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APPLICATION OF NEURAL NETWORKS ON RECENT DEVELOPMENT OF THE EARTHQUAKE EARLY WARNING SYSTEM FOR TAIWAN

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ABSTRACT

An earthquake early warning system has been developed to provide a time related information including vital parameters such as magnitude, the arrival time of strong shaking, and the intensity of the shaking, etc. The mechanism of the wave propagation is complicated and resulted to a high nonlinear function. The neural networks were used to model these nonlinearities and learn to predict the characteristics of the sensed earthquake accelerograms. By analyzing the three components of the earthquake signals, the neural networks instantaneously provide a seismic profile of the arrival ground motion, after the shaking is felt at the sensors. Each data sample, at a rate of 50 samples per second, consists of the first 10 seconds envelope of the complete earthquake accelerogram. The output of the neural networks provides estimates of damaging parameters, such as earthquake magnitude, time until peak ground acceleration (PGA) and intensities for 3 components (directions). The neural network based methodology is trained with 50149 accelerograms from 2505 earthquakes recorded in Taiwan. The proposed damaging parameters can be used for many site-specific applications. By producing accurate and informative warnings, the neural network based methodology has shown the potential to significantly increase the application of earthquake early warning system (EEWS) and to reduce the damages caused by catastrophic earthquake.

Introduction

Earthquake is one of the catastrophic natural disasters and usually caused tremendous damages to human beings. These damages include loss of human lives, public and private properties, huge adverse economic impacts, etc. and it is irreversible and painful. Since Taiwan is located between Euro-Asian and Philippines tectonic plates on the Pacific Earthquake Rim, Taiwan has suffered from the threatening of moderate earthquakes for a long time. Although it is very difficult to avoid the damages caused by earthquake due to its high frequency of occurrence, the damages can be reduced due to possible appropriate reaction if people can only receive the warning of the coming earthquake even by only few seconds. It becomes possible to issue a

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warning alarm before arrival of severe shaking (S-wave) and to provide sufficient time for quick response to prevent or reduce damages recently due to the development of the earthquake early warning system (EEWS). Thanks to the solid background of the current development of the information technology and the earthquake observation technology that makes the development of the EEWS remarkable. It is Dr. Cooper (1868) who originated the idea of EEWS in the U.S. based on the principle that the electronic signal is faster than the earthquake wave, and the typical research project goes ahead mainly in the California after that. The CUBE project was mainly leaded by Prof. Kanamori in 1990 with the collaboration of California Institute of Technology and United States Geological Survey (USGS). In Japan, JR's UrEDAS (Nakamura 1988) is famous for its practical system. Recently, the Real-time Earthquake Disaster Prevention System was developed and has already been used in Japan (Yoshioka 2006). However, the accuracy of the predicted ground motion is limited especially for a large scale earthquake since the Real-time Earthquake Information by JMA (Horiuchi et al. 2005) is based on point source information. While the ground motion prediction shall not be limited to only seismic intensity but shall be extended to more precise information such as further waveform information as well as peak ground acceleration (PGA) are required in some engineering applications with higher demands, and the so called “blind zone” (area within the 50 km of radius from the epicenter) of the regional EEWS needs to be eliminated, the EEWS are in need of improvement.

As part of the total solution of seismic hazard mitigation, an on-site earthquake early warning system (EEWS) has been developed. It provides time-related information including the magnitude of the earthquake, the expected arrival time of strong shaking, the seismic intensity and the peak ground acceleration (PGA) of the shaking, the dominant frequency of the earthquake and the estimation of structural response. The development of the on-site EEWS is divided into 2 stages. The 1st stage provides a basic prediction of the earthquake, and in the 2nd stage the response of the structure is estimated. In the 1st stage, we use the P-wave predicated PGA method and neural networks to model the nonlinearities caused by the interaction of different types of earthquake ground motion and the variations in the geological media of the propagation path, and develop learning techniques for the analysis of the earthquake seismic signal. In the 2nd stage, two different approaches are used to satisfy the different demands for the rapid estimation of structural responses. Both modules can estimate the structural response rapidly using the output of the first stage. The general modulus, which only uses the common data of the structure (height, structure type, floor, address …etc), is proposed to provide a low-cost, general-application and rapid estimation of the structural responses. At the same time, the customized modulus (scenario-based response predictor) provides a more accurate and detailed structural response estimation. By utilizing the large database collected by the Central Weather Bureau (CWB), rapid and precise results can be obtained after any major earthquake. In addition, the customized modulus can also include the actuation system, which can automatically respond and reduce the economic losses due to the earthquake. Figure 1 shows the framework of the on-site EEWS at 1st stage.

The neural network models are applied during this development of the on-site EEWS in both stages. These neural networks are used to analyze the first-arrival of the earthquake signals in as early as 3 seconds after the first ground motion is registered by the sensors at a rate of 50 samples per second. Then, the on-site EEWS instantaneously provides a profile of information consisting of the estimates of the hazard parameters at the 1st stage and the structure response at the 2nd stage. The system is trained using the seismogram data from 2371 earthquakes recorded in Taiwan. By producing accurate and informative warnings, the system has shown the potential to significantly minimize the hazards caused by the catastrophic earthquake ground motions. This paper will mainly focus on applying neural networks at recent development (stage 1) of the EEWS for Taiwan.

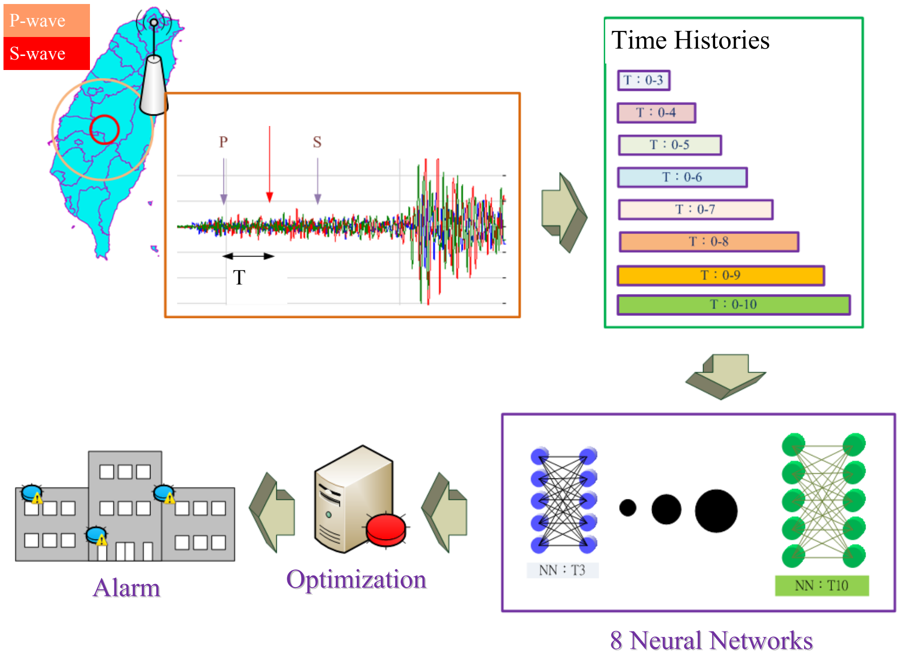

Fig.1 The framework of the on-site EEWS at 1st stage

On-Site Earthquake Early Warning System

Since 2007, Japan Meteorological Agency (JMA) began the general operation of the real-time earthquake information, which is composed of earthquake occurrence time, the magnitude as well as the earthquake location and is expected to provide warning and to reduce casualties and physical damages of earthquakes substantially through the use of JMA-NIED system (nationwide earthquake observation system). One of the technical limits is applicability to the near-source earthquakes. The EEWS developed in Taiwan by Central Weather Bureau (CWB) is similar to the one by JMA. While working with the sensor array from Taiwan Strong Motion Instrumentation Program (TSMIP), the EEWS has undergone various tests by cooperative research institutes since 2006, but the warning is only useful for the area located outside the 50 km radius of the earthquake epicenter.

Although the EEWS were expected to work efficiently at all the places including the observation point where the earthquake motion (P-wave) is first observed. The 'regional' EEWS was proposed and developed first by utilizing the difference of the velocity for the beginning P-wave and destructive S-wave of the earthquake as well as the epicenter locating technology. If the earthquake epicenter can be located within several seconds, more response time for the sites with certain distance from the epicenter of the earthquake can be obtained. Although the velocity of the waves depends on density and elasticity of the medium penetrated, the typical speed for the P-wave is around 5 km/sec and the speed for the S-wave is around 3 km/sec. If the area is far from the epicenter, say 100 kilometer, then we will have at most 15 seconds reaction time before the S-wave arrives if the sensor at the observation station was able to pick up the earthquake signal (P-wave) right away and locate the epicenter within 18 seconds, as shown in Eq.1.

$$100\ (\text{km}) \div 3\ (\text{km/sec}) - 18\ (\text{sec}) = 15\ (\text{sec}) \tag{1}$$

However, if the location is less than 50 kilometer from the epicenter of the earthquake, then the ‘regional’ (traditional) EEWS is almost useless since reaction time is less than one second. In the other words, there are so-called “blind zone”, where within the 50 kilometers radius from the epicenter, existed for the ‘regional’ EEWS. Therefore, the “on-site” EEWS has become increasingly important for areas located in the blind zone of the “regional” EEWS. In addition, the effort to integrate the regional warning with on-site warning to become a more robust EEWS is noticed.

The on-site EEWS (EEWS) is under development to provide a series of time related parameters. In addition, the neural networks were used in both stages to model the nonlinearities among the interaction of different types of earthquake ground motion and variations in the elastic property of geological media throughout the propagation path and to develop learning techniques for the analysis of earthquake seismic signal. The warning system is designed to analyze the first-arrival earthquake signals from three components in as early as 3 seconds after the first ground motion is felt by the sensors at a rate of 50 samples per second. Then the EEWS instantaneously provide a profile consists of the estimates of hazard parameters, such as magnitude, arrival time of S-wave, and maximum seismic intensity (peak ground acceleration, PGA) for both free-field and higher level (structure response). The neural network based system is trained using seismogram data from 2371 earthquakes recorded in Taiwan. By producing accurate and informative warnings, the proposed EEWS can be integrated with distributed networks for site-specific applications and the system has the potential to significantly reduce the damages caused by catastrophic earthquake ground motions.

Neural network

The neural networks are well known as the biologically inspired soft computing tools that possess the massively parallel structures. Their learning capabilities, provided by the unique structure, allow the development of the neural networks based methods for certain mathematically intractable problems. The neural networks are formed by many interconnecting artificial neurons. Signals propagate along the connections and the strength of the transmitted signal depends on the numerical weights that are assigned to the connections. Each neuron receives signals from the incoming connections, calculates the weighted sum of the incoming signals, computes its activation function, and then sends signals along its outgoing connections. Therefore, the knowledge learned by a neural network is stored in its connection weights. The neural networks have been applied to the ground motion generation, prediction and other difficult tasks since 1997 (Lin and Ghaboussi, 1997). Previous researches showed that the neural networks make it possible to provide more accurate, reliable and immediate earthquake information for society by combining the national EEWS and applying it to the planning of hazard mitigation (Kuyuk and Motosaka, 2009).

This paper presents a state-of-the-art neural networks based methodology for forward forecasting of ground motion parameters before S-wave arrival using initial part of P-waveform measured on-site. The estimated ground motion information can be used as warning alarm for earthquake damage reduction. The neural networks program developed by Lin using FORTRAN was used in this study. A combination of the quick-prop algorithm and the local adaptive learning rate algorithm were applied to the multiple layer feed-forward back-propagation neural networks to speed up the learning of the networks (Lin, 1999). The supercomputer is also used to train the neural networks. The validity and applicability of the method have been verified using the CWB observation data sets of 1012 earthquakes occurred in Taiwan.

Furthermore, a new concept of grouping neural networks called Expert Group Neural Network (EGNN) is also used in this study. The EGNN behaved like a group of experts, who grew up from different backgrounds with individual expertise, and were able to provide the appropriate comment when working together as a committee (Lin et al., 2006). The optimal solution among the comments will be chosen while solving this kind of problem. Eight feed forward back-propagation neural networks trained by different inputs constituted the EGNN as a committee of experts to provide the time related information from earthquake accelerograms. The architecture of each neural network among EGNN is set to be different. It consisted of one input layer with 450 to 1500 neurons, two hidden layers and one output layer with 11 neurons (as shown in Fig.2). Each of the EGNN was used to analyze the relationship between the initial few seconds of the earthquake accelerogram and the earthquake waveform information of that specific earthquake.

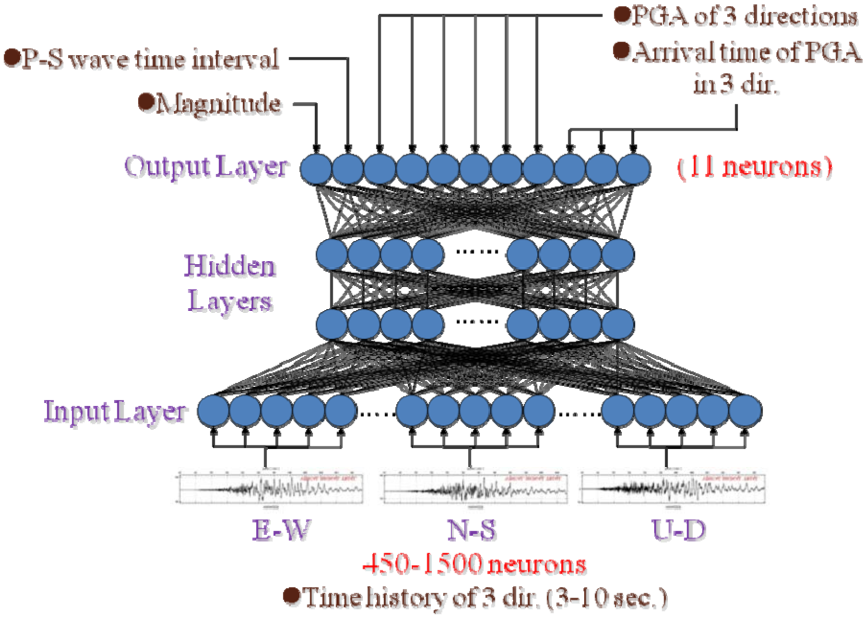

Fig.2 The architecture of neural networks NN:T-3~10

Proposed Methodology and Case Study

The neural networks were used in both stages of the on-site EEWS development. At the first stage development of the on-site EEWS while the parametric analysis study was conducted, the P-wave predicated PGA method [Wu and Kanamori 2005] and the neural networks were used to provide a basic prediction of the earthquake information such as the earthquake magnitude, seismic intensity, peak ground acceleration, and arrival time of S-wave for free field. In addition, the neural networks were able to predict the arrival time of PGA. The proposed method has been verified its validity and applicability. Furthermore, the neural networks were used at the 2nd stage development of the on-site EEWS to predict the seismic intensity, peak acceleration, arrival time of S-wave, and arrival time of peak acceleration for the roof of the specific building (structure response). In the first stage, the EGNN were trained with the data from first 3 seconds to 10 seconds of the earthquake accelerograms separately, as shown in Fig. 1. The earthquake magnitude, PGA (seismic intensity), arrival time of S-wave and arrival time of PGA were predicted using the waveform data from in-situ sensors. In this case, when the real-time information measured from the in-situ sensors is verified as earthquake using 1 second of time history after the arrival of P-wave at the site, then the initial 3 seconds of the earthquake accelerogram (P-waveform) was used as the input for the neural network (NN:T-3) to estimate the magnitude of the earthquake, the PGA (seismic intensity) in three directions, and the arrival time of the S-wave as well as those of PGA. At the same time, the sensors are recording and the initial 4, 5, .., and up to 10 seconds of P-waveform were used as the input for the neural networks (NN:T-4, NN:T-5, .., NN:T-10) to estimate the parameters for the on-site EEWS consequently. The best prediction was then chosen from these 8 results through certain optimization algorithm or time factor. The emergency response actions can be activated right after receiving the warning due to the seismic intensity predicted for the site as well as the remaining time before the strong S-wave or PGA occurred.

The training and testing (validation) data were prepared using the earthquake accelerograms recorded through TSMIP in Taiwan from 1992 through 2006, the magnitude of these earthquake ranged from 4.0 to 8.0 on the Richter Scale. There are a total of 50149 recorded accelerograms from 2505 earthquakes. Among them, the training data were randomly chosen using 40539 earthquake records (80% of the total) from 2371 recorded earthquakes while the test data were prepared using the remaining 9610 earthquake records (20% of the total) from 1012 recorded earthquakes

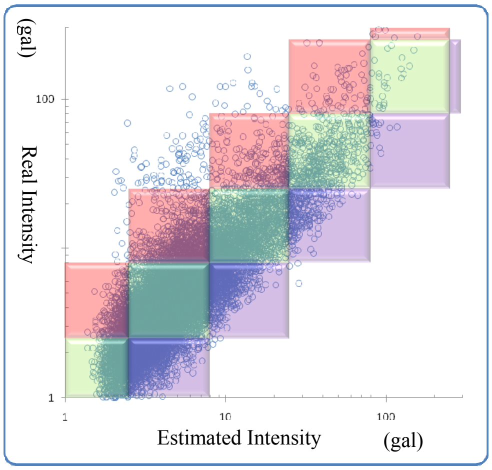

Fig. 3 Comparison of the real and estimated seismic intensity (NN:T-3)

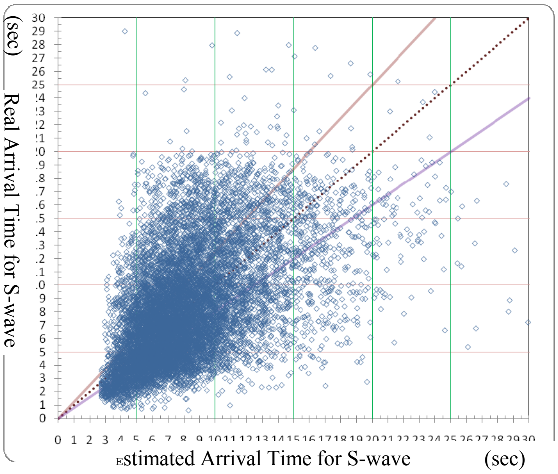

Fig. 4 Comparison of the real and estimated arrival time for S-wave (NN:T-3)

Figs. 3-4 compare the results of the prediction of seismic intensity as well as the arrival time of the S-wave for the model NN:T-3. The accuracy of the seismic intensity prediction (green area) is around 60% while the accuracy for the ± one degree seismic intensity (red, green and purple areas) is around 95% (Fig.3 R^2=0.6977). Figure 4 shows that R^2=0.28 as the accuracy for the estimated arrival time of the S-wave. If a tolerance of ±20% is considered feasible for warning people on the arrival time of S-Wave, then the accuracy is around 70%.

Figs. 5-6 compare the results of the prediction of seismic intensity as well as the arrival time of the S-wave for the model NN:T-10. The accuracy of the seismic intensity prediction (green area) is around 68% while the accuracy for the ± one degree seismic intensity (red, green and purple areas) is around 98% (Fig.3 R^2=0.7714). Figure 6 shows that R^2=0.48 as the accuracy for the estimated arrival time of the S-wave. However, the accuracy rises up to around 80% within ±20% tolerance for the purpose of warning people.

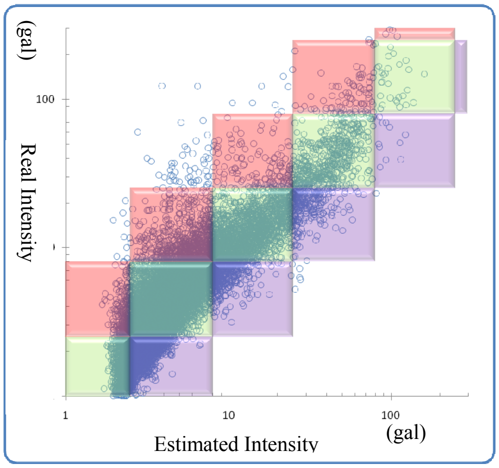

Fig. 5 Comparison of the real and estimated seismic intensity (NN:T-10)

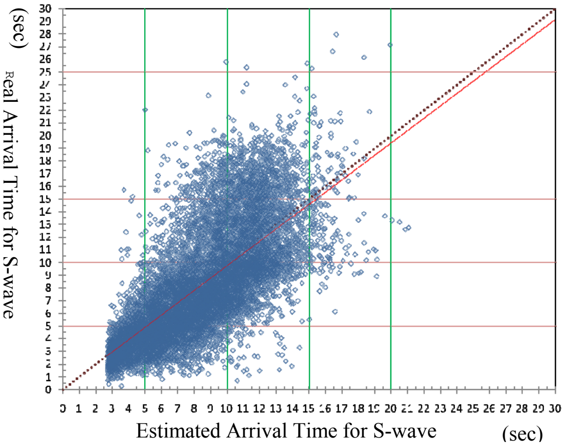

Fig. 6 Comparison of the real and estimated arrival time for S-wave (NN:T-10)

It has been found that the accuracy of the predicted peak ground motion is drastically improved compared the results of NN:T-10 to NN:T-3 since more earthquake information (7 seconds more of earthquake accelerogram) is provided for the neural network (NN:T-10), as shown in Tables 1 and 2. However, the disadvantage for model NN:T-10 is 7 seconds loss of time. Therefore, the result from NN:T-3 is recommended for the purpose of hazard mitigation and emergency response as long as the precision requirement is tolerable for certain applications. Besides, the results of the neural networks can be improved if more earthquake records can be obtained and more training can be done.

Table 1. Comparison of the arrival time for S-wave from the neural networks with several recorded earthquakes. (Unit: second)

EQ	**Real**	**T-3**	**T-4**	**T-5**	**T-6**	**T-7**	**T-8**	**T-9**	**T-10**
A	**4.75**	10.00	6.77	7.41	9.36	5.84	5.79	9.24	4.59
B	**10.33**	9.53	9.12	5.79	14.59	8.57	8.15	5.06	11.14
C	**9.29**	5.85	6.44	9.93	5.98	7.84	5.78	5.29	8.98

D	**5.50**	7.61	8.64	2.95	6.72	6.05	7.56	8.40	5.57
E	**6.79**	8.85	11.07	11.36	9.98	10.35	10.38	10.08	6.58
F	**11.43**	8.64	14.75	10.32	12.91	7.28	8.49	6.26	11.15
G	**5.07**	3.29	3.51	4.31	4.37	5.13	4.13	4.68	5.47
H	**9.94**	7.23	9.04	7.24	4.62	5.32	3.86	3.98	9.00
I	**8.99**	9.19	9.40	6.52	11.09	4.94	7.71	9.49	8.43
J	**9.69**	10.92	11.60	9.99	13.73	9.10	7.38	11.34	11.38
K	**8.18**	8.19	5.16	3.74	4.38	7.02	4.60	8.33	7.42

Table 2. Comparison of the seismic intensity from the neural networks with several recorded earthquakes. (Unit: degree)

EQ	**Real**	**T-3**	**T-4**	**T-5**	**T-6**	**T-7**	**T-8**	**T-9**	**T-10**
A	**2**	2	3	2	2	2	3	3	2
B	**3**	3	3	3	3	2	3	3	3
C	**2**	2	2	3	3	2	2	2	2
D	**4**	4	4	4	3	3	4	4	4
E	**2**	3	3	3	2	2	2	3	2
F	**3**	3	3	3	4	3	3	2	4
G	**3**	3	4	3	3	3	3	2	3
H	**5**	4	4	4	4	4	4	3	5
I	**4**	4	4	3	4	4	4	4	4
J	**3**	3	3	3	3	3	3	2	3
K	**3**	3	3	3	3	3	3	3	3

Conclusions

Preparedness is crucial when a severe earthquake occurs since most obstacles and dangers can be determined beforehand. In this paper, the authors presented the development of the on-site EEWS using neural networks as the recent research achievement of the project. The methodology using EGNN were described and its results shows great potential in 1^{st} stages of this application. The time issue is the key countermeasure during a large earthquake, thus a good optimization algorithm to determine immediately when and what information must be provided. Therefore, the challenge of using only 1 second of earthquake accelerogram to predict earthquake information is under development. In the same time, the structural response of Tai-Power building from above mentioned 2505 earthquake records are under preparation for the training of the neural networks used in the 2^{nd} stage development of the on-site EEWS. The accuracy and reliability of earthquake information is of the utmost importance and is of immense benefit in the mitigation of earthquake hazards. In the future, the verification of the reliability of the communication lines as well as the system is needed to ensure reliable operation of the EEWS. Therefore, the EEWS is able to consequently bring huge benefits on the earthquake hazard mitigation. With further research on the use of the observed earthquake records, and enhancing the accuracy and immediate response of the real-time ground motion prediction, the possibility of the on-site EEWS is within reach.

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