding result that using response spectrum could lead to a biased estimate of the resonant period (or frequency) for sites with multiple comparable peaks on an $\overline{HVS}(f)$ curve (Fig. 5). Meanwhile, Figure 13b also shows that T_{pI_FAS} has a better performance than T_{0I_FAS} at relatively short periods ($< \sim 0.7$ s) in characterizing linear site effects, lowering σ_{Res} by as much as 9%. However, at longer periods, T_{0I_FAS} appears to be advantageous over T_{pI_FAS} by an insignificant margin (less than 2%). When only sites with $T_{pI_FAS} \neq T_{0I_FAS}$ are used in the regression analysis, the difference in performance between T_{pI_FAS} and T_{0I_FAS} is more evident. In general, the highest peak period (or frequency) exhibits a better overall performance than the first peak period in depicting linear site amplification, which can be explained by the fact that the former corresponds to a larger velocity contrast than the latter. In addition, Figure 13b also illustrates that adding T_{0I_FAS} as a complementary proxy to T_{pI_FAS} can further lower the scatter to a small degree (less than 4%) over the examined period range.

In Figure 13a, the highest peak periods (T_{pI_PSA} and T_{pI_FAS}) show a better performance than V_{S30} in depicting linear site effects. However, the first peak period (T_{0I_FAS}) exhibits no evident advantage over V_{S30} , which is inconsistent with our previous results (Zhu *et al.*, 2019a). In the preceding study, we adopted the site period (T_0) data provided by Wang *et al.*, (2018) and showed that T_0 was a better site proxy than V_{S30} in characterizing site effects. This inconsistency arises

from the different definitions of significant peaks. Wang *et al.* (2018) obtained T_0 data following a rather stringent procedure, which led to 265 (56%) out of 473 KiK-net sites having T_0 . In contrast, resonant periods used in Figure 13 are picked up using only the first criterion [$C1: \log_{10} \overline{HVSR}(f_0) > 0.3$], which results in identifying resonant period at a higher percentage of sites (202 or 98% out of 207 sites). A stricter peak screening would exclude more sites in the regression (no significant peak, as evidenced in Table 2) and retain only these at which site response is fundamentally governed by strong resonance. At these sites, resonant period has enhanced performance compared to V_{S30} . However, even under such a relaxed definition, the highest peak periods (T_{p1_PSA} and T_{p1_FAS}) still outperform V_{S30} (Fig. 13a) due to their insensitivities to peak definition (Fig. 7b).

Conclusions

Following an automatic procedure, we obtained the resonant frequencies at 207 KiK-net sites using the horizontal-to-vertical spectral ratio ($HVSR$) technique on earthquake ground-motions. We then investigated the factors contributing to the discrepancy in resonant frequencies determined from $HVSR$, e.g., using Fourier (FAS) or response (PAS) spectral ratio and using the first or the highest peak frequency. Our results indicate that, due to the scenario-dependence of response spectral ratio, utilizing response spectrum to compute the $HVSR$ could bias the estimates of resonant frequency for sites having multiple significant peaks with comparable peak values. Thus, the Fourier spectrum should be preferred in computing $HVSR$.

For most KiK-net sites (more than 80%) investigated in this research, the first peak on an average $HVSR$ curve (in the frequency domain) coincides with the highest peak. However, our results show that the highest peak frequency (f_p) is less susceptible than the first peak frequency

(f_0) to the selection criteria of significant peaks and the extent of smoothing to spectrum. Besides, comparing to the surface-to-borehole spectral ratio (*SBSR*), *HVSR* can only provide a lower-bound estimate of predominant frequency at which the strongest amplification occurs. However, f_p tends to underestimate the predominant frequency less than f_0 . More importantly, f_p has a better overall performance than f_0 in characterizing linear site-effects. Thus, if the *HVSR* method is utilized to derive the resonant frequency of a seismic recording station, network operators should publish f_p as a priority. Ideally, operators should also release the average *HVSR* curve from which end-users can extract the resonant frequency using self-defined criteria.

In this study, we also confirm that the *HVSR* amplitude underestimates the level of amplification at relatively high frequencies. This underestimation is site-specific, depending on the ratio between the *HVSR* at downhole and the *SBSR* in the vertical direction. Since the *HVSR* at downhole rock can be approximated by a constant close to unity over the examined frequency range (0.25~20.0 Hz), thus the underestimation is primarily controlled by the vertical transfer function of a site. Hence it is intriguing to explore the usage of *HVSR* amplitudes for frequencies at which vertical amplification is insignificant in future investigations.

Data and Resources

Velocity profiles of KiK-net recording stations were downloaded from the <http://www.kyoshin.bosai.go.jp> (last accessed on 05/06/2018). Matlab was used to automatically identify the first as well as the highest peak frequencies. Supplemental content includes a table and a file. The table tabulates site resonant frequencies and other site information (latitude, longitude,

V_{S30} and $Z_{0.8}$) at the 207 KiK-net stations selected in this study. The file contains all average spectral ratios (e.g., *HVSR* and *SBSR*) at these 207 sites.

Acknowledgements

We are grateful to the National Research Institute for Earth Science and Disaster Prevention (NIED), Japan, for making the recordings and site data at KiK-net stations publicly available. We appreciate the very constructive feedback from the Associate Editor, Prof. Hiroshi Kawase. We sincerely thank Prof. Pierre-Yves Bard who gave feedback on an early version of the paper. We also thank the thorough reviews by Dr. Hadi Ghofrani and Dr. Dongyoup Kwak, as well as an anonymous reviewer whose suggestions have helped improve this article. Part of this work is supported by the Seismology and Earthquake Engineering Research Infrastructure Alliance for Europe (SERA) project funded by the EU Horizon 2020 programme under Grant Agreement Number 730900.

References

- Bard, P. Y. (1995). Effects of surface geology on ground motion: recent results and remaining issues, *Proc. of the 10th Eur. Conf. on Earthq. Eng.* **1**, 305-323.
- Bindi, D., L. Luzi, S. Parolai, D. Di Giacomo, G. Monachesi (2011). Site effects observed in alluvial basins: the case of Norcia (Central Italy). *Bull. Earthq. Eng.* **9**, 1941-1959.
- Bonilla, L. F., J. H. Steidl, J. C. Gariel, and R. J. Archuleta (2002). Borehole Response Studies at the Garner Valley Downhole Array, Southern California. *Bull. Seismol. Soc. Am.* **92**, 3165–3179.
- Bonnefoy-Claudet, S., F. Cotton, and P-Y Bard (2006). The nature of noise wavefield and its applications for site effects studies: A literature review, *Earth-Science Reviews*, doi:10.1016/j.earscirev.2006.07.004.

- Bora, S. S., F. Scherbaum, N. Kuehn, and P. Stafford (2016). On the relationship between Fourier and Response spectra: implications for the adjustment of empirical ground-motion prediction equations (GMPEs), *Bull. Seism. Soc. Am.* **106**, 1235-1253.
- Borcherdt, R. D. (1970). Effects of local geology on ground motion near San Francisco Bay, *Bull. Seism. Soc. Am.* **60**, 29-61.
- Dawood, H. M., A. Rodriguez-Marek, J. Bayless, C. Goulet, and E. Thompson (2016). A Flatfile for the KiK-net database processed using an automated protocol, *Earthq. Spectra* **32**, 1281-1302.
- Duval, A. M., P. Y. Bard, B. Lebrun, C. Lacave-Lachet, J. Riepl, and D. Hatzfeld (2001). H/V technique for site response analysis: Synthesis of data from various surveys, *Bollettino di Geofisica Teorica ed Applicata* **42**, 267-280.
- Derras, B., P. Y. Bard, and F. Cotton (2017). V_{S30} , slope, H_{800} and f_0 : performance of various site-condition proxies in reducing ground-motion aleatory variability and predicting nonlinear site response, *Earth, Planets and Space* **69**, 133 DOI 10.1186/s40623-017-0718-z.
- Fujimoto, K., and S. Midorikawa (2006). Relationship between average shear-wave velocity and site amplification inferred from strong motion records at nearby station pairs, *J. Japan Assoc. Earthq. Eng.* **6**, 11-22 (in Japanese with English abstract).
- Fujiwara, H., S. Kawai, S. Aoi, N. Morikawa, S. Senna, N. Kudo, M. Ooi, K. X. Hao, Y. Hayakawa, N. Yoyama, H. Matsuyama, K. Iwamoto, H. Suzuki, and Y. Liu (2009). A Study on subsurface structure model for deep sedimentary layers of Japan for strong-motion evaluation, *Technical Note of the National Research Institute for Earth Science and Disaster Prevention*, No. 337.
- Ghofrani, H., G. M. Atkinson, and K. Goda (2013). Implications of the 2011 M9.0 Tohoku Japan earthquake for the treatment of site effects in large earthquakes, *Bull. Earthq. Eng.* **11**, 171-203.
- Ghofrani, H., G., and M. Atkinson (2014). Site condition evaluation using horizontal-to-vertical response spectral ratios of earthquakes in the NGA-West2 and Japanese databases, *Soil Dyn. Earthq. Eng.* **67**, 30-43.

- Haghshenas, E., P. Y. Bard, N. Theodulidis, and SESAME WP04 Team (2008). Empirical evaluation of microtremor H/V spectral ratio, *Bull. Earthq. Eng.* **6**, 75-108.
- Hassani, B., and G. M. Atkinson (2016). Applicability of the site fundamental frequency as a V_{s30} proxy for Central and Eastern North America, *Bull. Seism. Soc. Am.* **106**, 653-664.
- Hassani, B., and G. M. Atkinson (2018). Application of a site-effects model based on peak frequency and average shear-Wave velocity to California, *Bull. Seism. Soc. Am.* **108**, 351-357.
- Kawase, H., F. J. Sánchez-Sesma, and S. Matsushima (2011). The Optimal Use of Horizontal-to-Vertical Spectral Ratios of Earthquake Motions for Velocity Inversions Based on Diffuse-Field Theory for Plane Waves, *Bull. Seism. Soc. Am.* **101**, 2001-2014.
- Konno K., and T. Ohmachi (1998). Ground-motion characteristics estimated from spectral ratio between horizontal and vertical components of microtremor, *Bull. Seism. Soc. Am.* **88**, 228-241.
- Kudo, K., Y. Sawada, and M. Horike (2004). Current studies in Japan on H/V and phase velocity dispersion of microtremors for site characterization, *the 13th World Conference on Earthquake Engineering*, Vancouver, B.C., Canada.
- Kwak, D. Y., J. P. Stewart, S. J. Mandokhail, and D. Park (2017). Supplementing $VS30$ with H/V spectral ratios for predicting site effects, *Bull. Seism. Soc. Am.* **107**, 2028-2042.
- Lachet, C., D. Hatzfeld, P. Y Bard., N. Theodulidis, C. Papaioannou, and A. Savvaidis (1996). Site effects and microzonation in the city of Thessaloniki (Greece). Comparison of different approaches, *Bull. Seism. Soc. Am.* **86**, 1692-1703.
- Lunedei, E., and P. Malischewsky (2015). A Review and Some New Issues on the Theory of the H/V Technique for Ambient Vibrations, Geotechnical, Geological and Earthquake Engineering book series: *Perspectives on European Earthquake Engineering and Seismology*, 371-394.
- Luzi, L., R. Puglia, F. Pacor, M. R. Gallipoli, D. Bindi, and M. Mucciarelli (2011). Proposal for a soil classification based on parameters alternative or complementary to $V_{s,30}$, *Bull. Earthq. Eng.* **9**, 1877-1898.

- Molnar, S., C. E. Ventura, R. Boroschek, and M. Archila (2015). Site characterization at Chilean strong-motion stations: Comparison of downhole and microtremor shear-wave velocity methods, *Soil Dyn. Earthq. Eng.* **79**, 22-35.
- Nakamura, Y. (1989). A method for dynamic characteristics estimation of subsurface using microtremor on ground surface, *Q. Rep. Railway Tech. Res. Inst.* **30**, 25-33.
- Nakamura, Y. (2019). What Is the Nakamura Method? *Seismol. Res. Lett.* **90**, 1437-1443.
- Nash, J. E., and J. V. Sutcliffe (1970). River flow forecasting through conceptual models: Part I, a discussion of principles, *J. Hydrol.* **10**, 282-290.
- Parolai, S., P. Bormann, and C. Milkereit (2001). Assessment of the natural frequency of the sedimentary cover in the Cologne area (Germany) using noise measurements, *J. Earthq. Eng.* **5**, 541-564.
- Pilz, M., and F. Cotton (2019). Does the 1D assumption hold for site response analysis? A study of seismic site responses and implication for ground motion assessment using KiK-net strong-motion data, *Earthq. Spectra* **2**, 883-905.
- Pitilakis, K., E. Riga, A. Anastasiadis, S. Fotopoulou, and S. Karafagka (2018). Towards the revision of EC8: proposal for an alternative site classification scheme and associated intensity dependent spectral amplification factors. *Soil Dyn. Earthq. Eng.* doi.org/10.1016/j.soildyn.2018.03.030
- Rong, M., L. Y. Fu, Z. Wang, X. Li, N. S. Carpenter, E. W. Woolery, and Y. Lyu (2017). On the amplitude discrepancy of HVSR and site amplification from strong-motion observations, *Bull. Seism. Soc. Am.* **107**, 2873-2884.
- Pousse, G. (2005). Analysis of K-NET and KiK-net data: implications for ground motion prediction - acceleration time histories, response spectra and nonlinear site response. *Doctoral Dissertation*, Joseph Fourier University Grenoble I.
- Riepl, J., P. Y. Bard, D. Hatzhel, C. Papaionnou, and S. Nechtschein (1998). Detail evaluation of site response estimation methods across and along the sedimentary valley of Volvi (EURO-SEISTEST), *Bull. Seism. Soc. Am.* **88**, 488-502.

- SESAME (2004). Guidelines for the implementation of the H/V spectral ratio technique on ambient vibrations measurements, processing and interpretation, *SESAME European research project*, WP12 - Deliverable D23.12.
- Stambouli, A. B., D. Zendagui, P. Y. Bard, and B. Derras (2017). Deriving amplification factors from simple site parameters using generalized regression neural networks: implications for relevant site proxies. *Earth, Planets and Space* **69**: 99 DOI 10.1186/s40623-017-0686-3.
- Stafford, P. J., A. Rodriguez-Marek, B. Edwards, P. P. Kruiver, and J. J. Bommer (2017). Scenario dependence of linear site-effect factors for short-period response spectral ordinates, *Bull. Seismol. Soc. Am.* **107**, 2859-2872.
- Steidl, J. H., A. G. Tumarkin, and R. J. Archuleta (1996). What Is a Reference Site? *Bull. Seismol. Soc. Am.* **86**, 1733-1748.
- Thompson, E. M., L. G. Baise, Y. Tanaka, and R. E. Kayen (2012). A taxonomy of site response complexity, *Soil Dyn. Earthq. Eng.* **41**, 32-43.
- Tokeshi, J. C., Y. Sugimura, and T. Sasaki (1996). Assessment of natural frequency from microtremor measurement using phase spectrum," *Proc. of the 5th World Conf. Earthq. Eng.* Acapulco, Mexico.
- Wang, S. Y. (2017). Study on site effect using ground motion data from KiK-net in Japan, *Doctoral Dissertation*, Institute of Engineering Mechanics, China Earthquake Administration, Harbin, China.
- Wang, S. Y., Y. Shi, W. P. Jiang, E. L. Yao, and Y. Miao (2018). Estimating site fundamental period from shear-wave velocity profile, *Bull. Seismol. Soc. Am.* **108**, 3431-3445.
- Willmott, C.J. (1981). On the validation of models. *Phys. Geogr.* **2**, 184-194.
- Zandieh A., and S. Pezeshk (2011). A Study of horizontal-to-vertical component spectral ratio in the New Madrid seismic zone, *Bull. Seismol. Soc. Am.* **101**, 287-296.
- Zhao, J. X., and H. Xu (2013). A comparison of V_{S30} and site period as site-effect parameters in response spectral ground-motion prediction equations, *Bull. Seismol. Soc. Am.* **103**, 1-18.

Zhu, C., M. Pilz, and F. Cotton (2019a). Which is a better proxy, site period or depth to bedrock, in modelling linear site response in addition to the average shear-wave velocity? *Bull. Earthq. Eng.* doi.org/10.1007/s10518-019-00738-6.

Zhu, C., F. Cotton, and M. Pilz (2019b). Testing the depths to 1.0 and 2.5 km/s velocity isosurfaces in a velocity model for Japan and implications for ground motion modelling, *Bull. Seism. Soc. Am.* doi: 10.1785/0120190016.

Authors and Affiliations

Chuanbin Zhu (corresponding author)

¹ GFZ German Research Centre for Geosciences, Telegrafenberg, 14473 Potsdam, Germany

chuanbin.zhu@gfz-potsdam.de

Fabrice Cotton

¹ GFZ German Research Centre for Geosciences, Telegrafenberg, 14473 Potsdam, Germany

² Also at University of Potsdam, Institute for Earth Sciences, Karl-Liebknecht-Str. 24-25, 14476
Potsdam, Germany

Marco Pilz

¹ GFZ German Research Centre for Geosciences, Telegrafenberg, 14473 Potsdam, Germany

List of Figure Captions

- Figure 1.** Consistency check on empirically-derived site resonant frequencies at selected KiK-net stations, Japan (Zhu et al., 2019). $f_{0,H/V}$ (Wang et al.), $f_{0,S/B}$ (Wang), $f_{0,S/B}$ (Pousse), and $f_{0,R/V}$ (Fujiwara et al.) are site frequencies derived by Wang et al. (2018) using horizontal-to-vertical (H/V) spectral ratio, by Wang (2017) and Pousse (2005) using surface-to-borehole (S/B) spectral ratio, and by Fujiwara et al. (2009) using radial-to-vertical (R/V) spectral ratio approaches, respectively. The solid line represents the 1-to-1 line, and the dashed lines correspond to $f_1/f_2=0.5$ and 2.0, respectively (after Zhu et al., 2019a).
- Figure 2.** (a) V_{S30} vs. $Z_{0.8}$ distribution of the 207 selected KiK-net stations; and (b) M_w - R_{rup} distribution of 1840 selected ground motions.
- Figure 3.** (a) Influence of using FAS and PSA on the identification of the highest peak frequencies f_{p1} , where solid line and dashed lines represent $|\log_{10}(f_{p1_PSA}/f_{p1_FAS})| = 0$ and 0.3, respectively; and (b) $[\overline{HVS\overline{R}}_{PSA}(f)/\overline{HVS\overline{R}}_{FAS}(f)]s$ for the 207 KiK-net sites and their average ($\pm$ one standard deviation). FAS and PSA were smoothed using Konno-Ohmachi window ($b=20$).
- Figure 4.** (a) Velocity profile of KiK-net site IWTH16, and (b) Source-site distance versus magnitude of 144 earthquakes recorded at IWTH16.
- Figure 5.** (a) $HVS\overline{R}_{FAS}(f)s$ and (b) $HVS\overline{R}_{PSA}(f)s$ of 144 recordings at KiK-net site IWTH16. Dots correspond to the highest peak frequency (f_{p1}) of each individual curve; Bold solid curve and dashed curves in each plot denote the mean spectral ratio $\overline{HVS\overline{R}}(f)$ and its variation (mean $\pm$ one standard deviation), respectively.
- Figure 6.** Identification of the highest peak frequency f_{p1} at KiK-net site IWTH16 from the average (a) $HVS\overline{R}_{FAS}$, and (b) $HVS\overline{R}_{PSA}$ of N sample recordings randomly selected from the 144 records (Fig. 5). For FAS , $N=3, 5, 7$ and 9; and for PSA , $N=3, 5, 7, 9, 13, 21$ and 59. For each N , the test was repeated 100 times.
- Figure 7.** Influence of peak definition on the identification of (a) the first peak frequency f_0 , and (b) the highest peak frequency f_p ; and (c) $HVS\overline{R}(f)s$ at site FKSH10. Solid and dashed bold lines in (c) represent the mean $HVS\overline{R}(f)$ and mean $\pm$ one standard deviation, respectively. $HVS\overline{R}s$ are computed on smoothed FAS with a Konno-Ohmachi window ($b=20$).
- Figure 8.** Influence of smoothing (Konno-Ohmachi) coefficient on the identification of (a) first peak frequency f_{03} , and (b) the highest peak frequency f_{p3} . Both f_{03} and f_{p3} are derived using $HVS\overline{R}$ on smoothed FAS . Solid line and dashed lines represent $|\log_{10}(f_1/f_2)| = 0$ and 0.3, respectively.
- Figure 9.** Spectral ratios at exemplary site (a) AKTH19 (with a major velocity contrast below borehole sensor), (b) NGNH10 (neither $\overline{HVS\overline{R}}(f)$ nor $\overline{SBS\overline{R}}(f)$ has a significant peak), (c) KKWH14 (either $\overline{HVS\overline{R}}(f)$ or $\overline{SBS\overline{R}}(f)$ has a significant peak), and (d) FKSH10 (both $\overline{HVS\overline{R}}(f)$ and $\overline{SBS\overline{R}}(f)$ have a significant peak). Vertical lines mark the locations of resonant frequencies. f_{02_HV} and f_{p2_HV} are the first and the highest peak frequencies, respectively, identified from $\overline{HVS\overline{R}}(f)$; and f_{02_SB} and f_{p2_SB} are the first and the highest peak frequencies, respectively, identified from $\overline{SBS\overline{R}}(f)$. All spectral ratios are calculated on FAS smoothed using a Konno-Ohmachi window with $b=20$.
- Figure 10.** First (f_{02_HV}) and highest (f_{p2_HV}) peak frequencies derived from $\overline{HVS\overline{R}}(f)$ versus those (f_{02_SB} and f_{p2_SB}) obtained from $\overline{SBS\overline{R}}(f)$ at 147 KiK-net sites. (a) f_{02_HV} vs f_{02_SB} , (b) f_{p2_HV} vs f_{02_SB} , (c) f_{02_HV} vs f_{p2_SB} , (d)

f_{p2_HV} vs f_{p2_SB} . Solid line, dotted lines and dashed lines in each plot represent $|\log_{10}(f_1/f_2)| = 0, 0.1$ and 0.3 , respectively. Other conditions are the same to those in Fig. 9.

Figure 11. (a) $\overline{HVS\bar{R}}_b(f)$ s and (b) $\overline{SBS\bar{R}}_v(f)$ s of 147 KiK-net sites. Bold solid and dashed curves in each plot represent the mean and mean $\pm$ one standard deviation, respectively. Other conditions are the same to those in Fig. 9.

Figure 12. Site amplification at $T=0.4$ s vs. (a) T_{pI_FAS} , and (b) V_{S30} (ln-ln units).

Figure 13. Standard deviation of residuals of amplification models using T_{pI_FAS} , T_{0I_FAS} , T_{pI_PSA} and V_{S30} as the sole predictor variable; and (b) Relative change in standard deviation using $AF(T_{pI_FAS})$ as a reference with positive and negative values denoting decrease and increase in σ_{Res} , respectively.

Figures

Figure 1. Consistency check on empirically-derived site resonant frequencies at selected KiK-net stations, Japan (Zhu et al., 2019). $f_{0,H/V}$ (Wang et al.), $f_{0,S/B}$ (Wang), $f_{0,S/B}$ (Pousse), and $f_{0,R/V}$ (Fujiwara et al.) are site frequencies derived by Wang et al. (2018) using horizontal-to-vertical (H/V) spectral ratio, by Wang (2017) and Pousse (2005) using surface-to-borehole (S/B) spectral ratio, and by Fujiwara et al. (2009) using radial-to-vertical (R/V) spectral ratio approaches, respectively. The solid line represents the 1-to-1 line, and the dashed lines correspond to $f_1/f_2 = 0.5$ and 2.0 , respectively (Adapted from Zhu et al., 2019a).

Figure 2. (a) V_{S30} vs. $Z_{0.8}$ distribution of the 207 selected KiK-net stations; and (b) M_w - R_{rup} distribution of 1840 selected ground motions.

Figure 3. (a) Influence of using *FAS* and *PSA* on the identification of the highest peak frequencies f_{p1} , where solid line and dashed lines represent $|\log_{10}(f_{p1_PSA}/f_{p1_FAS})| = 0$ and 0.3 , respectively; and (b) $[\overline{HVSR}_{PSA}(f)/\overline{HVSR}_{FAS}(f)]$ s for the 207 KiK-net sites and their average ($\pm$ one standard deviation). *FAS* and *PSA* were smoothed using Konno-Ohmachi window ($b=20$).

Figure 4. (a) Velocity profile of KiK-net site IWTH16, and (b) Source-site distance versus magnitude of 144 earthquakes recorded at IWTH16.

Figure 5. (a) $HVSR_{FAS}(f)$ s and (b) $HVSR_{PSA}(f)$ s of 144 recordings at KiK-net site IWTH16. Dots correspond to the highest peak frequency (f_{p1}) of each individual curve; Bold solid curve and dashed curves in each plot denote the mean spectral ratio $\overline{HVSR}(f)$ and its variation (mean $\pm$ one standard deviation), respectively.

and mean $\pm$ one standard deviation, respectively. *HVSRs* are computed on smoothed *FAS* with a Konno-Ohmachi window ($b=20$).

Figure 8. Influence of smoothing (Konno-Ohmachi) coefficient on the identification of (a) first peak frequency f_{03} , and (b) the highest peak frequency f_{p3} . Both f_{03} and f_{p3} are derived using *HVSR* on smoothed *FAS*. Solid line and dashed lines represent $|\log_{10}(f_1/f_2)| = 0$ and 0.3, respectively.

Figure 9. Spectral ratios at exemplary site (a) AKTH19 (with a major velocity contrast below borehole sensor), (b) NGNH10 (neither $\overline{HVSr}(f)$ nor $\overline{SBSr}(f)$ has a significant peak), (c) KKWH14 (either $\overline{HVSr}(f)$ or $\overline{SBSr}(f)$ has a significant peak), and (d) FKSH10 (both $\overline{HVSr}(f)$ and $\overline{SBSr}(f)$ have a significant peak). Vertical lines mark the locations of resonant frequencies. f_{02_HV} and f_{p2_HV} are the first and the highest peak frequencies, respectively, identified from $\overline{HVSr}(f)$; and f_{02_SB} and f_{p2_SB} are the first and the highest peak frequencies, respectively, identified from $\overline{SBSr}(f)$. All spectral ratios are calculated on *FAS* smoothed using a Konno-Ohmachi window with $b=20$.

Figure 10. First (f_{02_HV}) and highest (f_{p2_HV}) peak frequencies derived from $\overline{HVSR}(f)$ versus those (f_{02_SB} and f_{p2_SB}) obtained from $\overline{SB SR}(f)$ at 147 KiK-net sites. (a) f_{02_HV} vs f_{02_SB} , (b) f_{p2_HV} vs f_{02_SB} , (c) f_{02_HV} vs f_{p2_SB} , (d) f_{p2_HV} vs f_{p2_SB} . Solid line, dotted lines and dashed lines in each plot represent $|\log_{10}(f_1/f_2)| = 0, 0.1$ and 0.3 , respectively. Other conditions are the same to those in Fig. 9.

Figure 11. (a) $\overline{HVS\overline{R}}_b(f)$ s and (b) $\overline{SBS\overline{R}}_v(f)$ s of 147 KiK-net sites. Bold solid and dashed curves in each plot represent the mean and mean $\pm$ one standard deviation, respectively. Other conditions are the same to those in Fig. 9.

Figure 12. Site amplification at $T=0.4$ s vs. (a) T_{p1_FAS} , and (b) V_{S30} (ln-ln units).

Figure 13. Standard deviation of residuals of amplification models using T_{p1_FAS} , T_{01_FAS} , T_{p1_PSA} and V_{S30} as the sole predictor variable; and (b) Relative change in standard deviation using $AF(T_{p1_FAS})$ as a reference with positive and negative values denoting decrease and increase in σ_{Res} , respectively.

Tables

Table 1

Determination of site resonant frequency using spectral ratio techniques

Reference	Recording Stations	Approach	FAS or PSA*	Smoothing	Definition of Significant Peaks	f_0 or $f_p^\dagger$	Percentage of sites assigned f_0 or f_p
Hassani and Atkinson (2018)	California	HVSR ^{††}	PSA	No	Amplitude larger than both 1.5 times $\overline{HVSR}^\S$ and 2.0	f_p	554 (72%) out of 767 sites
Hassani and Atkinson (2016)	CENA	HVSR	PSA	No	Amplitude larger than both 1.5 times $\overline{HVSR}$ and 2.0	f_p	315 (59%) out of 535 sites
Wang et al. (2018)	KiK-net	HVSR	PSA	No	Amplitude larger than both 1.5 times $\overline{HVSR}$ and 2.0; and $0.5 \leq f_0/f_R^{++} \leq 2.0$	f_0	265 (56%) out of 473 sites
Wang (2017)	KiK-net	c-SBSR [#]	FAS	Parzen window (0.4 Hz)	Amplitude larger than 20% of the highest peak	f_0	249 (59%) out of 425 sites
Kwak et al. (2017)	K-NET & KiK-NET	HVSR	FAS	Konno-Ohmachi (b=20)	Amplitude larger than both 1.5 times $\overline{HVSR}$ and 2.0	f_0	1608 (97%) out of 1658 sites
Ghofrani et al. (2014)	KiK-net	HVSR	PSA	Konno-Ohmachi (b=20)	Amplitude larger than twice $\overline{HVSR}$	f_0	n.a.
Ghofrani et al. (2013)	KiK-net	HVSR	FAS	Konno-Ohmachi (b=20)	Amplitude larger than twice $\overline{HVSR}$	f_0	Single “peak” (60%); Two peaks (20%)
Fujiwara et al. (2009)	KiK-net	RVSR ⁺	FAS	n.a.	n.a.	f_0	All 674 (100%) sites
Pousse (2005)	KiK-net	SBSR [#]	FAS	Konno-Ohmachi (b=40)	Amplitude larger than 2 in a statistical sense; and within the frequency ranges $[0.5f_0, f_0]$ and $[f_0, 2f_0]$, there exists a frequency at which amplitude is at least 10% lower than the amplitude at f_0 .	f_0	501 (or 93%) out of 538 sites

* FAS and PSA – Fourier and response spectra, respectively;

[†] f_0 and f_p – the frequencies corresponding to the first and the predominant peaks, respectively;

^{††} $HVSR$ - horizontal-to-vertical spectral ratio;

[§] $\overline{HVSR}$ - $HVSR$ averaged over all usable frequencies at multiple stations;

^{||} *CENA* - Central & Eastern North-America;

[#] *SBSR* and c-*SBSR* - Surface-to-borehole spectral ratio and cross spectral ratio, respectively;

+ $RVS\bar{R}$ - radial-to-vertical spectral ratio;

++ f_R - Analytical fundamental frequency calculated from an available 1D velocity profile using the Rayleigh method.

Table 2

Influences of peak definition and smoothing on the number of significant peaks

Smoothing coefficient	Criteria	No peak	Single peak	Multiple peaks
	$C1$	6 (3%)	61 (29%)	140 (68%)
$b=20$	$C1, C2$	36 (17%)	113 (55%)	58 (28%)
	$C1, C2, C3$	38 (18%)	116 (56%)	53 (26%)
$b=30$	$C1, C2, C3$	22 (11%)	83 (40%)	102 (49%)
$b=40$	$C1, C2, C3$	16 (8%)	55 (27%)	136 (66%)

Table 3

Goodness-of-fit between resonant frequencies derived from $\overline{SBSR}(f)^*$ and $\overline{HVS\bar{R}}(f)^\dagger$

	f_{02_SB}		f_{p2_SB}	
	f_{02_HV} (Fig. 10a)	f_{p2_HV} (Fig. 10b)	f_{02_HV} (Fig. 10c)	f_{p2_HV} (Fig. 10d)
Nash-Sutcliffe model efficiency coefficient E	0.706	0.751	-0.022	0.216
Index of agreement d	0.910	0.923	0.675	0.745
Pearson's correlation coefficient r	0.889	0.878	0.655	0.700
Mean absolute error MAE	1.297	1.226	2.749	2.280
Sites with f_{HV}/f_{SB} out of range [0.5, 2.0]	8%	6%	22%	16%
Sites with f_{HV}/f_{SB} out of range [0.8, 1.25]	31%	29%	50%	40%

* $\overline{SBSR}(f)$ – Average surface-to-borehole spectral ratio over several recordings;

† $\overline{HVS\bar{R}}(f)$ – Average horizontal-to-vertical spectral ratio over several recordings;