SPECTRAL FORECASTING OF EARTHQUAKE GROUND MOTION USING REGIONAL AND NATIONAL EARTHQUAKE EARLY WARNING SYSTEMS FOR ADVANCED ENGINEERING APPLICATION AGAINST APPROACHING MIYAGI-KEN OKI EARTHQUAKES

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ABSTRACT :

Application of earthquake early warning systems (EEWSs) mainly focuses on alerting or providing information to the public services such as the emergency, fire departments, and hospitals; however, next generation EEWS will provide information to control the structures equipped with active/semi-active devices or critical systems from the destructivity of earthquake ground motion. Providing consistent and continuous spectral representation of earthquake wave amplitude for the usage of advance civil engineering applications would definitely help to reduce seismic response. Numeric simulations have been proving that structural control can be effectively achieved if the content of propagating waves is known before arriving at the building of interest. It is therefore particularly valuable to forecast Fourier Amplitude Spectrum (FAS) in this respect for real time engineering applications. In this study it is proposed that FAS of earthquake ground motion can be forecasted in far-site ranges after detection of earthquake in terms of initial ground motion, source parameters, and site amplification in frequency domain which are provided by different EEWSs. For this purpose, the authors have developed a regional warning system in Miyagi Prefecture against Miyagi-ken offshore earthquakes and integrated with the JMA/NIED, national Japan EEWS. Our system is providing a real-time online waveform data from the nearest inland point to the Miyagi subduction area to the center located in Tohoku University, Sendai. Artificial neural network methodology is utilized to integrate the information from the hybrid configuration. 39 numerical simulations have been performed for verification in the Sendai city basin where four earthquakes were selected by blind prediction using the remaining 35 recorded earthquakes in the same basin. The results indicated that the methodology of FAS forecasting will provide great contribution to structural control considering non resonance phenomena with the usage of feed forward control algorithms.

KEYWORDS: Spectral forecasting, earthquake early warning system

1. INTRODUCTION

The term “early warning” is recently used with a variety of meaning in seismology and earthquake engineering communities. As a general definition, early warning is the provision of appropriate information, allowing people exposed to a hazard to take action in order to keep away from or reduce their risk and get ready for effective reaction. In the last few decades, there have been several ongoing researches and improvements in the earthquake early warning systems in the active seismic zones such as Japan, Mexico, Turkey, and Taiwan. Many studies pointed out the main problems for automatic application of earthquake early warning to real time risk reduction. Considerations were focused on mainly forecasting source parameters of earthquake in real time. The basic problem is the development of real-time algorithms for the fast determination of earthquake source parameters as well as the estimation of their reliability. Information of real-time event detection and location, real-time fault mapping, fast magnitude/moment determinations and the concept of energy magnitudes, only a few seconds after the first P-wave detection is the couples of problems that are challenging scientists and need further investigations together with new approaches.

On the other hand, different from problem definitions described above, we introduced a new and dissimilar perception, called "forward forecasting" which forecasts the amplitude or frequency of ground motion in far sites for the utilization of engineering purposes (Figure 1). Former problems are mainly studied by seismologists where latter issue has not yet been discussed adequately by engineers due to unawareness of the newest technology and its application. In order to mitigate the earthquake hazard, apart from warning society and the proper executions for the damage reduction such as automatic shutdown systems of gas and pipelines, manufacturing operations, slowdown of bullet trains etc, the main attention, from engineering point of view, focuses on transmission of necessary information to special or critical buildings or facilities and usage of active or semi-active control devices in the intelligent structures before the destructive energy of earthquake reaches. The questions are: what kind of parameters or functions and how these EEW information will be applied to the structures and, above all, much critically, how or which methods will be used to find the desired functions yet need to be answered and further discussions are needed from the same point of view.

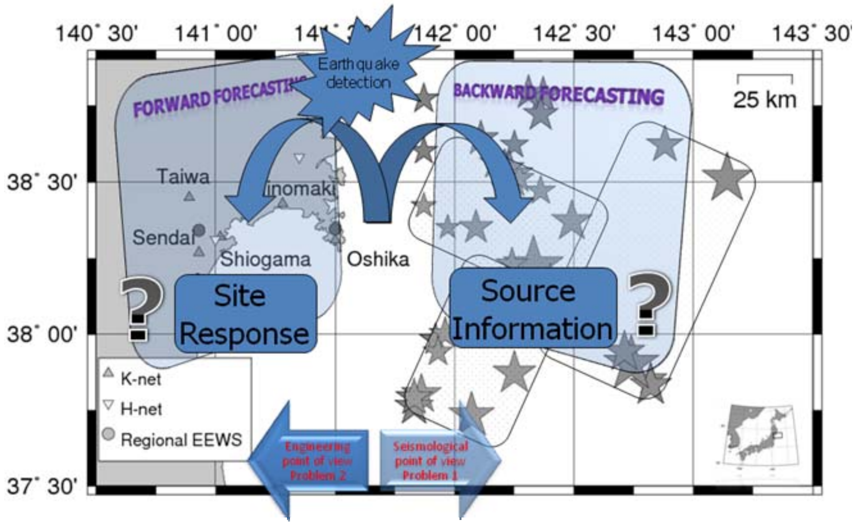

Figure 1 Description forward and backward forecasting

Fourier amplitude spectra are the most likely function to be predicted in order to be utilized by controlling structures and these functions are targeted in this study. Several researchers tried to predict Fourier amplitude spectra (Sokolov et al. 2000, Trifunac and Lee 1989) using source information of earthquakes with multi-regression analysis without consideration of the EEWSs. Trufinac et. al. (1989) basically suggested that Fourier amplitude spectra of strong motion acceleration can be scaled in terms of earthquake source parameters, and geological site conditions without any consideration of waveform information. He developed several different regression models considering different parameters in frequency domain. Bose (2006) also tried to predict FAS based on the Early Warning Information (EWI) using artificial networks. Except FAS, other parameters like PGA and PGV, or functions like response spectra are not beneficial for real-time seismic control of structures. Nevertheless these parameters also worthwhile to predict and the authors of this study predicted successively in Miyagi prefecture by using ANN approach and hybrid EEWS (Kuyuk and Motosaka 2008, Kuyuk et. al. 2008). Moreover, FAS is a critical tool to describe ground motion during wave propagation and to control the structures for EEWS applications. It is widely used in seismological studies such as estimating seismic hazard and ground motion prediction (Sokolov et al. 2000) and engineering studies (Bose, 2006).

From engineering perspective, significant advances in both active and passive devices capable of altering the dynamic characteristics of a structure in real time are achieved in recent years. Kobori et al. (1993) first have proposed non-resonance control systems, so-called active variable system (AVS). This system seeks a non-resonant condition during shaking by altering the structures' stiffness based on the measured input motion in the same structure. The stiffness is changed by locking or unlocking variable stiffness devices in "V" bracings. They made great success by employment of a feed forward control algorithm. Then, Pnevmatikos et al. (2004) investigated the usage of AVS system, given that the frequency content of upcoming ground motion to eliminate resonance/near-resonance phenomena in structures considering EEW applications is known. They numerically proved that control can be achieved in cases when the FAS are assumed to be known. However, question is not yet answered on how the FAS could be estimated. Up until now all the methods and attempts to forecast FAS as well as response spectra were very rough (or much smoothed) and far from distinguishing the fundamental frequency (Sokolov et al. 2000,Trifunac and Lee 1989). However, with the present advances in the field it is now inevitable to integrate sophisticated EEWS technology and control devices for real time structural control in the near future.

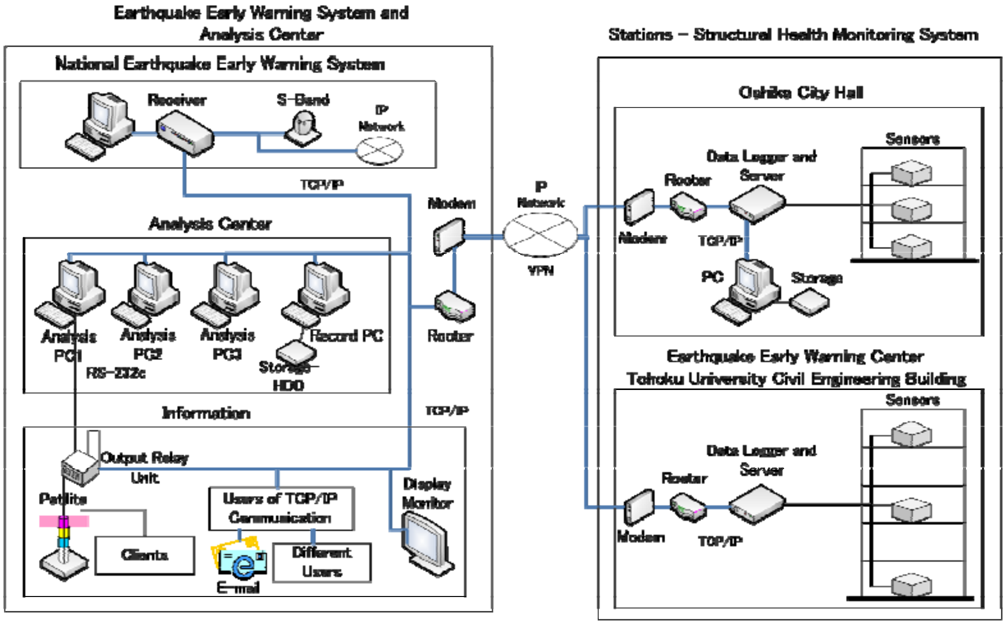

Figure 2 Overall of regional warning system description

One of the main problems was the technological background in application considering forward forecasting; at the present no EEWS is providing initial ground motion to engineering purposes, even the most advanced system in Japan which has one of the most reliable EEWS in the world with adequate high dynamic range and bandwidth instruments. This system has finished infrastructure all over the country and was tested since July 2002 (Horiuchi et al., 2005). Big step was made in October / 2007 when JMA started to serve source information, time of impending S wave and JMA intensity to public and private companies. Although this information is valuable for EEW application, actually it is not adequate to make proper actions to control the structure etc.

The authors have been using this system since 2006 and they have developed an independent regional warning system in Sendai, Miyagi prefecture, where one of the most seismically active zones is located (Miyagi fault systems) in Japan, to increase reliability and supplementing the national EEW configuration. The system has multi purposes such as structure health monitoring, real time application for structures and is described in Motosaka et al (2008). It is the fastest EEWS that can serve waveform with variable packets (set for this application as 0.2 sec packet) to client with transmission speed less than 0.2 sec for each packet.

Two separate systems are integrated to be mutually beneficial for the advanced engineering application purposes. The location of stations in the region and the configuration of the regional warning system is shown in Figure 1 and Figure 2 respectively, where in the first figure, circle symbols represent the regional configuration, triangles are the K-net along the main towns in the area and reversed white triangles are the H-net data (national EEWS). The location of regional network in Oshika site was chosen as the same location with K-net station (MYG011) which enables us to use K-net acceleration records for blind prediction. The authors discussed the advantages and disadvantages of both systems and were successful in integrating the independent systems for advanced civil engineering structures. Based on our experience, the national EEWS information reaches the Disaster Control Research Center (Tohoku University, Sendai) in 5.5 sec average after detection of an earthquake in the nearest point. This delay reflects the transmission delay that is caused due to the distance between Sendai and Tokyo where the JMA/NIED center is located. Therefore, in our hybrid approach the source information is known after detection of earthquake in 5.5 sec and then further information and calculations are provided by our regional system.

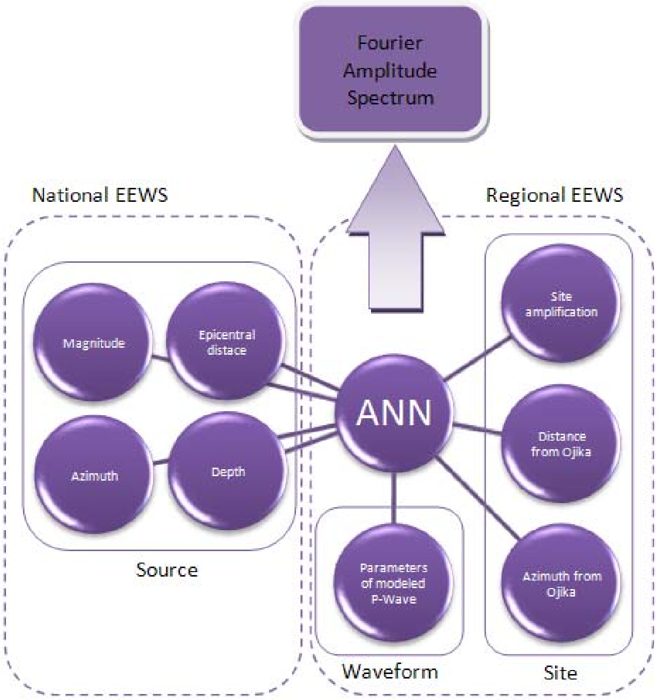

Figure 3 İllustration of the methodology and input parameters

With consideration of the above, a new approach is developed in the present study. The FAS of an impending earthquake could be successfully forecasted at four locations in Sendai basin applying artificial neural network methodology using source parameters of an earthquake, initial ground motion in the near field and the site amplification in frequency domain at the site of interest. The information is provided by a hybrid EEWS.

2. METHODOLOGY

In this study, 195 accelerometer records resulted from 39 earthquakes in the east-west Japan (Miyagi Prefecture, Taiwa MYG009, Ishinomaki MYG010, Oshika MYG011, Shiogama MYG012, Sendai, MYG013) that were recorded by the K-net during January, 1996 to September, 2007 are utilized. Earthquakes that occurred in a window bounded by 37.5N-38.8N latitude to 141.7 to 150 degrees longitude in the region are located in Figure 1. In order to achieve a high quality of modeling and accurate training, the range of the earthquake parameters is limited to 4.1-7.2 for magnitude (M), 43-532 km for epicenteral distance (E) and 14-99 km for depth (D). 195 different ground motions (N-S component) in five locations are considered and 156 FAS is prepared at four far sites (extracting the nearest location) and tought to the ANN.

Artificial Neural Networks based methodology is used to combine all information considering past earthquakes occurred in Miyagi-ken oki (Figure 3). In fact, ANN have been used to model or solve nonlinear complex engineering problems, however, is not widely used in seismology and its applications for earthquake engineering considering EEWS are quite new. The great characteristic of the ANN is the ability to learn from experience and examples as well as the adaptability with the varying environments. Namely, ANN methodology is trying to find relations that maps from a set of given patterns (input data) to an associated set of known values (target output data). This is done by a number of simple, highly interconnected processing elements by adjusting weights of these neurons and optimizing errors between estimated outputs and target outputs. Satisfactorily trained and tested network is able to generalize rules and respond unknown situations to forecast required result. The weights which connect each node with the previous and nest layer nodes are optimized for a particular problem after training. The weights are updated by pre-defined an error function which a common root mean square error defined as;

$$E = \frac{1}{2} g\left(y - h_w(x)\right)^2 = \frac{1}{2} \bullet Err^2 \tag{2.1}$$

where y is the desired and the $h_w(x)$ is the predicated outputs. The adjusted weights can be described as

$$w_i^{j,new} = w_i^j + \frac{\partial E}{\partial w_i^j} \tag{2.2}$$

where the changes in error function with respect to weight in each node is

$$\frac{\partial E}{\partial w_i^j} = Err \bullet \frac{\partial Err}{\partial w_i^j} = Err \bullet \frac{\partial}{\partial w_i^j} g\left(y - \sum_{i=0}^{n} w_i x_i\right) = -Err \bullet g'(in) \bullet x_i \tag{2.3}$$

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

$$= w_i^j + \alpha \bullet Err \bullet g'(in) \bullet x_i \tag{2.4}$$

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

In this study common feed-forward network architecture is used and three hidden layer networks are challenged to get the best results. Statistical verification is used to determine optimum design of ANN. We carry out simultaneous analysis for all 156 records of FAS at 40 selected set of discrete frequencies for the interval from 0.1 to 10 Hz which is adequate for engineering applications. Among the 639 trials of different architecture of ANN three-hidden layer is selected depending on the test results. For each frequency of 39 earthquakes 40 different ANN structures are used for each frequency value including all of the 156 datasets. It took several weeks to conduct such a huge training on the supercomputer of Tohoku University. Weights are initiated randomly and adjusted in learning process described above equations. As an activation function, a common type sigmoid transfer $S(x)$ function in the hidden neurons is used.

$$S(x) = 1/\left(1 + e^{-z_i}\right) \tag{2.5}$$

where $z_i = \sum_{j=1}^{n} w_{ij} * x_j$

x_j is the action of the j input neuron and is $S(x)$ the action of the i th hidden layer neuron. Training is successfully accomplished after about 6000 epochs. Once trained, previously unseen earthquake profiles were fed through the network. Four earthquakes in four sites, totally 16 FAS test patterns, are randomly selected as a test set and extracted from training process. After decision of best structure for each problem, unused or unseen data is used to validate the methodology.

The procedure implemented for ANN here is done in 8 steps: in the first step, number of the input neurons that have influence on the particular problem and output neurons are determined. For this case the followings are used as input parameters: a) source parameters (magnitude, epicenteral distance, depth and azimuth), b) amplitude and frequency of the initial simplified waveforms, c) site amplification for the particular frequency; and as output- frequency amplitude for corresponding frequency. In step 2, input variables of the training and testing are calculated. In step 3, input data is normalized. In step 4, network is designed with three-hidden layer. For each layer, the configuration of 20-15, 15-10, 10-5 neurons are tested. In step 5, specification of training algorithm is decided (sigmoid function, training rate, maximum error, number of maximum iteration, etc). In step 6, training is initiated with described topology. In step 7, outputs are unnormalized and network is tested with unseen test data. In step 8, decision algorithm is executed according to test results using statistical methods. In order to find out optimized design, average and standard deviations of results in each test data variables are searched.

In order to evaluate the initial ground motion a new and easy applicable methodology which describes the content of initial ground motion in near field was needed to forecast the frequency dependent FAS. One parameter derived from the early portion of waveform (fundamental frequency or time dependent PGA) is not sufficient for this purpose. We proposed that primary motion can be described combining simplified waveforms as the sum of sinus functions as in Eqn 2.6.

$$y = \sum_{i=1}^{n} a_i * \sin\left(b_i * x + c_i\right) \qquad (2.6)$$

where a is the amplitude, b is the frequency and c is the phase constant for each wave term. They selected n as 8 due to sufficient representation of the motion.

Furthermore, site amplification factors are indispensible to evaluate the response of sites. Velocity structure of Sendai basin is reported and available in the Earthquake Damage Survey Report for Sendai city. We calculated site-amplification factors from the seismological bedrock to engineering bedrock by the linear one-dimensional wave propagation theory for obliquely incident S-wave. The S-wave velocity of the seismological bedrock is assumed to be 3000 m/sec and this deep structure is basically represented by four sedimentary layers. Then amplification factors from engineering bedrock to surface outcrop are calculated by equivalent linear one-dimensional program. The normalized shear modulus G/G_{max} and damping ratios with respect to shear strain and soil profiles are adopted from (Earthquake Damage Survey Report for Sendai City, 2003). Lastly, the two site amplification factors are combined for each site. Nonlinearity depends on the ground motion taken into account in frequency domain in four sites for each 39 earthquake.

3. RESULTS AND DISCUSSION

Providing consistent and continuous spectral representation of earthquake wave amplitude for the usage of advance civil engineering structures would help in the studies of controlling structural responses. It is well known that the explanatory shape of the FAS cannot be modeled accurately by only basic source information such as magnitude and site-to-station distance. Indeed real time estimation of stress drop, velocity with which faulting might progress along a postulated fault plane and the spatial amplitude distribution is formidable Hence, from a practical point of view, it is worthwhile to consider only those parameters which are readily available in EEW application regarding the structural control. The gain of this approach is that, without a complete and possibly indecisive analysis, the approximate FAS can be estimated for a given expected earthquake using online obtainable information.

Methodology is presented by couple of scenario earthquakes for the ANN approach which is applied to four main locations in the Miyagi area of interest, Shiogama, Ishinomaki, Taiwa and Sendai stations. Magnitude 7.2 earthquake FAS is given in Figure 4. Gray lines represent the observed Fourier amplitude (FA) where the black lines are the forecasted FA. To combine the discrete points, a piecewise-polynomial approximation is used. The cubic spline data interpolation is performed using spline algorithm. Basically, for the coefficients of the cubic polynomials, which make up the interpolating spline, a tridiagonal linear system is constructed and is being solved for the required intervals. The difference between computed and observed FAS in Figure 4 clearly shows that the scaling characteristic of earthquake ground motion in terms of earthquake source, initial ground motion, and site amplifications can be expected to yield satisfactory answers in all cases for Miyagiken-oki earthquakes. These figures are the captures of FAS in 5.5 sec after first detection of P wave in Oshika.

The error at Taiwa in fundamental frequency is basically due to limitation of forecasted points. In case if the peak amplitude is in the middle of the forecasted points, these errors are unavoidable. Although it is adequate in here as a preliminary study, increase in the frequency of data set for prediction by at least two times could be a solution. With the increasing points which are accompanied with increase in computation efforts, the compatibility in high frequency ranges will also be better. Since high frequency ground motion attenuates faster than low frequency with distance, high frequency ranges are biased in Taiwa city, which means prediction of high frequencies in far ranges become rather difficult. However, it is no more important to predict high frequencies in far ranges such as Taiwa city, since low frequency motions become more critical, especially for high rise buildings with long periods.

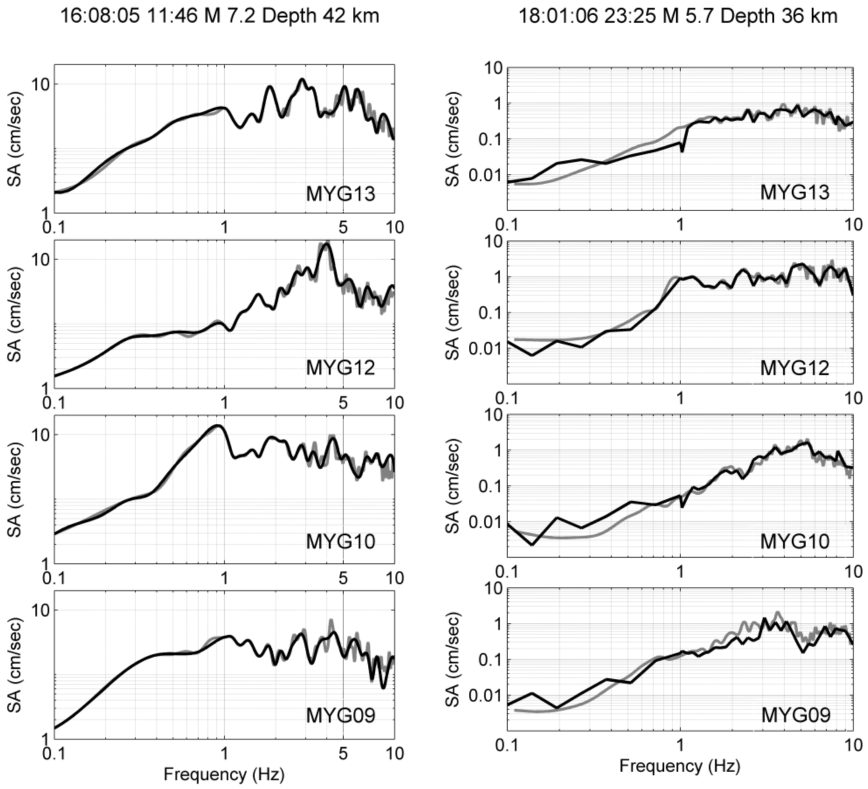

Figure 4 The result of FAS prediction in four site in Miyagi prefecture (earthquake of M 7.2 is selected among the training set where the second earthquake is the result of verification)

Due to resonance/near-resonance phenomena, control algorithm will arrange the stiffness of the structure in order to adjust the natural frequency of the structure and shift the building frequencies as far as possible from the ground motion dominant frequency. For instance, the content of FAS motion message will be served to the AVS-equipped structure so that it would allow for a small but satisfactory window for moving the hydraulics of the AVS system to compensate for the frequency content of the arriving seismic signal. The test so far suggests that the forecasted FAS are very realistic for $4.1 < M < 7.4$ and for horizontal ground motion. To understand these amplitudes we need more accelerometers recorded in the same area and so we must patiently wait for this data to become available. On the other hand, in different locations, like California, where there is more data available, the same methodology could be applied.

It is considered that the data set used in this study is not adequate to describe the strong motion greater than M = 7. Thus, the study is seriously affected by this shortage. Nevertheless, this data does represent the largest collection of the uniform accelerograms and can be used as an interim basis for the preliminary development of the ANN model. In addition, nature of ANN methodology is the same as humans. As human learns by doing and experiencing complex problems, so the presented model in this method should be updated upon the earthquakes' data becomes available, especially for $7 < M$ earthquakes, and thus enhance it, just like the humans grow professionally overcoming challenges.

It should be emphasized here that although the ANN method is not yet implemented, the preliminary efforts have been made showing that the simulations are successful and the method is applicable. From this point of view, the K-net data is utilized and it is assumed that the estimation in source parameters has little or no error. Therefore, the results presented in this paper can be taken as suggestive of the solution to estimate the trends of FAS in real time applications. In spite of the above limitations and errors discussed, it is the only approach towards solution of the prediction problem; a simple methodology which is extracted from actual recording is evaluated to use these results on interim basis as a vehicle for the development of better active control devises and analyzing techniques in the future.

4. CONCLUSION

In this study, one of the most important problem in real-time earthquake ground motion prediction for EEWS; "Does the frequency contents of impending ground motion can be predictable depending on real time earthquake information for targeted locations?" is tried to solve. The authors proposed a new philosophy incorporating ANN methodology in order to forecast frequency content of earthquake ground motion in Miyagi prefecture for the usage of advanced civil engineering applications with available data provided by a hybrid EEWS, where a regional warning system is designed for high accurate and reliable ground motion prediction. Previous earthquake records of K-net's Oshika station, installed in the same point where also the regional warning system station is located, are used for accurate ground motion prediction. The initial ground motion in the Oshika site is introduced for first time for this purpose and as well as frequency dependent site amplifications are take into account and used as inputs of ANN. The achieved results are that FAS of earthquake ground motion can be forecasted in real-time in far-site ranges after detection of an earthquake in terms of the initial ground motion recorded in the near-source site, the source parameters, and the site amplification in frequency domain, which are provided by different EEWSs. The proposed methodology is verified by blind prediction in four sites with different soil conditions where four earthquakes were selected by blind prediction using the remaining 35 recorded earthquakes. The results indicated that the methodology of FAS forecasting will provide great contribution to structural control considering non resonance phenomena with the usage of feed forward control algorithms.

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