Paper:

Real-Time Ground Motion Forecasting Using Front-Site Waveform Data Based on Artificial Neural Network

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Real-time earthquake information made available by the Japan Meteorological Agency (JMA) publicly since October 2007 is intended to dramatically reduce human casualties and property damage following earthquakes. Its current limitations, however, such as a lack of applicability to near-source earthquakes and the insufficient accuracy of seismic ground motion intensity leave much to be desired. The authors have suggested that the forward use of front-site waveform data leads to improve accuracy of real-time ground motion prediction. This paper presents an advanced methodology based on artificial neural networks (ANN) for the forward forecasting of ground motion parameters, not only peak ground acceleration and velocity but also spectral information before S wave arrival using the initial P waveform at a front site. Estimated earthquake ground motion information can be used as a warning to lessen human casualties and property damage. Fourier amplitude spectra estimated highly accurately before strong shaking can be used for advanced engineering applications, e.g., feed-forward structural control. The validity and applicability of the proposed method have been verified using Kyoshin Network (K-NET) observation datasets for 39 earthquakes occurring in the Miyagi Oki area.

Keywords: earthquake early warning system, real-time ground motion forecasting, front-site waveform, artificial neural network

1. Introduction

Earthquake early warning systems (EEWS) enable to issue warning alarm before severe shaking starts, thereby reducing human casualties and property damage. EEWS developments depend partly on advances in information and earthquake observation technology. EEWS would be efficiently worked at a site with epicentral distance lager than 35 km and also with certain distance from the earthquake observation point where earthquake motion is firstly observed. Sendai, Japan, having a population of 1 million, is an ideal candidate for EEWS application in the anticipated Miyagi-ken Oki earthquake of which occurrence probability is very high, namely 70% in next 10 years and more than 90% in 20 years.

The Japan Meteorological Agency (JMA) began providing real-time earthquake information in October 2007. The information includes earthquake occurrence time, location of hypocenter, and magnitude, and is therefore expected to utilize for reduction of human casualties and property damage. Kanamori classified EEWS into on-site and regional warnings [1], but JMA EEWS would be called as a national warning due to use of nationwide earthquake observation, i.e., by the JMA and National Research Institute for Earth Science and Disaster Prevention (NIED) [2].

One technical restriction on the national warning is a lack of applicability to near-source earthquakes. An on-site warning [3] should be effective in near-source earthquakes. The regional system comprising 6 observation points on a circle with a radius of 30 km around a nuclear power plant in Lithuania developed to provide an earthquake warning lead time of 4-8 sec [4]. These systems use a threshold, rather than direct source information, for issuing alarms. Technical development to combine on-site and national warnings (real-time earthquake information from the JMA) has been performed in some places.

Real-time earthquake information provided by the JMA [5] is based on point source information, limiting the accuracy of predicted ground motion, especially in large earthquakes under only the backward use of earthquake observation data. In higher engineering applications, ground motion prediction is requested not only for determining seismic intensity, peak ground acceleration (PGA) and peak ground velocity (PGV), but also for more precise information such as spectral information. And further more waveform information is expected to be predicted. The authors have suggested the forward use of front-site waveform data to improve accuracy of real-time ground motion prediction (refer to **Fig. 1**).

The regional earthquake early warning system (REEWS) [6] we developed is compatible with Japan's national earthquake early warning system (NEEWS),

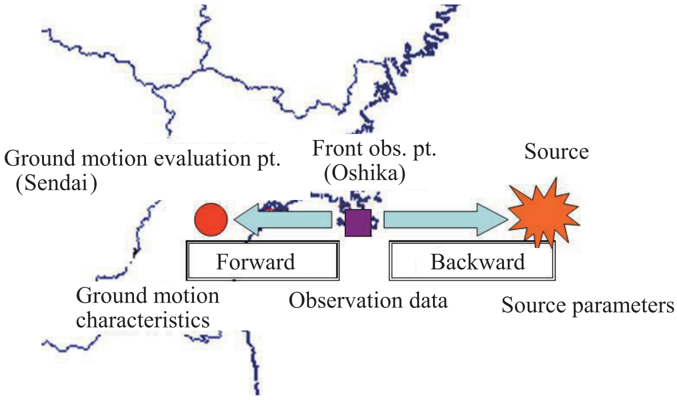


Fig. 1. Forward use of earthquake observation data at front site.

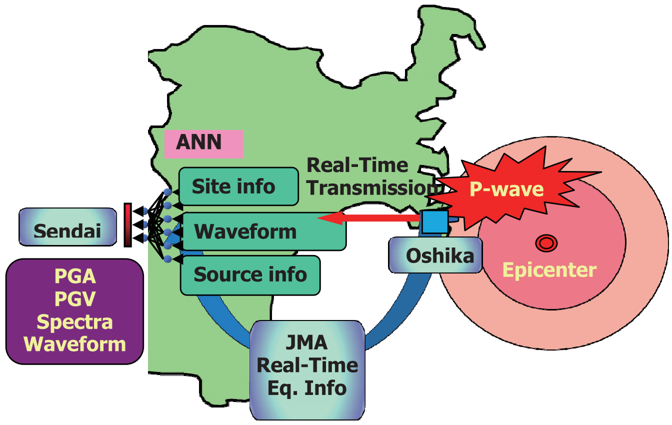


Fig. 2. Conception of the accurate real-time ground motion prediction based on the regional EEWS combined with real-time earthquake information form JMA.

implemented by the JMA and the NIED, e.g., for online structural monitoring. Information on both national and regional systems is integrated for determining alarms more accurately, and our proposed methodology is implemented in Sendai taking advantage of both systems under test at the Earthquake Disaster Research Laboratory, Disaster Control Research Center, Graduate School of Engineering, Tohoku University.

This paper investigates EEWS applications in Sendai, Miyagi Prefecture, Japan, and the development of an artificial neural network (ANN) model for the Sendai basin to predict earthquake ground motion parameters. The ANN models the ground profile based on EEWS. Accuracy of ground motion forecasting PGA and PGV using front-site waveform data is verified for earthquakes in the Miyagi Oki area by comparing results to those of a conventional attenuation formula. The ANN-based method is applied to spectral ground motion forecasting.

As for the conception of real-time ground motion prediction using front-site waveform data, Nagashima et al. proposed different methodology based on the system identification a technique using recursive filter [7].

2. Peak Ground Motion Forecasting Using Front-Site Waveform Data

2.1. Overview

The ground motion estimation we propose using front-site waveform data and an ANN, as shown in **Fig. 2**, [8] has had its validity and applicability verified [9]. Real-time ground motion parameters PGA and PGV at 4 sites, including Sendai, were predicted using front-site waveform data at Oshika for the anticipated Miyagi-ken Oki earthquake. In this study, assuming that the time at which the source information from JMA reaches as real-time earthquake information is 5.5 sec after P wave arrival at the front site, the initial 5.5 sec of the P-waveform was used as front-site waveform data.

It is noted that the authors have attempt to forecast the N-S component of earthquake ground motion in a primary study because this component was found to generally have greater peak ground motion in Miyagi Prefecture. It is also noted that the NS component of the initial part of P wave at Oshika site as front-site waveform data in a primary study even though the vertical component is generally dominant in P waves. The authors considered that the same components at Oshika and far sites have a correlation.

K-NET observation datasets for 39 earthquakes occurring in the Miyagi Oki area were used in our study investigation. Comparing proposed and conventional attenuation formula results [10], it was found that the proposed methodology dramatically improved accuracy of the predicted peak ground motions.

2.2. ANN Specifications in EEWS Application

The ANN is defined as a computational process that presents and evaluates mapping from one space, Oshika, to another space, Sendai, using a dataset representing mapping (Garret (1994) [11]). No fixed rule exists for selecting ANN specifications. Scientists and engineers generally choose the number of hidden layers and nodes, activation functions, rates, and algorithms to suit their applications, and a plethora of reports deals with this process. Internal processes are often called black boxes due to the paucity of comprehensible explanations clarifying them. Users need not understand such internal processes to use them in supervised learning algorithms for mapping input versus output. ANN-based methodology combines information on past earthquakes in the Miyagi-ken Oki area, and has been used to model or solve nonlinear complex engineering problems. Although ANN applied to determine source parameters using P waveforms for the EEWS by Kanda [12], this methodology is not widely used in seismology, and its earthquake engineering and EEWS applications are insufficient. The application of ANNs to real-time forecasting of ground motion parameters for PGA, PGV, and spectra using P wave information at the front site is quite new. The advantage of the ANN is its ability to “learn” from experience and examples and its adaptability to varying environments. ANN methodology finds relationships that map from a set of given patterns (input data) to an associated set of known values(target output data). This is done using simple, highly interconnected processing elements by adjusting neuron weights and optimizing error between estimated and targeted output. A well-trained and tested network generalizes rules and responds to unknown situations to forecast the required results. Weights connecting nodes with previous and nested layer nodes are optimized for a particular problem after training. Weights are updated by a predefined error function for which common root mean square error defined as follows:

$$E = \frac{1}{2} g\left(y - h_w(x)\right)^2 = \frac{1}{2} \bullet Err^2 \quad \ldots\ldots \quad (1)$$

where y is the desired output and $h_w(x)$ is the predicated output. Adjusted weights are described as follows:

$$w_i^{j,new} = w_i^j + \frac{\partial E}{\partial w_i^j} \quad \ldots\ldots\ldots\ldots \quad (2)$$

where error function changes for node weights is

$$\frac{\partial E}{\partial w_i^j} = Err \bullet \frac{\partial Err}{\partial w_i^j} = Err \bullet \frac{\partial}{\partial w_i^j} g\left(y - \sum_{i=0}^{n} w_i x_i\right)$$
$$= -Err \bullet g'(in) \bullet x_i \quad \ldots\ldots\ldots\ldots \quad (3)$$

and updated $w_i^{j,new}$ is

$$= w_i^j + \alpha \bullet Err \bullet g'(in) \bullet x_i \quad \ldots\ldots\ldots \quad (4)$$

where α is the learning rate and $g'(in)$ is activation function output.

We undertook 639 trials with feed-forward network architecture using one, two, and three hidden layer networks for optimum learning and results. Depending on test result of PGA and PGV of different structures for each problem, 18-11-7 and 16-14-5 number of neurons in three hidden layers are selected. Training was completed through 6000 epochs. Once trained, the network was fed previously unseen earthquake profiles, then 12 and 10 test patterns were arbitrarily selected and tested for each case. We determined optimum ANN design with statistical verification, then used the mean of tested examples and the deviation of results to choose an architecture.

The authors defined PGA and PGV for a location at a far site, Sendai, as a function of source information – magnitude, depth, epicenteral distance, and azimuth – initial waveform information – P wave, and $PGA_{5.5}$ – and site information – relative location of target site from the front site, Oshika, and on-site soil conditions. Source information reaches Sendai from Tokyo within an average of 5.5 sec. Other information is provided by our system.

Figure 3 shows the information required to construct the ANN for peak ground motion parameters, PGA, and PGV. Two different ANN structures are used to forecast PGA and PGV

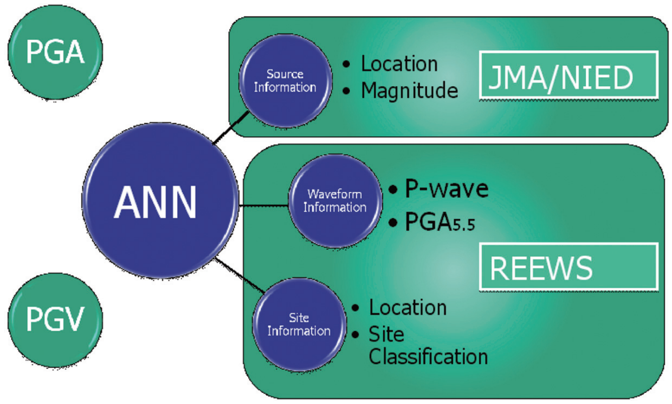


Fig. 3. Information for ANN construction in the peak ground motion prediction.

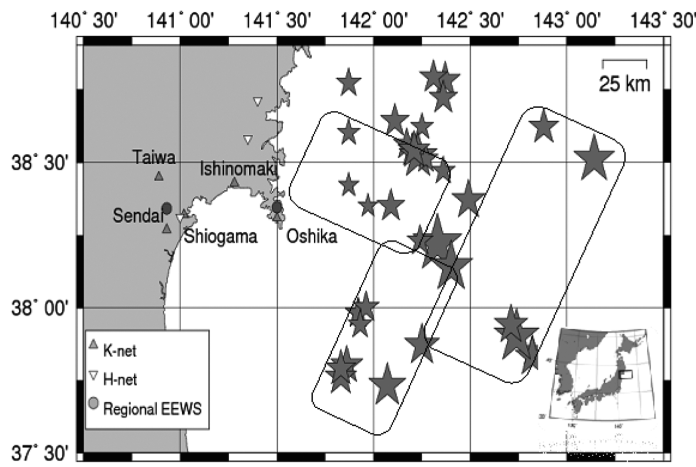


Fig. 4. Locations of the K-NET observation sites and the epicenter distribution of the 39 earthquakes occurred in Miyagi Oki area used in the study.

2.3. Database Used in Forward Ground Motion Forecasting

The 39 earthquake events recorded by the K-NET at Miyagi Prefecture, Taiwa (MYG009), Ishinomaki (MYG010), Oshika (MYG011), Shiogama (MYG012), and Sendai (MYG013) stations in the Miyagi-Oki area are used as an input for ANN-based regional EEWS.

Figure 4 shows the epicenter distribution of the 39 earthquakes (M4.0-M7.2) occurring in the Miyagi Oki area and used in ANN construction and verification of real-time ground motion prediction using the ANN.

2.4. Modeling Initial Ground Motion

One of the biggest problems in EEWS is evaluating initial ground motion – generally the first 3 sec of the P wave – used to determine the frequency of seismic ground motion. Researchers have tried to prove that the predominant frequency correlates with earthquake magnitude. The authors looked at the problem from a different aspect. Initial ground motion is modeled to predict parameters of impending seismic motion at far sites. The P wave car-

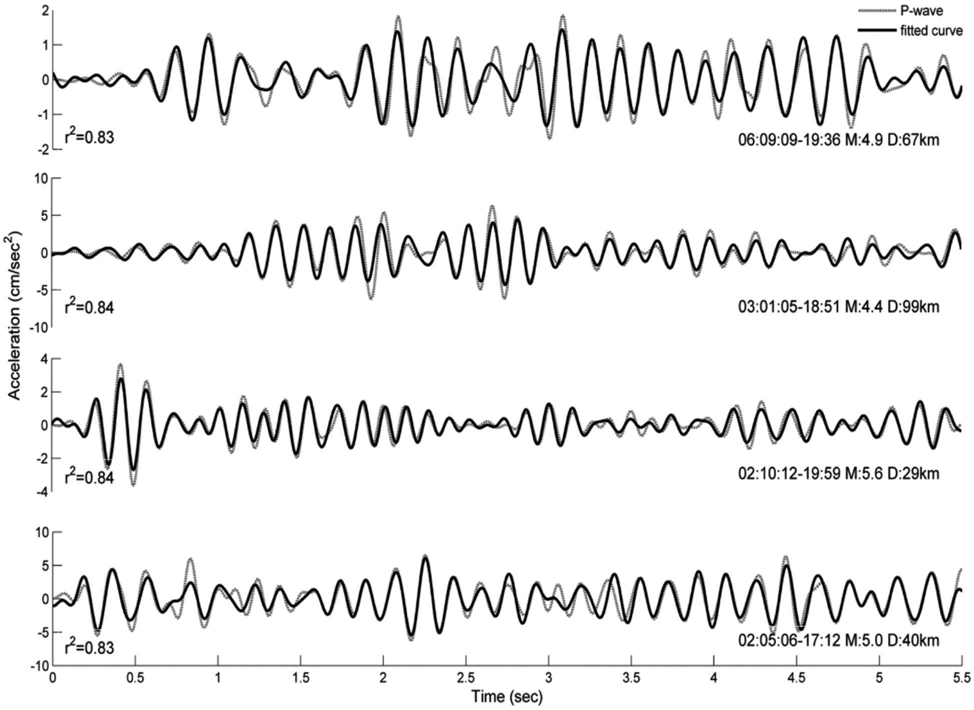


Fig. 5. Waveforms of the initial part (5.5 s) and the approximated waveforms.

ries earthquake information, so stationary 5.5-sec primary motion is simplified as the sum of sinus functions as follows:

$$y = \sum_{i=1}^{n} a_i * \sin(b_i * x + c_i) \quad \ldots\ldots\ldots \quad (5)$$

where a is amplitude, b frequency, and c the phase constant for each wave term. n is selected as 8 due to its sufficient representation of random motion. Amplitude and sinus wave frequency are assumed to be related to ground motion parameters. Note that a band-pass filter between 0.1 to 8 Hz – the most acceptable range for engineering use – is applied to the original waveform before sinus wave approximation.

Initial motion parameters derived from simplified waveforms are used to train the ANN model. Four examples of the first 5.5 sec of the waveform recorded in Oshika are plotted as shown in **Fig. 5** – simplified waveforms are in black. The proposed model fits well enough to represent the P wave.

2.5. Results and Comparison with Conventional Empirical Formula Results

Earthquake observation data for 35 of our 39 earthquakes together with positional and site-repartition information are used as training data to construct the ANN structure shown in **Fig. 3**. The initial 5.5 sec of P waveform information and PGA at the Oshika site (MYG011) of K-NET were used as front-site waveform data. The dataset for the remaining 4 earthquakes was used as test data in blind prediction of PGA and PGV at the 4 sites, i.e., Sendai (MYG013), Taiwa (MYG009), Shiogama (MYG012), and Ishinomaki (MYG010). Note that the site effect of different locations is considered as changes in average shear wave velocity of the unconsolidated layer based on National Earthquake Hazards Reduction Program (NEHRP) standards.

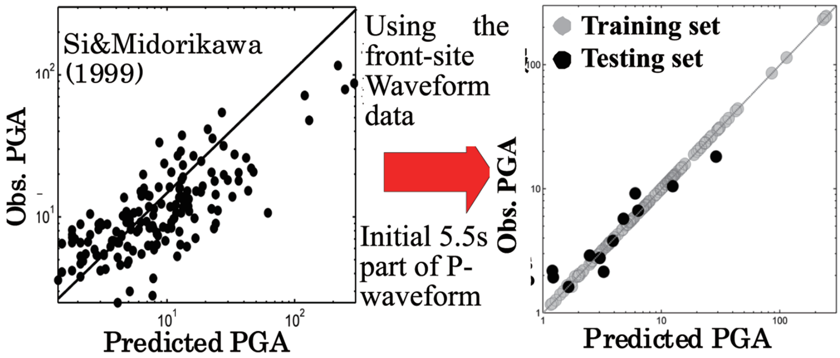
Figure 6 compares results in peak ground motion prediction for (a) PGA and (b) PGV. The vertical axis shows observed and the horizontal axis predicted values. Results for the proposed method are compared to those for the conventional attenuation formula [10]. **Table 1** lists data averages and standard deviation. It is found that the proposed method dramatically improved accuracy in peak ground motion prediction.

3. Spectral Ground Motion Forecasting Using Front-Site Waveform Data

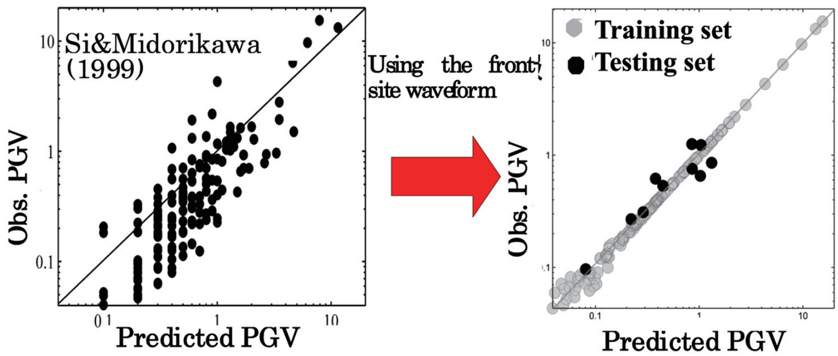
3.1. Methodology

If the frequency content of ground motions can be accurately predicted before severe earthquake shaking occurs, predicted information can be used in advanced engineering applications such as structural vibration control. We have predicted Fourier spectra using ANN at 4 K-NET sites – Sendai (MYG013), Taiwa (MYG009), Shiogama (MYG012), and Ishinomaki (MYG010). Front waveform data at K-NET Oshika (MYG011) was used as input data. The dataset for the 39 earthquakes mentioned earlier occurring in the Miyagi Oki area were used in our investigation ([13]).

Figure 7 shows the information required to construct the ANN for spectral ground motion. As with the case of peak ground motion prediction, parameters of the modeled initial 5.5 sec P waveform at the K-NET Oshika site



(a) PGA



(b) PGV

Fig. 6. Comparison of the results in the peak ground motion prediction.

Table 1. Comparison of the average and the standard deviation of the results by the proposed method and those by the conventional attenuation formula.

	Training set		Testing set		Total set	
	Mean	Std. deviation	Mean	Std. deviation	Mean	Std. deviation
PGA	1.00	0.01	0.99	0.32	1.00	0.09
PGV	1.00	0.10	0.98	0.33	1.00	0.12
PGA	Multi regression analysis (Si and Midorikawa)				1.53	0.97
PGV	Multi regression analysis (Si and Midorikawa)				1.97	1.20

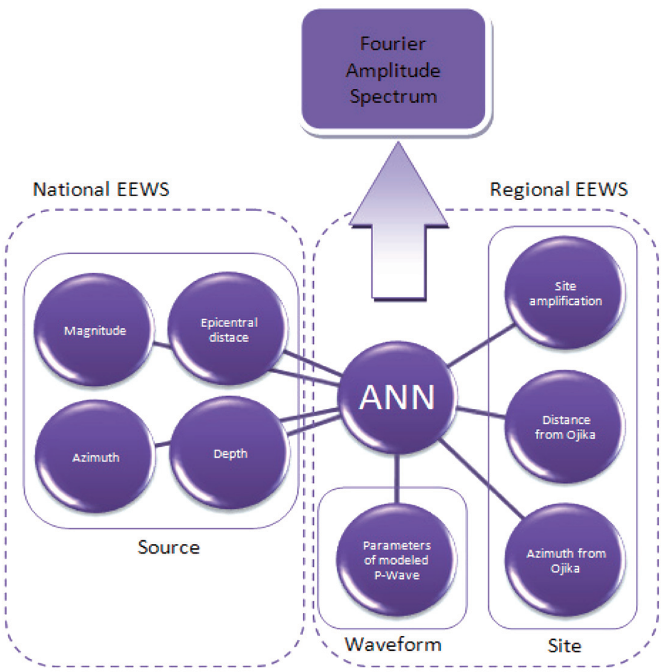


Fig. 7. Information for ANN construction in the spectral ground motion prediction.

(MYG011) were used as front-site waveform information. Training data used to construct the three-layer ANN included frequency-dependent site amplification and positional information – the distance and azimuth from the Oshika site.

Note that site-amplification factors from seismological bedrock to engineering bedrock are considered by linear one-dimensional wave propagation theory for obliquely incident S waves.

Earthquake observation data for 35 of the 39 earthquakes was used for the training data and data for the remaining 4 was used for real-time spectral prediction in the form of blind prediction. The frequency range is 0.1 Hz - 10 Hz and spectral values were predicted at the 40 frequencies.

3.2. Results

Figure 8 compares predicted and observed Fourier spectra at the 4 evaluation sites. Results for training and test data showed that spectral prediction was highly accurate.

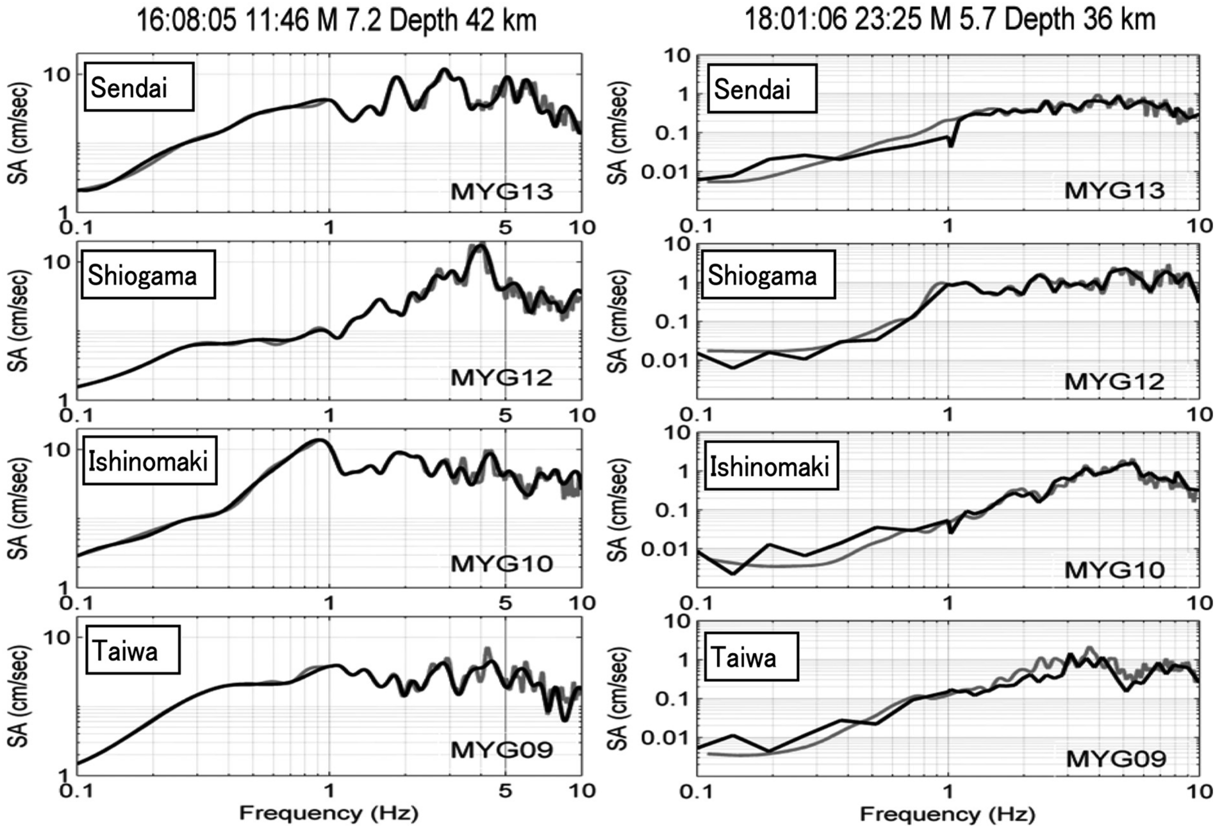


Fig. 8. Comparison of the predicted and the observed Fourier spectra of ground motions (left: Training data, right: Testing data).

As stated, advanced engineering applications such as feed-forward control of active or semiactive structural vibration control can be used if spectral information at the evaluation site is available before shaking occurs. Real-time waveform prediction may be realized in the near future.

4. Conclusions

The authors have succeeded in predicting the peak ground acceleration and velocity of earthquake ground motion at far sites before severe shaking. ANN is used to learn the characteristic ground profile between these stations. Source parameters, modeled initial waveforms, and site condition are used to forecast Sendai ground shaking parameters.

Our method has several advantages in real-time EEWS. First, it considers forecasting of upcoming event far-field parameters, not prediction. Second, enhancing this study enabled us to evaluate ground shaking features before hazardous ground motion arrival in Miyagi Prefecture. Third, our proposal is easy to implement and maintenance is comparatively inexpensive. Fourth, the proposed system uses the advantages of both national and regional EEWS. Fifth, this approach opens the way for studies considering earthquake hazard reduction depending on initial ground motion.

The critical question EEWS must answer is how an event affects far urban areas and what the response of structural and nonstructural elements from engineering point of view. Perhaps the most important purpose of the EEWS is real-time seismic risk management and reduction. Rather than alerting the public to potential earthquake consequences, the EEWS is more applicable to protecting critical systems and structures. For foreseeable future, the EEWS should be focused on protecting the computing performance of engineered system structures of interest at far sites so that real-time analysis provides response spectra at a site before ground motion hits. Semi-active control devices may change the stiffness or dumping of the structure.

Acknowledgements

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