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Research Article

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Improved Site-dependent Statistical Relationships of V_s , V_p and Resonant Frequency versus Bedrock Depth in Japan

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Abstract

Combining both processing techniques of horizontal-to-vertical spectral ratio (HVSr) and surface-to-borehole spectral ratio (SBR), using the KiK-net and K-NET database in Japan, could be used in the present study to establish relationships of V_s , V_p and resonant frequency (f) versus depth to bedrock half-space (h) based on the site-dependent variability in different lithologies. Remarkable correlations of the average V_s and V_p of layers overlying the bedrock half-space (*i.e.* $\bar{V}_s$ and $\bar{V}_p$) versus h are inversely resembling the relationships of f versus h and their maxima of ≤ 1000 m/s and ≤ 3000 m/s, respectively. Moreover, their ranges are decreasing gradually through site class of B, C, D and E resembling the ranges of the V_{s30} according to NEHRP Provision (2000). Underestimation in the correlation coefficients resulted from HVSr at K-NET sites due to shallow and limited ranges of h whenever compared with those resulted from HVSr and SBR at KiK-net sites. Rebuilding the f versus h based on site-dependent variability in different lithologies could strongly decrease scattering and deviations of data points. Although such relationships are site-specific and highly dependent on each region's geologic conditions, fair comparisons based on site information and site-dependent variability of different bedrock lithologies between previous relationships of f versus h in the literature and the present study relationships are showing remarkable and reasonable similarities. This indicates significant importance of introducing the seismic site classification of different lithologies as a crucial controlling factor in establishing the previous and the present nonlinear regression relationships.

Keywords: Horizontal-to-vertical spectral ratio, Transfer function, Resonant frequency, bedrock depth, S-wave velocity, Seismic site classification, KiK-net and K-NET (Japan).

1. Introduction

The statistical nonlinear regression relationships of the fundamental resonant frequency (f) and S -wave velocity (V_s) versus bedrock depth (h) are usually used to estimate the depth to the bedrock half-space. The general form of the relationship of f versus h could be defined as

$$h = af^{-b} \quad (1)$$

where a and b are correlation coefficients or fitting curve parameters.

Nakamura (1989) used the horizontal-to-vertical spectral ratio (HVSr) method to estimate the characteristics of the ground motion from the employment of the microtremor observation. Then it has been applied to weak and strong earthquake recordings (Lermo and Chavez-Garcia 1993, and Wen 2006) for estimating the fundamental resonant frequency of a site. HVSr method could be used to invert a 1D velocity structure based on the diffuse field theory using microtremors (Sánchez-Sesma *et al.* 2011) or earthquake recordings (Kawase *et al.* 2011 and Nagashima *et al.* 2014). Yamanaka *et al.* (1994) examined inferring subsurface structure using measurements of long-period microtremors in the northwestern part of the Kanto Plain in Japan where the sediment thickness varied from 0 km to 1 km. They found that the ellipticities of Rayleigh waves in earthquake ground motions were consistent with those of the microtremors in peak periods and amplitudes. Additionally, Bard and SESAME team (2004) concluded that HVSr calculated using ambient vibrations is showing overall good agreement in the fundamental resonant frequencies with the standard spectral ratios of earthquakes using reference site derived. In the literature, previous existing relationships of f versus h based on HVSr calculations of microtremor measurements were established by Ibs-von Seth and Wohlenberg (1999), Delgado *et al.* 2000(a and b),

Parolai *et al.* (2002), Scherbaum *et al.* (2003), Hinzen *et al.* (2004), García – Jerez *et al.* (2006), D'Amico *et al.* (2008), Harutoonian *et al.* (2013), Tün *et al.* (2016) and Moon *et al.*, (2019). Thabet (2019) established relationships of f versus h based on HVSr calculations of earthquake database of KiK-net. It is important to mention that all these statistical nonlinear regression relationships are strongly site-specific.

Early introduction of the empirical transfer function (ETF) in the valuable study conducted by Borchardt (1970) is considered as the base of other later studies. Calculating the ETF is usually done using a standard spectral ratio (SSR), and requires a pair of instruments, one located at a surface soil site under investigation (generally on alluvium) and the other at a nearby surface reference rock site. The ETF represents resonant frequencies of the soil column. These resonant frequencies are only descriptive of that portion of the soil column between the two sensors and are not necessarily representative of the site's global behavior experienced by an earthquake event. Satoh *et al.* (1995) conducted their study to evaluate the local site effects due to surface layers overlying the engineering bedrock and to remove them by using one-dimensional (1D) soil models. They could estimate the engineering bedrock waves, which are supposed to be observed on the outcrop of the engineering bedrock, from borehole records. They concluded that the resonant frequency determined from SBR at a borehole site should not be treated as the resonant frequency of the site. Microtremor measurements were carried in the western lower Rhine embayment (Germany) by Ibs-von Seth and Wohlenberg (1999) to estimate the resonance frequency using the classical spectral ratios and taking advantage of hard rock basement sites used as reference stations.

In the present study, the surface-to-borehole spectral ratios (SBR) are calculated using database of the Kiban Kyoshin network (KiK-net) in Japan. Seismic downhole array sites of KiK-net are invaluable tools in the present attempts to understand and accurately estimate the fundamental resonant frequency (f). Ground motions recorded at various depths within these seismic vertical arrays are used to calculate the surface-to-borehole spectral ratios (SBR), and consequently estimate the peak frequencies as the seismic waves travel from bedrock half-space to the ground surface. Rong *et al.* (2016) compared HVSRs of the S -wave with one dimensional equivalent-linear numerical simulation on 21 sites in western China and suggested that the HVSR from observed earthquake ground motion resembles the SBR of nonlinear site-response.

Thabet (2019) established site specific nonlinear regression relationships of h versus f using HVSRs for the KiK-net data from Japan. Strong scattering is dominated in the relationships of h versus f at bedrock depths of < 30 m and $30 \sim 100$ m, although the HVSR frequency peaks are clear, unique, and sharp. Some KiK-net sites are excluded from the study conducted by Thabet (2019) because they are exhibiting strong non-stationary and undergo high scattering and perturbations in their resulted HVSRs. According to Thabet (2019), there are 192 out of the accepted 324 KiK-net sites having their bedrock depths < 20 m, which corresponds to 59.3%. This means that bedrock depths < 20 m are strong responsible for the strong scattering that is dominated in the relationships of h versus f at bedrock depths of < 30 m and $30 \sim 100$ m (Thabet, 2019). Additionally, those 192 out of the whole 698 KiK-net sites constitute approximately 27.5% of the whole KiK-net sites. Therefore, it is hoped to expect obtaining ≈ 287 accepted K-NET sites out of the whole 1045 K-NET sites in the present study, when

processing with HVSR analyses. Therefore, KiK-net and K-NET seismic sites in Japan are used in the present study. HVSR and SBR analyses have been used to determine the fundamental resonant frequency (*i.e.* f_{HVSR} and f_{SBR} , respectively) using KiK-net sites. In addition, K-NET sites are also used to determine their f_{HVSR} using HVSR analyses. In total, all the available earthquake records from 1997 to 2019 at 698 KiK-net and 1045 K-NET seismic sites are used. Borchardt (1994) stated that time average *S*-wave velocity of the upper 30 m (V_{s30}) provides accurate site characterization and permits seismic site classification unambiguously. V_{s30} is the main parameter for site classification in terms of seismic response by EuroCode8, the National Earthquake Hazard Reduction Program (NEHRP), the Electrical Power Research Institute (EPRI), and the American Society of Civil Engineers (ASCE). Seismic site classification (NEHRP Provision, 2000) is shown in Table 1. In this study, site-dependent relationships of f_{HVSR} , f_{SBR} , and *P*-wave and *S*-wave velocity (*i.e.* V_p and V_s , respectively) versus h in Japan are provided for more improvement to reveal the influence of different physical and geological parameters on these statistical site-specific nonlinear regression relationships. Moreover, the applicability and discrepancy between HVSR and SBR are revealed and discussed.

2. Data Set

The data from the KiK-net and K-NET in (last accessed, January 2020) Japan are used to establish the proposed statistical nonlinear regression relationships based on the seismic site classification. The KiK-net consists of 698 seismic vertical array sites equipped with a pair of uphole/downhole accelerometers, and the K-NET consists of 1045 sites equipped with seismic surface accelerometers (refer to Figure 1).

KiK-net site data have high variety of stratigraphic and lithologic columns and V_P and V_S structures to depths between 100 m and 3500 m. 613 of KiK-net sites have borehole depths < 250 m, 42 sites have borehole depths between 250 m $\sim$ 500 m, and 42 sites have deeper boreholes > 500 m in depth, that are constructed on thick sediment within large plains, such as Kanto plain or Osaka basin. As a result, it will be possible to define the bedrock half-space.

The K-NET consists of 1045 strong-motion observation sites with a spacing of 25 km. This spacing of the K-NET is essential to record strong motions in the epicentral region of a crustal earthquake with more than magnitude of 7 anywhere in Japan. Beneath each K-NET site, the observed detailed N -value (*i.e.* blow count of standard penetration test), V_P and V_S structures, bulk densities (ρ) and lithologic column are provided down to a depth of 20 m. The vertical resolution of these observed data is 1 m. These observed data is a valuable opportunity to test and experience the present strong scattering that is dominated in the regression relationships of h versus f at bedrock depths of < 30 m.

Those KiK-net and K-NET sites show very wide lithological variation. In the present study, regression relationships of h versus f are established considering seven distinct lithological conditions. They are clay, sand, gravel, limestone, volcanic igneous, plutonic igneous and metamorphic groups. This lithology classification is basically depending on the dominant lithology layers.

All KiK-net and K-NET sites are classified according to the definition of National Earthquake Hazards Reduction Program (NEHRP Provision, 2000) site classes. According to Boore (2004), there are common three extrapolation methods to estimate the $\bar{V}_S(30)$, and consequently the NEHRP seismic site class from shallow velocity models of depths < 30 m, which is the case in K-NET data. These extrapolation methods are 1) assuming constant velocity, 2) using the correlation between $\bar{V}_S(30)$ and $\bar{V}_S(d)$, and 3) based on velocity statistics to determine site class. In the present paper, the simplest method assuming that the lowermost velocity of the model extends to 30 m is adapted (see equation 2).

$$\bar{V}_S(30) = 30 / (t(d) + \frac{30 - d}{V_{eff}}) \quad (2)$$

where V_{eff} is the assumed effective velocity (*i.e.* velocity at the bottom of the velocity model) from the bottom depth of K-NET site (d) to 30 m.

The high majority of KiK-net and K-NET sites have a class of C or D. Minority of the sites has a class of B or E, whereas sites have a class of A are not involved. This can be explained by the differences of local geologic and lithologic conditions.

In the present study, the KiK-net and K-NET enormous earthquake database collected covers the period between 1997 and 2019. Waveforms are recorded with a sampling frequency of 100 Hz for the majority of the used events and 200 Hz for some events. All the available events with PGAs (*i.e.* Peak Ground Accelerations) of ≤ 10 cm/s² are used in the present analyses in accordance with Régnier *et al.* (2013) in order to characterize the linear behaviour at each site. This implied that linear behaviour is prevailing avoiding later modification due to nonlinear response. This enormous earthquake database for each

KiK-net and K-NET site is prepared using multiple earthquakes approach (Thabet, 2019), and is simply assuming several consequent earthquakes records as a continuous time series to lengthen the total time window of each record. Between each two adjacent earthquake records, the effect due to conjunction points is negligible because the frequencies of interest are low (*i.e.* ≤ 50 Hz). Figure 2 shows an example of 737-earthquake surface records at IBRH15 site. Adopting multiple earthquake approach enable us to exclude sites having recorded earthquakes with strong non-stationary and may undergo high scattering and perturbations, which may significantly affect the physical meaning of the HVSR and SBR peak frequencies. As a result, the included or accepted sites in the present study have the lowest level of scattering (*i.e.* acceptable low standard deviation values) indicating that propagation path effects, which are represented in shallow or deep earthquakes and far-field or near-field earthquakes, could not control the resulted HVSR or SBR curves.

3. Methods of Analyses

The HVSR technique (Nogoshi and Igarashi 1970 and 1971; Nakamura 1989 and 2000) has been extensively studied with earthquake recordings to quantify the site effect produced by the sedimentary covering in specific frequency bands (Field and Jacob 1993; Lachet and Bard 1994; Lermo and Chavez-Garcia 1994; Bindi *et al.* 2000; Fäh *et al.* 2001). The HVSR is defined as the ratio of the quadratic mean of horizontal Fourier amplitude of ground motion (*i.e.* EW and NS components) and the vertical Fourier amplitude of ground motion at the free surface. The calculation is illustrated in

$$HVS\!R = \frac{\sqrt{EW^2 + NS^2}}{\sqrt{2}V} \quad (3)$$

where EW, NS, and V are the Fourier amplitude spectra of the east–west, north–south, and vertical components of the ground motion, respectively.

GEOPSY software suite (<http://www.geopsy.org>) is used for HVSR processing the prepared conjugated three-component events at the surface of each KiK-net and K-NET site. These lengthy time-window conjugated records provide fulfillment of the widely accepted framework guidelines of the European research project SESAME (Bard and SESAME team, 2004). These guidelines have been consulted and followed concerning HVSR processing. Therefore, the reliability and quality of these HVSR calculations are assessed depending on three basic requirements. They are : (a) the expected fundamental resonant frequency of interest must be more than 10 significant cycles in each time window, (b) the total number of the significant cycles must be more than 200 and it is recommended to be raised around two times at low fundamental resonant frequencies, and (c) the acceptable low standard deviation values that are calculated for the amplitudes of the time windows, which is recommended to be less than 2 for peak frequencies higher than 0.5 Hz or 3 for peak frequencies lower than 0.5 Hz. The identification of the clear peak frequency (f_0) is met when the HVSR curve exhibits two quantitative criteria for a clear HVSR peak frequency as proposed by Bard and SESAME team (2004). Those criteria are the amplitude and stability conditions and the threshold values of amplitude and frequency are summarized in Table 2. Amplitude conditions require that the HVSR amplitude of the peak frequency must be higher than 2 (*i.e.* $A_0 > 2$). The stability conditions require the following: 1) the peak frequency should appear at the same frequency on the HVSR curves corresponding to mean + and – one standard deviation

(*i.e.* σ_f is within a percentage $\pm 5\%$) of the peak frequencies estimated from individual time windows of the orthogonal components at one KiK-net or K-NET site, 2) σ_f (*i.e.* standard deviation of f_0 estimated from individual time windows) must be lower than a frequency dependent threshold $\varepsilon(f)$, and 3) $\sigma_A(f_0)$ (*i.e.* standard deviation of the HVSR amplitudes of the peak frequencies estimated from individual time windows) must be lower than a frequency dependent threshold $\theta(f)$.

A seismogram can be visualized as the convolution of the source effect, propagation path effect, site effect, and instrument response as:

$$A_{ij}(t) = S_i(t) * P_{ij}(t) * G_j(t) * I_j(t) \quad (4)$$

where $S_i(f)$ is the source effect, $P_{ij}(f)$ is the propagation path effect, $G_j(f)$ is the site effect, $I_j(f)$ is the instrument response, of the i^{th} event, and for the j^{th} station at free surface. “ $*$ ” denotes the convolution operator.

Denoting Fourier transform, equation 4 can be written as in Equation 5. The spectral ratio is obtained by dividing the Fourier spectrum of the acceleration at the j^{th} station at free surface by the spectrum at the k^{th} station at borehole as in Equation 6.

$$A_{ij}(f) = S_i(f)P_{ij}(f)G_j(f)I_j(f) \quad (5)$$

$$\frac{A_{ij}(f)}{A_{ik}(f)} = \frac{S_i(f) * P_{ij}(f) * G_j(f) * I_j(f)}{S_i(f) * P_{ik}(f) * G_k(f) * I_k(f)} = \frac{G_j(f)}{G_k(f)} \quad (6)$$

If the distance between stations j and k is much less than their hypocentral distances from the source, the source and path effects would be eliminated. The instrument response can be removed assuming similar instrument units at surface and in borehole. The exact site response can thus be obtained from equation 6.

In this study, SBR is defined as spectral ratios between the horizontal Fourier amplitude motions recorded on the free surface and in the borehole at each KiK-net site. Equations 7 and 8 show the SBR of both horizontal components (*i.e.* EW and NS, respectively).

$$SBR_{ew} = H_{s,ew}/H_{b,ew} \quad (7)$$

$$SBR_{ns} = H_{s,ns}/H_{b,ns} \quad (8)$$

where “ s “ and “ b “ terms are referred to motions recorded on the free surface and in the borehole, respectively.

The Fourier amplitude spectra for surface and borehole horizontal components at each KiK-net site are calculated using GEOPSY software suite (<http://www.geopsy.org>). Fulfilling Bard and SESAME team (2004) guidelines, the reliability and quality of the SBR calculations are also assessed depending on the previously explained three basic requirements. As a result, f_{SBR} could be estimated for both horizontal components (*i.e.* EW and NS) and defined as f_{SBR-EW} and f_{SBR-NS} , respectively. Calculating the f_{SBR-EW} and f_{SBR-NS} is carried out for two reasons. The first reason is to estimate the effects of lateral or horizontal variation in the lithology. The second reason is to estimate the directional or structural control dependency on site resonance.

Previous work by Ibs-von Seth and Wohlenberg (1999) defined the bedrock depths based on the interface between the soft sedimentary covers of different thicknesses of Tertiary and Quaternary ages ($V_s < 1000$ m/s), and Paleozoic hard rock basement ($V_s \geq 2500$ m/s). Delgado *et al.* 2000(a) defined the bedrock depths based on the interface between

the Upper Miocene sedimentary fill (*i.e.* conglomerates, sandstones and marls) of Bajo Segura basin ($V_S \geq 85$ m/s), and the basement of the basin which is composed of limestones and marls of Triassic to Cretaceous age ($V_S \geq 200$ m/s). Özalaybey *et al.* (2011) depended on geological evaluation and gravity data to estimate the bedrock depths in Izmit basin. García – Jerez *et al.* (2006) estimated the sedimentary cover thicknesses (*i.e.* depth to bedrock half-space) in Zafarraya basin by means of close geoelectrical surveys. In this study, h is estimated at each KiK-net and K-NET site according to the adopted approach by Thabet (2019). The seismic impedance contrasts of V_P and V_S between each adjacent two layers are calculated using equation 9 and 10, respectively.

$$IC_P = \frac{|\sigma V_P|_{i+1}}{|\sigma V_P|_i} \quad (9)$$

$$IC_S = \frac{|\sigma V_S|_{i+1}}{|\sigma V_S|_i} \quad (10)$$

where σ is the density of each layer i (note: 1 is the surficial layer and i^{th} for underlying layers).

The appropriate h is assigned to its f_{HVSr} , f_{SBR-EW} and f_{SBR-NS} , whereas the unreasonable h is excluded from any further analyses due to difficulties or suspicion in assigning the accurate and proper bedrock half-space. However, exclusion of KiK-net and K-NET sites from further analyses is executed depending on designed filtering process as illustrated in Figure 3 and Figure 4, respectively. The rejected or excluded sites from further analyses are due to many reasons. They are organized on a base of step-by-step process as: 1) the unavailability of velocity structures, geotechnical or seismological database at some KiK-net and K-NET sites, 2) K-NET sites exhibiting

peak resonance frequencies < 2.5 Hz, 3) the clarity criteria according to SESAME guidelines (Bard and SESAME team, 2004) is not satisfied, 4) presence of unclear peak frequency such as broad peak frequency or a multiplicity of local maxima, and 5) difficulties in relating the peak resonance frequency with its proper impedance contrast bedrock half-space. The present *PS* logging seismic velocity structures of KiK-net and K-NET are considered as reliable and applicable (Thabet, 2019). Consequently, HVSR inversions are carried out using inversion code program developed by Nagashima *et al.* (2014 and 2017), which is specifically designed for calculating the theoretical earthquake HVSR (eHVSR) based on the diffuse field concept. Therefore, it will be possible to confirm the physical meaning for assigning bedrock half-space according to Equation 9 and 10.

4. Results and Discussion

Out of 698 KiK-net sites processed with HVSR and SBR methods and 1045 K-NET sites processed with HVSR method, 366 and 483 KiK-net sites processed with HVSR and SBR, respectively, and 339 K-NET sites processed with HVSR method could be accepted and included in the further analyses. Table 3 shows the ranges of h and f of the accepted sites in the present study. The engineering bedrock has S -wave velocity of 400 m/s to 700 m/s according to seismic microzonation study by Nath (2007), while Miller *et al.* (1999) defined the bedrock by considering S -wave velocity of ≥ 244 m/s using MASW survey. Delgado *et al.* (2000b) defined the geotechnical bedrock by considering S -wave velocity > 250 m/s of the Triassic carbonate rocks and Triassic to Cretaceous limestones. However, the engineering bedrock has S -wave velocity of ≥ 350 m/s, whereas the seismological or seismic bedrock corresponds to S -wave velocity of ≥ 3000 m/s (Satoh *et*

al., 2001, Kawase *et al.*, 2011 and Kawase *et al.*, 2018). In the present paper, 302 and 37 out of the 339 K-NET sites processed with HVSR method have *S*-wave velocity of bedrock > 350 m/s ~ 2000 m/s and < 350 m/s, respectively. 348 and 18 out of the 366 KiK-net sites processed with HVSR method have *S*-wave velocity of bedrock > 350 m/s ~ 3000 m/s and < 350 m/s, respectively, whereas 453 and 30 out of the 483 KiK-net sites processed with transfer function method have *S*-wave velocity of bedrock > 350 m/s ~ 3000 m/s and < 350 m/s, respectively. As a result, those minor sites with *S*-wave velocity of bedrock < 350 m/s have intermediate layer within the sediments (*i.e.* highest impedance contrast interface) and responsible for producing peak resonance frequency.

Figure 5 shows three examples of KiK-net sites that are producing clear sharp and unique single HVSR and SBR fundamental resonant frequencies of > 3 Hz, $1 \sim 3$ Hz and < 1 Hz that are processed at SZOH34, YMTH15 and ISKH06 sites, respectively. In the supplementary material, Figures S1 through S10 are showing various examples of KiK-net sites processed with HVSR and SBR and K-NET sites processed with HVSR. The examples exhibit clear, sharp and unique single HVSR or SBR peak frequencies. Figures S11, S12 and S13 are showing various examples of discarded KiK-net sites processed with HVSR and SBR and K-NET sites processed with HVSR. Tables S1, S2 and S3 are showing the whole discarded KiK-net and K-NET sites with their discard codes. There are 23 KiK-net sites and 34 K-NET sites with no available velocity structure or any geotechnical database. Four K-NET sites have their soil condition data to a depth of only 5 m. Due to the depth limitation in K-NET database to ≤ 20 m, so that, 388 K-NET sites are discarded because they have peak resonance frequency < 2.5 Hz which is corresponding to > 20 m depth. There are 291, 106 and 197 KiK-net sites processed with HVSR and SBR and K-NET sites processed with HVSR, respectively, not satisfying the

clarity criteria according to SESAME guidelines (Bard and SESAME team, 2004). Discarded 7, 62 and 21 KiK-net sites processed with HVSR and SBR and K-NET sites processed with HVSR, respectively, have unclear peak frequency such as broad peak frequency or a multiplicity of local maxima. Due to difficulties in relating the peak resonance frequency with its proper impedance contrast bedrock half-space, 11, 24 and 62 KiK-net sites processed with HVSR and SBR and K-NET sites processed with HVSR, respectively, are discarded. It is important to know that Thabet (2019) used 324 KiK-net sites processed with HVSR method, whereas the present study could success to increase the accepted or included sites up to 366 KiK-net sites processed with HVSR method. This improvement is due to adopting multiple earthquake approach, which enable us to include all the available ground motion records with PGAs $\leq 10 \text{ cm/s}^2$. Consequently, the effect of strong non-stationary, which may significantly affect the physical meaning of the HVSR and SBR, could be minimized or eliminated in the resulted peak frequencies. The other improvement in the present study is the accepted or included 483 KiK-net sites processed with SBR. As depicted from equation 6, SBR proves its efficiency in assessing the site response based on surface-to-borehole KiK-net sites. This indicates the applicability and productivity of SBR method in establishing regression relationships of h versus f . Moreover, the variability between SBR_{ew} and SBR_{ns} is tested through comparison between f_{SBR-EW} and f_{SBR-NS} as shown in Figure S14. This indicates that the lateral variation between EW and NS components considering the resonance peak frequencies are insignificant, particularly for sites having peak frequencies $< 1 \text{ Hz}$. Figure S14 is also showing two comparisons between $f_{HVSR-KiK}$ versus f_{SBR-EW} and f_{SBR-NS} . Both comparisons are based on the same KiK-net sites having accepted $f_{HVSR-KiK}$, f_{SBR-EW} and f_{SBR-NS} . f_{SBR-EW} and f_{SBR-NS} tend to be equal to or slightly higher than their corresponding $f_{HVSR-KiK}$. This indicates that f_{SBR-EW} and f_{SBR-NS} are

comparable to their corresponding $f_{HVS\text{R}-KiK}$. Figure S15 shows that the class of C and D are the dominant site classes as depicted from the accepted KiK-net and K-NET sites.

Figure 6 shows an example of assigning the HVS_R fundamental and secondary resonant frequencies to their deep and shallow bedrock half-spaces, respectively, at KYTH08 KiK-net site. In this example, the first highest IC_P and IC_S are directly indicating the deep bedrock half-space at 350 m depth, whereas the second highest IC_P and IC_S are directly indicating the shallow bedrock half-space at 10 m depth. As shown in equations 8 and 9, IC_P and IC_S are the main basics for inferring the reliable bedrock half-space to its corresponding peak frequency.

Generalized nonlinear regression relationships of the $f_{HVS\text{R}}$, estimated using KiK-net sites ($f_{HVS\text{R}-KiK}$) and K-NET sites ($f_{HVS\text{R}-K}$), f_{SBR-EW} and f_{SBR-NS} versus their corresponding h are superimposed as shown in Figure 7. Significant scattering in the fundamental resonant frequencies at bedrock depths < 100 m is dominant. These strong deviations of the data points would be analyzed based on seismic site classification and bedrock lithology. Applying the quarter wavelength theory in Figure 7 will result in identification of shallow and deep sites with average overlying S -wave velocities of 100 m/s $\sim$ 200 m/s and 400 m/s $\sim$ 800 m/s, respectively. This is a theoretical interpretation of the observed relationships of f versus h , whereas Figure 8 is showing the delineated average overlying S -wave velocities obtained from the PS logging seismic velocity structures of KiK-net and K-NET. The most interesting point is that these nonlinear regression relationships of f versus h are strongly corresponding to the average S -wave and P -wave velocities overlying the bedrock half-space ($\bar{V}_S$ and $\bar{V}_P$, respectively, are

illustrated in equations 11 and 12) versus h (Figure 8), whereas the bedrock V_S and V_P have insignificant relation with their corresponding f versus h (Figure S16). These results indicate the importance to establish nonlinear regression relationships of f versus h depending on seismic site classification of each lithology, because there is higher dependency on the $\bar{V}_S$ and $\bar{V}_P$ than the bedrock V_S and V_P .

$$\bar{V}_S = h / \sum_{i=1}^n \frac{h_i}{V_{Si}} \quad (11)$$

$$\bar{V}_P = h / \sum_{i=1}^n \frac{h_i}{V_{Pi}} \quad (12)$$

where h is the total thickness of the layers above the bedrock half-space. h_i , V_{Si} and V_{Pi} are the thickness, S -wave and P -wave velocities of each individual layer. n is the number of these layers.

In this study, KiK-net and K-NET sites are classified according to their seismic site classification to class of B, C, D and E. Each site class consists of different lithological conditions of bedrock half-space and classified to seven major groups: clay, sand, gravel, limestone, volcanic igneous, plutonic igneous and metamorphic. Table S4 explains detailed lithologies in each lithology group. Figure S17 shows statistical review of the number of peak frequencies lying in these different lithological conditions of the bedrock half-space and the overlying layers, too. It is obvious that the dominant lithology belongs to the gravel group. Moreover, the differences between the lithological conditions of the bedrock half-space and the overlying layers are insignificant. This indicates that the interface between the overlying layers and bedrock half-space is lying within the same lithology group.

Figure 7 shows the highest scattering in the f versus h at depths < 100 m. Therefore, this generalized f versus h relationship is rebuilt according to different seismic site classification of the seven major lithology groups. Figure 9 shows two examples of the f versus h relationships in gravel and volcanic igneous lithology group of class C and D, whereas the detailed f versus h relationships in each lithology group with different site class are shown in Figure S18. Reasonable fit could be achieved in the $f_{HVS\text{R}-KiK}$, $f_{HVS\text{R}-K}$, f_{SBR-EW} and f_{SBR-NS} versus their corresponding h relationships. Significant differences are present in the f versus h relationships produced from HVS\text{R} and SBR analyses. Example of the f versus h relationships in clay lithology group is showing good matched correlations produced from HVS\text{R} and SBR analyses of class C, whereas significant difference between $f_{HVS\text{R}-KiK}$ and f_{SBR-EW} and f_{SBR-NS} is present in this clay lithology group of class D.

Remarkable correlations could be seen in the $\overline{V_S}$ and $\overline{V_P}$ versus h and f relationships as shown in Figure S19. Poor fitting could be clearly seen in the bedrock V_S and V_P versus h relationships as shown in Figure S20. This reflects the strong dependency of the resulted $f_{HVS\text{R}-KiK}$, $f_{HVS\text{R}-K}$, f_{SBR-EW} and f_{SBR-NS} on average P -wave and S -wave velocity structure of the layers over the bedrock half-space. The bedrock V_S and V_P have has insignificant influence on the resulted fundamental resonant frequency. This interesting point concludes that the presence of the bedrock half-space is determined based on the highest IC_P and IC_S as explained earlier, and not based on the bedrock V_S or V_P .

Table S5 summaries the correlation coefficients (*i.e.* a and b) with their characterizing maximum $\bar{V}_S$ and $\bar{V}_P$ and the bedrock V_S and V_P as depicted from Figures S19 and S20. Among the different lithological groups of different site classes, the high majority of the maximum $\bar{V}_S$ and $\bar{V}_P$ are not exceeding 1000 m/s and 3000 m/s, respectively. Moreover, a general gradual decreasing in the maximum $\bar{V}_S$ and $\bar{V}_P$ is observed thorough site class of B, C, D and E. Depending on these observations, different gradual ranges for each site class are proposed as shown in Table 4. These gradual ranges and their $\pm$ errors are calculated based on the average values and their standard deviations of the maximum $\bar{V}_S$ and $\bar{V}_P$ in Table S5. Moreover, these gradual ranges of the maximum $\bar{V}_S$ and $\bar{V}_P$ resemble the ranges of V_{s30} in the NEHRP Provision (2000), because the high majority of $f_{HVSr-KiK}$, f_{HVSr-K} , f_{SBR-EW} and f_{SBR-NS} are corresponding to h of ≤ 30 m (refer to Figure 7). This explains the high importance of studying these nonlinear regression relationships considering the seismic site classification in each lithology group.

It was hoped that the HVSr processing results at K-NET sites would interpret and solve the strong scattering in the f versus h relationships at h of < 20 m, but it is obvious that f_{HVSr-K} versus h relationship has strong scattering too (Figure 7). Rebuilding the f_{HVSr-K} versus h relationship based on seismic site classification in each lithology group could enhance the data scattering. The resulted correlation coefficients of a and b are generally lower than those resulted from the $f_{HVSr-KiK}$, f_{SBR-EW} and f_{SBR-NS} versus h relationships (Table S5). This underestimation indicates that the ranges of h and f have strong influence on the resulted a and b coefficients. Also, it is an indication that deep bedrock half-spaces are governing and guiding the overall f versus h relationships.

Ibs-von Seth and Wohlenberg (1999) studied sand formations of class C in western Lower Rhine Embayment, Germany. The ranges of h and f in this previous study were 15 m ~ 1600 m and 5 Hz ~ 0.1 Hz, respectively, and investigated with application of Nakamura's technique and transfer function technique using microtremor measurements. Scherbaum *et al.* (2003) presented relationships of $\bar{V}_S$ versus h of sand formations of class C at three arrays near Pulheim, Chorweiler and Llsdorf in Cologne city area, Germany. Their results consider the uppermost 200 ~ 300 m analyzing the fundamental mode Rayleigh wavefield in the frequency range of 0.7 Hz ~ 2.2 Hz. Therefore, both studies are used in fair comparison with sand lithology group of class C of the present study as shown in Table 5.

D'Amico *et al.* (2008) mapped the f of the shale sedimentary cover (*i.e.* h) of class C in the city of Florence, Italy. Their ranges of h and f are < 5 ~ 153 m and 0.1 ~ 20 Hz, respectively. The correlation coefficients of a and b and their characterizing ranges of $\bar{V}_S$ and bedrock V_S are compared with clay group of class C in the present study.

Harutoonian *et al.* (2013) conducted HVSr microtremor measurements in a dynamically compacted gravelly fill area in Western Sydney, Australia. The ranges of h and f are 13.3 ~ 1.2 m and 4.2 ~ 27 Hz, respectively. Therefore, their correlation coefficients of a and b and the characterizing ranges of $\bar{V}_S$ and bedrock V_S are fairly compared with those resulted from HVSr processing of K-NET sites belonging to gravel lithology group with class of D.

Finally, resulted ranges of h and f from Moon *et al.* (2019) study are 10 ~ 45 m and 2 ~ 9 Hz, respectively. They studied the bedrock depths of weathered Bukit Timah granite formation in Singapore using microtremor measurements. The sites used in this study belong to site class of D. As a result, the comparison is built with igneous plutonic lithology group with class of D.

Because of similarities in the site information and measurement parameters of these previous studies and the present study, fair comparison could be achieved considering the site-dependent lithology groups, as shown in Table 5. Interestingly, remarkable and reasonable similarities could be seen in the correlation coefficients of a and b and their characterizing ranges of $\bar{V}_S$ and bedrock V_S . It is important to note that these previous and present relationships are site-specific and highly dependent on each region's geologic conditions. Therefore, the target of these comparisons is only to introduce the seismic site classification of different lithologies as a crucial controlling factor in establishing the previous and the present nonlinear regression relationships.

eHVSr inversion based on the diffuse field concept is conducted using an example IBRH11 KiK-net site. The inverted V_S and V_P structures could interpret reliably the presence of the bedrock half-space using the criteria of the highest IC_P and IC_S , although the underestimation of the V_S and V_P structures beneath the bedrock half-space. Figure S21 is showing the example eHVSr inversion at IBRH11 KiK-net site. The determination of the bedrock half-space using the inverted V_S and V_P structures are close with those provided from KiK-net. Observed and inverted HVSr curves are fitted with respect to peak amplitudes and fundamental resonant frequencies. Thabet (2019)

conducted HVSR inversions based on diffuse field approach using 30 KiK-net sites. He showed reasonable fitting between the observed and the inverted f and h .

5. Conclusions

With the results discussed earlier, it is possible to retrieve the following conclusions. The present study introduces additional improvements to the study conducted by Thabet (2019). These improvements consist of SBR and HVSR processing using database at the 698 KiK-net and the 1045 K-NET sites. The seismic database includes all the available earthquakes with PGAs of $\leq 10 \text{ cm/s}^2$ at each site. Additionally, HVSR and SBR processing using the adopted conjugated records could increase the number of accepted sites due to enhancement in the requirements of SESAME guidelines (Bard and SESAME team, 2004). Moreover, the relationships of $\bar{V}_S$ and $\bar{V}_P$ versus h are inversely resembling the relationships of f versus h , whereas the relationships of bedrock V_S and V_P versus h have insignificant importance. The shallow and limited ranges of h and f underestimate the correlation coefficients of a and b resulted from f_{HVSR-K} versus h relationship whenever compared with those resulted from the $f_{HVSR-KiK}$, f_{SBR-EW} and f_{SBR-NS} versus h relationships. This indicates that deep bedrock half-spaces are governing and guiding the overall f versus h relationships. Relationships of f_{SBR-EW} and f_{SBR-NS} versus their corresponding h are strongly resembling relationships of $f_{HVSR-KiK}$ versus h indicating that SBR analyses is productive and efficient tool to delineate the fundamental resonant frequency. Overall, rebuilding the f_{SBR-EW} , f_{SBR-NS} and $f_{HVSR-KiK}$ versus their corresponding h based on site-dependent variability in different lithologies could strongly decrease scattering and deviations of data points. Remarkable correlations could be seen in the $\bar{V}_S$ and $\bar{V}_P$ versus h relationships reflecting the strong

dependency of the $f_{HVS\text{R}-KiK}$, $f_{HVS\text{R}-K}$, f_{SBR-EW} and f_{SBR-NS} on the $\bar{V}_S$ and $\bar{V}_P$. The high majority of the maximum $\bar{V}_S$ and $\bar{V}_P$ is not exceeding 1000 m/s and 3000 m/s, respectively. The ranges of maximum $\bar{V}_S$ and $\bar{V}_P$ are decreasing gradually through site classes of B, C, D and E resembling the ranges of the V_{s30} of the seismic site classification according to NEHRP Provision (2000). Therefore, the presence of the bedrock half-space is determined based on the highest IC_P and IC_S without respect to the bedrock V_S or V_P . HVSR inversions based on the diffuse field approach could interpret the presence of the bedrock half-space using the criteria of the highest IC_P and IC_S . Interestingly, fair comparisons based on site information and site-dependent variability of different bedrock lithologies between previous relationships of f versus h in the literature and the present study relationships are showing remarkable and reasonable similarities.

It is important to note that these previous and present relationships are site-specific and highly dependent on each region's geologic conditions. The main achievement of the present study is only to introduce the seismic site classification of different lithologies as a crucial controlling factor in establishing the previous and the present nonlinear regression relationships of the depth of high impedance contrast interface versus the peak resonance frequency and the average overlying S -wave velocity. Practically, inverting the layered S -wave velocity structure is possible using known resonance frequency from HVSR analyses, particularly in regions with deployed strong motion observation system, and consequently reliable inference of the bedrock depth, average overlying S -wave velocity, and seismic site classification. As a result, the usefulness of these present nonlinear regression relationships is the possibility to quickly obtain a general idea of the subsurface lithology. Moreover, using these present nonlinear regression relationships

based on known subsurface lithology and seismic site classification could be used to provide an initial guess and to constrain ranges of the depths and average overlying *S*-wave velocity to feed into the HVSR inversion process.

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Availability of data and material

Any data in this research work would be available upon request immediately.

Code availability

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Authors' contributions

The submitting author confirm that he is a single author named in the manuscript is aware of the submission and has agreed for the paper to be submitted to PAAG. I am acknowledging the consent requirements. I am very appreciated for your careful consideration.

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Figure 1: Location map of KiK-net and K-NET seismic stations. Blue triangles are the 698 KiK-net seismic sites. Red circles are the 1045 K-NET seismic sites.

Figure 2. Example of more than one-day time window of the conjugated three-component (*i.e.* Z, N, and E are UD, NS, and EW components, respectively) of 737 events recorded at IBRH15 site prepared for processing in GEOPSY software suite. (Note: the shown 737 earthquake events are all the recorded events at IBRH15 site from 1997 to 2019 with amplitudes less than 10 cm/s^2)

Figure 3: Flowchart showing the designed filtering process to discard or accept KiK-net site in the present regression relationship.

Figure 4: Flowchart showing the designed filtering process to discard or accept K-NET site in the present regression relationship.

Figure 5. Examples of peak frequencies at ISKH06, YMTH15, and SZOH34 KiK-net sites resulted from HVSR (upper curves) and SBR of both horizontal components (middle and lower curves). (Note: red curves are the average HVSR or SBR curves, whereas the pale gray curves are the minimum and maximum)

Figure 6. Example of bedrock depth assignment at KYTH08 site.

Figure 7: Fundamental resonant frequency versus bedrock depth obtained from HVSR and SBR of KiK-net sites and from HVSR of K-NET sites. (Nonlinear regression equations from top to bottom are corresponding to HVSR of KiK-net, SBR of EW and NS components of KiK-net, and HVSR of K-NET, respectively)

Figure 8: Average overlying ($\bar{V}_S$ and $\bar{V}_P$) versus h corresponding to f versus h in Figure 7

Figure 9: An example of average overlying V_s versus h corresponding to f versus h in gravel and volcanic igneous lithology groups of class C and D.

Figure 9: cont.

Table 1. Seismic site classification according to NEHRP Provision (2000)

Site Class	Site Characterization	V_{s30} Range
A	Hard rock	$V_{s30} > 1500$ m/s
B	Firm to hard rock	$1500 \text{ m/s} \geq V_{s30} > 760$ m/s
C	Dense soil and soft rock	$760 \text{ m/s} \geq V_{s30} > 360$ m/s
D	Stiff soil	$360 \text{ m/s} \geq V_{s30} > 180$ m/s
E	Soft soil	$V_{s30} \leq 180$ m/s

Table 2: Threshold parameters for the identification of a clear peak frequency according to guidelines by Bard and SESAME team (2004)

(σ_f)	$\pm 5\%$				
Amplitude (A_0) of peak frequency	> 2				
Peak frequency range (Hz)	< 0.2	$0.2 \sim 0.5$	$0.5 \sim 1.0$	$1.0 \sim 2.0$	> 2.0
$\varepsilon(f_0)$ (Hz)	$0.25 f_0$	$0.20 f_0$	$0.15 f_0$	$0.10 f_0$	$0.05 f_0$
$\theta(f_0)$ for $\sigma_A(f_0)$	3.0	2.5	2.0	1.78	1.58

Table 3. Resulted ranges of h and f in the present study.

	Min. f (Hz)	Max. f (Hz)	Min. h (m)	Max. h (m)
HVSR KiK-net	0.16	25.28	1	1000
SBR KiK-net	0.18	25.00	1	1350
HVSR K-net	2.54	26.35	1	18

Table 4. Proposed ranges of the maximum $\bar{V}_S$ and $\bar{V}_P$ (refer to Table S5) overlying bedrock half space according to the present study.

Site Class	Max. $\bar{V}_S$ Range	Max. $\bar{V}_P$ Range
B	1023 m/s (± 152) $\geq \bar{V}_S > 778$ m/s (± 110)	2597 m/s (± 609) $\geq \bar{V}_P > 2133$ m/s (± 195)
C	778 m/s (± 110) $\geq \bar{V}_S > 675$ m/s (± 137)	2133 m/s (± 195) $\geq \bar{V}_P > 2024$ m/s (± 116)
D	675 m/s (± 137) $\geq \bar{V}_S > 398$ m/s (± 147)	2024 m/s (± 116) $\geq \bar{V}_P > 1525$ m/s (± 386)
E	$\bar{V}_S \leq 398$ m/s (± 147)	$\bar{V}_P \leq 1525$ m/s (± 386)

Table 5. Existing correlation coefficients (*i.e.* a and b) with their characterizing ranges of $\bar{V}_S$ and bedrock V_S results (refer to Table S5).

Lithology / site class	Literature / present study	HVSr – KiK-net		SBR-EW		SBR-NS		HVSr – K-NET		$\bar{V}_S$ (m/s)	Bedrock V_S (m/s)
		a	b	a	b	a	b	a	b		
Sand / C	Ibs-von Seth and Wohlenberg, 1999	96 ± 4	1.39 ± 0.03	146 ± 19	1.38 ± 0.21	146 ± 19	1.38 ± 0.21			380 ~ 705	2500 ~ 3100
	Scherbaum <i>et al.</i> , 2003	99	1.31								
		111	1.28								
		102	1.19								
	This Study	103	1.24	135	1.32	137	1.33	62	1.12	120 ~ 813	400 ~ 2700
Clay / C	D’Amico <i>et al.</i> , 2008	140	1.17							200 ~ 750	> 800
	This study	128	1.19	141	1.22	136	1.19	58	1.05	192 ~ 668	400 ~ 2770
Gravel / D	Harutoonian <i>et al.</i> 2013							73	1.17	150 ~ 300	> 400
	This study	91	1.33	119	1.45	118	1.41	75	1.26	60 ~ 740	130 ~ 1700
Plutonic Igneous / D	Moon <i>et al.</i> , 2019	92	1.06							200 ~ 400	333 ~ 584
	This study	86	1.02	134	1.25	127	1.19	31	0.83	159 ~ 473	280 ~ 2600

Figures

Figure 1

Location map of KiK-net and K-NET seismic stations. Blue triangles are the 698 KiK-net seismic sites. Red circles are the 1045 K-NET seismic sites. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research

Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Figure 2

Example of more than on-day time window of the conjugated three-component (i.e Z, N, and E are UD, NS, and EW components, respectively) of 737 events recorded at IBRH15 site prepared for processing in GEOPSY software suite. (Note: the shown 737 earthquake events are all the recoded events at IBRH15 site from 1997 to 2019 with amplitudes less than 10 cm/s²)

Figure 3

Flowchart showing the designed filtering process to discard or accept KiK-net site in the present regression relationship.

Figure 4

Flowchart showing the designed filtering process to discard or accept K-NET site in the present regression relationship.

Figure 5

Examples of peak frequencies at ISKH06, YMTH15, and SZOH34 KiK-net sites resulted from HVSR (upper curves) and SBR of both horizontal components (middle and lower curves). (Note: red curves are the average HVSR or SBR curves, whereas the pale gray curves are the minimum and maximum)

Figure 6

Example of bedrock depth assignment at KYTH08 site.

Figure 7

Fundamental resonant frequency versus bedrock depth obtained from HVSR and SBR of KiK-net sites and from HVSR of K-NET sites. (Nonlinear regression equations from top to bottom are corresponding to HVSR of KiK-net, SBR of EW and NS components of KiK-net, and HVSR of K-NET, respectively)

Figure 8

Average overlying (V_s and V_p) versus $\bar{f}$ corresponding to f versus $\bar{f}$ in Figure 7

Figure 9

An example of average overlying V_s versus f corresponding to f versus V_s in gravel and volcanic igneous lithology groups of class C and D.

Supplementary Files

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- [Supplementarymaterialmostafathabet.pdf](#)