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

APPLICABILITY OF THE EARTHQUAKE BEDROCK MOTION ESTIMATION METHOD BASED ON THE DIFFUSE FIELD CONCEPT

F. Nagashima (1) and H. Kawase (2)

(1) *Program specific assistant professor, DPRI Kyoto University, nagashima@sere.dpri.kyoto-u.ac.jp*
(2) *Program specific professor, DPRI Kyoto University, kawase@sere.dpri.kyoto-u.ac.jp*
…

Abstract

The subsurface structure plays an important role in the strong ground motion estimation, and the input motion to the subsurface structure also has a large impact on the estimation. There are several ways to estimate the input motion, one of which is simulating the wave from the source, and the other is extracting the site amplification from the observed motion. To remove the site amplification effect from the observed strong motion and obtain a correct input motion, we should consider the nonlinearity of the subsurface structure. However, the nonlinear deconvolution is strongly dependent on the nonlinear characteristics of soils, and therefore we need to select proper characteristics and apply them to the suitable layers based on the detailed information corrected by the borehole sampling of in-situ soil columns.

We have investigated the ground motion characteristics based on Diffuse Field Concept for earthquake (DFCe) and proposed a new method to estimate the incident wave at the seismological bedrock based on DFCe. If both the applicability of DFCe and the linearity of the vertical amplification factor can be assumed during a strong shaking, the spectrum of the horizontal incident wave at the seismological bedrock is obtained by the linear calculation using the vertical motion observed on the surface and the vertical amplification factor. The nonlinear horizontal amplification factor can also be calculated as the ratio of the observed horizontal motion on the surface with respect to the estimated bedrock motion, in which the nonlinearity in the horizontal record is reflected.

We applied the proposed method to several strong motions and estimated input motions at the seismological bedrock. First, we calculated Horizontal-to-Vertical spectral Ratio of earthquake (EHVR) of weak motions and took average of them. Then we identified one-dimensional subsurface P- and S-wave velocity structures based on DFCe, where the horizontal-to-vertical ratios of theoretical amplification factors were calculated from the identified structures to explain the observed EHVR. Next, we compared the averaged EHVR and Surface-to-Borehole spectral Ratio of earthquake (ESBR) of weak motions to those of the observed strong motion and judged which wave portion of the strong motion was satisfied the assumptions of the vertical linearity and DFCe. We estimated the incident spectrum at the seismological bedrock by using the transfer function of the selected portion. Several strong motions were not satisfied the vertical linearity, and therefore we could not apply the proposed method to those motions. In the S-wave portions of a couple of strong motions, apparent effects of source radiation pattern were seen, and so pure DFCe cannot be assumed. However, in the coda portions of those motions, the effects of the radiation pattern disappeared and the degree of nonlinearity seems to be similar with those of the S-wave portions, and so we first estimated the horizontal amplification factors of the coda portions and then we deconvolved the whole waves, which included P-wave, S-wave and coda, by the estimated horizontal amplification factors to obtain the input motions. We validated the estimated incident waves by comparing them with previous studies and by comparing the surface motions calculated from the incident waves (through the equivalent linear analysis) with the observed ones.

Keywords: diffuse field concept, seismological bedrock, incident wave, deconvolution, S-wave

1. Introduction

One of the main objectives of subsurface structure investigation is to improve the accuracy of seismic motion and subsequent damage prediction. Obtaining site amplification factors closer to reality can enhance the prediction accuracy. Investigation of the subsurface structure has been conducted to estimate actual site amplification factors. Many methods, both invasive (boring and PS logging) and non-invasive (e.g. microtremors array investigations, reflection methods, and seismic interferometry), have been proposed. Sánchez-sesma et al. (2011) [1] derived the exact solution for the microtremors horizontal-to-vertical spectral ratio (MHVR) assuming a diffuse field. They interpreted the MHVR as the square root of the horizontal-to-vertical ratio of the imaginary part of the Green's function when the source and receiver are at the same position and evaluated not only the frequencies of peaks and dips of the MHVR but also the amplitude. Kawase et al. (2011) [2] showed the exact solution of the earthquake horizontal-to-vertical spectral ratio (EHVR) developed from the diffuse field concept in the same way as microtremors but for plain body waves of earthquake. They claimed that, even for seismic motion, the average of many seismic motions can be considered as a vertical incident plane wave to a one-dimensional structure under the assumption of a diffuse field. This exact solution interprets the EHVR as being proportional to the horizontal-to-vertical spectral ratio of the transfer function amplitude of the subsurface structure above the seismological bedrock. The low frequency part of the EHVR has a signal-to-noise (SN) ratio higher than MHVR, and higher-order peaks of the fundamental peak frequency will affect the high frequency response, so the entire form of the EHVR over a wide spectrum range can constrain the subsurface structure and the resultant site amplification factors.

The incident wave is necessary, in addition to site amplification factors, for seismic motion prediction. Characterized source simulation is used to estimate past and future seismic motions. The incident wave can also be created by processing observed records. A common method is to remove site amplification factors from observed records and use the result as the incident wave at the bedrock. The nonlinear effects in seismic motion parameters due to the plastic deformation of the subsurface structure must be considered when removing site amplification factors of strong motions. The nonlinear behavior is typically represented using the relation between the shear strain inside the soil and the decreasing characteristics in the shear modulus and between the shear strain and the intrinsic soil attenuation. Many nonlinear characteristics have been proposed from laboratory tests using samples of various soil types from a wide variety of places [3, 4]. For convolution and deconvolution analysis of strong motions, the nonlinear characteristics suitable for the analysis site must be selected and must be assigned appropriately to the subsurface structure. Different choices and assignments could lead to a different solution, and calculations may even diverge, and a solution could not be obtained. Therefore, nonlinear characteristics must be handled with much care. Reference material, such as results of boring investigations, is necessary for assignment.

Based on the diffuse field concept of earthquake, we have proposed a method to estimate the horizontal incident spectrum at the seismological bedrock based on linear calculations using vertical motion observed at the surface. The same method can be used to estimate the horizontal site amplification characteristics during strong motion using a linear calculation of surface observation records and the vertical transfer function. The validity of these methods has been verified in a number of strong motion records [5]. This paper reports the effectiveness and applicability of the proposed methods using strong motion records observed at three KiK-net observation sites, namely, KMMH16, TCGH07, and WKYH01.

2. How to estimate seismological bedrock waves based on the diffuse field concept of earthquake

The EHVR can be expressed as Eq. (1) based on the diffuse field concept of earthquake [2].

$$\mathrm{EHVR}(f) = S_{\mathrm{horizontal}}(f) / S_{\mathrm{vertical}}(f) = (\alpha/\beta)^{1/2} * |\mathrm{TF}_{\mathrm{horizontal}}(f)| / |\mathrm{TF}_{\mathrm{vertical}}(f)| \qquad (1)$$

Here, f is the frequency, S is the seismic motion spectrum amplitude observed on the ground surface, TF is the transfer function obtained from the subsurface structure above the seismological bedrock, and α and β are the P-wave and S-wave velocities (Vs and Vp) of the seismological bedrock, respectively. The transfer function is the site amplification factor here. If the diffuse field assumption is valid, the exact solution of the EHVR can be obtained through Eq. (1), and the subsurface structure that reproduces the observed EHVR, which is the horizontal-to-vertical ratio of the site amplification factors, can be identified. Eq. (1) can be rewritten as

$$S_{horizontal}(f) \,/\, |TF_{horizontal}(f)| = (\alpha/\beta)^{1/2} * S_{vertical}(f) \,/\, |TF_{vertical}(f)| \qquad (2)$$

S/TF is the spectrum amplitude at the bottom of the structure where TF was obtained, thus the incident spectrum in the horizontal direction at the seismological bedrock is proportional to that in the vertical direction according to Eq. (2). Based on the concept of spectrum separation, the incident spectrum at the seismological bedrock consists of source and propagation path terms, and the horizontal and vertical components of the product of source and propagation path terms are proportional in a field where energy is equipartitioned and sufficiently diffused. Eq. (1) can be summarized regarding the TF in the horizontal direction as

$$|TF_{horizontal}(f)| = S_{horizontal}(f) \,/\, \{(\alpha/\beta)^{1/2} * S_{vertical}(f) \,/\, |TF_{vertical}(f)|\} \qquad (3)$$

The TF in the horizontal direction is expressed using observation records on the ground surface and the TF in the vertical direction. Eqs. (2) and (3) can be applied to strong motion records if the assumption that “the diffuse field holds for a strong motion” is valid. Moreover, the right hand side of Eqs. (2) and (3) could be obtained using linear calculation under the assumption that “the vertical TF is not significantly nonlinear even during strong motion” [6, 7]. In other words, the horizontal incident spectrum at the seismological bedrock during strong motion can be obtained by linear calculations of the vertical motion. Moreover, instabilities in nonlinear and equivalent linear analysis coming from the selection and assignment of nonlinear characteristics can be avoided because the horizontal transfer function including nonlinearity effects can be obtained by a linear calculation of surface observation records and the vertical TF. We have already applied Eqs. (2) and (3) to a number of strong motion records and confirmed that the proposed method using Eqs. (2) and (3) is applicable under the aforementioned assumptions.

3. Verification of linearity of transfer functions

Figs. 1 to 3 show comparisons of the spectral ratios of S-wave portions of the main shock from the 2016 Kumamoto Earthquake measured at KMMH16, the 2013 North Tochigi Prefecture Earthquake at TCGH07, and the 2011 North Wakayama Prefecture Earthquake at WKYH01 against the averaged ratios of the weak motion records at each observation site, respectively. These earthquakes occurred close to the observation sites, thus the distances between the observation sites and the epicenter were short. Observations are conducted at the bottom of borehole in addition to the ground surface at these KiK-net observation sites, thus the main shock records and the weak motion average were compared for EHVR using surface and borehole observation records and the surface-to-borehole spectral ratio (SBR). The surface and borehole EHVRs and the horizontal SBR of the main shock shifted their peaks to longer periods than the weak motion averages, which possibly reflected the effect of plastic deformation of the subsurface structure from strong motion. For the vertical SBR, at KMMH16 and WKYH01, there was no significant difference, which suggests that the vertical TF was not nonlinear. However, an increase in the vertical SBR for the strong motion was found at TCGH07. The linearity of the vertical TF must hold to apply the proposed method, thus it cannot be applied to the 2013 North Tochigi Prefecture Earthquake at TCGH07. At KMMH16, there was some difference between the main shock and the weak motion average in the surface and borehole EHVRs between 1.0 and

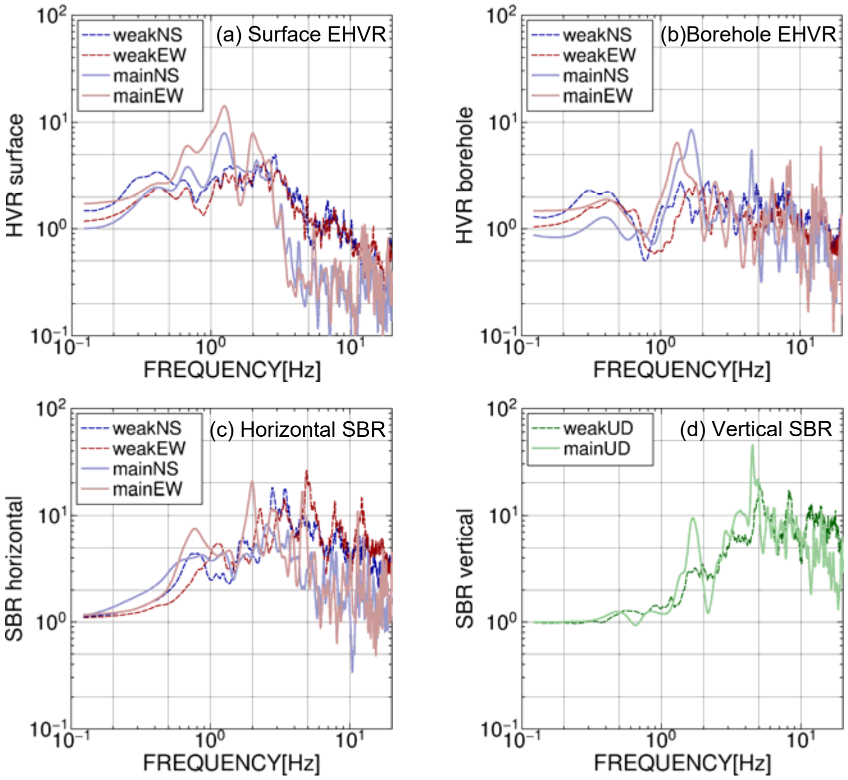


Fig. 1 – The 2016 Kumamoto Earthquake and the average of weak motion at KMMH16

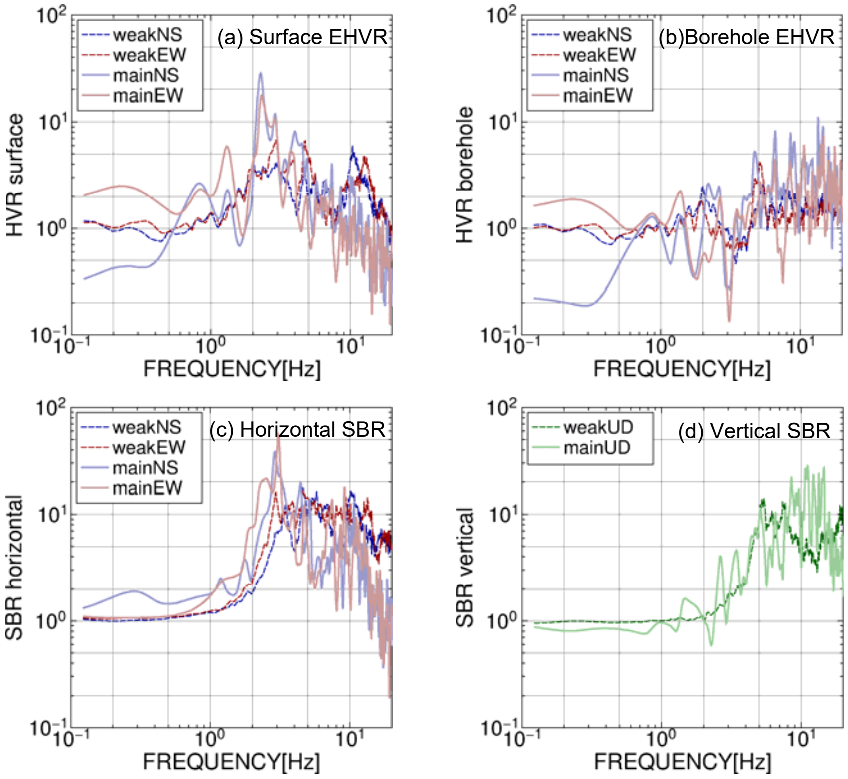


Fig. 2 – The 2013 North Tochigi Pref. Earthquake and the average of weak motion at KTCGH07

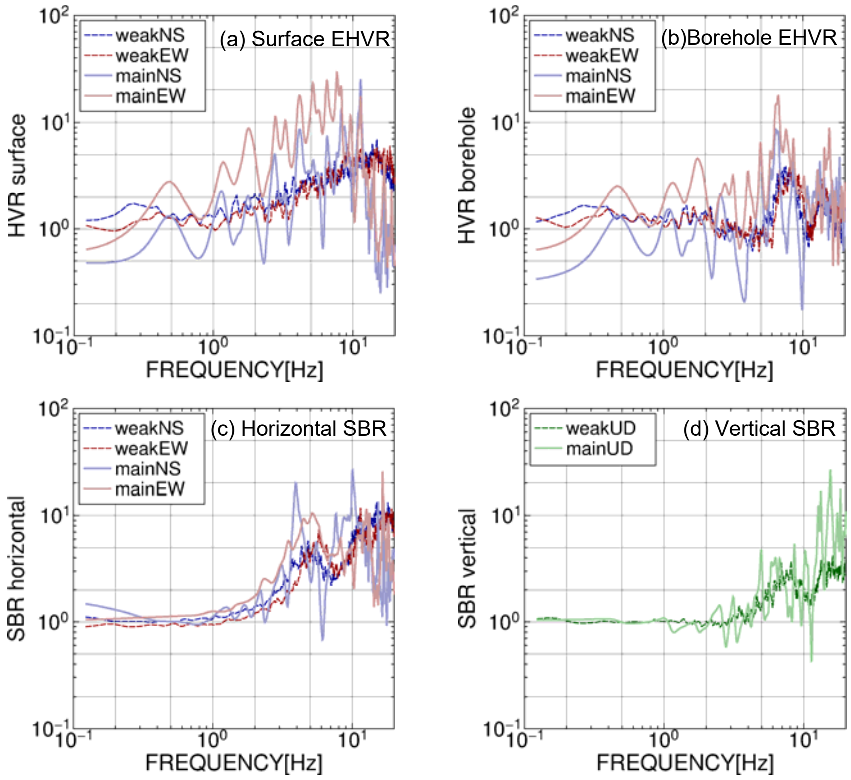


Fig. 3 – The 2011 North Wakayama Pref. Earthquake and the average of weak motion at WKYH01

2.0 Hz. However, there was no corresponding difference in the horizontal and vertical SBR in this frequency range. Similarly, at WKYH01, there was a difference between the main shock and the weak motion average in the surface and borehole EHVRs between 0.5 and 10 Hz, but there was no corresponding difference in the horizontal and vertical SBR. The results suggest that the difference in EHVR at low frequencies is not caused by nonlinearity of the site amplification characteristics but rather by source radiation characteristics that propagated from somewhere deeper than the underground observation sites. Please note that larger fluctuations in the mainshock ratio than the weak motion average is inevitable since weak motion ratios are the geometric averages and so small fluctuations are averaged out.

In summary, the proposed method cannot be applied to TCGH07 because the linearity of the vertical TF cannot be assumed. At KMMH16 and WKYH01, the diffuse field cannot be assumed for the S-wave part of the main shock because of the source radiation characteristics, thus the proposed method cannot be directly applied. This means that paying careful attention to whether the observation records satisfy the assumptions is necessary when applying the proposed method. However, the diffuse field assumption may hold when the coda part is used, as discussed later, thus allowing us to use of the proposed method. Therefore, KMMH16 and WKYH01 are analyzed hereon using coda.

4. Estimation of the horizontal incident wave at the seismological bedrock based on the proposed method

The vertical TF is necessary to apply the proposed method. The subsurface structure which reproduced the ground surface EHVR well was identified using the diffuse field concept. We used the hybrid heuristic searching method [8] to find Vs, Vp and thickness of each layer by minimizing the residual between the theoretical and observed EHVR. The EHVR was resampled such that the intervals of frequency sampling were equal on the log scale. The subsurface structure that provided a good reproduction of the observed EHVR was obtained for both KMMH16 and WKYH01 (Figs. 4 and 5, respectively).

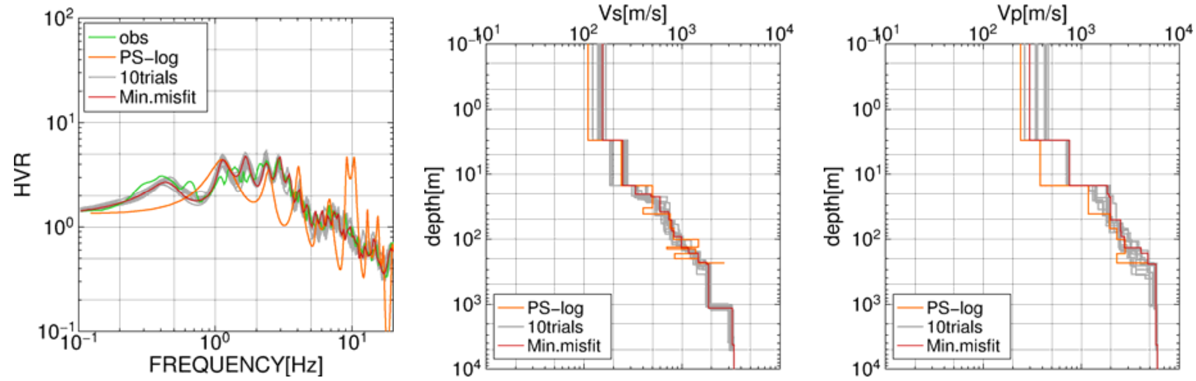


Fig. 4 – Identification results of KMMH16

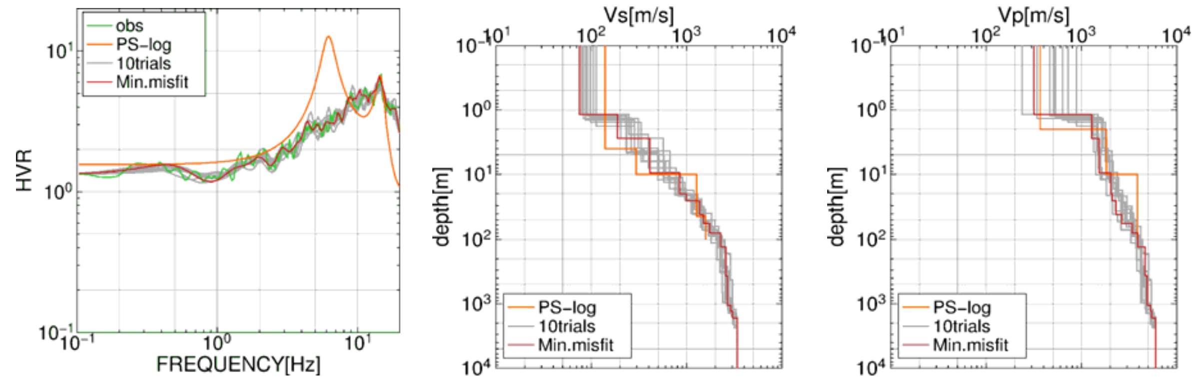


Fig. 5 – Identification results of WKYH01

Eqs. (2) and (3) became applicable because the subsurface structure was identified and the theoretical vertical TF was obtained. However, the source radiation characteristics that strongly affect the S-wave of the main shock remained, as shown in Figs. 1 and 2, resulting in insufficient diffusion. Therefore, a diffuse field could not be assumed. As a result, the proposed method could not be applied to the S-wave part of the main shock. We searched a window for spectrum calculation to the coda side where the effect of source radiation characteristics was smaller but there was still some influence from nonlinearity of the ground subsurface. Then the incident wave at the seismological bedrock was estimated by evaluating the horizontal TF including nonlinearity effects using Eq. (3) and then removing the horizontal TF from the entire strong motion waveform (assuming that the nonlinear characteristics remain during the whole duration of the strong motion).

Figs. 6 and 7 show the horizontal TF obtained using Eq. (3) and the theoretical horizontal TF from the identified structure at KMMH16 and WKYH01, respectively. The KMMH16 and WKYH01 spectra were smoothed using Parzen windows with 0.3 and 2.0 Hz widths, respectively. The estimated TF using the S-wave part show effects from source radiation characteristics in addition to the decrease in amplitude at high frequencies due to nonlinearity. The estimated TF from the coda part has reduced source radiation characteristics while retaining the decrease in amplitude at high frequencies in the same level as in the S-wave part.

Fig. 8 shows the incident spectra of the whole waveforms at the seismological bedrock deconvolved by using the estimated horizontal TF calculated from the coda part using Eq. (3). The incident waveforms derived by combing the phase of borehole records with the spectra are given in Fig. 9. These generated incident waves were verified by comparing simulated seismic motions at the surface with observed records. The seismic motion was derived by assigning nonlinear characteristics [4] using boring records as reference information to the identified subsurface structure, and then performing equivalent linear analysis [9] using the estimated incident wave in Fig. 9 as input. The comparison is shown in Fig. 10. The equivalent linear analysis result matched well with the surface observation records, therefore demonstrating the reasonableness of the proposed method.

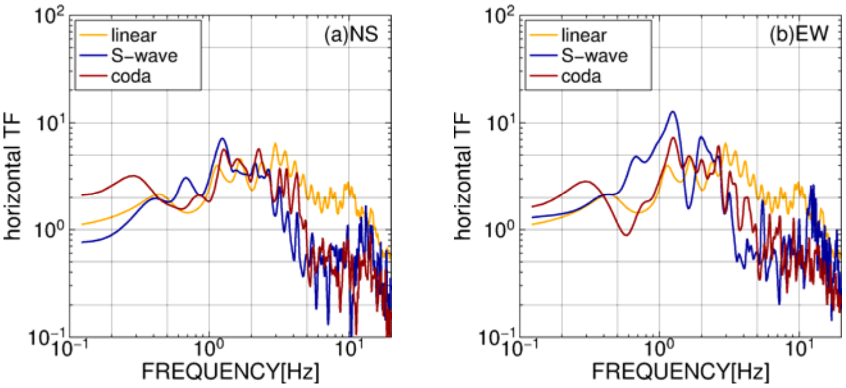


Fig. 6 – Estimated horizontal transfer function of the 2016 Kumamoto Earthquake at KMMH16

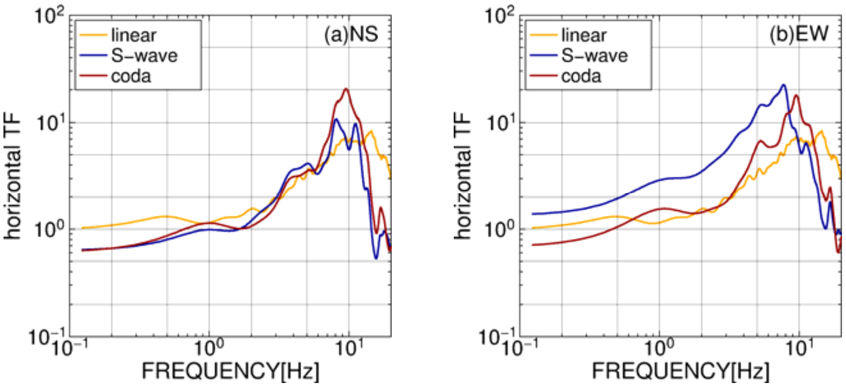


Fig. 7 – Estimated horizontal transfer function of the 2011 North Wakayama Pref. Earthquake at WKYH01

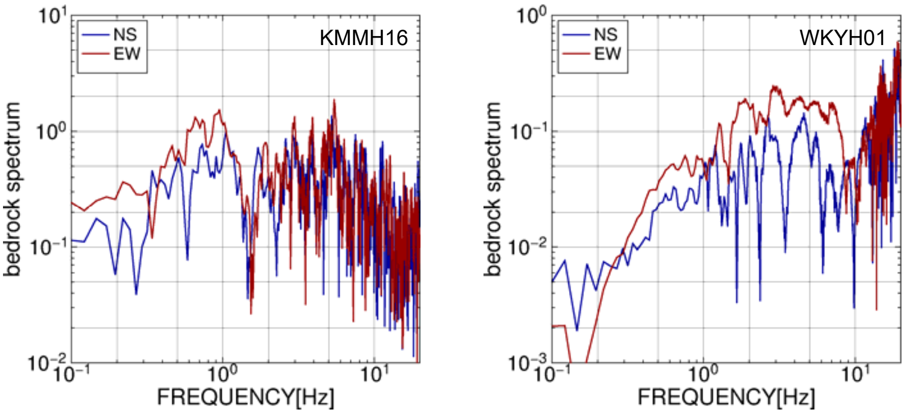
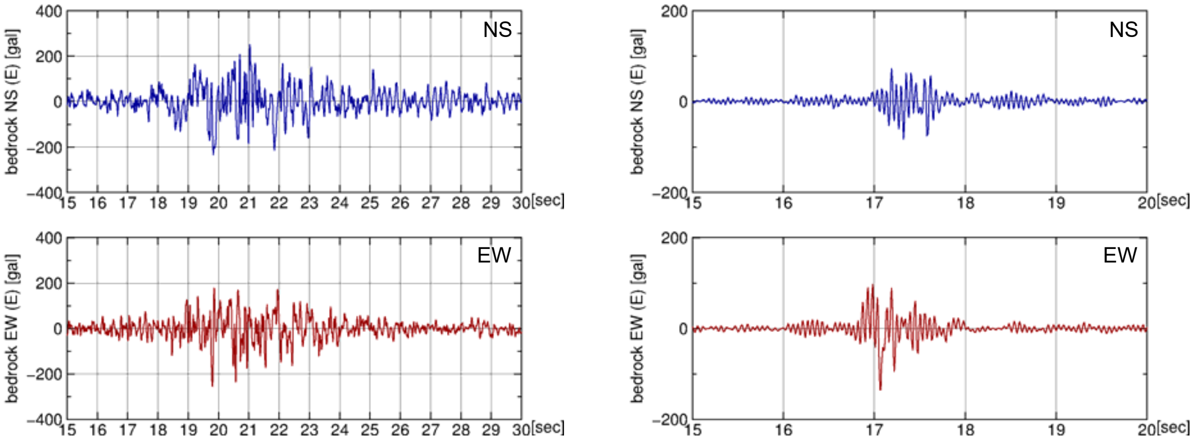
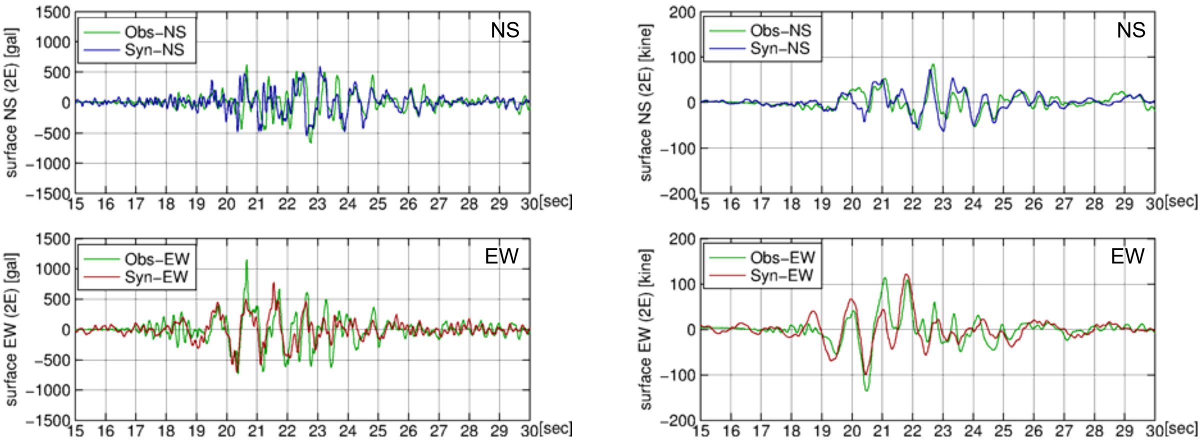


Fig. 8 – Estimated incident wave spectrum at the seismological bedrock

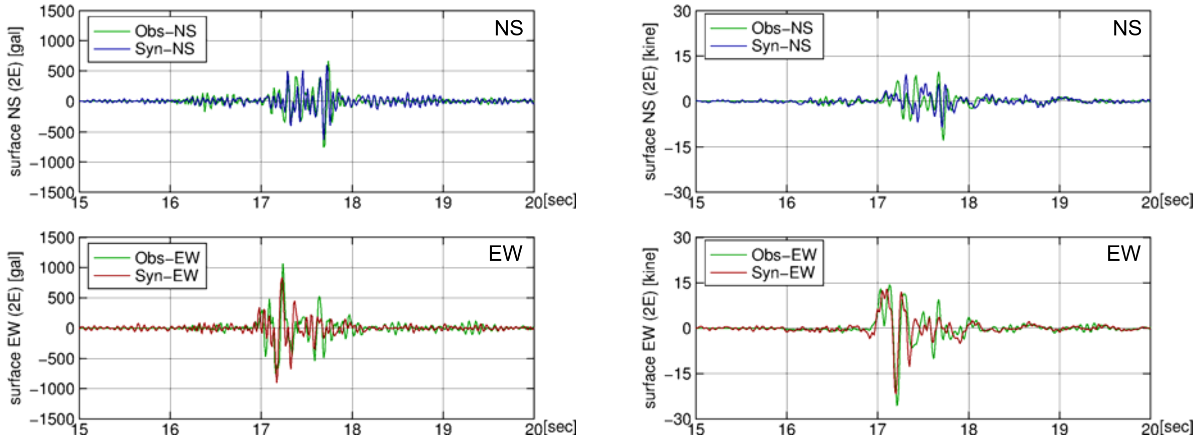


(a) KMMH16 (b)WKYH01

Fig. 9 – Estimated seismological bedrock incident wave



(a) acceleration (KMMH16) (b) velocity (KMMH16)



(c) acceleration (WKYH01) (d) velocity (WKYH01)

Fig. 10 – Comparison of equivalent linear analysis results and surface observation records

5. Summary

We estimated the horizontal TF during strong shaking, based on the diffuse field concept of earthquake, from observed records on the surface and the theoretical vertical TF above the seismic bedrock without nonlinear parameters. The seismological bedrock incident wave, that was obtained by removing the horizontal TF from the coda part with the proposed method, proved its validity from agreement of the observed surface motion and the simulated seismic motion from equivalent linear analysis using the estimated incident wave as input. Our proposed method needs the assumption of a diffuse field and linearity of the vertical TF. We showed the applicability of the proposed method to strong motions which contain source radiation characteristics in their S-wave part by using their coda part instead. Validity of the calculated input waveforms are shown through the equivalent-linear ground response analysis. We plan to increase the application of the proposed method to further accumulate information on the applicability limit and to continue investigations on the linearity of the vertical TF, which is a necessary assumption.

6. Acknowledgements

We acknowledge use of strong motion records from KiK-net operated by the National Research Institute for Earth Science and Disaster Resilience. A part of the work was supported by JSPS KAKENHI Grant-in-Aid for Young Scientists (B) No. 17K12999.

7. References

[1] Sánchez-Sesma, F. J., R. L. Weaver, H. Kawase, S. Matsushima, F. Luzón, and M. Campillo : Energy partitions among elastic waves for dynamic surface loads in a semi-infinite solid, Bull. Seism. Soc. Am., Vol.101, No.4, 2011, pp.1704-1709.

[2] Kawase, H., F.J. Sánchez-Sesma, and S. Matsushima : The optimal use of horizontal-to-vertical (H/V) spectral ratios of earthquake motions for velocity structure inversions based on diffuse field theory for plane waves, Bull. Seism. Soc. Am., Vol.101, No.5, 2011, pp.2001-2014, doi:10.1785/0120100263.

[3] Koyamada, K., Miyamoto, Y., and Miura, K.; Nonlinear property for surface strata from natural soil samples (in Japanese). Proceedings of the 38th Japan National Conference on Geotechnical Engineering, 2003, pp. 2077-2078.

[4] Imazu, M., Fukutake, K.; Dynamic deformation characteristics of gravel materials (in Japanese). Proceedings of the 21st Japan National Conference on Soil and Mechanics and Foundation Engineering, 1986, pp.509-512.

[5] Nagashima, F., H. Kawase and S. Matsushima : Estimation of horizontal seismic bedrock motion from vertical surface motion based on horizontal-to-vertical spectral ratios of earthquake motions, In: 16th world conference on earthquake engineering, No. 3685, Santiago, 2017.

[6] Kato, K., Takemura, M., Ikeura, T., Takahashi, K., Uetake, T.; Characteristics of the bedrock incident spectrum estimated from vertical strong motion records (in Japanese). Summaries of technical papers of annual meeting, Architectural Institute of Japan, 1994, pp.361-362.

[7] Sato, H., Kanatani, M.; Attenuation characteristics of seismic motion based on earthquake observation records Part 2: Proposal of new equivalent linear analysis technique considering attenuation characteristics during strong motion for precise vertical motion simulation (in Japanese). Central Research Institute of Electric Power Industry Research Report, Central Research Institute of Electric Power Industry, Tokyo, 2006.

[8] Nagashima F., Matsushima S., Kawase H., Sánchez-Sesma, F. J., Hayakawa T., Satoh T. & Oshima M. : Application of horizontal-to-vertical (H/V) spectral ratios of earthquake ground motions to identify subsurface structures at and around the K-NET site in Tohoku, Japan. Bull. Seism. Soc. Am., Vol.104, No.5, 2014, pp.2288-2302.

[9] Yoshida, N.; DYNEQ A computer program for DYNamic response analysis of level ground by EQuivalent linear method, Faculty of Engineering, Tohoku Gakuin University, 2008, http://boh0709.ld.infoseek.co.jp/.