

The 17th World Conference on Earthquake Engineering

17th World Conference on Earthquake Engineering, 17WCEE Sendai, Japan - September 13th to 18th 2020

DIRECT ESTIMATION OF S-WAVE SITE AMPLIFICATION FACTORS FROM HORIZONTAL-TO-VERTICAL RATIOS OF EARTHQUAKES

H. Kawase⁽¹⁾, E. Ito⁽²⁾, and K. Nakano⁽³⁾

⁽¹⁾ Program-Specific Professor, DPRI, Kyoto University, kawase@sere.dpri.kyoto-u.ac.jp

⁽²⁾ Program-Specific Researcher, DPRI, Kyoto University, ito@sere.dpri.kyoto-u.ac.jp

⁽³⁾ Researcher, Technical Research Institute, HAZAMA ANDO CORP., nakano.kenichi@ad-hzm.co.jp

Abstract

It is important to deduce the horizontal site amplification factor (HSAF) in the main S-wave portion for evaluating sitespecific design earthquake ground motions and elucidating the relationship between the subsurface structures and their amplification effects. The methods to obtain the HSAF include a theoretical calculation method based on the welldefined subsurface structure, an empirical method based on the spectral ratio between borehole and surface sensors, and another empirical method based on the spectral ratio of a sedimentary site with a nearby rock outcrop site. These methods have their own problems. The theoretical method has difficulty in verifying the adequacy of a velocity structure and determining the velocity structure at the site down to the seismological bedrock. The empirical method that uses borehole observation data has difficulty in eliminating the effects of reflected waves at the surface in the observed borehole seismograms, the so-called cancellation effects. The empirical method of using data observed at a reference rock site for input to the denominator often has difficulty in finding such a nearby site where the bedrock is exposed, and there is an issue of whether the reference site can really be a site without site amplification.

On the other hand, the generalized spectral inversion technique (GIT) allows us to determine HSAF with respect to an appropriately selected reference site, when there are many earthquakes observed at many sites. Fortunately, Japan has three nationwide strong-motion observation networks, namely, K-NET, KiK-net, and the JMA Seismic Intensity network that provide many strong motion records. Basically, a large integrated dataset is required to separate source, path, and site effects in the GIT analysis. On the other hand, only three components of earthquake ground motions at a single station are required to obtain the horizontal-to-vertical spectral ratio of earthquakes (EHVR). Although Nakamura in 1989 proposed that EHVR, as well as MHVR (Microtremor HVR), can be viewed as HSAF under the hypothesis of no vertical amplification from the bedrock to the surface, our GIT results revealed that there exists reasonable amount of the vertical site amplification factor (VSAF) at almost all the sites.

We propose here a new method to directly estimate HSAF of the main S-wave portion from EHVR. As vertical amplification is included in the denominator of EHVR, the ratio cannot be viewed as HSAF without modification. We have therefore used GIT for K-NET, KiK-net, and the JMA Seismic Intensity network data to determine VSAF at each site with the same constraint as the horizontal components. Then we deduced the average amplification factors from a total of 1,678 sites where ten or more earthquakes per site were observed. We called the resultant empirical factors as the vertical amplitude correction function (VACF). VACF can be categorized for peak frequency of EHVR and its amplitude, however, VACF averaged over all the sites can also be used for simplicity. By multiplying EHVR with VACF, we can easily obtain HSAF. We have verified the effectiveness of this approach by using the sites with seven to nine earthquakes not used in the above-mentioned averaging. On the average 75 % of sites can be successfully reproduced by the proposed method and 15 % sites do not show large HSAF. We need to carefully investigate the remaining 10 % sites why their individual VSAFs are not close to the average VACF.

Keywords: Horizontal amplification; Horizontal-to-Vertical Ratios; Microtremors; Site Effect; Nakamura Method



17th World Conference on Earthquake Engineering, 17WCEE Sendai, Japan - September 13th to 18th 2020

1. Introduction

The main purpose of the site classification or velocity determination at a target site is to obtain or estimate the horizontal site amplification factor (HSAF) at that site during future earthquakes because HSAF would have significant effects on the strong-motion characteristics. To that end, we have been investigating various kinds of methods to delineate the S-wave velocity structures and the subsequent HSAF as precisely as possible. Among the empirical methods, the generalized spectral inversion technique (GIT) initially proposed by Andrews (1986) [1] allows us for determining, on a stable basis, the HSAF for appropriately selected reference sites, when there are many earthquakes observed at many sites. Fortunately, Japan has the dense strong-motion observation networks of K-NET, KiK-net, and the JMA Seismic Intensity (Shindokei) network, which are nationwide networks of strong-motion observation already containing many strongmotion records. Kawase and Matsuo (2004) [2] have used observation records obtained from 1996 until 2002 to separately perceive and elucidate the basic properties of source, propagation path, and site amplification. A subsequent study by Kawase (2006) [3] has focused on nonlinear site amplification effect in the records with high peak ground acceleration (PGA). With recent data added, Nakano et al. (2015) [4] have conducted spectral inversion analyses not only on Fourier spectra but also on response spectra, and they have determined the HSAFs and the site factors of the response spectra with respect to the outcrop equivalent of the seismological bedrock at a reference observation site YMGH01, by eliminating the effect of weathered rock layers from the surface records, and then have analyzed the relevant characteristics in detail.

However, the GIT analysis requires the earthquake ground motions of many earthquakes observed at many locations. On the other hand, only three components of earthquake ground motion are required to determine the horizontal-to-vertical spectral ratio of earthquakes (hereinafter referred to as EHVR). Nakamura (1989) [5] has proposed that the HSAF (he called it QTS, Quasi-Transfer Spectra) can be estimated directly by using the horizontal-to-vertical ratio of microtremors (MHVR). Since then, many researchers have studied the following issues based on either observation or theory: (a) whether the MHVR and EHVR are the same; (b) whether the EHVR and HSAF are the same. Although discussions are still ongoing, the majority of researchers have concluded the following: the MHVR and EHVR are similar to each other but not the same; and in both the MHVR and EHVR, their peak frequencies are about the same as that of the HSAF, but the amplitudes are underestimated. Even though we deal with the EHVR in the present paper, we do not adopt Nakamura's interpretation. As a quantitative answer to the issue (a), we have already shown the empirical spectral ratios, EMR, between EHVR and MHVR for 100 sites in Japan (Kawase et al., 2017, 2018) [6-7]. This paper will provide a quantitative answer to the issue (b), the empirical correction between HSAF and EHVR as needed.

Let us assume that a sufficient number of small earthquakes have been observed at a certain site. Because it is too laborious to determine the HSAF using GIT every time, there is a real need to use the EHVR that can be determined from only one site. In particular, it is difficult to apply GIT to earthquakes so small that their magnitude or source locations cannot be determined accurately, or their seismograms cannot be recorded simultaneously at different sites. We, therefore, propose in this study a simple method to correct the vertical site amplification factor (VSAF), which represents the largest challenge in determining the HSAF from the EHVR. Contamination with surface waves is eliminated in this method because we use only the main S-wave portion as extracted.

2. Theory based on Diffuse Field Concept

The theoretical background of the proposed method is based on the theory of diffuse wavefield. When observing earthquake ground motion propagated as S-waves from various seismic sources to one location, the Fourier transform of the autocorrelation function of normalized ground motion, or the power spectrum, is given as follows, as shown by Kawase et al. (2011) [8]:

17th World Conference on Earthquake Engineering, 17WCEE Sendai, Japan - September 13th to 18th 2020

$$\left\langle \frac{\left|u(P,\omega)\right|^{2}}{\int \left|u(P,\varpi)\right|^{2} d\sigma} \right\rangle = K \times \left|TF(\omega)\right|^{2} = -K \times \rho_{H} c_{H} \omega \operatorname{Im}[G^{Eq}(P,P,\omega)]$$
(1).

The corresponding EHVR is given by

$$EHVR = \frac{H(\omega)}{V(\omega)} = \sqrt{\frac{\operatorname{Im}[G_{horizontal}^{Eq}(0,0;\omega)]}{\operatorname{Im}[G_{vertical}^{Eq}(0,0;\omega)]}}$$
(2)

$$=\sqrt{\frac{\alpha_{H}}{\beta_{H}}}\frac{\left|TF_{horizontal}\left(\omega\right)\right|}{\left|TF_{vertical}\left(\omega\right)\right|}$$
(3).

Here, α_H and β_H are the P-wave and S-wave velocities, respectively, of the seismological bedrock, and $TF_{horizontal}(\omega)$ or $TF_{vertical}(\omega)$ is the transfer function in the horizontal or vertical direction from the seismological bedrock to the surface at circular frequency ω . Refer to Kawase et al. (2011) [8] for the other symbols. In the diffuse field theory, a diffuse wavefield is assumed to be formed in the entire propagation path from the hypocenter to the seismological bedrock immediately below the observation site, and energy is assumed to be uniformly distributed in the semi-infinite uniform soil including the hypocenter. A resulting characteristic of the theory is that the amplitude of the incident wave to the bedrock is uniquely determined by the square root of the ratio of the P-wave velocity to the S-wave velocity as shown in Eq. (3), thanks to the equipartition of energy.

According to the GIT concept, the S-wave Fourier spectrum of horizontal motion, $F_{S_{ij}}$, of earthquake *i* observed at site *j* is decomposed into the logarithmic sum of the source term $S_{S_{i}}$, the path term $P_{S_{ij}}$, and the site amplification factor (HSAF) $H_{S_{j}}$, as shown in the following equation:

$$\log F_{S_{ij}} = \log S_{S_{i}} + \log P_{S_{ij}} + \log H_{S_{j}}$$
(4).

All the above variables are spectra having mutually independent frequency components. Likewise, the S-wave portion Fourier spectra of vertical motion, $G_{S_{ij}}$, is decomposed into the following equation:

$$\log G_{S_{ij}} = \log S_{S_{i}} + \log P_{S_{ij}} + \log V_B H_B R + \log V_{S_{j}}$$
(5).

This assumes that ground motion is propagated as S-waves until reaching the seismological bedrock immediately below the observation site and then these S-waves are converted to P-waves, which are observed as the vertical motion on the ground surface. The conceptual wave propagation process of the S-wave GIT is shown in Fig.1 Here, V_{S_j} is the vertical site amplification factor (VSAF). The third term in Eq. (5), V_BH_BR , is a coefficient for converting S-wave amplitude into P-wave amplitude on the seismological bedrock, and it is the inverse of the aforementioned horizontal-to-vertical amplitude ratio of the incident wave to the bedrock in the diffuse wavefield of the seismological bedrock. This coefficient arises because the main subject being addressed here is S-waves propagated and scattered through the medium from the hypocenter to the point on the seismological bedrock to the surface. Please note that HSAF and VSAF are the general terms referring to the site amplifications in horizontal and vertical directions, while H_{S_j} and V_{S_j} are the specific terms derived from GIT.

With the above preparation, we now discuss the relationship between the EHVR and HSAF. From Eqs. (4) and (5), the EHVR is given by

$$EHVR = \left\langle \frac{F_{S_{-ij}}}{G_{S_{-ij}}} \right\rangle = \left\langle \frac{H_{S_{-ij}}}{V_{S_{-ij}} * V_B H_B R} \right\rangle$$
(6).



The 17th World Conference on Earthquake Engineering

17th World Conference on Earthquake Engineering, 17WCEE Sendai, Japan - September 13th to 18th 2020

Then the HSAF is therefore given by

$$HSAF = \left\langle H_{S_{-ij}} \right\rangle = EHVR * \left\langle V_{S_{-ij}} * V_B H_B R \right\rangle$$
(7).

Here, $\langle \rangle$ represents the averaging operation. Eq. (7) means that the HSAF is obtained by multiplying the EHVR by both the VSAF and the reciprocal of the horizontal-to-vertical spectral ratio on the bedrock. From Eq. (3), the transfer function of theoretical vertically-incident P-waves can be used for the VSAF if we know the P-wave velocity structure from the seismological bedrock to the surface. Because it is unrealistic to assume that only the P-wave velocity is known whereas the S-wave velocity is unknown, we would like to use the empirical VSAF, that is, $V_{S,j}$, in Eq. (5) obtained by the GIT analysis.

Since applying Eq. (7) to the same site is a circular argument, we determine an empirical correction function averaged over multiple sites, as in Kawase et al. (2018) [7] for MHVR. Expressing this correction function after averaging as VACF (vertical amplification correction function), we obtain the S-wave amplification ratio at an arbitrary site by the following simple equation.

$$HSAF = EHVR * VACF$$
(8).

In this case, VACF means the spectral ratio of the vertical amplitude on the ground surface with respect to the horizontal amplitude on the outcrop of the seismological bedrock. It is possible to determine VACF directly by using the GIT with respect to the horizontal motion on the reference bedrock.



Fig. 1 - Concept of S-wave propagation at the seismological bedrock and subsequent site amplification

3. Results

3.1 Separated site factors from GIT

The conditions and method of seismic wave analysis using the GIT are not described here but refer to Nakano et al., (2015) [4]. What is important is that the range of the JMA magnitude investigated is from 4.5 to 8.0, and only a duration of 5 sec to 15 sec from the arrival of S-waves is analyzed according to the magnitude. While no limit was set to the number of earthquakes at one site, in category-specific averaging, we only used 1,678 sites where ten or more earthquakes had been observed. For verification purposes, we used 103 sites in which the number of earthquakes observed ranged from seven to nine.

First, we check the fundamental characteristics of the separated HSAF and VSAF in comparison to the theoretical one-dimensional (1-D) S-wave and P-wave amplification factors from the seismological bedrock

The 17th World Conference on Earthquake Engineering 17th World Conference on Earthquake Engineering, 17WCEE Sendai, Japan - September 13th to 18th 2020



to the surface. Fig. 2 shows three examples among K-NET stations. Black lines are separated HSAF and VSAF from the observed strong motions by GIT, while red lines are 1-D theoretical HSAF and VSAF. For theoretical calculations, we used boring data for upper 20m and J-SHIS data for the deeper part. The matching between the observation and the 1-D theory is quite good for HSAFs. The matching in VSAF is not as good as HSAF but still it is apparent to have significant VSAF in both the observation and the 1-D theory.



Fig. 2 – Comparisons of HSAFs and VSAFs in observation and theory.

$3.2 V_B H_B R$

We then address the vertical-to-horizontal spectral ratio V_BH_BR in the seismological bedrock. Fig. 3 shows, in a blue curve, the averaged ratio of the observed vertical spectral value with respect to the corrected horizontal spectral value as the outcrop motion equivalent to the seismological bedrock at the reference site (YMGH01), that is V_BH_BR . The figure shows that the ratio fluctuates gently around unity. In the range between 0.12 Hz and 20 Hz, the average minus one standard deviation is in good agreement with the square root of the ratio of S-wave velocity to P-wave velocity (red broken line) in the bedrock, which is expected from the diffuse wavefield theory in Eq. (3). As this value is about 0.8 in the case of a Poisson solid, it can be said that the vertical motion is nearly equal to the horizontal motion in the seismological bedrock.



Fig. 3 – Comparison of V_BH_BR at the reference station YMGH01 with that of DFC theory.



The 17th World Conference on Earthquake Engineering

17th World Conference on Earthquake Engineering, 17WCEE Sendai, Japan - September 13th to 18th 2020

3.3 VACF

We try to correct the EHVR by using the VSAF obtained by the simultaneous GIT analysis for both vertical and horizontal motions. Eq. (7) suggests that the correction through VSAF×VBHBR is necessary. Since the only constraint condition (reference point) in the GIT analysis of Nakano et al. (2015) [4] is the horizontal motion spectrum at the outcrop equivalent to the extracted seismological bedrock at YMGH01, the VACF in Eq. (8) is directly determined from the vertical site factors obtained by GIT. If the GIT analysis is conducted only for vertical motion, V_BH_BR should be corrected because the vertical motion at the reference point will be given as a norm in that case.

The 1,678 observation sites where ten or more seismic spectra were available were grouped into two groups divided by whether the peak amplitude of the EHVR was no less than 5 or less than 5. The sites were further classified into four categories according to different peak frequency ranges (1 Hz or less, between 1 Hz and 5 Hz, between 5 Hz and 10 Hz, and 10 Hz or more) to determine the average VACF for each category. The results are shown in Fig. 4a. The figure indicates that a) there are only negligible differences due to peak amplitude, b) there are relatively small differences due to peak frequency, c) the amount of correction increases as peak frequency decreases, and d) the correction amplitude is by a factor of about 3 at around 1 Hz and by a factor of 2.5 in the range between 1 Hz and 5 Hz. While the finding that spectra are not significantly affected by the characteristics of EHVR may appear unexpected given that the EHVR is correlated with both the P- and S-wave transfer functions, the similarity in the average characteristics of VACF does not necessarily mean that the P-wave velocity structure is similar throughout the nation. Nevertheless, it is evident that the fluctuation with frequency is smaller in the VSAF than in the HSAF as shown in Fig. 2.

Since the differences among the eight categories in Fig. 4a are relatively small, we calculated the average VACF of all sites without categorization for the sake of simplicity, which is shown in Fig. 4b. In the verification given below, we used this simple average VACF.



Fig 4 – Vertical Amplification Correction Function VACF (a) for eight categories based on the EHVR peak frequency and amplitude and (b) for all the 1,678 sites used.

The 17th World Conference on Earthquake Engineering

17th World Conference on Earthquake Engineering, 17WCEE Sendai, Japan - September 13th to 18th 2020



3.4 Validation of the VACF method

We verified the capability of the proposed VACF method in reproducing the observed HSAF from the observed EHVR. While we have obtained average values (Fig. 4) by using the sites whose number of observed earthquakes was 10 or more, we have separately made a comparison using sites whose number of earthquakes was seven to nine, which have not been subjected to the aforementioned averaging. As shown in the eight examples given in Fig. 5, the HSAF obtained by the GIT was reproduced successfully even though



Fig. 5 – Comparison of the observed HSAF (black line) and the simulated HSAF (red broken line) obtained from the EHVR multiplied by the empirical VACF in Fig. 4b. The dotted lines represent the simulated HSAF using the average \pm one standard deviation, and the thin blue line represents the EHVR used. "Res" in the header means the average residual (ratio) between observed and simulated.



17th World Conference on Earthquake Engineering, 17WCEE Sendai, Japan - September 13th to 18th 2020

a simple correction function in Fig.4b was used. Among these examples, the difference in estimation was particularly large at JMA D18 ("Res" in the figure is the average log-residual, which is the average spectral ratio), and this was because the actual VSAF was greater than the average at this site. As long as this method is used, it is inevitable that such sites will be found with a certain probability. When a conservative HSAF value is required, it is desirable to use the average correction function plus one standard deviation as a multiplication factor shown in Fig. 4b.

To grasp the average trend of our simulation results, we compared the simulated HSAF obtained by using the VACF (Fig. 4b) and the EHVR with the observed HSAF for a total of 103 sites whose numbers of observed earthquakes were seven to nine. We also compared the uncorrected EHVR directly with the HSAF (i.e., Nakamura method). Fig. 6 shows their maximum and average amplitudes (\bigcirc : HSAF, \bigcirc : EHVR) on the left and right sides, respectively. Fig. 7 shows the average log-residuals of all frequencies (black bar: EHVR red bar: simulated HSAF). The average operation is performed in the frequency range from 0.1 Hz to 15 Hz. Note that the average of the log-residuals is reverted to a real number (ratio) with the power of 10,



Fig. 6 – Comparison of the simulated HSAF or the EHVR (vertical axis) plotted against the observed HSAF (horizontal axis). (a) maximum amplitude, (b) average amplitude.



Fig. 7 – The averaged log-residuals between the observed EHVR and the observed HSAF (black bar), compared with the averaged log-residuals between the simulated HSAF and the observed HSAF (red bar). Two sites with extraordinary high residuals in the simulated HSAF are the sites of the JMA network, namely BE9 and D03, where significant attenuation in high-frequency range was found in both HSAFs and VSAFs.

8

17th World Conference on Earthquake Engineering, 17WCEE Sendai, Japan - September 13th to 18th 2020

meaning perfect matching when the ratio is unity. Whereas amplitude was obviously underestimated in the EHVR, data points became more closely distributed around the line of 1:1 after the correction. The log-residual data also indicates the improvement of matching in more than 60% of the sites. More than half of the remaining sites had small residuals in both the EHVR and the simulated HSAF, and the percentage of sites in which errors increased significantly after the correction was only about 10%. We found that the amplitudes of both the observed HSAF and VSAF in the high-frequency range are abnormally smaller than the average value in Fig. 7 at those sites where the degrees of matching are worsened after the correction, such as JMA BE9 and JMA D03. These sites may be under special conditions, and this is a subject of future investigation.

4. Conclusions

We proposed a simple method to deduce the horizontal site amplification factor (HSAF) in the main S-wave portion directly from the EHVR of observed earthquake ground motion. In this method, we have formulated a correction procedure based on the diffuse field theory; focused on observation records from 1,678 sites where ten or more earthquakes have been observed in the strong-motion networks K-NET, KiK-net, and JMA seismic intensity network; used the generalized spectral inversion technique (GIT) to determine the vertical site amplification factor (VSAF, to be precise, VSAF multiplied by V_BH_BR); and then averaged it to obtain the empirical vertical amplification correction function (VACF). The findings obtained are as follows:

1) The vertical-to-horizontal spectral ratio at the reference observation site (V_BH_BR) was nearly unity and agreed with the theoretical solution within the range of variation.

2) The amplitude of the VSAF, on average, was 30% to 40% of the HSAF obtained by GIT and the EHVR was obviously smaller than the HSAF by the amount of VSAF. Using the EHVR with no correction in place of the HSAF as proposed by Nakamura (1989) [5] will result in underestimation of HSAF.

3) It was possible to obtain the VACF on a very stable basis by reading out the peak amplitude and peak frequency of EHVR at each site and averaging the data in the corresponding category; there were only negligible differences due to peak amplitude; there were relatively small differences due to peak frequency; the amount of correction increased as the peak frequency decreased; and the VACF was the largest when EHVR peak frequency was 1 Hz or less, where the factor of about 3 was needed.

4) For the validation exercise of applicability, we applied the obtained VACF to 103 sites whose number of observed earthquakes was seven to nine so that they have not been used in the averaging. As a result, the observed HSAF has been successfully reproduced in about 90% of the sites, although some other sites have shown nearly doubled differences.

In summary, this paper proposed a new simple method, in which the main S-wave portion of earthquake ground motion is extracted, the average horizontal-to-vertical spectral ratio of this portion is determined, and this ratio is multiplied by the empirical correction function (VACF) to obtain the horizontal S-wave site amplification factor. Although this method inevitably entails errors in the VACF estimation due to site-specific characteristics, it is capable of evaluating the site effects of S-waves based on observed values in a wide frequency range from 0.1 Hz to 15 Hz. It should be noted that the proposed method obtains the horizontal S-wave amplification factor from the seismological bedrock, rather than the engineering bedrock, to the ground surface. For the sake of reliability, it is advisable to determine the average horizontal-to-vertical ratio of at least about 10 earthquakes.

5. Acknowledgments

A part of this study was supported by the JSPS Kakenhi Grant-in-Aid for Basic Research (A) No.26242034 and Grant-in-Aid for Basic Research (B) No.19H02405. Information provided by and discussions done with Profs. Pierre-Yves Bard, Cecile Cornou, and Alan Yong were highly appreciated.



The 17th World Conference on Earthquake Engineering

17th World Conference on Earthquake Engineering, 17WCEE Sendai, Japan - September 13th to 18th 2020

References

- Andrews, D.J. (1986): Objective determination of source parameters and similarity of earthquakes of different size, *Earthquake Source Mechanics* (eds. S. Das, J. Boatwright and C. H. Scholz), American Geophysical Union, Washington, D.C., 1986. doi: 10.1029/GM037p0259.
- [2] Kawase, H. and H. Matsuo (2004): Amplification characteristics of K-NET, KiK-NET, and JMA Shindokei network sites based on the spectral inversion technique, *13th World Conf. on Earthquake Engineering*, Vancouver, Canada, Paper No. 454.
- [3] Kawase, H. (2006): Site effects derived from spectral inversion method for K-NET, KiK-net, and JMA strongmotion network with special reference to soil nonlinearity in high PGA records, *Bull. Earthq. Res. Inst.*, Tokyo Univ. 81, 309–315.
- [4] Nakano, K., S. Matsushima, and H. Kawase (2015): Statistical properties of strong ground motions from the generalized spectral inversion of data observed by K-NET, KiK-net, and the JMA Shindokei Network in Japan, *Bull. Seism. Soc. Am.*, 105: 2662-2680, doi:10.1785/0120140349.
- [5] Nakamura Y. (1989): A method for dynamic characteristics estimation of subsurface using microtremor on the ground surface, *Railway Tech. Res. Inst.*, Q. Rep. 30(1): 25-30
- [6] Kawase, H., Y. Mori, and F. Nagashima (2017): Difference of horizontal-to-vertical spectral ratios of observed earthquakes and microtremors and its application to S-wave velocity inversion based on the diffuse field concept, *Earth, Planets and Space*, Vol.70, No.1, Open Access, doi: 10.1186/s40623-017-0766-4.
- [7] Kawase, H., F. Nagashima, K. Nakano, and Y. Mori (2018): Direct evaluation of S-wave amplification factors from microtremor H/V ratios: Double empirical corrections to "Nakamura" method, *Soil Dyn. Earthquake Eng.*, Open Access, doi: 10.1016/j.soildyn.2018.01.049.
- [8] 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, 2011-2014.