Development of the On-site Earthquake Early Warning System in Taiwan

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SUMMARY:
Taiwan is located at the junction of the Eurasian and Philippine Sea Plates, which is a part of the circum-Pacific seismic belt with high earthquake activities. On average, more than 4,000 earthquakes occur each year in the surrounding area of Taiwan; however, current human technology is not yet capable of accurately forecasting earthquake occurrences in an effective manner (useful information including magnitude, location, time, etc.) to alert affected people before a damaging earthquake actually hits. Generally, the earthquake source is situated deep inside the earth such that its seismic wave trains always travel through complicated soil/rock stratum, and hence the wave speed varies along its travel path. The seismic waves can be briefly categorized into two major types, P- and S-waves. The velocity of P-wave is about 5-7 km/sec, while the more destructive S-wave travels at about 3-4 km/sec. This study develops an on-site Earthquake Early Warning System (EEWS) utilizing the physical signature that P-wave travels faster than S-wave. The proposed EEWS machine uses the signal from the on-site sensors, requires only a fairly minimal computational time, and is suitable for providing earthquake early warning to the site that is close to the epicenter. In addition, the proposed on-site EEWS is integrated with a disaster reduction control system using a demonstration house that has been tested on NCREE's shaking table. The integrated on-site EEWS can provide the early earthquake warning through broadcast, TV and LED text display. Also, it can automatically park the elevator, shut down the gas, switch off the electricity power, open the emergency door, and turn on the lights along the escape route. Combining the on-site EEWS and disaster reduction control system, the life and economic loss can be greatly reduced. According to the validation tests conducted in the field and laboratory, the proposed on-site EEWS has reached an 80% successful rate of accurately predicting the earthquake intensity levels, and is able to automatically send an alarm message at least eight seconds before the peak S-wave trains come even when the site is in the proximity of the earthquake epicenter.

Keywords: Earthquake Early Warning, Disaster Reduction Control, On-site EEWS

1. INTRODUCTION

Taiwan is located at the junction of the Eurasian and Philippine Sea Plates, which is a part of the circum-Pacific seismic belt. As such, Taiwan has frequency seismic activities with more than 4,000 earthquake occurrences each year, among which over 200 earthquakes are sensible. The earliest seismic occurrence report in history can be traced back to the Wanli period of the ancient Ming Dynasty. Over the past hundred years, a considerable number of disastrous earthquakes occurred in Taiwan. A big earthquake in 1935 caused a death toll of 3,276 people in the area of Hsinchu and Taichung; over 12,000 people were injured, more than 17,000 buildings collapsed, and over 36,000 buildings were seriously damaged. Devastating earthquakes occurred in Chiayi in 1940, in Tainan in 1946, and in Tainan and Chiayi in 1964. The 1999 Chi-Chi Earthquake resulted in the death of 2,434 people and nearly 11,000 buildings collapsed. Though each of these earthquakes caused heavy casualties and property losses, modern technologies remain unable to predict earthquakes and make evacuation plans. Seismological monitoring networks, historical earthquake data, and local geological conditions are required in order to determine potentially hazardous areas and make earthquake rescue plans.

Similar to Taiwan, Japan is also located on the Pacific seismic belt and is profoundly affected by earthquakes. The Japan Meteorological Agency (JMA) constructed an Earthquake Early Warning (EEW) system in October 2007 to reduce earthquake disasters, and promoted the system throughout Japan. This EEW system can issue effective warnings mainly because a good concentration of seismic stations (approximately one station every 20 km) has been established by the JMA and computers can rapidly pinpoint the location of the earthquake and hence determine the path of seismic wave propagation. Because seismic waves generated from seismic sources propagate within earth, the wave speed is affected by various stratum media of dissimilar features. Seismic waves can be categorized into P- and S-waves. The speed of P-waves is approximately 5 to 7 km/sec, while the speed of S-waves, which can easily damage the earth’s surface, is approximately 3 to 4 km/sec. This study develops an Earthquake Early Warning System (EEWS) by taking advantage of the speed difference between P- and S-waves. The EEWS estimates the arrival of S-waves based on P-waves information collected in the very early stage of an earthquake event, and predicts the potential structural damage of buildings due to S-waves arrival to reduce the socio-economical impact of earthquakes on the affected region by increase the response time before the peak earthquake tremble strikes.

2. DEVELOPMENT OF THE EARTHQUAKE EARLY WARNING SYSTEM IN TAIWAN

The Central Weather Bureau of Taiwan has already established a centralized seismography network and a regional Earthquake Early Warning System. The regional EEW system can monitor and analyze earthquake data collected from seismometers distributed throughout Taiwan, and warning can be issued following the computer calculation. With the data collected from multiple seismometers, the accuracy of the earthquake alarm is secured. On the opposite side, data collection and calculation with the multiple inputs requires some time. For inland earthquakes, the average time for data processing is approximately 18 to 20 seconds; however, seismic waves may have travelled a considerably long distance during this period of time, and areas in the proximity of epicenters (say, within a radius of 50~70km) would not receive warnings before peak seismic trembles strike. These areas are called the “blind zone” of earthquake warning systems. The island of Taiwan is relatively small; its dimensions in the north-south and east-west directions are about 300 km and 100 km, respectively. The epicenters of disastrous earthquakes are primarily located within the island. For example, the epicenter of the Chi-Chi Earthquake in 1999 was in the Chi-Chi Township; its blind zone potentially includes regions from Hsinchu County to Tainan County, and unfortunately this blind zone is also the area most severely hit by the earthquake. Therefore, to minimize the blind zone is a critically important task. Thus, the National Center for Research on Earthquake Engineering began to develop an on-site earthquake early warning system. As aforementioned, the development of the On-site Earthquake Early Warning System (On-site EEWS) takes advantage of the speed difference between P- and S-waves. The EEWS estimates the arrival of S-waves based on P-waves information collected in the very early stage of an earthquake event, and predicts the potential structural damage of buildings due to S-waves arrival to reduce the socio-economical impact of earthquakes on the affected region by increase the response time before the peak earthquake tremble strikes. As only the data collected by on-site seismic sensor is used, the data processing time is dramatically reduced, and the quake alarm can be issued earlier such that the area of the blind zone can be reduced.

3. DEVELOPMENT OF THE ON-SITE EARTHQUAKE EARLY WARNING SYSTEM IN NCREE

The On-site Earthquake Early Warning System includes the trigger module, on-site EEW algorithm, rapid prediction of structural response and automatic broadcast / disaster reduction control. Figure 1 shows the framework of the On-site EEWS proposed by NCREE. The trigger module is able to separate valuable earthquake signals from the noise induced by human and/or vehicles. Two on-site EEW algorithms (body wave method and artificial neural network, or NN in short) are used to predict earthquake parameters (magnitude, intensity, etc.) from the waveform of P-waves. Using the signals of the wave profile, they estimate the seismic intensity and scale of subsequent earthquakes. These two methods have been used to study and test hundreds of thousands of earthquake records over the years in Taiwan; these methods have accurately and effectively estimated earthquake parameters, such as the scale and intensity of earthquakes. The rapid prediction of structural response can provide the estimation of the structural response at any position of the structure in a few milliseconds. With this module, the floor response at any point of the structure can be predicted and the important facilities and high-tech factory can take suitable measures to reduce the seismic loss. Three different methods (scenario simulation, simplified formulation and NN) are used in this module. The scenario simulation and NN need to run lots of simulations (such as FEM analysis and model training) in advance. As a result, it can get a good prediction and be very useful for the high-tech factory and power plant. The simplified formulation method assumes the structure as a simplified beam element and can get a quick and approximate estimation. As this method can fit most types of normal structures and less computation in advance, it is suitable for the generic stock of regular structures. As the response time of the EEWS is always very limited (about 10~30 sec), how to respond in such an extremely short notice is critically important. The last module is the automatic broadcast / disaster reduction control system. It can broadcast the earthquake alarm through sound, LED display, TV, SMS, E-mail, etc. At the same time, the exit door will open automatically and emergency lights along the escape route are turned on. The gas is shut down. The elevator parks at the next closest floor and the elevator door opens, etc. All these automatic systems can help people reduce seismic loss using very limited response time. After the development of the software, the National Center for Research on Earthquake Engineering started to conduct the integration test with an embedded real-time calculation platform (dSPACE, Micro-box) to link the on-site high-precision seismometers and embed the warning technology into the real-time computing core to further implement the related technologies. The photos of the real-time calculation platform “MicroBox” and seismometer EpiSensor ES-T used in this study are shown in Figure 2. The specification of MicroBox x86Based real-time computation platform is listed in Table 1. The specifications of EpiSensor ES-T are listed in Table 2. The on-site high-precision seismometer can collect the micro-vibration of P-wave. The trigger and On-site EEW algorithm are embedded into the real-time computational platform. As a result, a rapid and reliable computation can be expected. The real-time computational platform (MicroBox) can output the signal to drive the automatic broadcast / disaster reduction control system when the alarm is issued.

Table 1. Specifications of MicroBox x86Based real-time computation platform

A/D	8 channels, +/-10 volts, 16 bits, single-ended
D/A	4 channels, +/-10 volts, 16 bits
Encoder	4 channels, 24 bits, 0V/5V, A/B/Index
DI/O	16 channels (8 from parallel-port), TTL
Can	2 ports, CAN2.0b compatible, speed up to 1Mbps
Size	255(W) x 152(D) x 82(H) mm, 2.0 kg
Power consumption	9~36 volts, Min. 50 W

Table 2. Specifications of EpiSensor ES-T

Dynamic range	155 dB+
Bandwidth	DC to 200 Hz
Full-scale range	± 0.5g (User selectable)
Linearity	< 1000 µg/g2
Hysteresis	< 0.1 of full scale
Power consumption	35mA from +/- 12V (Low Noise Amp)
Cross-axis sensitivity	< 1% (including misalignment)
Zero point thermal drift	< 500 µg/°C (1g sensor)
Physical size	13.3 cm diameter, 6.2 cm high

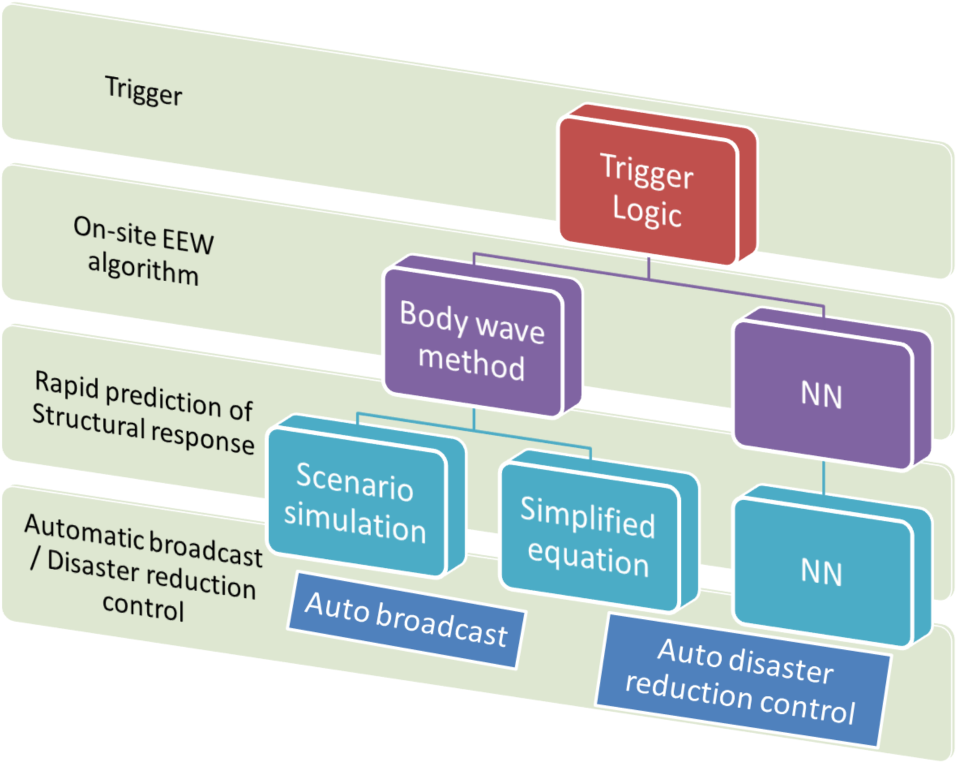


Figure 1. Framework of On-site EEWS proposed by NCREE

Figure 2. MicroBox x86Based real-time computation platform (left) and EpiSensor ES-T (right).

3. VERIFICATION OF THE ON-SITE EEWS

The feasibility and reliability of the entire On-site Earthquake Early Warning System must be verified before it is implemented in the field. Three steps of verification tests were done step by step. The first step of the verification test combined the high-precision seismometer (EpiSensor ES-T) and MicroBox x86Based real-time computational platform, and was tested on the shaking table. Forty earthquake records were tested repeatedly five times each (i.e., 40*5 = 200 tests). Figure 3 shows the relation of alarm time vs. epicentral distance and compares the estimated and actual intensities. According to the figure, the alarm time is longer when the epicentral distance is farther and the results of the five repetitive tests were fairly similar, which means that the proposed system is reliable and repeatable. Most of the estimated intensities were within in the allowable range (i.e., actual intensity ± 1).

The second step is the integration test of the whole system. It includes a high-precision seismometer (EpiSensor ES-T), MicroBox x86Based real-time computational platform and an automatic broadcast / disaster reduction control system. All these items were installed in a demonstration house tested on the tri-axial shaking table at NCREE. Taking the 1999 Chi-Chi Earthquake for example, employing the system could provide an additional 7s, 17s, and 27s of early warning time for Dali Township in Taichung County, the Hsinchu Science Park, and Da-an District in Taipei City, respectively. Figure 4 shows the response time provided by the proposed on-site EEWS in different locations. The response time provided by the proposed system is considerably lengthened, compared to the existing seismic warning system of Taiwan High Speed Rail Corporation (i.e., ground acceleration > 40gal). Figure 5 shows that, in case of the Chi-Chi Earthquake, the proposed earthquake early warning system is able to issue a warning of seismic attack 34.02s before the peak S-wave trains arrive in Taipei County. Compared to the existing warning system of Taiwan High Speed Rail Corporation, the proposed earthquake early warning system provides an additional 27.3s of response time. The on-site EEWS was first introduced to the general public through a press conference on Feb. 22, 2012 at NCREE. The on-site EEWS and the automatic disaster reduction control and warning system were installed in the demonstration house and tested on the shaking table as shown in Figure 6. The integrated on-site EEWS could provide the early earthquake warning through broadcast, TV and LED text display. Before the destructive S-wave arrival, the proposed system issued an alarm, the elevator parked on the next closest floor, the door opened, the gas was shut down, the emergency lights along the escape route were turned on, and the LED display and audio broadcast system automatically sent the warning message. All the automatic control system and warning system can help people use the limited response time and hence dramatically reduce the seismic loss. To further verify the earthquake early warning system and to promote earthquake awareness education, this project established nine EEWS demonstration stations in Fanghe Junior High School in Taipei City, Yilan Elementary School in Yilan City, Luodong Branch of Secom Ltd., National Kang Ping Elementary School and Chung Cheng University in Chiayi, Hualien Train Station, Guangfu Elementary School in Hualien county, etc. Figure 7 shows the framework of the EEWS demonstration station. Each of the demonstration stations can simultaneously receive regional Earthquake Early Warning messages issued by the Central Weather Bureau and on-site Earthquake Early Warning messages provided by the National Center for Research on Earthquake Engineering. Both the CWB-operated regional system and on-site EEWS can trigger the alarm. The seismic broadcast system and LED display will immediately announce the earthquake warning to people nearby the demonstration station. The affected people can also receive short text messages and e-mails via cellular phones. While building on-site EEWS machines, NCREE also helped to train school teachers and students to use the system for earthquake preparedness and practicing emergency evacuation in case of an earthquake attack according to the earthquake drill plan at schools. Earthquake drills involving the school staffs and students utilizing the proposed EEWS have been held at least once a year at each demonstration station to reinforce earthquake awareness through sufficient practices.

Figures 8 and 9 show the real earthquake events recoded by the EEWS demonstration station. A 5.8-magnitude sensible earthquake occurred at 10.1km southeast of Yilan County on April 30, 2011. The three seismic stations including Yilan Elementary School, Chung Cheng University, and Luodong Branch of Secom Ltd. all functioned well and successfully issued earthquake warnings. Figure 8 shows the measured acceleration records at Luodong Branch of Secom Ltd. in the north-south, east-west, and up-down directions. The red arrow indicates the time when the alarm was issued and estimation of seismic intensity was announced. The green arrow indicates the time of peak vibration and the measured seismic intensity. It can be seen that the estimated seismic intensity agreed well with the measured intensity. Luodong Branch of Secom Ltd. is located only 3km from the epicenter, but it still had 9.07s of response time before the peak tremble came. National Chung Cheng University, which was 187km away from the epicenter, had 28s of response time. According to the long-term test results (~200 cases), the proposed on-site EEWS has reached an 80% successful rate of accurately predicting the earthquake intensity levels, and is able to send an alarm signal at least eight seconds before the peak S-wave comes even in the proximity of the earthquake epicenter.

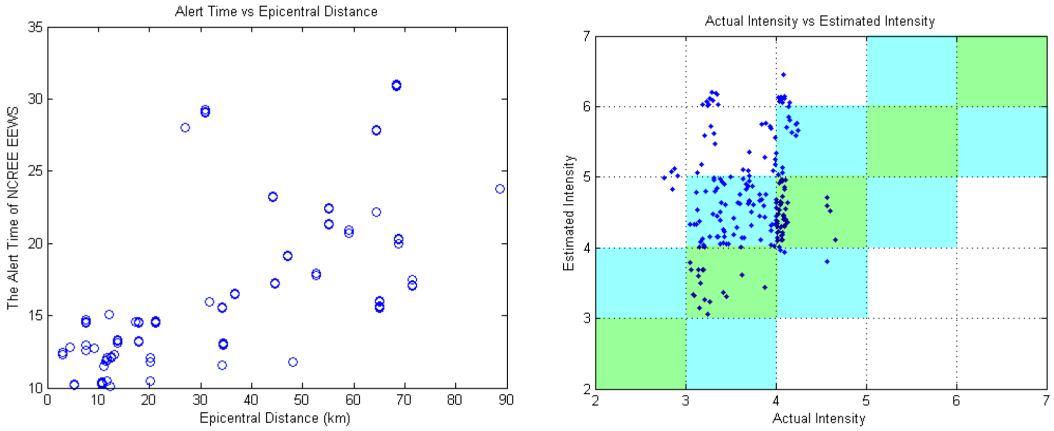
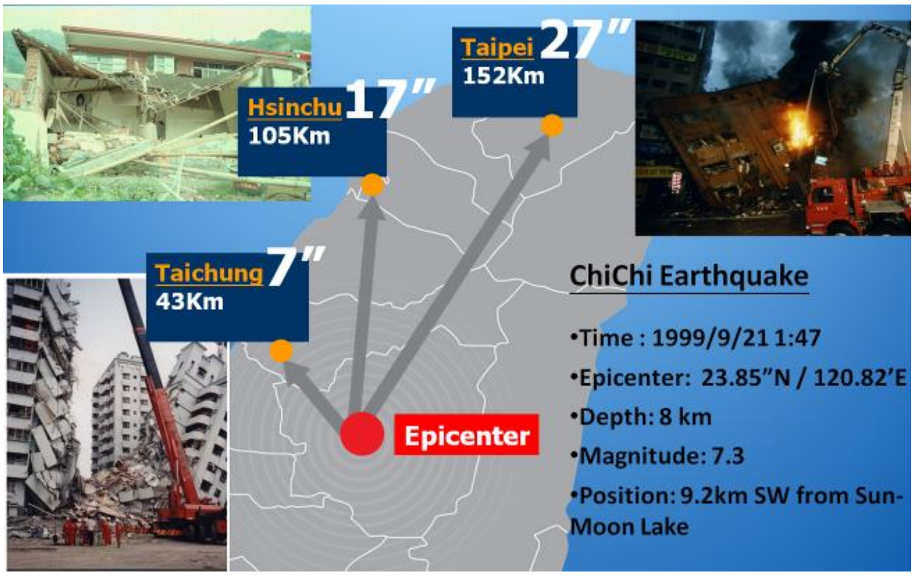


Figure 3. Validation test results from the shaking table: (1) Relation of alarm time vs. epicentral distance (left); (2) Comparison of estimated and actual intensities (right).



ChiChi Earthquake
- Time : 1999/9/21 1:47
- Epicenter: 23.85"N / 120.82'E
- Depth: 8 km
- Magnitude: 7.3
- Position: 9.2km SW from Sun-Moon Lake

Figure 4. The response time provided by the proposed on-site EEWS in case of the historical Chi-Chi earthquake.

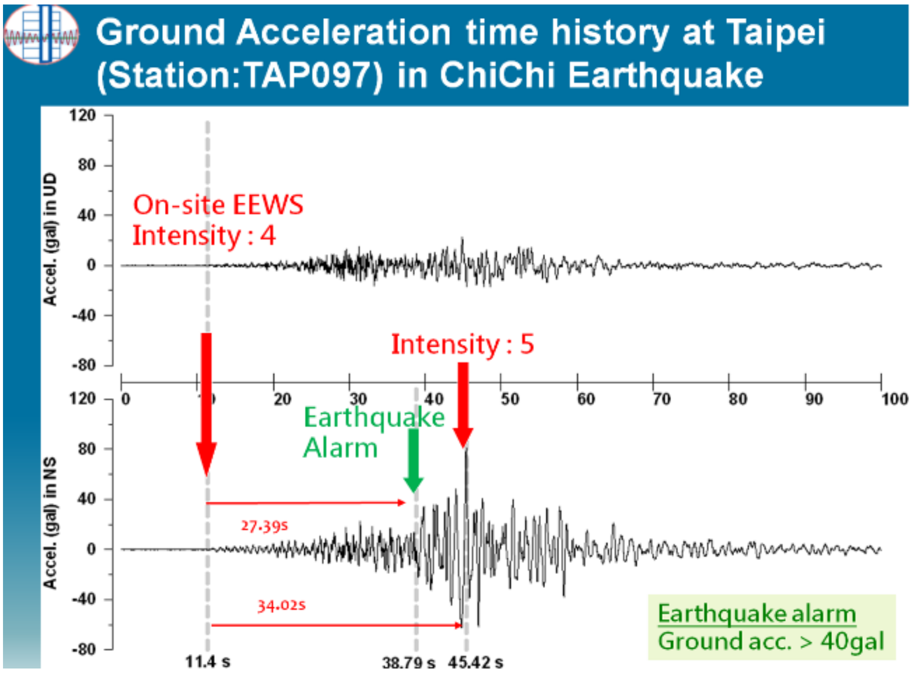


Figure 5. Ground acceleration time histories and the alarm message.

Figure 6: The EEWS press conference and demonstration test on NCREE’s shaking table.

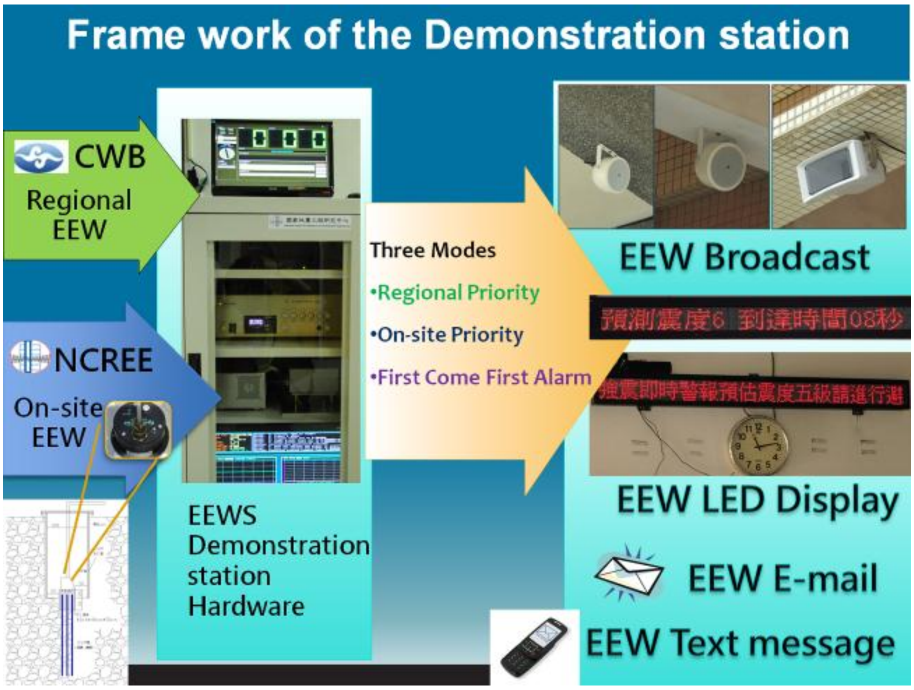


Figure 7: The framework of the EEWS demonstration station.

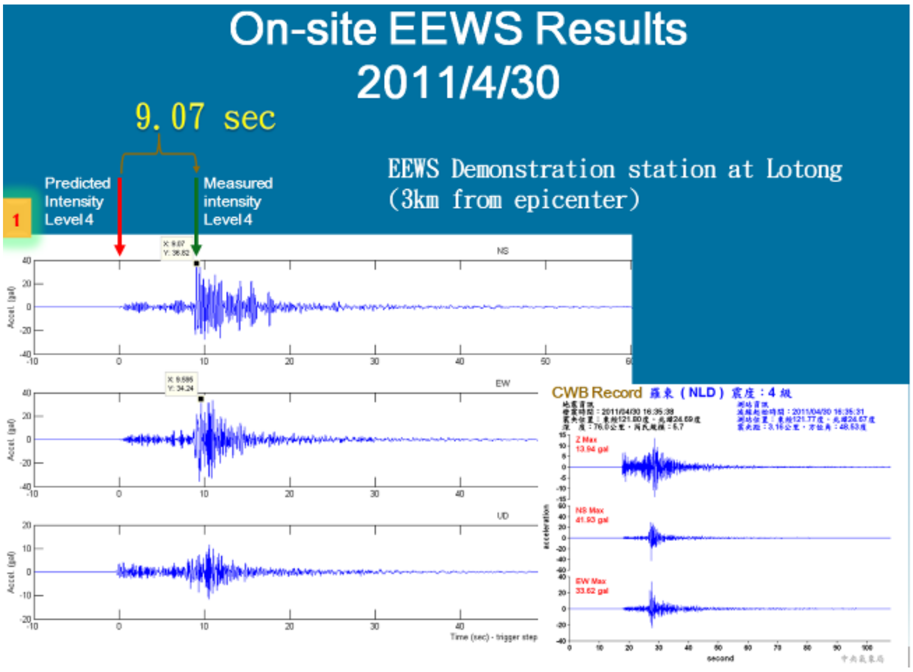


Figure 8: The recorded time histories of ground acceleration at Luodong Branch of Secom Ltd. on April 30, 2011.

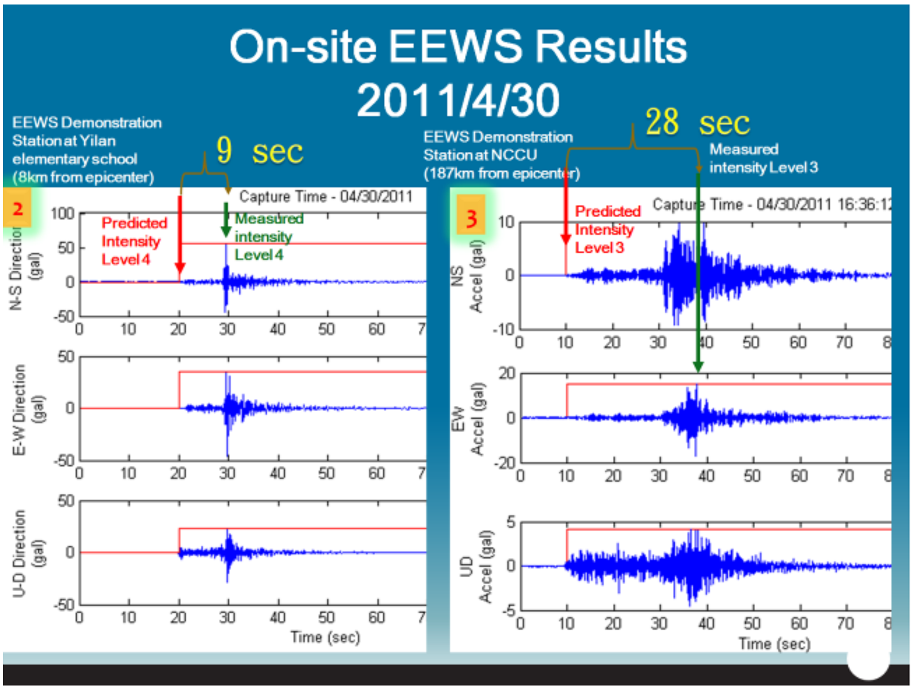


Figure 9: The recorded time histories of ground acceleration
at Yilan Elementary School and National Chung Cheng University on April 30, 2011.

4. CONCLUSIONS

Because of seismotectonic setting in the surrounding area of Taiwan, earthquakes occur frequently in the country. The Central Weather Bureau of Taiwan collated earthquake data from 1901 to 2006 and found that 97 damaging earthquakes had occurred, 52 of which had actually resulted in life casualties. The 1999 Chi-Chi Earthquake had the most profound socioeconomic impact. Because big earthquakes have tremendously destructive power, disaster prevention is crucial; nevertheless, current human technologies cannot provide precise early warnings well in advance. The proposed earthquake early warning system can provide from a few to tens of seconds of warning time before the peak tremor of an earthquake arrives. Although the warning time is short, it is still sufficient for implementing disaster prevention measures and finding body covers. The National Center for Research on Earthquake Engineering has studied the core technologies for over 10 years; the proposed on-site EEWS has passed the validation tests using the tri-axial shaking table. The integrated on-site EEWS can automatically announce an early earthquake warning through broadcast, TV and LED text display. Also, it can automatically park the elevator, shut down the gas, switch off the electricity power, open the exit door, and turn on the lights along the escape route. Combining the on-site EEWS and disaster reduction control system, the life and economic loss can be greatly reduced. According to the validation test results, the proposed on-site EEWS has reached an 80% successful rate of accurately predicting the earthquake intensity levels, and is able to automatically send an alarm message at least eight seconds before the peak S-wave trains come even in the proximity of the earthquake epicenter. The National Center for Research on Earthquake Engineering of Taiwan is currently promoting and dispatching the EEWS machines to provide the Taiwanese people with more advanced disaster prevention devices and to reduce the damage caused by future earthquakes.

REFERENCES

Allen, R. M. (2007), The ElarmS Earthquake Early Warning Methodology and Application across California, Earthquake Early Warning Systems, P. Gasparini, G. Manfredi, J. Zschau (Eds), 21-44.

Bana-Hani, K., Ghaboussi, J. and Schnider, S.P. (1999a), Experimental Study of Identification and Control of Structures Using Neural Networl Part 1: Identification, Earthquake Engng. Struct.Dyn. 28(9), 995-1018.

Blume, J. A. (1968) “Dynamics Characteristics of Multi-story Buildings”, Journal of the Structural Division, ASCE, 94, 337-402.

Chassiakos, A. G. and Masri, S. F. (1996), Modeling Unknown Structural Systems Through the Use of Neural Networks, Earthquake Engng. Struct.Dyn. 25, 117-128.

Huang, C. S., Hung S. L., Wen, C. M., Tu, T. T. (2002), A neural network approach for structural identification and diagnosis of a building from seismic response data, Department of Civil Engineering, National Chiao Tung University, Taiwan.

Joghataie, Ghaboussi, J. and Wu, X. (1995) "Learning and architecture determination through automatic node generation," International Conference on Artificial Neural Networks in Engineering, ANNIE '95, St. Louis, Missouri.

Learh, R. R. Jr. and Dowla, F. U. (1996), Earthquake Early Warning System Using Real-time Signal Processing, IEEE Workshop on Neural Networks for Signal Processing.

Lin, C. C. J. (1999) "A neural network based methodology for generating spectrum compatible earthquake accelerograms" PhD thesis, Dept. of Civil and Environmental Engineering, Univ. of Illinois at Urbana Champaign, Urbana, Illinois.

Wurman, G., Allen, R. M. and Lombard, P. (2007), Toward earthquake early warning in northern California, Journal of Geophysical Research, Vol. 112, B08311.