A TECHNIQUE FOR EMPIRICAL ESTIMATION OF NON-STATIONARY SITE EFFECTS OF GROUND MOTIONS USING THE MEYER-YAMADA WAVELET

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ABSTRACT :

We propose a new technique for evaluating empirical site effects in time domain, extending the concept of Birgören and Irikura (2005). They developed a method for estimating site effects in time domain using the Meyer-Yamada wavelet. They evaluated coherent site effects by averaging wavelet coefficients for many seismic records. After that, Akazawa and Irikura (2007) improved reliability of the procedure by automatic synchronization of the S-wave phases. However, site effects consist of coherent and incoherent signals. For this reason, their procedures that use simple averaging, lead to an underestimation of the site effects. In this study, we propose a new averaging technique to evaluate both the coherent and incoherent signals. The applicability of the proposed technique is demonstrated for log sweep wave and the observed seismic records.

KEYWORDS: Site Effects, Non-stationary, Wavelet Analysis, Seismic Record, Coherent Signal, Incoherent Signal

1. INTRODUCTION

Seismic ground motion characteristics are generally expressed as a convolution of source, propagation path and site effects. Especially the site effects make a great impact on amplitude and phase of ground motion on the surface. In order to evaluate site effects, we frequently use theoretical method. However, the best method of it is to use seismic records to properly estimate broadband site effects. A lot of estimated site effects are based on the spectral amplitude information (e.g., Borcherdt, 1970, Aguirre and Irikura, 1997). However, for making an accurate estimation of ground motion, site effects in time domain (hereinafter called "non-stationary site effects"), including phase information, need to evaluate.

Birgören and Irikura (2005) developed a method for estimating the non-stationary site effects using many seismic records. In their procedure, source and propagation path effects are removed from wavelet coefficients of Mayer-Yamada wavelet (Meyer, 1989, Yamada and Ohkitani, 1991), and the non-stationary site effects are estimated by averaging many record's wavelet coefficients obtained in this manner (hereinafter called "non-stationary wavelet coefficients"). The reliability of their procedure depends on how to synchronize properly the plus-minus polarity of the phases of the records. Akazawa and Irikura (2007) improved reliability of the procedure by automatic synchronization of the S-wave phases.

It was expected that higher-accuracy results can be obtained by using more seismic records. However, in fact, the amplitude values of obtained non-stationary site effects become underestimated. In this study, first, the required non-stationary site effects are clearly defined. Next, the method how to average wavelet coefficients in order to properly estimate non-stationary site effects is considered. Then, we propose a new averaging technique to evaluate both the coherent and incoherent signals, extending the concept of Birgören and Irikura (2005) procedure. Finally, the applicability and reproducibility of the proposed technique are demonstrated for the log sweep signal and for the observed seismic records.

2. ON REQUIRED NON-STATIONARY SITE EFFECTS

The ground motion $O_{im}(t)$ on the mth site for ith event is expressed as

$$O_{im}(t) = S_i(t) * P_{im}(t) * G_m(t), \tag{2.1}$$

where $S_i(t)$ and $P_{im}(t)$ are time history characteristics of source and propagation path effects, respectively, and $G_m(t)$ is non-stationary site effects. Non-stationary site effects are site specific characteristics at the station and are defined separately for each station. If this assumption is true, the true non-stationary site effects common for all records should be able to obtain by averaging non-stationary site effects obtained from the individual records. However, in fact, the more records are used, the smaller amplitudes of obtained result. Therefore, non-stationary site effects represented by seismic records $G_{im}(t)$ are considered to contain not only coherent signal $G_m^{coh}(t)$ but also incoherent signal $G_{im}^{incoh}(t)$.

$$G_{im}(t) = G_m^{coh}(t) + G_{im}^{incoh}(t). \tag{2.2}$$

Phase of $G_{im}^{incoh}(t)$ is considered to be random. In frequency domain, amplitudes $|g_{im}(f)|$ and phases $\arg g_{im}(f)$ of non-stationary site effects $g_{im}(f)$ are given by

$$|g_{im}(f)| = \sqrt{g_m^{coh}(f)^2 + g_{im}^{incoh}(f)^2} \tag{2.3}$$

and

$$\arg g_{im}(f) = \arg g_m^{coh}(f) + r(f) \tag{2.4}$$

, respectively. $g_m^{coh}(f)$ and $g_{im}^{incoh}(f)$ are respectively coherent and incoherent signal of non-stationary site effects in frequency domain, and $r(f)$ is random function. $g_{im}(f)$ can be expressed by the following equation using equations (2.3) and (2.4).

$$g_{im}(f) = |g_{im}(f)| \exp\{l \cdot \arg g_{im}(f)\}, \tag{2.5}$$

where l is imaginary unit. The required non-stationary site effects at target station $g_{im}(f)$ are estimated by averaging $g_{im}(f)$ of many individual seismic records.

$$g_m(f) \approx \overline{g}_m(f) = \sqrt{\frac{1}{n}\sum_{i=1}^{n} g_{im}(f)^2} = \exp\{l \cdot \arg g_{im}(f)\} \sqrt{\frac{1}{n}\sum_{i=1}^{n} |g_{im}(f)|^2}, \tag{2.6}$$

where n is the number of seismic records. It consists of coherent and incoherent signals.

3. PROCEDURE OF THE AVERAGING OF WAVELET COEFFICIENTS FOR PROPERLY ESTIMATING OF NON-STATIONARY SITE EFFECTS

The advantage of the Meyer-Yamada's wavelet is that the wavelet spectrum We_j approximately correspond to the power spectrum $Pa(f)_j$ at the geometric mean frequency $2^{j+1}/(3T_d)$ in the jth scale, and this property is the main reason of employing this wavelet (Birgören and Irikura, 2005).

$$Pa(f)_j \approx We_j = A_j \sum_k |\alpha_{j,k}|^2, \tag{3.1}$$

where k is an integer value denoting position of the wavelet, $\alpha_{j,k}$ is wavelet coefficient, T_d is time length in sec and $A_j = T_d/2^j$. Average power spectrum of a number of data series $\overline{P}a(f)_j$ is given by

$$\overline{P}a(f)_j \approx \overline{W}e_j = A_j \frac{1}{n}\sum_{i=1}^{n}\sum_k |\alpha_{j,k,i}|^2, \tag{3.2}$$

where $\overline{W}e_j$ is average wavelet spectrum, n is number of data series and $\alpha_{j,k,i}$ is wavelet coefficient of i data series. Dividing $\alpha_{j,k,i}$ into coherent signal $\alpha_{j,k}^{coh}$ and incoherent signal $\alpha_{j,k,i}^{incoh}$, we can express equation (3.2) by the following equation.

$$\bar{P}a(f)_j \approx \bar{W}e_j = A_j \frac{1}{n}\sum_{i=1}^{n}\sum_k \left|\alpha_{j,k}^{coh} + \alpha_{j,k,i}^{incoh}\right|^2 . \tag{3.3}$$

Equation (3.3) is given as equation evaluating both coherent and incoherent signals. The requirement of procedure for averaging the wavelet coefficients, which is purpose of this study, is to fulfill equation (3.3). Following to (Birgören and Irikura, 2005) and (Akazawa and Irikura, 2007) procedures, we can define average value of the wavelet coefficient $\bar{\alpha}_{j,k}'$ at the same spatial scale and position.

$$\bar{\alpha}_{j,k}' = \frac{1}{n}\sum_{i=1}^{n}\alpha_{j,k,i} = \frac{1}{n}\sum_{i=1}^{n}\left(\alpha_{j,k}^{coh} + \alpha_{j,k,i}^{incoh}\right). \tag{3.4}$$

From equation (3.4), the wavelet spectrum $\bar{W}e_j'$ is given by

$$\bar{W}e_j' = A_j \sum_k \left|\bar{\alpha}_{j,k}'\right|^2 = A_j \sum_k \left|\alpha_{j,k}^{coh} + \frac{1}{n}\sum_{i=1}^{n}\alpha_{j,k,i}^{incoh}\right|^2 . \tag{3.5}$$

If $\alpha_{j,k,i}^{incoh}$ is white noise, incoherent signal is disappeared and coherent signal enhanced.

$$\bar{W}e_j' = A_j \sum_k \left|\alpha_{j,k}^{coh}\right|^2 . \tag{3.6}$$

The reason for underestimating of true site effects by using (Birgören and Irikura, 2005) and (Akazawa and Irikura, 2007) procedures is explained by equation (3.6). Focusing on the power of the wavelet coefficients, we propose following equation.

$$\bar{\alpha}_{j,k}'' = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left|\alpha_{j,k,i}\right|^2} . \tag{3.7}$$

The wavelet spectrum $\bar{W}e_j''$ calculated from equation (3.7) is expressed as

$$\bar{W}e_j'' = A_j \sum_k \left|\bar{\alpha}_{j,k}''\right|^2 = A_j \frac{1}{n}\sum_k \sum_{i=1}^{n}\left|\alpha_{j,k,i}\right|^2 . \tag{3.8}$$

$\bar{W}e_j''$ equals $\bar{W}e_j$ of equation (3.2). Therefore, the averaging by using equation (3.7) fulfills the requirement of procedure of averaging wavelet coefficients. The following equation follows from equations (3.1), (3.2) and (3.7).

$$\bar{P}a(f)_j \approx \bar{W}e_j = \bar{W}e_j'' \approx \bar{P}a(f)_j'' . \tag{3.9}$$

Next, we consider the procedure of averaging of non-stationary wavelet coefficients in order to properly estimate non-stationary site effects. According to Birgören and Irikura (2005) procedure, the wavelet coefficient $\alpha_{j,k,i}^{G}$ (hereinafter called "site amplification wavelet coefficient") is given by

$$\alpha_{j,k,i}^{G} = \alpha_{j,k,i}^{O} \big/ \left(S(f)_{j,i}P(f)_{j,i}\right), \tag{3.10}$$

where $\alpha_{j,k,i}^{O}$ is wavelet coefficient of seismic record of the ith event, $S(f)_{j,i}$ and $P(f)_{j,i}$ are source and propagation path scalar terms at the geometric mean frequency. From equations (3.1) and (3.10), the relational expression between power spectrum $Pa^G(f)_{j,i}$, wavelet spectrum $We_{j,i}^{G}$ (hereinafter called "site amplification power spectrum" and "site amplification wavelet spectrum", respectively) and the site amplification wavelet coefficient is expressed by the following equation.

$$Pa^G(f)_{j,i} \approx We_{j,i}^{G} = A_j \sum_k \left|\alpha_{j,k,i}^{G}\right|^2 \tag{3.11}$$

where

$$Pa^{G}(f)_{j,i} = Pa^{O}(f)_{j,i} \big/ \left(S(f)_{j,i} P(f)_{j,i}\right)^{2} \tag{3.12}$$

$$We^{G}_{j,i} = We^{O}_{j,i} \big/ \left(S(f)_{j,i} P(f)_{j,i}\right)^{2} . \tag{3.13}$$

Here, $Pa^{O}(f)_{j,i}$ and $We^{O}_{j,i}$ are power spectrum and wavelet spectrum of seismic record, respectively. The average value of site amplification power spectrum obtained from many seismic records is calculated as

$$\overline{P}a^{G}(f)_{j} \approx \overline{W}e^{G}_{j} = A_{j} \frac{1}{n} \sum_{i=1}^{n} \sum_{k} \left|\alpha^{G}_{j,k,i}\right|^{2} , \tag{3.14}$$

where $\overline{W}e^{G}_{j}$ is average site amplification wavelet spectrum. Equation (3.14) corresponds to equation (3.2) for a general data series. Therefore, the following equation is very effective procedure for estimating non-stationary site effects, which evaluates both the coherent and incoherent signals.

$$\overline{\alpha}^{G}_{j,k}{''} = \sqrt{\frac{1}{Ne'} \sum_{i=1}^{Ne} \left|\alpha^{G}_{j,k,i}\right|^{2}} . \tag{3.15}$$

However, the wavelet coefficients calculated from equation (3.15) is an unsigned value. Therefore, proper sign, plus or minus, should be given to the coefficients.

4. PROPOSITION OF A NEW AVERAGE TECHNIQUE FOR NON-STATIONARY SITE EFFECTS

Using the site amplification wavelet coefficients averaged by equation (3.15), the site amplification power spectrum around the geometric mean frequency of each scale j is approximated by equation (3.9). Therefore, obtained amplitude property should correspond to the average property. However, the phase property depends on the sign of the wavelet coefficient. Therefore, $\overline{\alpha}^{G}_{j,k}{''}$ should be given a sign, which can be explained qualitatively. In this study we assign sign $sign_{j,k}$ of the site amplification wavelet coefficient $\overline{\alpha}^{G}_{j,k}{'}$ averaged by the (Akazawa and Irikura, 2007) procedure.

$$sign_{j,k} = \overline{\alpha}^{G}_{j,k}{'} \big/ \left|\overline{\alpha}^{G}_{j,k}{'}\right| , \tag{4.1}$$

where

$$\overline{\alpha}^{G}_{j,k}{'} = \frac{1}{n} \sum_{i=1}^{n} \alpha^{G}_{j,k,i} . \tag{4.2}$$

We propose the following equation as a new averaging technique for estimating non-stationary site effects.

$$\overline{\alpha}^{G}_{j,k} = sign_{j,k} \cdot \overline{\alpha}^{G}_{j,k}{''} = \frac{\overline{\alpha}^{G}_{j,k}{'}}{\left|\overline{\alpha}^{G}_{j,k}{'}\right|} \sqrt{\frac{1}{n} \sum_{i=1}^{n} \left|\alpha^{G}_{j,k,i}\right|^{2}} . \tag{4.3}$$

Equation (4.3) fits requirements for the non-stationary site effects expressed by equation (2.6), and therefore, proposed technique is excellent for estimating non-stationary site effects. Inversely transforming the site amplification wavelet coefficients $\overline{\alpha}^{G}_{j,k}$, we obtain non-stationary site effects waveform $G(t)$ (hereinafter called "site amplification waveform").

$$G(t) = \sum_{j=0}^{n-1} \sum_{k=0}^{2^{j}-1} \overline{\alpha}^{G}_{j,k} \psi_{j,k}(t) , \tag{4.4}$$

where $\psi_{j,k}(t)$ is analyzing wavelet. The proposed technique gives average amplitude property (envelope) depending on frequency and coherent phase of seismic record. This technique has feature that calculated result doesn't depend on sign of the site amplitude wavelet coefficient and that the obtained site amplitude wavelet spectrum agrees with the $\overline{W}e^{G}_{j}$ value expressed by equation (3.14). Additionally, the site amplitude power

spectrum obtained by this technique should correspond to the average spectrum of many seismic records.
The amplitude values obtained by (Birgören and Irikura, 2005) and (Akazawa and Irikura, 2007) procedures are underestimated, especially at later phases. On the other hand, the proposed technique is expected to be able to estimate non-stationary site effects at target station almost exactly. Additionally, even if the set of records include records with inverse sign phases, the coherent signals of such records are canceled out by coherent signals of records with true sign phases. However, because in that case incoherent signals become amplified, it is important that the plus-minuses of waveform are synchronized by method of Akazawa and Irikura (2007).

5. EVALUATION OFAPPLICABILITY OF THE PROPOSED TECHNIQUE

This chapter evaluates applicability of proposed technique by using log sweep signal and seismic records. For comparison, it evaluates similarly the applicability of (Akazawa and Irikura, 2007) procedure, too. Power spectra below are smoothed by Parzen window with window range 0.1Hz.

5.1. Testing by Log Sweep Signal

This section evaluates accuracy of averaging using log sweep signal with amplitude 1.0, time length 40sec and frequency range 0.05-20Hz. Cosine taper is applied for both ends of 1sec. Additionally, append of trailing zeros extend waveform data to 81.92sec. We create 10 waveform data combining the modified log sweep signal and different white noise series, each having amplitude of 1.0 (hereinafter collectively called "estimation data"). Figure 1 shows example of the estimation data. We set $S(f)_{j,i}$ and $P(f)_{j,i}$ values to 1.0, because we doesn't aim at estimating of the non-stationary site effects.

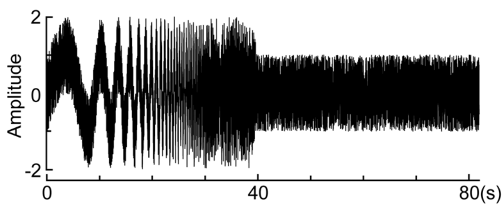

Fig.1 Example of estimation data.

Figure 2 shows obtained waveforms with log sweep signal for 0-81.92sec and 35-36sec, and Figure 3 shows obtained wavelet spectra and power spectra with log sweep signal and average estimation data, respectively. In all the figures, results obtained by Akazawa and Irikura (2007) approximately correspond to log sweep signal. On the other hand, results obtained by proposed technique approximately correspond to average evaluation data. The wavelet spectra, for example, agree well with the average evaluation data. These results suggest that proposed technique can properly average both amplitude and phase.

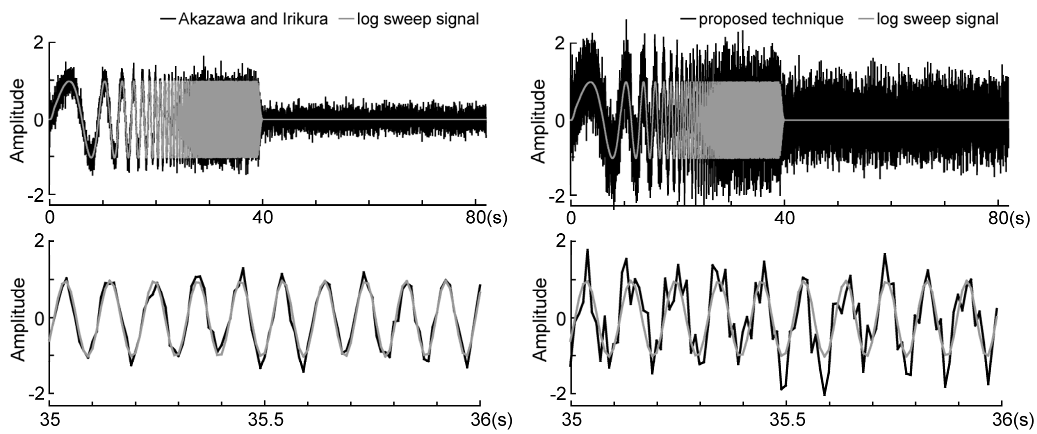

Fig.2 Waveforms obtained by Akazawa and Irikura (2007) procedure (left) and proposed technique (right).

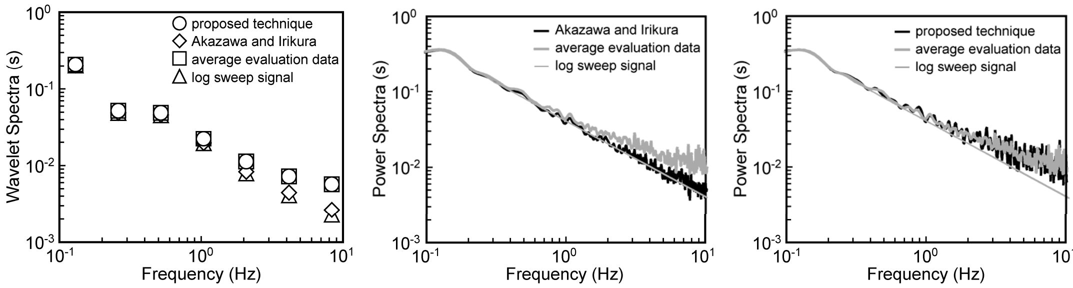

Fig.3 Obtained wavelet spectra (left), power spectra for Akazawa and Irikura (2007) procedure (center) and power spectra for proposed technique (right).

5.2. Testing by Seismic Records

This section evaluates accuracy of obtained non-stationary site effects using seismic records. The evaluation use the same station FKS of the strong motion observation network of The Committee of Earthquake Observation and Research in the Kansai Area (CEORKA) and the same seismic records and seismic parameters, which were used in (Akazawa and Irikura, 2007). Table 1 lists used events, and Figure 4 shows locations of the epicenters and the FKS site.

Table 1 List of used events for evaluation.

No.	Origin Time (JST)	Depth (km)	M_J	M_0 (dyne*cm)	f_c (Hz)
1	1999.02.12 03:16:45.8	15	4.0	9.68×10^{21}	2.6
2	1999.03.12 23:24:25.9	15	3.9	5.46×10^{21}	2.1
3	1999.07.15 19:25:46.2	14	3.8	4.73×10^{21}	2.2
4	1999.08.02 04:58:14.4	14	3.9	5.10×10^{21}	1.8
5	2000.05.16 04:09:25.9	16	4.3	2.64×10^{22}	1.5
6	2000.05.16 05:43:11.1	15	3.6	1.59×10^{21}	3.0
7	2000.05.20 23:39:12.7	16	3.7	1.96×10^{21}	3.0
8	2000.08.27 13:13:13.7	11	4.1	6.92×10^{21}	1.8
9	2001.03.30 04:50:10.5	16	3.7	1.62×10^{21}	3.1
10	2003.10.08 23:35:11.7	14	4.2	6.83×10^{21}	2.3
11	2004.11.30 16:02:06.3	9	3.3	7.00×10^{20}	3.9
12	2005.02.14 00:22:05.1	13	4.1	7.04×10^{21}	2.0

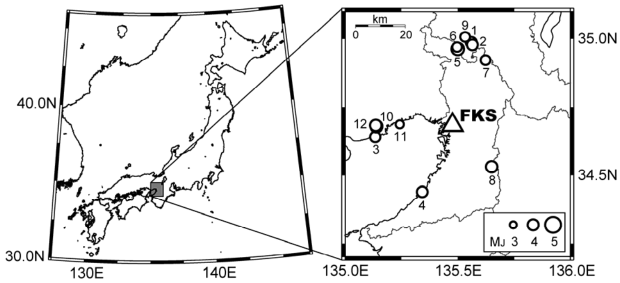

Fig.4 Location of FKS site and epicenter of used events for evaluation.

Figure 5 shows obtained site amplification waveforms, site amplification wavelet spectra and site amplification power spectra for transverse component, respectively. In the figures we call $\overline{We}_j^G$, expressed by equation (3.14), "average wavelet spectra", and average of site amplification power spectra calculated from inverse transform wave of $\alpha^G_{j,k,i}$, expressed by equation (3.10), "average power spectra". From equations (3.11) and (3.14), the average power spectra correspond to $Pa^G(f)_j$, expressed by equation (3.14). At first, let's evaluate waveforms. The direct S-waves have almost no difference between both methods. On the other hand, later phases approximately agree with each other, however, their amplitude values, calculated by proposed technique, are lager than the amplitude values calculated by (Akazawa and Irikura, 2007) procedure. Now, let's evaluate spectra. All the spectra calculated by (Akazawa and Irikura, 2007) procedure are underestimated, compared with the average spectra. On the other hand, for proposed technique, the wavelet spectra agree with the average wavelet spectra, and power spectra approximately correspond to the average power spectra. These results show that proposed technique can properly estimate non-stationary site effects at target station.

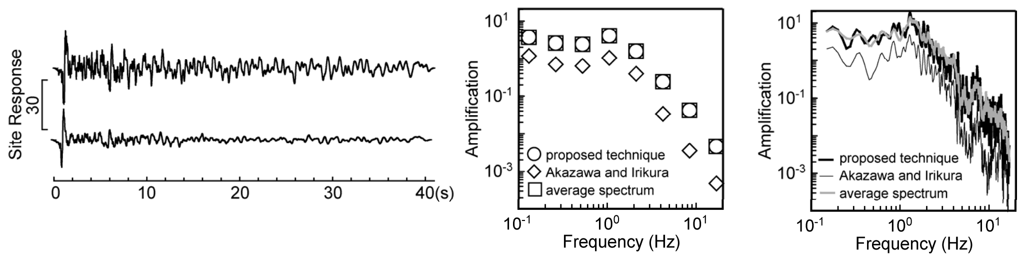

Fig.5 Obtained site amplification waveforms (left), site amplification wavelet spectra (center) and site amplification power spectra (right) for transverse component.

6. REPRODUCIBILITY EVALUATION OF A SMALL EVENT RECORD

This chapter evaluates repeatability of small event (M_{JMA}3-5) records using proposed technique. Additionally, for comparison, it similarly evaluates repeatability of (Akazawa and Irikura, 2007) procedure, too. The target station is the FKS site, and the non-stationary site effects obtained in Section 5.2 are used.

6.1. Procedure for Creating Reproduction Wave

This section shows procedure for creating reproduction wave using the proposed technique and (Akazawa and Irikura, 2007) procedure. Method estimate non-stationary site effects by dividing wavelet coefficient of seismic record by source and propagation path factors, as shown in equation (3.10). Therefore, to create reproduction wave we use the procedure backward.

(1) Wavelet coefficients $\alpha^{S}_{j,k,M,I}$ are calculated by multiplying site amplification wavelet coefficients $\overline{\alpha}^{G}_{j,k,M}$, obtained by both methods, by source and propagation path factors for Ith event ($S(f)_{j,I}$ and $P(f)_{j,I}$).

$$\alpha^{S}_{j,k,M,I} = S(f)_{j,I}\, P(f)_{j,I}\, \overline{\alpha}^{G}_{j,k,M} \,. \tag{6.1}$$

(2) Waveform $f^{S}_{M,I}(t)$ is calculated by the inverse transform of $\alpha^{S}_{j,k,M,I}$.

$$f^{S}_{M,I}(t) = \sum_{j=0}^{n-1} \sum_{k=0}^{2^j-1} \alpha^{S}_{j,k,M,I}\, \psi_{j,k}(t) \,. \tag{6.2}$$

6.2. Reproducibility of Small Event Record

This section creates seismic wave using procedure shown in Section 6.1, and evaluates the reproducibility of methods by comparing with seismic records. First, let's evaluate for some events used in Section 5.2. Parameters are the same. Figure 6 shows examples of velocity waveforms and velocity Fourier spectra calculated by two methods for radial and transverse components, respectively. The Fourier spectra are smoothed by Parzen window with window range 0.1Hz. The results obtained by (Akazawa and Irikura, 2007) procedure are underestimated in overall, comparing with seismic records. The difference is prominent in later phases. On the other hand, the results obtained by proposed technique roughly correspond to the seismic records, although some of results cannot reproduce direct S-wave and path related surface waves.

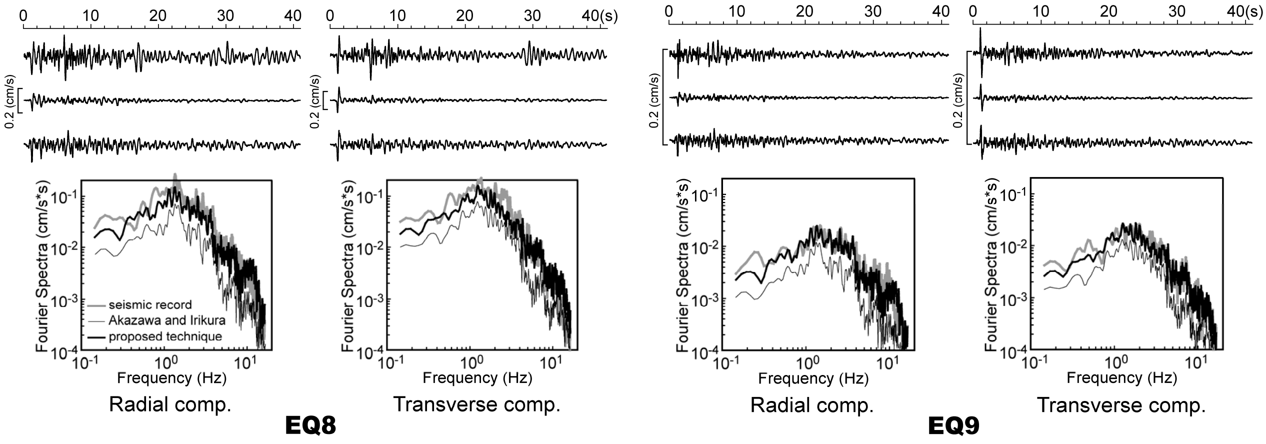

Fig.6 Examples of velocity waveforms (top: seismic record, middle: (Akazawa and Irikura, 2007) procedure, bottom: proposed technique) and velocity Fourier spectra re-created for events used in Section 5.2.

Now, let's try to evaluate for the events unused in Section 5.2. Table 2 lists such events, and Figure 7 shows locations of their epicenters. In Table 2, seismic moments M_0 are calculated by F-net, and corner frequencies f_c are calculated from seismic records obtained by underground strong-motion seismographs of KiK-net. The other parameters are the same as in Section 5.2. Figure 7 shows velocity waveforms and velocity Fourier spectra. The results show the same trend with Figure 6. Thus, we can conclude that the proposed technique has high reproducibility for small events.

Table 2 List of events
(unused in Section 5.2)

No.	Origin Time (JST)	Depth (km)	M_J	M_0 (dyne*cm)	f_c (Hz)
13	2002.07.16 20:08:58.1	16	4.2	5.62×10^{21}	2.1
14	2006.05.15 01:42:13.0	3	4.5	3.75×10^{22}	0.8

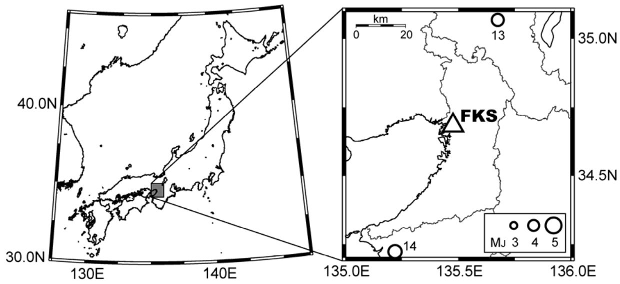

Fig.7 Location of FKS site and epicenter of events (unused in Section 5.2)

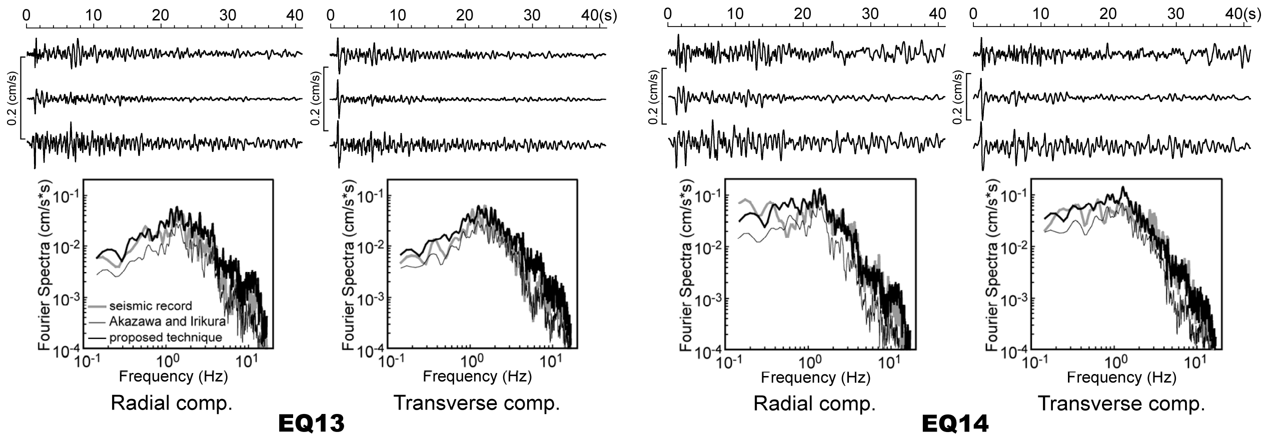

Fig.8 Velocity waveforms (top: seismic record, middle: (Akazawa and Irikura, 2007) procedure, bottom: proposed technique) and velocity Fourier spectra re-created for events unused in Section 5.2.

7. CONCLUSIONS

Using synthetic (log sweep signal) and observed waveforms we confirm that (Birgören and Irikura, 2005) and (Akazawa and Irikura, 2007) procedures underestimate site effects due to presence of the incoherent signal. We proposed a new averaging technique to evaluate both the coherent and incoherent signals, extending the concept of (Birgören and Irikura, 2005) procedure. The proposed technique gives average amplitude property (envelope), depending on frequency, and coherent phase property of seismic record. The applicability of the proposed technique was demonstrated for the log sweep signal and for the observed seismic records.

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