I Point-by-point response to the reviews

Part 1 R1:

1. Quotation of the general comment: "It is suggested that the abstract need to be revised to be as concise and understandable as possible"

Reply: Thank you very much for your suggestion. We revised the manuscript to make it as concise and understandable as possible.

2. Quotation of the general comment: "IIR method is seldom introduced in this article, and the method is the key to this article. What work has the author done on IIR method? "

Reply: Thank you very much for your suggestion. Yes, the method is important in this article, we explain it in the article simple. We will explain it in detail here.

First, the frequency-dependent relative site amplification factors are assumed to be modelled by a following linear system of first- and second order filters,

$$F(s) = G_0 \prod_{n=1}^{N} \left(\frac{\omega_{2n}}{\omega_{1n}}\right) \cdot \frac{s+\omega_{1n}}{s+\omega_{2n}} \cdot \prod_{m=1}^{M} \left(\frac{\omega_{2m}}{\omega_{1m}}\right)^2 \cdot \frac{s^2+2h_{1m}\omega_{1m}+\omega_{1m}^2}{s^2+2h_{1m}\omega_{1m}+\omega_{2m}^2} \quad (1)$$

where N and M stand for the numbers of the first and second-order filters, respectively, and $s = i\omega$. Here ω are angular frequencies and h are damping factors that characterize the frequency dependence, respectively.$s^2 + 2h\omega + \omega_m^2$ represents a damping oscillation.

Then, we need to use the following formula (2) to transfer the continuous-time system representations to discrete-time system

The bilinear transform is introduced as:

$$s = \frac{2}{\Delta T} \cdot \frac{1-Z^{-1}}{1+Z^{-1}} \quad (2)$$

Then the pre-warping equation

$$\omega \rightarrow \frac{2}{\Delta T} \tan\left(\frac{\omega \Delta T}{2}\right) \quad (3)$$

whereΔT is the sampling interval of the digital waveforms and $z = \exp(s\Delta T)$. Formula (3) is applied to ω_{1n}, ω_{2n} , ω_{1m} , ω_{2m}, By the above two steps, the transfer function$F(z)$ is obtained, Eq. (2) and Eq. (3) are the necessary procedures to obtain the coefficients of a causal recursive filter for real time processing.

Next, we will show the detailed process for the IIR method:

In this method， the filter is modelled as the formula (1) ， $F(s)$ is written as combined formula of first order and second order s ，

$$F_{1n}(s)= (\frac{\omega_{1n}}{\omega_{2n}}).\frac{s+\omega_{1n}}{s+\omega_{2n}} ,$$

$$F_{2m}(s)=(\frac{\omega_{2m}}{\omega_{1m}})^2.\frac{s^2+2h_1\omega_{1m}+\omega_{1m}{}^2}{s^2+2h_2\omega_{2m}+\omega_{2m}{}^2} \qquad (4)$$

Then we will explain how to transfer formula (4) to IIR filter

$$F_{1n}(z)=g_0.\frac{a_0+a_1z^{-1}}{1+b_1z^{-1}} ,$$

$$F_{2m}(z)=g_0.\frac{a_0+a_1z^{-1}+a_2z^{-2}}{1+b_1z^{-1}+b_2z^{-2}} \qquad (5)$$

For $F_{1n}(z)$, the recursive filter is given as

$$y_k = g_0(a_0x_k + a_1x_{k-1}) - b_1y_{k-1} \qquad (6)$$

For $F_{2m}(z)$, the recursive filter is given as

$$y_k = g_0(a_0x_k + a_1x_{k-1} + a_2x_{k-2}) - (b_1y_{k-1} + b_2y_{k-2}) \qquad (7)$$

Where x_k and y_k stands for the input discrete waveform time history and the output discrete waveform time history.

Through the bilinear transform formula (2) and the pre-warping formula (3) ，

For $F_{1n}(z)$, a_0, g_0, a_1 and b_1 is given as:

$$g_0 = \frac{\tan(\frac{\omega_{2n}\Delta T}{2})}{\tan(\frac{\omega_{1n}\Delta T}{2})} \cdot \frac{1}{1+\tan(\frac{\omega_{2n}\Delta T}{2})}$$

$$a_0 = 1+\tan(\frac{\omega_{2n}\Delta T}{2}),$$

$$a_1 = \tan(\frac{\omega_{2n}\Delta T}{2})-1,$$

$$b_1 = \frac{\tan(\frac{\omega_{2n}\Delta T}{2})-1}{1+\tan(\frac{\omega_{2n}\Delta T}{2})}, \qquad (8)$$

For $F_{2m}(z)$, a_0, g_0, a_1, a_2, b_1 and b_2 is given as,

$$g_0 = \left\{\frac{\tan(\frac{\omega_{2n}\Delta T}{2})}{\tan(\frac{\omega_{1n}\Delta T}{2})}\right\}^2 \cdot \frac{1}{1+2h_2\tan(\frac{\omega_{2n}\Delta T}{2})+\tan^2(\frac{\omega_{2n}\Delta T}{2})},$$

$$a_0 = 1+2h_1\tan(\frac{\omega_{1m}\Delta T}{2})+\tan^2(\frac{\omega_{1m}\Delta T}{2}),$$

$$a_1 = 2\tan^2(\frac{\omega_{1m}\Delta T}{2})-2,$$

$$a_2 = 1-2h_1\tan(\frac{\omega_{1m}\Delta T}{2})+\tan^2(\frac{\omega_{1m}\Delta T}{2}),$$

$$b_1 = \frac{2\tan^2(\frac{\omega_{2m}\Delta T}{2}) - 2}{1 + 2h_2\tan(\frac{\omega_{2m}\Delta T}{2}) + \tan^2(\frac{\omega_{2m}\Delta T}{2})},$$

$$b_2 = \frac{1 - 2h_2\tan(\frac{\omega_{2m}\Delta T}{2}) + \tan^2(\frac{\omega_{2m}\Delta T}{2})}{1 + 2h_2\tan(\frac{\omega_{2m}\Delta T}{2}) + \tan^2(\frac{\omega_{2m}\Delta T}{2})} \quad (9)$$

The above formulas gives detailed explain about how to model site amplification factor as the IIR filter.

We searched the possible combination of N and M trough iteration process. As the give N and M, We use the least-square method to determine parameters such asG_0,ω_{1n}, ω_{2n} , ω_{1m} , ω_{2m}. If we get the similar residual, we should choose the smaller N and M, because it could be more easily implemented for hardware filter design.

3. Quotation of the general comment: “Somethings are wrong in Table 1 and Table 2.For example, in Table 1 Surface in PGA includes Obs. and Sim., but it only includes Obs. Now. And value 8.3 in the Sim. in Table 1 is calculation error. Please check it carefully”.
Reply: Thank you very much for your carefully checking this manuscript, Yes, it does make a mistake in the table, the data shows in the fig.6 is 5.6255 and 0.67548, so the value 8.3 is calculated correctly, we carefully check the data and redesign the Table 1 and Table 2. In the revised manuscript, these errors have been fixed.

4.Quotation of the general comment: “English expression needs improvement, such as, (1) Pay attention to the comparative level in English, Line 25, It also shows good performance: : :, should be “It also shows better performance : : :” (2) There is something wrong with the presentation of the month, Line 8, Septemper.1, 2000, should be “Sept. 1, 2000” or “September 1, 2000” (3) It’s better to use the third person in the manuscript unless you have done so already, such as Line 9 and Line 11, I selected 673, I selected data, : : : (4) Attention should be paid to the singular and plural forms in English expressions, for example in Line 14, There exists 20 meter : : : it should be “There exists 20 meters : : :”
(5) What does “the he M5.2” mean in Line 2 and Line 3 below the table 4? (6) : : :: : :”
Reply: Thank you very much for your suggestion. We fill check the grammar error and

type error in the manuscript and improve the English expression in the manuscript following your detailed suggestion.

Part II R2

5. Quotation of the general comment: “1) the authors state in the title the term "Earthquake Early Warning System" (EEWS). I suggest to remove this term from the title since the authors fail to prove the relation of their proposal to the purposes of an EEWS. More specific: a) all the introduction section presents a classical historical review of EEWSs without pointing the (possible) relation between authors proposal and EEWS. b) In section 4, the only reference to the (possible) embedding of results to an operational EEWS are given by the statement at the end of p.15: "It will have good potential application in the future EEW system". This is obviously not adequate and does not prove the usability of the proposed method for the purposes of EEWS. What the reader will expect to see is for example, block diagrams of where and how the proposed method will co-integrate with other elements of EEWS, the performance of EEWS with the addition of proposed method (even in simple term of false alarms/missed alarms) and so on. c) In addition, at discussion section, the authors didn’t provide a satisfactory discussion of how an EEWS will be benefited from the proposed method. ”

Reply: a) In fact, this method could be used to real-time or near real-time seismic hazard mitigation system, such as the seismic intensity repaid report system and the earthquake early warning system. Usually, in the real-time and near-time seismic hazard mitigation system, the site amplification factor was given as a scalar value. So it could not reflect the different amplification for different frequency. The proposal that completely remove the term “earthquake early warning system” is reasonable. Then the title of this paper could be changed to” Study on real-time site amplification correction”.

B) Yes, we presents a classical historical review of EEWs, we need to point the relation between our paper and EEWS clearly.

These EEWs include the current conventional system in the world, many of present EEWs needs to quickly determine the earthquake hypocenter and magnitude based on amplitude or frequency content of start portion of waveform firstly, then predict the strengths of ground motions at various sites by applying a ground motion prediction equation (GMPE) that uses the hypocenter distance and magnitude. In fact, The EEW magnitude is not important to the public. We need to predict the ground motion more accurately for giving useful information to the public. This method based on the front detection station to predict ground motion real-timely at the target station without any hypocentral parameters. It skips the procedure to calculate the EEW magnitude use the start potion of the waveform. We can obtain the waveform real-timely at the target station. We compared the simulation waveform at the target station with the observed waveform, then compared the seismic intensity. For the damaged area, the more accurate seismic intensity and peak ground acceleration prediction is useful and important. In this method, we do not need to give the EEW magnitude to the public and we just predict waveform at target stations, then predicted ground motion are calculated based on the predicted waveform. So we could not give the term of false alarms/missed alarms. We compare the prediction acceleration and statistic the seismic intensity with the observed one and compare our simulation results with other methods. For the ARV method and station correction method, the seismic intensity residual within +-0.5 is 55% and 59% respectively. The seismic intensity residual within +-1 is 84% and 93% respectively for ARV method and station correction method. The average 1 degree seismic intensity error of the current JMA EEW system (JMA, 2018) is 74.74% for all the eleven years statistical data. The best result is 93.7% in 2017, the

worst result is 34.6% in 2010.So we can conclude that frequency-dependent correction of site amplification method show better performance than the scalar value site amplification methods (ARV, Station Correction) and the operational current JMA EEW system in predicting ground motion.

For "c) In addition, at discussion section, the authors didn't provide a satisfactory discussion of how an EEWS will be benefited from the proposed method." We will make more detailed and clearly discussion of how an EEWS will be benefited from the proposed method in the revised manuscript. How an EEWS will be benefited from the proposed method?

A: This method based on the front detection station to predict ground motion real-timely at the target station without any hypocentral parameters. It skips the procedure to calculate the EEW magnitude and epicenter distance or hypocenter distance using the start potion of the waveform. We can obtain the waveform real-timely at the target station. It highly improve the accuracy of predicting ground motion real-timely compared with the scalar value site amplification factor.

B: Usually, the JMA seismic intensity is calculated in the frequency domain, if we adopted the procedure proposed by Kunugi et al. (2013) for real-time calculation of JMA seismic intensity in the time domain. This allowed this method to be applied in real time. It is could be used for the next generation of earthquake early warning system.

We also provide a paragraph discussing potential pitfalls and drawbacks for application to the earthquake early warning system. Please refer to the 12th Reply.

6. Quotation of the general comment: "The abstract must be reorganized in a more concise form. At the current version this is not informational because there are many unnecessary

details. Authors must provide very clearly what is the problem, the method and materials used and what is the contribution"

Reply: Thank you very much for your valuable suggestion. We will reorganized the abstract in a more concise form and remove many unnecessary details. We will provide clearly what is the problem, the method and material used and what is the contribution. After revised, the abstract shows as follows:

"The site amplification factor was usually considered as scalar values, such as amplification of peak ground acceleration or peak ground velocity, increments of seismic intensity in the earthquake early warning system or seismic intensity repaid report system. This paper focus on evaluation of infinite impulse recursive filter method that could produce frequency-dependent site amplification and compare the performance of the scalar value method with the infinite impulse recursive filter method. A large amount of strong motion data of IBRH10 and IBRH19 of Kiban Kyoshin network (Kik-net) triggered in more than one thousand earthquakes from 2004 to 2012 were selected carefully and used to get the relative site amplification, then we model the relative site amplification factor by casual filter. Then we make simulation from borehole to surface and also simulation from front-detection station to far-field station. Compare different simulation cases, it can easily be found that this method could produce different amplification factor for different earthquakes and could reflect the frequency-dependent of site amplification. Through these simulation between two stations, we can find that the frequency-dependent correction for site amplification shows better performance than the ARV method and station correction method. It also shows better performance than the average level and the highest level of Japan Meteorological Agency (JMA) earthquake early warning system in ground motion prediction. This method pays attention to the amplitude and ignore the phase characteristic,

this problem may be improved by the seismic interferometry method. Although there are some problems needed to be considered and solved carefully, frequency-dependent correction for site amplification in the time domain highly improve the accuracy of predicting ground motion real-timely."

7. Quotation of the general comment: "A native English speaker must furnish the grammar and syntax of the manuscript. In the present form it is not recommendable for publication."

Reply: Thank you very much for your valuable suggestion. We will seek professional help to the native English speaker to furnish the grammar and syntax of the revised manuscript.

8. Quotation of the general comment: "Authors must check the presentation of their tables. There are abbreviations that are not explained before. There are titles that are not properly aligned (i.e Table 3 "Amplifi-cation((IBRH....)" and units are missed."

Reply: Thank you very much for carefully checking the manuscript. We will check the manuscript carefully and explain the related abbreviations in proper position. We check and revised all the table in the manuscript. We make the titles aligned proper and improve the units in the revised manuscript. In the table, the abbreviation for Amplification is Amp. The abbreviation for Observation is Obs. The abbreviation for Simulation is Sim. The abbreviation for Component is comp. The abbreviation for Residual is Res. The abbreviation for Borehole is Boh. The abbreviation for Surface is Suf.

Table 3 Information for M5.2 earthquake (IBRH10 & IBRH19 for 201202191454)

	PGA(gal)			PGA Amp.		Ijma			
	IBRH19	IBRH10		Amp. (IBRH10/IBRH19)		IBRH19	IBRH10		Res. (Obs.-Sim.)
Comp.	Obs.	Obs.	Sim.	Obs.	Sim.	Obs.	Obs.	Sim.	
NS	17.7	50.9	69.7	2.8	3.9	2.2	3.5	3.7	0.2
EW	13.6	45.7	53.2	3.3	3.9				
UD	11.2	23.7	38.9	2.1	3.5				

9. Quotation of the general comment: "Please provide the same level of information on each figure caption. For example at fig.7, authors define each graphic element where at fig.5 they don't."

Reply: Thank you very much for carefully checking the manuscript. We define each graphic element at fig.3, fig.4, fig.5 in the same level of information as fig.7.

Figure 3. Surface to Borehole Spectral Ratios at IBRH10: (a) EW2/EW1, (b) NS2/NS1, (c) UD2/UD1. The blue lines stand for the spectra ratio for every earthquake event and the black one stands for the average spectra ratio for all the events.

Figure 4. Surface to Borehole Spectral Ratios at IBRH19: (a) EW2/EW1, (b) NS2/NS1, (c) UD2/UD1.The blue lines stand for the spectra ratio for every earthquake event and the black one stands the average spectra ratio for all the events.

Figure 5. spectral ratios of IBRH10 to IBRH19 for: (a) EW1, (b) EW2, (c) NS1, (d) NS2.The blue lines stand for the spectra ratio for every earthquake event and the black one stands the average spectra ratio for all the events. (To be continued)

Figure 5. Spectral ratios of IBRH10 to IBRH19 for: (e) UD1, (f) UD2. The blue lines stand for the spectra ratio for every for every earthquake event and the black one stands the average spectra ratio for all the events. (Continued)

10. Quotation of the general comment: "What averaging method was used for smoothed spectra?"

Reply: In this study, Parzen window of 0.3Hz bandwidth was used to smooth the spectra.

11. Quotation of the general comment: "Authors must provide a paragraph discussing the performance of their method to similar ones as they refer to them in introduction in order to strength their findings."

Reply: Thank you very much for your suggestion. In this paper, we provided some sentence to discussing the performance of the method to the similar ones.

The ARV method: amplitude ratio of peak ground velocity at the ground surface relative to the engineering bedrock of averaged S-wave velocity 700 m/s based on topographic data. So it is a scalar value site amplification correction method determined by the PGV increment.

Station Correction method: It is also a kind of scalar value method determined by comparing the attenuation relation with observed seismic intensities from recent earthquakes proposed by Iwakiri et al. 2011.

We will reorganized these related sentence to one paragraph in the revised manuscript.

We compared the frequency-dependent correction of site amplification factor with ARV method and Station correction method. The station correction method based on site amplifications obtained empirically from observed seismic intensity data. For the ARV

method and station correction method, the seismic intensity residual within +-0.5 is 55% and 59% respectively. The seismic intensity residual within +-1 is 84% and 93% respectively for ARV method and station correction method. The average 1 degree seismic intensity error of the current operational JMA EEW system (JMA, 2018) is 74.74% for all the eleven years statistical data. The best case is 93.7% in 2017, the worst case is 34.6% in 2010.When we use the causal filter to model the frequency-dependent site amplification factor.69.7% of the seismic intensity residual is less than 0.5. 98.1% of the seismic intensity residual is less than 1.From the analysis and compared with two method and one operational EEW statistical report, we can conclude that this method could highly improve the accuracy of the ground motion estimation.

The method we compared in the manuscript represents two kinds of scalar value site amplification method. We will collect much more material about ground motion estimation accuracy of the operational EEW system in the world except for the Japan EEW system. Then we can compare their performance with this method to strength our findings.

12. Quotation of the general comment: "Authors must provide a paragraph discussing potential pitfalls and drawbacks or their proposal in relation to local conditions and/or network density"

Reply: Thank you very much for your suggestion. We provide a paragraph discussing potential pitfalls and drawbacks or their proposal in relation to local conditions and network density. The paragraph shows as follows:

Through compare different simulation cases, it can be easily find that frequency-dependent correction of site amplification factor could produce different amplification factor for different earthquakes. It could produce the frequency-dependent site

amplification factor. It highly improves the situation that scalar value site amplification methods which could not produce different amplification factor for different earthquakes. It skips the procedure to calculate the EEW magnitude and epicenter distance or hypocenter distance using the start potion of the waveform. We can obtain the waveform real-timely at the target station. It highly improve the accuracy of predicting ground motion real-timely compared with the scalar value site amplification factor. The simulation from borehole to surface is not suitable for earthquake early warning system. But it shows that this method shows good performance for real time simulating waveforms of the target station. Compare the two different simulation cases, it shows that the smaller distance between two stations, the seismic intensity prediction is more accurate. But for earthquake early warning purpose, we need to save much lead time for warning to the public that needs the distance between two stations much larger. It means that the method have relation with network density. We could use the frequency-dependent site implication factor to predict the seismic intensify more accurately in the seismic intensity quick report system with high network density. For earthquake early warning purpose, we need to use large amount of historical ground motion records to model the relative site amplification and search the optional casual filter parameter firstly. In the area with sparse network and low seismicity, we could not get the relative site amplification easily because of little amount of strong motion records. We need to consider other methods to estimate relative site amplification factor. We can adopt the method such as coda normalization method (Philips and Aki, 196), generalized spectrum inversion method (Iwata and Irikura, 1986; Kato et al., 1992). There are the cases that some simulation did not work very well.1.9% of the seismic intensity residuals is larger than 1.One of possible reason is azimuth dependency of site amplification (Cultrea et al.2002). We did not consider azimuth dependency in designing

the frequency-dependent site amplification factor filter. If we design multiple frequency-dependent site amplification factor correction filter regarding the azimuth dependency of site amplification, we would be able to predict the target ground motion more precisely. Another possible reason is the accuracy of the input relative spectrum ratio, this situation may be improved by more precisely characterize the input spectral ratio and complicated filter design. For example, we can use a large number of first and second order filter to model the spectral ratio, but it is more complicated and time consuming for the hardware design when the number of filter grows larger. We need to make trade between the accuracy of the input spectral ratio and the difficulty of the filter design. This method pays attention to the amplitude characteristic and ignore the phase characteristic, there are few research on how to consider the phase in the earthquake early warning system. This situation may be improved the seismic interferometry method (Yamada et al. 2010). Because the site amplification factor was assumed as linear system, so the nonlinearity of weak ground motion and strong ground motion (Noguchi et al .2012) was not taken into consider in this study. More research are needed to solve these problems.

Reference:

Cultrera, G., Rovelli, A., Mele, G., Azzara, R., Caserta, A., and Marra. F.: Azimuth-dependent amplification of weak and strong ground motions within a faultzone (Nocera Umbra, central Italy), Journal of Geophysical Research, 108, B3, DOI: 10.1029/2002JB001929, 2003.

Iwata, T., and Irikura, K.: Separation of source, propagation and site effects from observed S-waves.,Zisin II, 39:579–593, 1986. (In Japanese with English abstract).

Kato, K., Takemura, M., Ikeura, T., Urao, K., Uetake, T: Preliminary analysis for evaluation of local site effects from strong motion spectra by an inversion method,J. Phys. Earth, 40:175–191, 1992.

Kunugi, T., Aoi, S., Nakamura, H., Suzuki, W., Morikawa, N., Fujiwara, H.: An improved approximating filter for real-time calculation of seismic intensity. Zisin (J. Seismol. Soc. Jpn., 2nd ser.) 65:223–230.,Doi:10.4294/zisin.65.223 (in Japanese with English abstract and figure captions), 2013.

Noguchi, S., Sato, H., and Sasatani, T: Characterization of nonlinear site response based on strong motion records at K-NET and KiK-net stations in the east of Japan., Proc. of 15th World Conference on Earthquake Engineering, Lisbon, Portugal, 24–28 September 2012, abstract number 3846.

Phillips, W. S., Aki, K.: Site amplification of coda waves from local earthquakes in central California, Bulletin of the Seismological Society of America, 76:627-648, 1986.

Yamada,M., Mori,J., Ohmi,S.: Temporal changes of subsurface velocities during strong shaking as seen from seismic interferometry, Journal of Geophysical Research 115,B03302, 2010.

II a list of all relevant changes made in the manuscript

1: P1. Changed the title to "Study on Real-time Site Amplification Factor Correction"

2: P1. Rewrite the abstract according the suggestion.

3: P2, P3, P4. Checked and corrected the spelling mistake.

"Hz","September 1, 2000", "May 16, 2004 to December 31, 2012,", "exists", "the".

4: P5. “Parzen window of 0.3Hz bandwidth was used to smooth the spectra"

5:P6. Figure 3. Surface to Borehole Spectral Ratios at IBRH10: (a) EW2/EW1, (b) NS2/NS1, (c) UD2/UD1. The blue lines stand for the spectra ratio for every earthquake event and the black one stands for the average spectra ratio for all the events.

6: P7. Figure 4. Surface to Borehole Spectral Ratios at IBRH19: (a) EW2/EW1, (b) NS2/NS1, (c) UD2/UD1.The blue lines stand for the spectra ratio for every earthquake event and the black one stands the average spectra ratio for all the events.

7: P8. Figure 5. spectral ratios of IBRH10 to IBRH19 for: (a) EW1, (b) EW2, (c) NS1, (d) NS2.The blue lines stand for the spectra ratio for every earthquake event and the black one stands the average spectra ratio for all the events. (To be continued)

8: P9. Figure 5. Spectral ratios of IBRH10 to IBRH19 for: (e) UD1, (f) UD2. The blue lines stand for the spectra ratio for every for every earthquake event and the black one stands the average spectra ratio for all the events. (Continued)

9:P9. In the table, the abbreviation for Amplification is Amp. The abbreviation for Observation is Obs. The abbreviation for Simulation is Sim. The abbreviation for Component is comp. The abbreviation for Residual is Res. The abbreviation for Borehole is Boh. The abbreviation for Surface is Suf.

10:P9, P10, P13, P14.Reformat the table correctly and checked the calculation.

12:P15.Provide a paragraph discussing the performance of their method to similar ones as they refer to them in introduction in order to strength their findings.

13:P20. Provide a paragraph discussing potential pitfalls and drawbacks or their proposal in relation to local conditions and network density.

14:P21. check some misspelling, sections "Code/Data availability", "Author contribution", and "Competing interests" were included according to the manuscript preparation guidelines.

15. P21. Add some related reference article.

III a marked-up manuscript version

Study on Real-time Site Amplification Factor Correction

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Abstract. The site amplification factor was usually considered as scalar values, such as amplification of peak ground acceleration or peak ground velocity, increments of seismic intensity in the earthquake early warning system or seismic intensity repaid report system. This paper focus on evaluation of infinite impulse recursive filter method that could produce frequency-dependent site amplification and compare the performance of the scalar value method with the infinite impulse recursive filter method. A large amount of strong motion data of IBRH10 and IBRH19 of Kiban Kyoshin network (Kik-net) triggered in more than one thousand earthquakes from 2004 to 2012 were selected carefully and used to get the relative site amplification, then we model the relative site amplification factor by casual filter. Then we make simulation from borehole to surface and also simulation from front-detection station to far-field station. Compare different simulation cases, it can easily be found that this method could produce different amplification factor for different earthquakes and could reflect the frequency-dependent of site amplification. Through these simulation between two stations, we can find that the frequency-dependent correction for site amplification show better performance than the ARV method and station correction method. It also shows better performance than the average level and the highest level of Japan Meteorological Agency (JMA) earthquake early warning system in ground motion prediction. This method pays attention to the amplitude and ignore the phase characteristic, this problem may be improved by the seismic interferometry method. Although there are some problems needed to be considered and solved carefully, frequency-dependent correction for site amplification in the time domain highly improve the accuracy of predicting ground motion real-timely.

1 Introduction

In recent decades, real-time strong ground motion prediction has become an important part of earthquake early warning systems. In the world, there are many countries deployed operational earthquake early warning systems like Mexico (Espinosa-Aranda et al. 1995; Espinosa-Aranda et al. 2009), Japan (Kamigaichi et al. 2004; Hoshiba 2008;Nakamura et al. 2009), Taiwan (Wu et al. 2002; Hsiao et al. 2009), Turkey (Erdik et al. 2003; Alcik et al. 2009), and Romania (Wenzel et al. 1999; Ionescu

et al. 2007) Also there are many some earthquake early warning system under developing and testing like the Unites States (Allen et al .2003; Allen et al. 2009; Bose et al. 2009;), Italy (Zollo et al. 2006; Zollo et al. 2009), and China (Peng et al. 2011). Usually, the earthquake early warnings systems can be categorized as offsite (also known as regional EEW) and onsite warnings. The offsite warning utilizes a few seconds of seismogram observed at the first station, and then estimate the source parameter, such as magnitude, epicentre distance or others. Then according to the parameter estimated, a warning can be manually or automatically issued based on some rules made before an earthquake occurs. Hoshiba et al., 2008 mentioned that the Japan earthquake early warning system has been operational nationwide since October, 2007 by Japan Meteorological Agency. Approximately 1,100 stations from JMA network and the high sensitivity seismograph network (Hi-net) were used to determine the hypocenter of Japan Meteorological Agency earthquake early warning system. In order to disseminate the warning quickly, hypocentre estimation should be done just after the first detection of the P phase at a single station. In order to ensure the reliability of the estimation, the B-Delta Method (Odaka et al., 2003) and Network Method (Horiuchi et al., 2005; Horiuchi et al., 2009) are used in combination. Usually, the current Japan Meteorological Agency earthquake early warning system works well. But after the main shock of the 2011 great Tohoku Earthquake, the earthquake early warning system did not work well due to high aftershocks activity and high background noise, as well as power failure and wiring disconnections (Hoshiba, 2011). Earthquakes that occurred nearby simultaneously in different locations also made the system provide false information. The site amplification factor was usually considered as scalar values, such as amplification of peak ground acceleration or peak ground velocity, increments of seismic intensity, in the conventional earthquake early warning system. There are some research papers on how to improve the site amplification factor for considering more accuracy calculating Japan Meteorological Agency seismic intensity of Japan earthquake early warning system (e.g., Iwakiri et al., 2011). Among them we chose the new idea proposed by Hoshiba (2013) and used it to design casual Filter for modelling the site amplification factor of Kik-net stations .We focus on full evaluate the performance of this method by selecting large amount of Kik-net data triggered in more than one thousand earthquakes, then we make simulation from borehole to surface and also simulation from front-detection station to far-field station. Then compare the statistical simulation result with other methods considering the accuracy of the seismic intensity prediction and clarify the advantages and some problem need to be considered when utilizing it to the earthquake early warning system.

2 Data

The hypocentre parameters including origin time, location of hypocentre, and magnitude were obtained from the JMA seismic catalogue. The strong motion data were downloaded from the website (http://www.kyoshin.bosai.go.jp/).The advantage of this network is that all stations have a borehole of 100 m or more in depth, with acceleroagraphs installed both on the ground surface and at the bottom of boreholes. The site information measured in the boreholes includes soil type along with P and S wave velocity profiles. The sampling frequency is 200Hz for the records before November 2007 and is 100Hz thereafter. In this analysis, we use records observed at 2 stations. One of them with site code IBRH10 has been in operation since September

1, 2000 and the other with site code IBRH19 since May 15, 2004, respectively. Until Decmber.31, 2012, IBRH10 and IBRH19 recorded 1119 and 910 events respectively. We selected 673 strong ground motion records which was recorded at the surface and borehole sensor when both of these two stations were triggered by an earthquake. The inner distance between IBRH10 and IBRH19 is 14.6 km. We selected strong motion data with hypocentre distance larger than at least three times of the inner distance. The number of earthquakes is up to 553 and the range of magnitude was between 3.3 and 9. The recording time spans from May 16, 2004 to December 31, 2012. Excluding the earthquake which occurred in the sea area, the number of earthquakes ranging from Magnitude 3.3 to Magnitude 7 adds up to 208 (Figure 1). There exists 20 meter soft sediment at station IBRH10.The layer of appears at the depth of 518m.The IBRH19 is almost a completely rock site station. The site profiles can be downloaded from the Kik-net website.

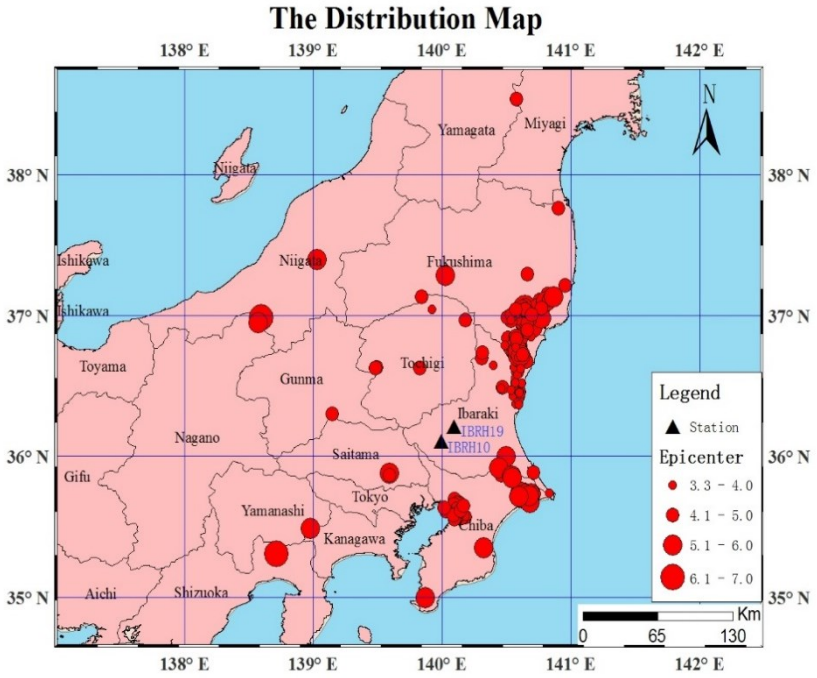


Figure 1. The station and epicentre distribution map used for this research.

3 Theory and Methodology

Source parameters including hypocentre location and magnitude are determined within a few seconds after an earthquake occurrence. Then the ground motions are estimated based on these parameters. While the EEW using a few parameters, parameter uncertainty leads to another error in the ground motion prediction. A new method was proposed by Hoshiba (2013). The method predicts ground motion using ground motions observed at front stations in the direction of incoming waves. The idea of this method were shown in Figure 2. In this method, the observed information is sent directly forward to the target

point. The core idea of this method is that the frequency-dependent site amplification factor can be reproduced by a casual recursive filter based on historical relative spectrum ratio between two stations. In the method the far-field simulated waveform can be obtained by real-time filtering of the observed waveform recorded in the front detection station.

Seismic ground motions are often modelled by convolution of source, propagation and site amplification factors. Site amplification factor plays important role in determine seismic wave amplitude except for propagation effect and source effect. Usually, the site amplification factor was evaluated in frequency domain. However, for earthquake early warning systems it is not suitable as this procedure needs some length windowed waveform for FFT in frequency domain. In many previous studies, site amplification factors are estimated using following equation. (e.g., Iwata and Irikura (1988))

$$O_{kl}(f) = S_k(f)G_l(f)T_{kl}(f) \quad (1)$$

Where f is frequency in Hz, $O_{kl}(f)$, $S_k(f)$, $G_l(f)$, and$T_{kl}(f)$represent the observed seismic spectrum from event *k* at site *l*, the source spectrum characterizing the event *k*, the site amplification factor at site *l*, and the propagation factor between event *k* and site *l* respectively, and *f* is the frequency of the seismic waves.

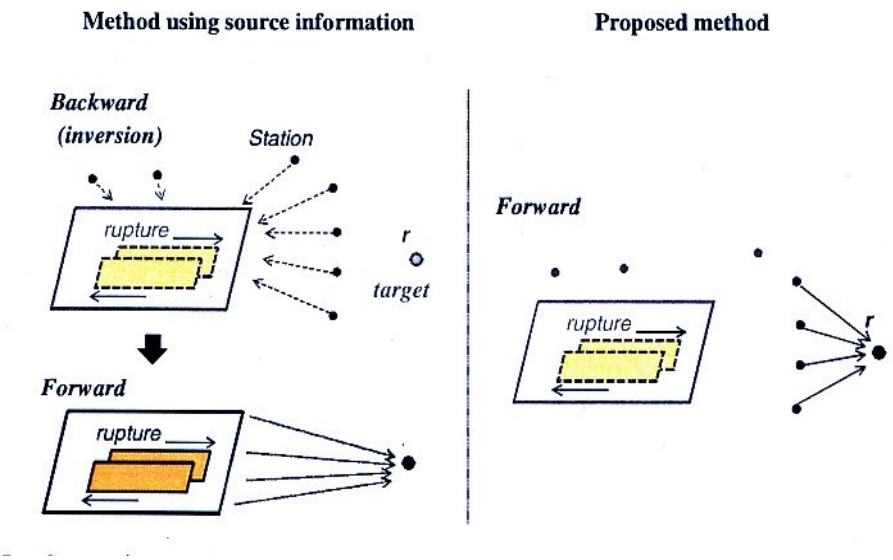


Figure 2. Comparison of the method proposed by Hoshiba with the network method. (Modified after Hoshiba, 2013)

The frequency-dependent relative site amplification factors are assumed to be modelled by a following linear system of first- and second –order filters,

$$\mathrm{F(s)} = G_0 \prod_{n=1}^{N} \left(\frac{\omega_{2n}}{\omega_{1n}}\right) \cdot \frac{s+\omega_{1n}}{s+\omega_{2n}} \cdot \prod_{m=1}^{M} \left(\frac{\omega_{2m}}{\omega_{1m}}\right)^2 \cdot \frac{s^2+2h_{1m}\omega_{1m}+\omega_{1m}^2}{s^2+2h_{1m}\omega_{1m}+\omega_{2m}^2} \quad (2)$$

where N and M stand for the numbers of the first and second-order filters, respectively, and $s = i\omega$. Here ω are angular frequencies and h are damping factors that characterize the frequency dependence, respectively.$s^2 + 2h\omega + \omega_m^2$ represents a damping oscillation (Hoshiba, 2013).G_0,ω_{1n}, ω_{2n} , ω_{1m} , ω_{2m} are estimated for given values of N and M by using the least-squares method in logarithmic scales. We focus on the amplitude characteristics, ignoring phase characteristics. The bilinear transform (also known as Tustin's method) is introduced as

$$s = \frac{2}{\Delta T} \cdot \frac{1-Z^{-1}}{1+Z^{-1}} \quad (3)$$

Which is used in digital signal processing and discrete-time control theory to transform continuous-time system representations to discrete-time. Then the pre-warping equation

$$\omega \rightarrow \frac{2}{\Delta T} \tan\left(\frac{\omega \Delta T}{2}\right) \quad (4)$$

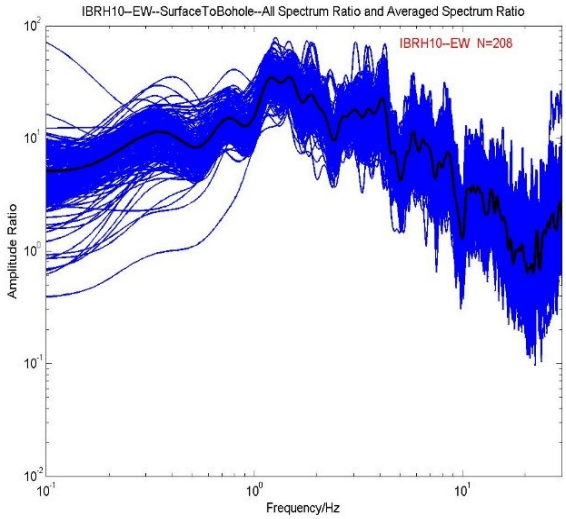
is applied to ω_{1n}, ω_{2n} , ω_{1m} , ω_{2m} , Then the transfer function$F(z)$ is obtained, whereΔT is the sampling interval of the digital waveforms and $z = \exp(s\Delta T)$. Eq. (3) and Eq. (4) are the necessary procedures to obtain the coefficients of a causal recursive filter for real time processing.

4 Result analysis

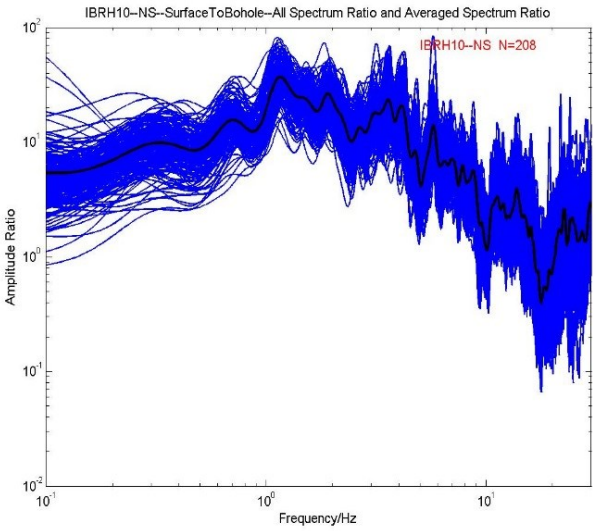
4.1 Spectral Ratios

We use the strong motion data recorded by IBRH10 and IBRH19 during these 208 earthquakes. The spectral ratio results obtained are shown in Figure 3(a) to Figure 6(f). Parzen window of 0.3Hz bandwidth was used to smooth the spectra. The spectral ratios of EW component and NS component of IBRH10 have similar tendencies. It is approximately 30 at around 1.3~1.5Hz; whereas it is less than 2 at around 20HZ (Figure 3(a) and (b)).The spectral ratio of UD component of IBRH10 is approximately 10 at around 2~3Hz whereas it is less than 2 at around 25HZ (Figure 3(c)).The Spectral ratios of EW component and NS component of IBRH19 also have similar tendencies. It is approximately 6 at around 5Hz and 4 at 13Hz, respectively, whereas it is less than 2 at less than 2 Hz (Figure 4(a) and (b)). The spectral ratio of UD component of IBRH19 is approximately 5 at 5Hz and 4 at 25Hz, respectively, whereas it is less than 2 at around 3HZ (Figure 4(c)). The spectral ratio of the borehole component of IBRH10 to IBRH19 is almost flat, as this ratio is calculated from bedrock to bedrock. The maximum site amplification is 2.5 at about 20Hz, and the spectral ratio is nearly 1 at the rest of the frequency (Figure 5(a), (c) and (e)). The spectral ratios of the EW component and NS component of IBRH10 surface to IBRH19 surface are approximately 20 at 1Hz to 2Hz, whereas it is less than 1 from 17Hz to 30 Hz (Figure 5(b) and (d)). The spectral ratio of the UD component of IBRH10 surface to IBRH19 surface is approximately 10 at 1.5Hz, whereas it is less than 1 from 22Hz to30 Hz (Figure 5(f)).

(a)



(b)



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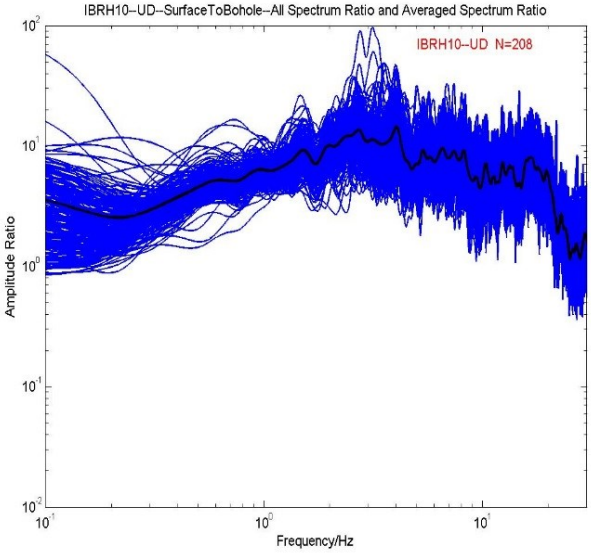
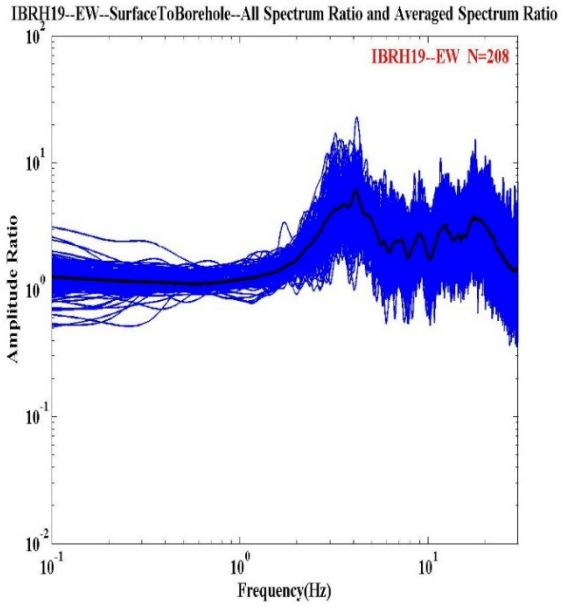


Figure 3. Surface to Borehole Spectral Ratios at IBRH10: (a) EW2/EW1, (b) NS2/NS1, (c) UD2/UD1. The blue lines stand for the spectra ratio for every earthquake event and the black one stands for the average spectra ratio for all the events.

(a)



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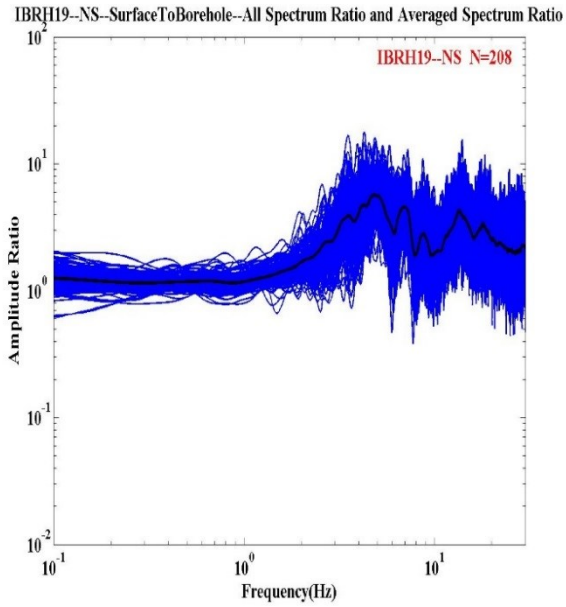

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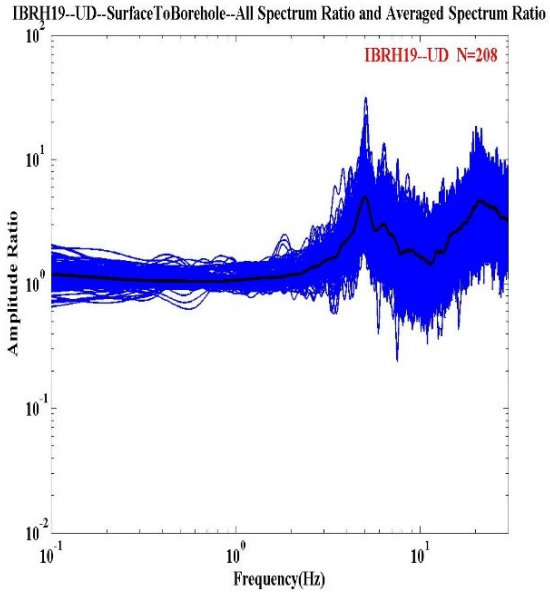
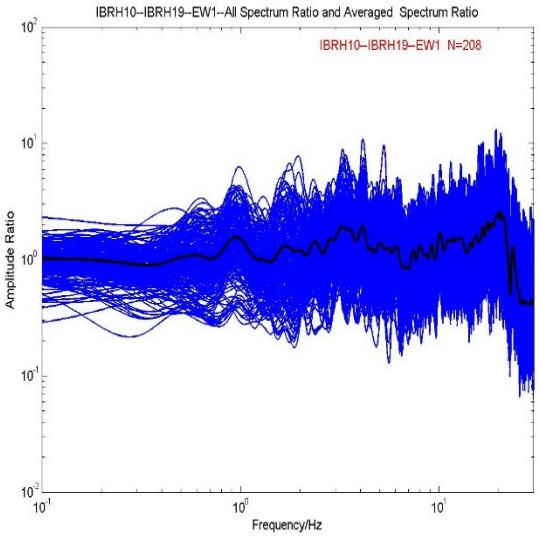


Figure 4. Surface to Borehole Spectral Ratios at IBRH19: (a) EW2/EW1, (b) NS2/NS1, (c) UD2/UD1.The blue lines stand for the spectra ratio for every earthquake event and the black one stands the average spectra ratio for all the events.

(a)



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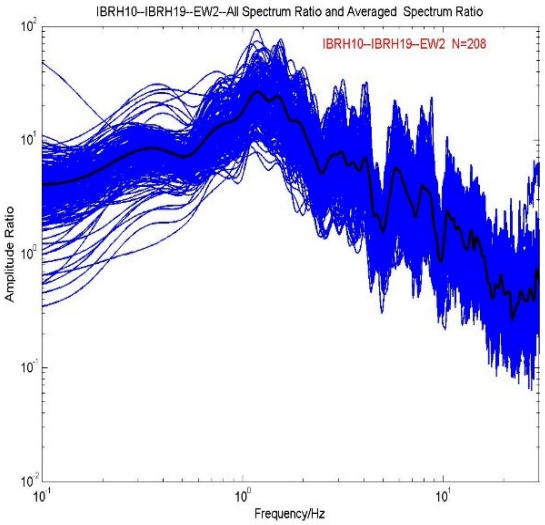

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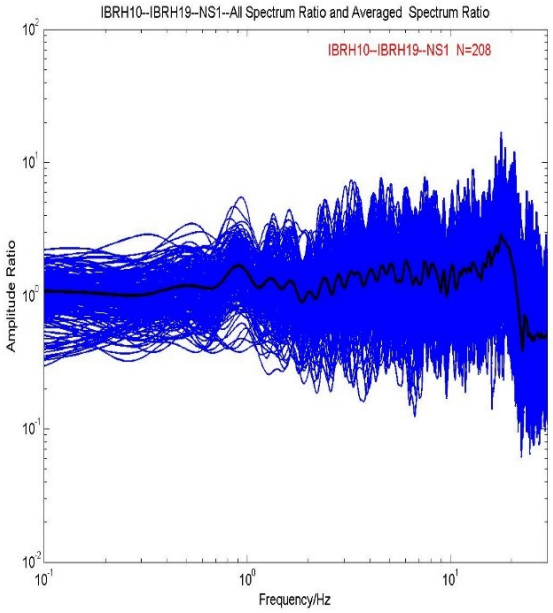
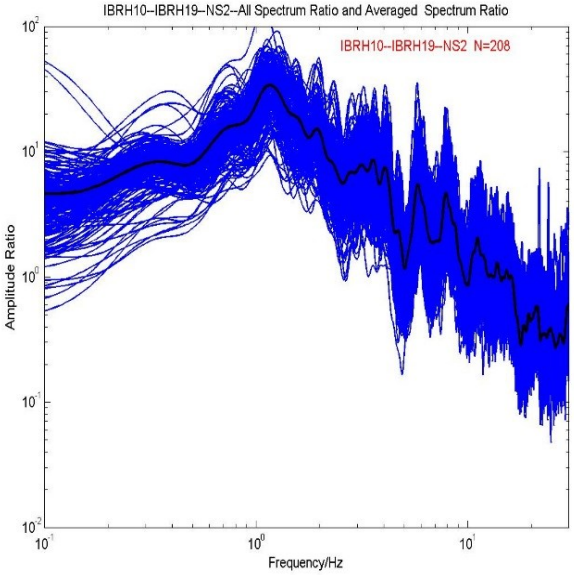
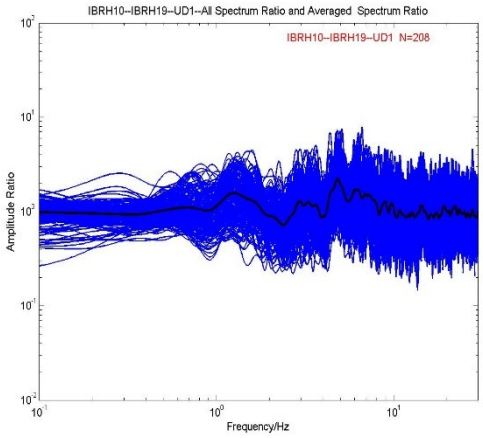


(d)

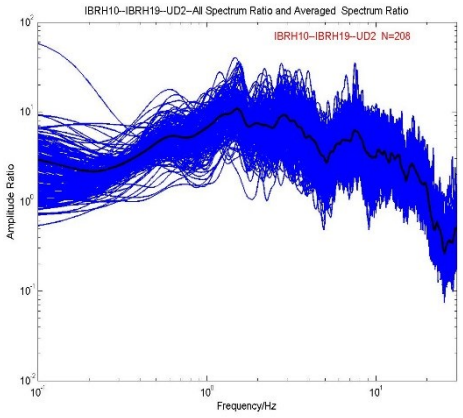


Figture 5. spectral ratios of IBRH10 to IBRH19 for: (a) EW1, (b) EW2, (c) NS1, (d) NS2.The blue lines stan for the spectra ratio for every earthquake event and the black one stands the average spectra ratio for all th events. (to be continued)

(e)



(f)



Figture 5. spectral ratios of IBRH10 to IBRH19 for: (e) UD1, (f) UD2. The blue lines stand for the spectra ratio for every for every earthquake event and the black one stands the average spectra ratio for all the events (Continued)

4.2 Simulation from borehole to surface

Firstly, we make the simulation from borehole to surface, although it is not useful for earthquake early warning system. But it could be used to make full evaluation of this method. We use the strong motion data recorded by IBR10 borehole sensor to simulate the surface station acceleration waveforms and spectrum. Figure 6(a) to Figure 6(d) shows the simulation results for the M4.5 earthquake which occurred on November 21, 2009. The information about the site amplification factors and the increment of seismic intensity are summarized in in Table1.In the table, the abbreviation for Amplification is Amp. The abbreviation for Observation is Obs. The abbreviation for Simulation is Sim. The abbreviation for Component is comp. The abbreviation for Residual is Res. The abbreviation for Borehole is Boh. The abbreviation for Surface is Suf.

Table 1 Information for M4.5 earthquake (IBRH100911211539)

	PGA (gal)			PGA Amp.		I_{jma}					
	Boh.	Suf.		Amp. (Suf./Boh.)		Bore.	Surf.		Difference (Suf.-Boh.)		Res. (Sim.-obs.)
Comp.	Obs.	Obs.	Sim.	Obs.	Sim.	Obs.	Obs.	Sim.	Obs	Sim.	
NS	1.9	13.2	16.8	6.9	8.8						
EW	1.4	7.5	12.1	5.4	8.6	1.1	3.1	3.3	2.0	2.2	0.2
UD	0.7	4.1	5.6	5.9	8.3						

Figure 7(a) to Figure 7(d) show the simulation results for the M4.6 earthquake which occurred on December 7, 2012. The information about the site amplification factors and the increment of seismic intensity are summarized in Table 2.

Table 2 Information for M4.6 earthquake (IBRH101212070532)

	PGA (gal)			PGA Amp.		I_{jma}					
	Boh.	Suf.		Amp. (Suf./Boh.)		Boh.	Surf.		Difference (Suf.-Boh.)		Res. (Sim.-obs.)
Comp.	Obs.	Obs.	Sim.	Obs.	Sim.	Obs.	Obs.	Sim.	Obs	Sim.	
NS	0.7	2.7	3.6	3.9	5.1						
EW	0.6	3.3	4.0	5.5	6.7	0.0	1.2	1.3	1.2	1.3	0.1
UD	0.4	2.9	2.4	7.3	6						

For these two examples, compared the simulated acceleration and spectrum with the observed acceleration and spectrum of the surface records, the result simulated well. The different amplifications of maximum acceleration between Table 1 and Table 2 reflect the differences of the frequency contents of the incident waveforms that cannot be reproduced by a scalar site amplification factor (e.g., amplification of peak ground acceleration or peak ground velocity, or increment of seismic intensity).

The seismic intensity is calculated according to the method described in the paper (Yamazaki et al. 1998). Figure 8 shows the seismic intensity residuals. The average seismic intensity residuals of these 208 earthquakes is 0.139. The standard deviation of the difference is 0.254. 98.6% of the seismic intensity residuals is less than 0.5. 100% of the seismic intensity residuals is less than 1. As the minimum resolution for the seismic calculation is 0.1 degree, It is reasonable that we consider these simulations show good performance.

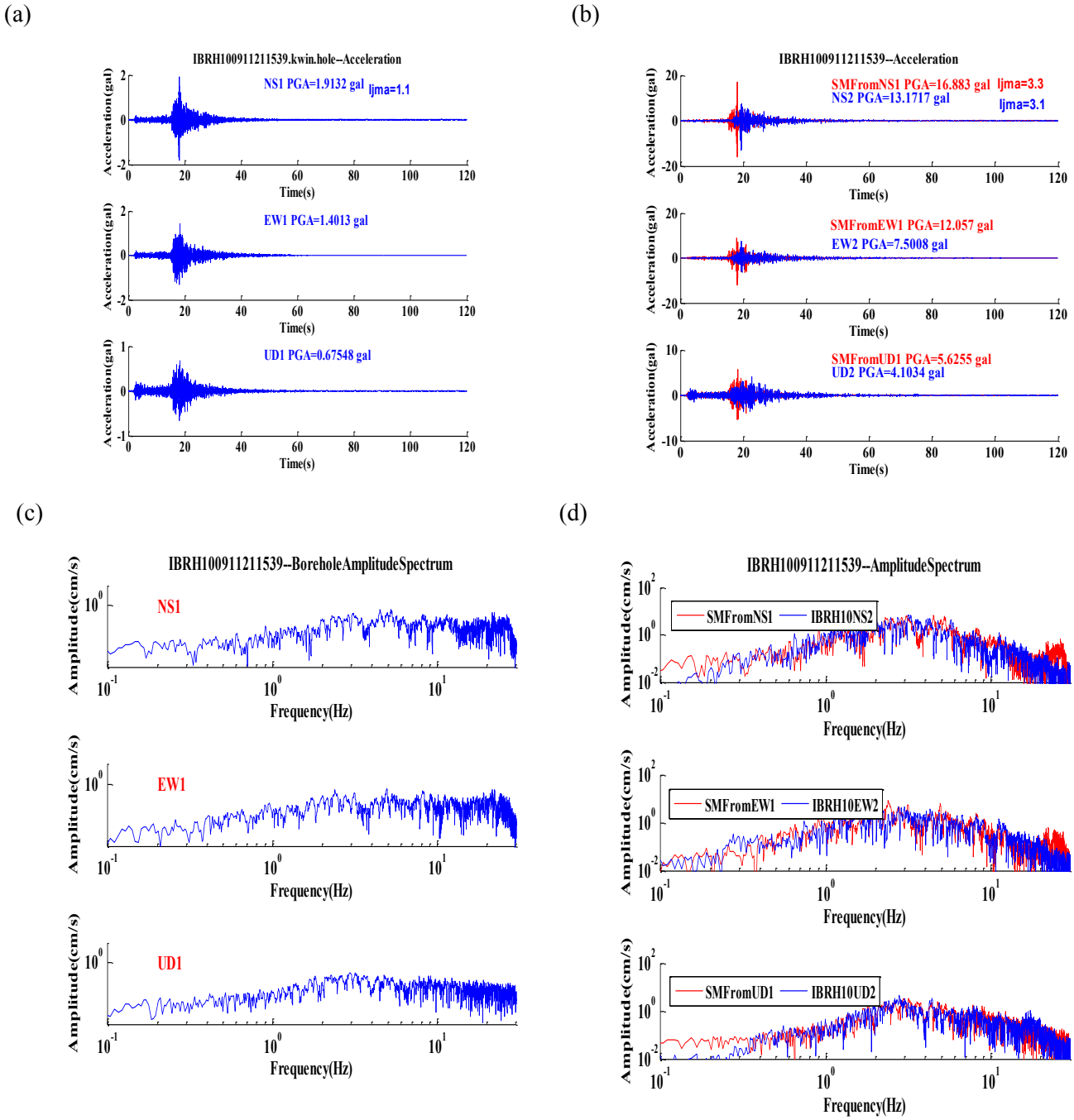


Figure 6. An example of the results of simulation for IBRH100911211539: (a) the observed accerlation at the borehole, (b) the observed surface acceleration waveform (blue) compared with the simulated one (red), (c) the spectra of the observed surface record, (d) the spectra of the observed surface record (blue) compared with the simulated one (red).

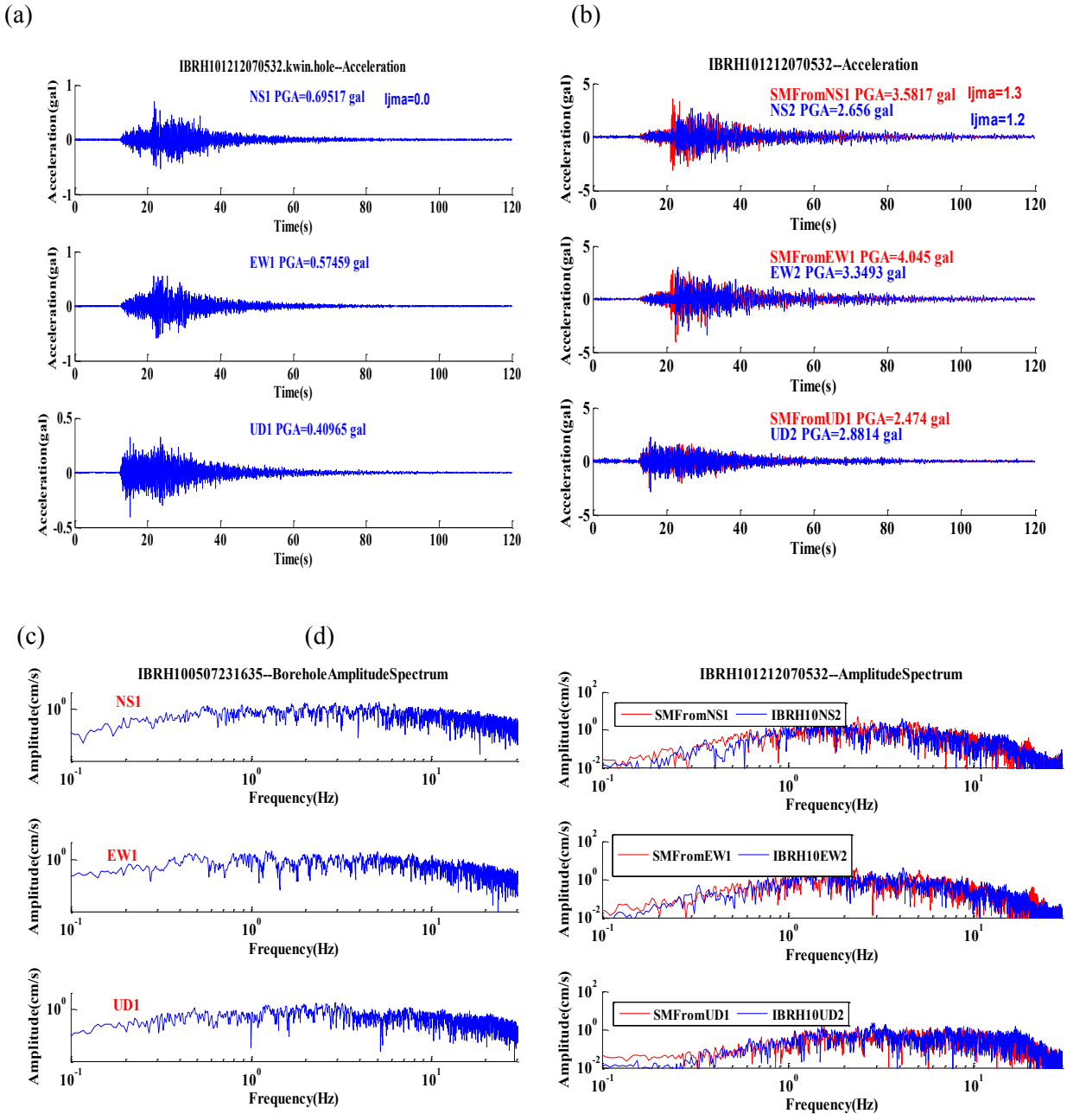


Figure 7. An example of the results of simulation for IBRH101212070532: (a) the observed accerlation at the borehole, (b) the observed surface acceleration waveform (blue) compared with the simulated one (red), (c) the spectra of the observed surface record, (d) the spectra of the observed surface record (blue) compared with the simulated one (red).

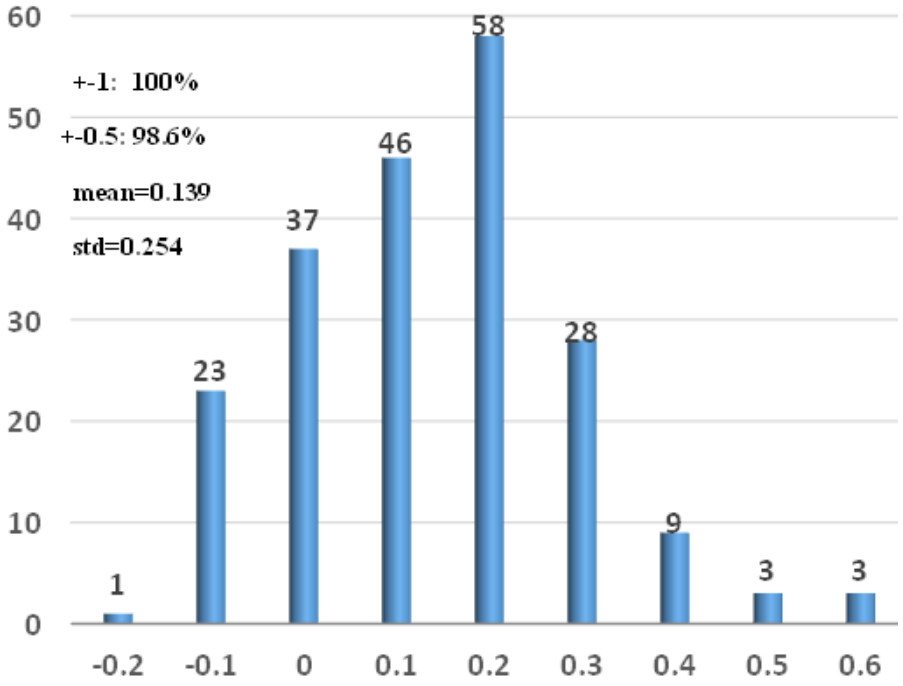


Figure 8. The seismic intensity residuals between observed data and simulated data.

4.3 Simulation Between Front-detection Station and Far-flied Station

Then, Using the surface strong motion data of IBRH19,we get simulated waveforms for IBRH10. Figure 9(a) through Figure 9(d) show the simulation results for the M5.2 earthquake which occurred on Feb. 19, 2012. The information about site amplification factors and the increment of seismic intensity are summarized in Table 3.

Table 3 Information for M5.2 earthquake (IBRH10 & IBRH19 for 201202191454)

	PGA(gal)			PGA Amp.		I_{jma}			
	IBRH19	IBRH10		Amp. (IBRH10/IBRH19)		IBRH19	IBRH10		Res. (Obs.-Sim.)
Comp.	Obs.	Obs.	Sim.	Obs.	Sim.	Obs.	Obs.	Sim.	
NS	17.7	50.9	69.7	2.8	3.9	2.2	3.5	3.7	0.2
EW	13.6	45.7	53.2	3.3	3.9				
UD	11.2	23.7	38.9	2.1	3.5				

The simulation results for the M5.1 earthquake occurred on April 14,2011 is shown in Figure 10(a) to Figure 10(d) . The comparison information about the site amplification factors and the increment of seismic intensity are summarized in Table 4.

Table 4 Information for M5.1 earthquake (IBRH10 & IBRH19 for 201104140735)

	PGA(gal)			PGA Amp.		I_{jma}			
	IBRH19	IBRH10		Amp. (IBRH10/IBRH19)		IBRH19	IBRH10		Res. (Obs.-Sim.)
Comp.	Obs.	Obs.	Sim.	Obs.	Sim.	Obs.	Obs.	Sim.	
NS	7.1	25.4	16.7	3.6	2.4	1.3	2.7	2.7	0
EW	7.1	18.1	17.6	2.5	2.5				
UD	4.3	14.6	16.7	3.4	3.9				

Compared the observed the surface record acceleration and spectrum with the simulated acceleration and spectrum, it shows that the simulation result is well. The acceleration amplification factor for the he M5.2 earthquake which occurred on Feb. 19, 2012 is 3.9,3.9,3.5 respectively, while the acceleration amplification factor for the he M5.1 earthquake which occurred on April 14,2011is 2.4,2.5,3.9 respectively. Comparing the simulation results for these two earthquakes, the different amplifications of acceleration between Table 3 and Table 4 shows the different frequent contents of the waveforms that cannot be reproduced by a scalar site amplification method.

Although most of the simulation result shows good performance, there exists the case that the simulation did not work well. For example, Figure 11(a) to Figure 11(d) shows the simulation results for the M5.3 earthquake occurred on March 16, 2011. The information about the site amplification factors and the increment of seismic intensity are summarized in Table 5.Compared the observed acceleration and spectra with simulated acceleration and spectra, it indicates that the simulation did not work well for the M5.3 earthquake occurred on March 16, 2011.

Table 5 Information for M5.3 earthquake (IBRH10 & IBRH19 for 201103162239)

	PGA(gal)			PGA Amp.		I_{jma}			
	IBRH19	IBRH10		Amp. (IBRH10/IBRH19)		IBRH19	IBRH10		Res. (Obs.-Sim.)
Comp.	Obs.	Obs.	Sim.	Obs.	Sim.	Obs.	Obs.	Sim.	
NS	6.1	10.7	34.9	1.8	5.7	1.5	2.7	3.8	1.1
EW	5.0	12.6	36.1	2.5	7.2				
UD	3.9	6.2	22.2	1.6	5.7				

The seismic intensity is calculated according to the method described in the paper(Yamazaki et al. 1998). Figure 12 shows the seismic intensity residual. The average seismic intensity residual is 0.35 for all our data set. The standard deviation of seismic intensity residual is 0.36. 69.7% of the seismic intensity residual is less than 0.5. 98.1% of the seismic intensity residual is less than 1. Japan Meteorological Agency used ARV method (amplitude ratio of peak ground velocity at the ground surface relative to the engineering bedrock of averaged S-wave velocity 700 m/s) based on topographic data. Iwakiri et al. 2011 proposed the station correction method. The station correction method based on site amplifications obtained empirically from observed seismic intensity data.

We compared the performance of this method with the ARV method and station correction method. For the ARV method and station correction method, The seismic intensity residual within +-0.5 is 55% and 59%, respectively. The seismic intensity residual within +-1 is 84% and 93% respectively for ARV method and station correction method. The comparison result between different methods are shown in Table 6. The statistical 1 degree seismic intensity error of the current JMA EEW system (JMA,2018) was shown in figure 13. The average 1 degree seismic intensity error is 74.74% for all the eleven years data. The best case is 93.7% in 2017,the worst case is 34.6% in 2010.From the analysis mentioned above, we can conclude that this method could improve the accuracy of the seismic intensity estimation. It highly improve the accuracy of predicting ground motion real-timely. It could be used to the earthquake early warning system.

Table 6. The comparison result

Method	mean residual	standard deviation	+-0.5	+-1.0
ARV(Iwakiri et al. 2011),	0.25	0.63	55%	84%
Station Correction (Iwakiri et al. 2011),	0.19	0.55	59%	93%
This paper	0.35	0.36	69.7%	98.1%

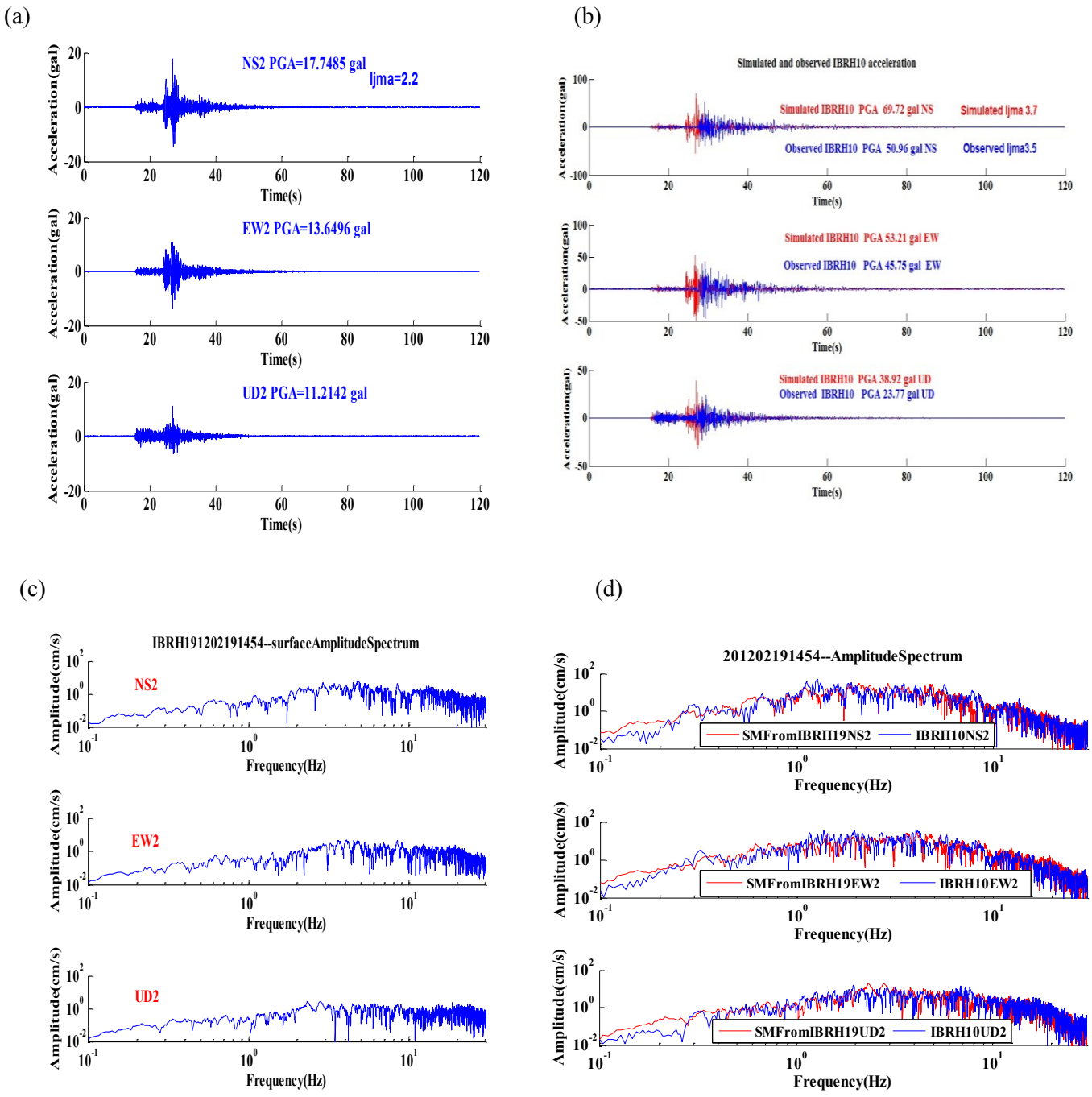


Figure 9. An example of simulation from IBRH19 (surface) to IBRH10 (surface) for the earthquake 201202191454: (a)the observed surface acceleration forIBRH19, (b) the observed surface acceleration waveform (blue) compared with the simulated one (red), (c) the spectral of observed surface record for IBRH19, (d)the observed spectra of surface record at IBRH10 (blue) compared with the simulated one (red)

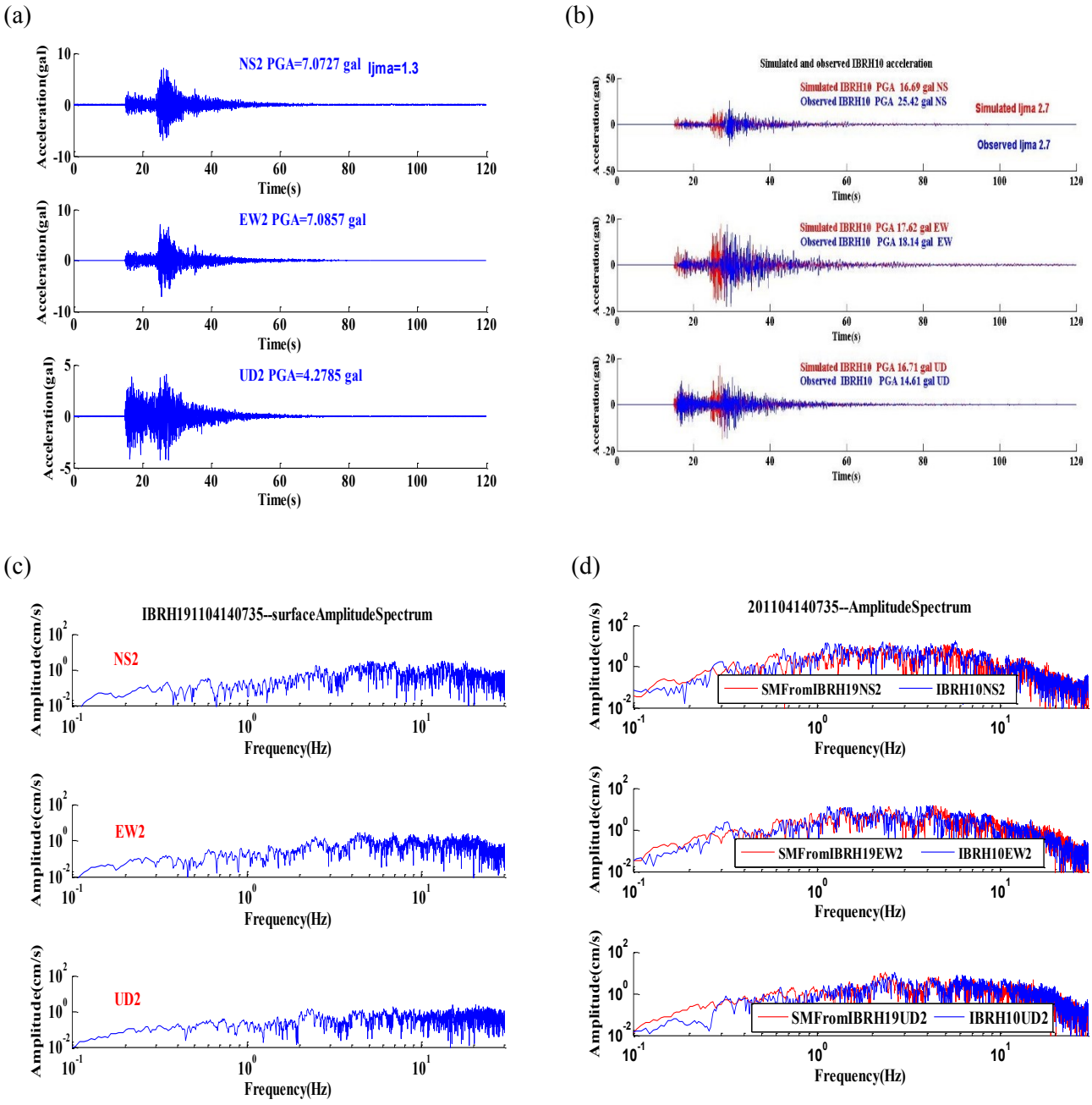


Figure 10. An example of simulation from IBRH19 (surface) to IBRH10 (surface) for the earthquake 201104140735: (a) the observed surface acceleration forIBRH19, (b) the observed surface acceleration waveform (blue) compared with the simulated one (red), (c) the spectral of observed surface record for IBRH19, (d) the observed spectra of surface record at IBRH10 (blue) compared with the simulated one (red)

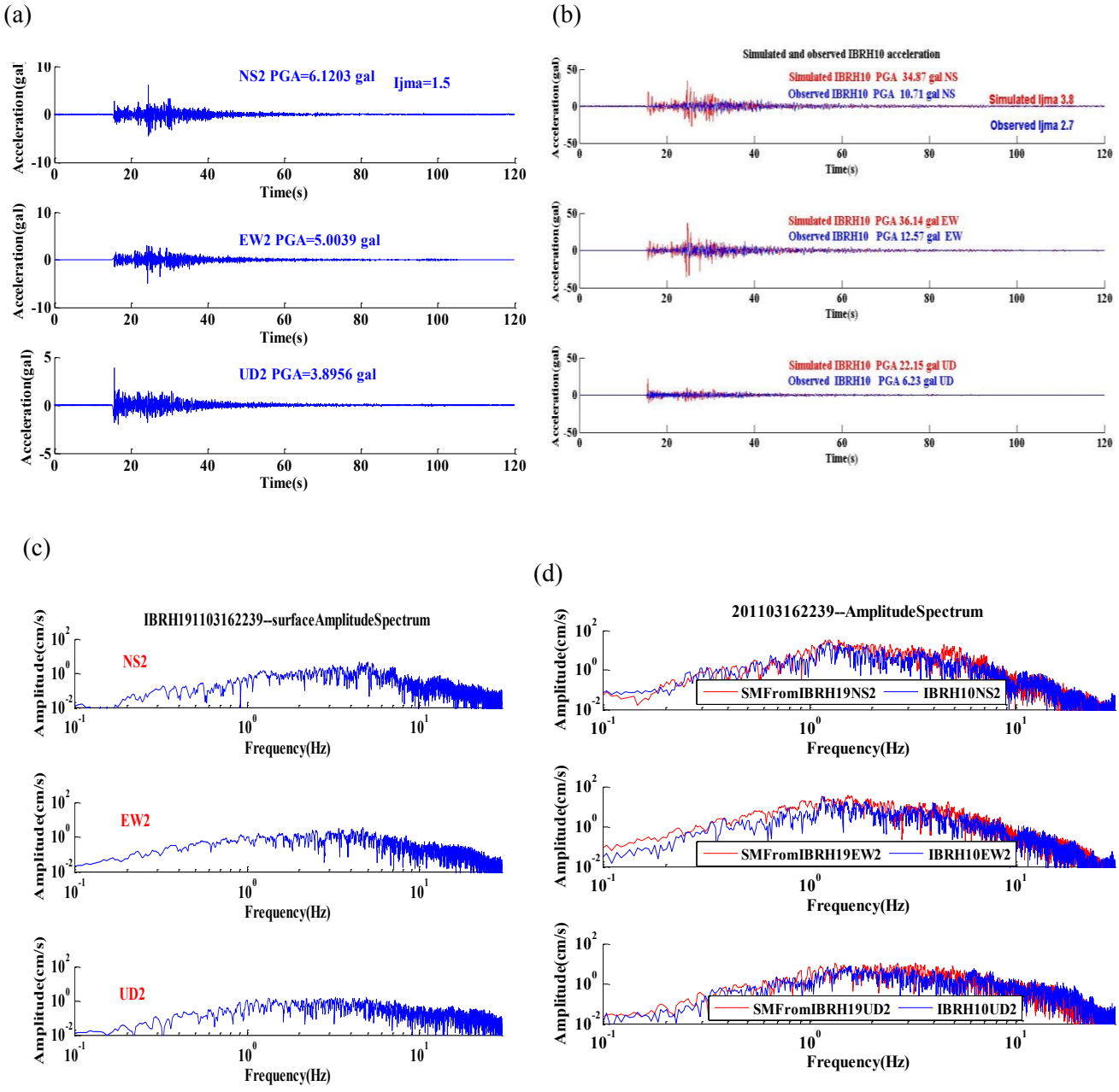


Figure 11. An example of simulation from IBRH19 (surface) to IBRH10 (surface) for the earthquake 201103162239: (a) the observed surface acceleration for IBRH19, (b) the observed surface acceleration waveform (blue) compared with the simulated one (red), (c) the spectral of observed surface record for IBRH19, (d) the observed spectra of surface record at IBRH10 (blue) compared with the simulated one (red)

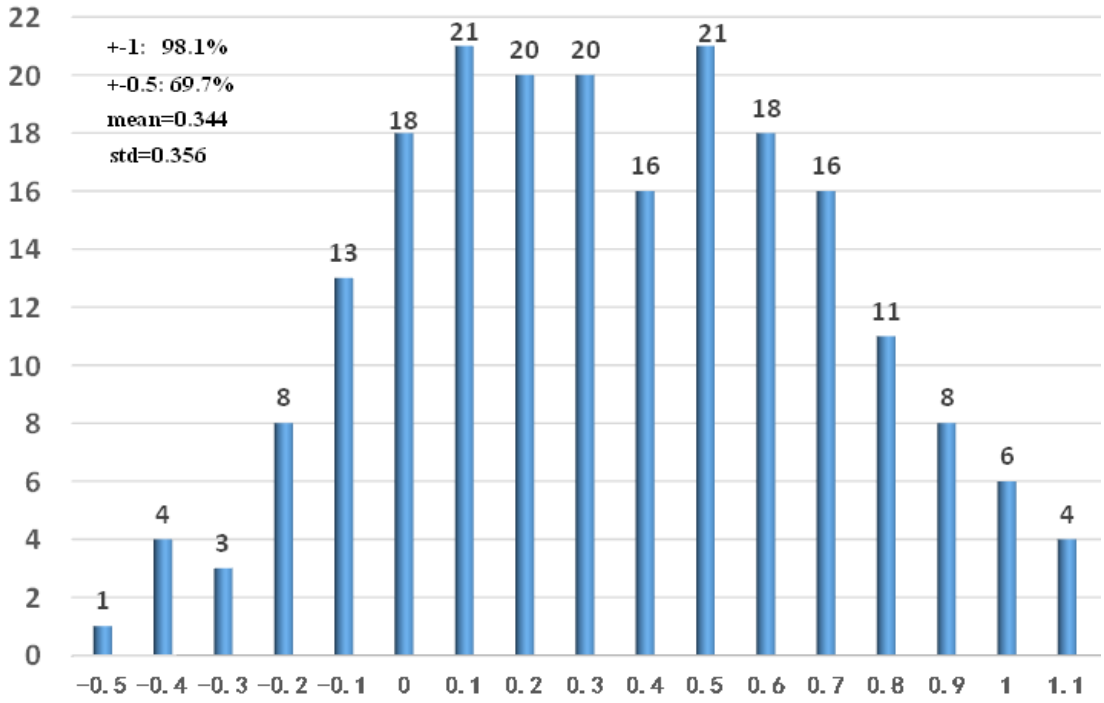


Figure 12. The seismic intensity residuals between the observed data and simulated data.

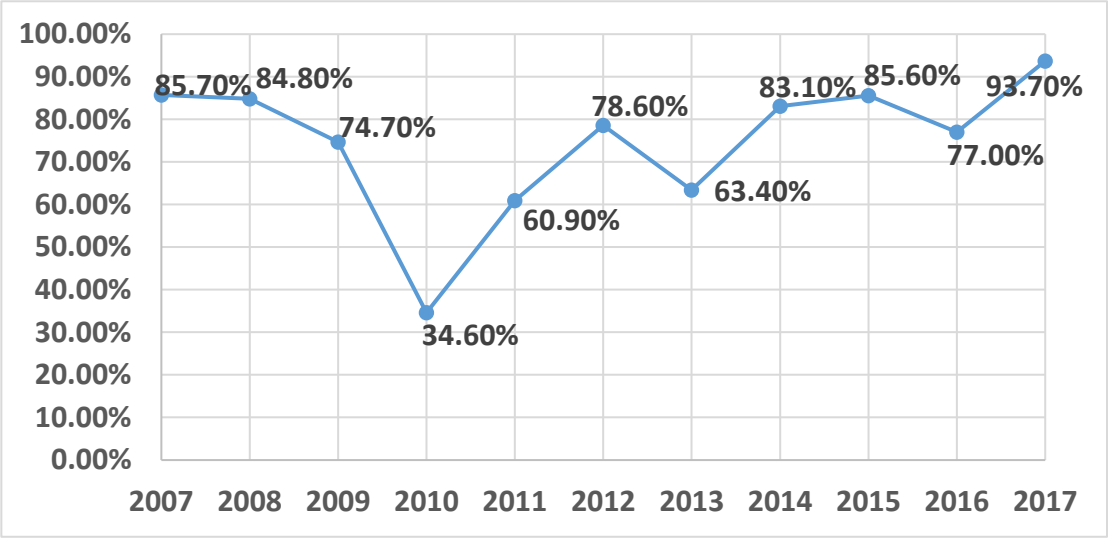


Figure 13. The percent ratio diagram for 1 degree seismic intensity error in the current Japan EEW System

5 Discussion

Through compare different simulation cases, it can be easily find that frequency-dependent correction of site amplification factor could produce different amplification factor for different earthquakes. It could produce the frequency-dependent site amplification factor. It highly improves the situation that scalar value site amplification methods which could not produce different amplification factor for different earthquakes. It skips the procedure to calculate the EEW magnitude and epicenter distance or hypocenter distance using the start potion of the waveform. We can obtain the waveform real-timely at the target station. It highly improve the accuracy of predicting ground motion real-timely compared with the scalar value site amplification factor. The simulation from borehole to surface is not suitable for earthquake early warning system. But it shows that this method shows good performance for real time simulating waveforms of the target station. Compare the two different simulation cases, it shows that the smaller distance between two stations, the seismic intensity prediction is more accurate. But for earthquake early warning purpose, we need to save much lead time for warning to the public that needs the distance between two stations much larger. It means that the method have relation with network density. We could use the frequency-dependent site implication factor to predict the seismic intensify more accurately in the seismic intensity quick report system with high network density. For earthquake early warning purpose, we need to use large amount of historical ground motion records to model the relative site amplification and search the optional casual filter parameter firstly. In the area with sparse network and low seismicity, we could not get the relative site amplification easily because of little amount of strong motion records. We need to consider other methods to estimate relative site amplification factor. We can adopt the method such as coda normalization method(Philips and Aki,196),generalized spectrum inversion method(Iwata and Irikura,1986;Kato et al.,1992) There are the cases that some simulation did not work very well.1.9% of the seismic intensity residuals is larger than 1.One of possible reason is azimuth dependency of site amplification(Cultrea et al.2002). We did not consider azimuth dependency in designing the frequency-dependent site amplification factor filter. If we design multiple frequency-dependent site amplification factor correction filter regarding the azimuth dependency of site amplification, we could be able to predict the target ground motion more precisely. Another possible reason is the accuracy of the input relative spectrum ratio, This situation may be improved by more precisely characterize the input spectral ratio and complicated filter design. For example, we can use a large number of first and second order filter to model the spectral ratio, but it is more complicated and time consuming for the hardware design when the number of filter grows larger. We need to make trade between the accuracy of the input spectral ratio and the difficulty of the filter design. This method pays attention to the amplitude characteristic and ignore the phase characteristic, there are few research on how to consider the phase in the earthquake early warning system. This situation may be improved the seismic interferometry method (Yamada et al. 2010). Because the site amplification factor was assumed as linear system, so the nonlinearity of weak ground motion and strong ground motion(Noguchi et al .2012) was not taken into consider in this study. More research are needed to solve these problems.

6 Conclusion

In this paper, we make full evaluation of the method that model the relative site amplification factor by historical strong ground motion data and then implementing the relative site amplification factor by the casual filter. First, we calculated the spectrum ratio for IBRH10 and IBRH19, then we got the surface simulated acceleration time series and spectrum for IBRH10 from borehole records at IBRH10. Similarly, we got the IBRH10 simulated surface acceleration time series and spectrum from the surface strong ground motion records of IBRH19.At last, we calculated the seismic intensity residual between the observed data and simulated data, and then compared the accuracy with the previous method and statistical report. This method highly improve the accuracy of predicting ground motion real-timely. The result shows as following:

(1) The spectra ratio is calculated between borehole record and surface record from the same station. Then we use infinite impulse recursive filter method to model our relative spectra ratio. The average seismic intensity residual of these earthquakes is 0.139. The standard deviation of these seismic intensity residuals is 0.254. 98.6% of these seismic intensity residuals is less than 0.5. 100% of these seismic intensity residuals is less than 1.

(2) The spectra ratio is calculated between IBRH10 and IBRH19 surface records. Similarly, we use infinite impulse recursive filter method to model the relative spectra ratio between two stations. The average seismic intensity residual of these earthquakes is 0.35. The standard deviation of these seismic intensity residuals is 0.36. 69.7% of these seismic intensity residuals is less than 0.5. 98.1% of these seismic intensity residuals is less than 1.This method shows better performance than the ARV method and station correction method. The average 1 degree seismic intensity error of all the eleven years statistical data of the current Japan Meteorological Agency earthquake early warning system is 74.74%. This method also shows better performance than the current operational Japan Meteorological Agency earthquake early warning system. This method highly improve the accuracy of predicting ground motion real-timely.

Data availability.

The hypocenter parameters including origin time, location of hypocenter, and magnitude used in this study, which were routinely determined by JMA, were obtained from the JMA seismic catalog. The KiK-net strong motion data can be downloaded from NIED website (http://www.kyoshin.bosai.go.jp/).Thanks to JMA and NIED for their hard work.

Author contributions.

XQ completed the core work and wrote the text content, QM and JZ were the technical director in chief, and HY supervised the strong motion data processing and related analysis. All authors discussed the editors' opinions and revised the paper.

Competing interests.

The authors declare that they have no conflict of interest.

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