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Performance of On-site Earthquake Early Warning Systems for Different Sensor Locations

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Abstract**—**Regional earthquake early warning (EEW) systems are not suitable for Taiwan, as most destructive seismic hazards arise due to in-land earthquakes. These likely cause the lead-time provided by regional EEW systems before a destructive earthquake wave arrives to become null. On the other hand, an on-site EEW system can provide more lead-time at a region closer to an epicenter, since only seismic information of the target site is required. Instead of leveraging the information of several stations, the on-site system extracts some P-wave features from the first few seconds of vertical ground acceleration of a single station and performs a prediction of the oncoming earthquake intensity at the same station according to these features. Since seismometers could be triggered by non-earthquake events such as a passing of a truck or other human activities, to reduce the likelihood of false alarms, a seismometer was installed at three different locations on the same site and the performance of the EEW system for these three sensor locations were discussed. The results show that the location on the ground of the first floor of a school building maybe a good choice, since the false alarms could be reduced and the cost for installation and maintenance is the lowest.

Keywords**—**Earthquake early warning, Single station approach, Seismometer location

I. Introduction

OVER the last two decades, effective EEW techniques have emerged due to advancements in digital seismology, communications, automatic processing, and algorithms for the rapid estimation of earthquake parameters [1]. Based on the requirements of information for algorithms to estimate earthquake parameters, EEW techniques can be divided into two groups: regional warning and on-site warning. Generally, since regional warning techniques leverage information of several stations next to the epicenter, the accuracy of earthquake parameter estimation of regional warning techniques is usually higher than that of on-site warning techniques. However, for regions closer to the epicenter where seismic intensity is usually much higher than regions outside, the lead-time before a destructive wave arrives provided by a regional warning can be null. On the other hand, an on-site warning can provide more lead-time at the region closer to an epicenter since only the seismic information on the target site is required. Therefore, an increase in accuracy and lead-time of an on-site warning is a key point in improving the effectiveness of EEW techniques.

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An on-site warning system issues an alarm a few seconds after a trigger based on the initial P-wave motion at a single station. According to the records of EEW stations at the National Center for Research on Earthquake Engineering (NCREE), the present on-site warning system may be triggered by certain vibration signals that are not caused by an earthquake movement, which may consequently lead to many false alarms at the station. Normally, seismometers for EEW systems are mounted on a surface of a free field where no civil structures are around within a certain range. However, these seismometers could be triggered by non-earthquake events. The EEW stations of NCREE in Taiwan are mostly implemented at schools where regular human activities take place. In order to reduce the possibility of false alarms due to non-earthquake events, a seismometer was installed at three different locations, namely on the ground of the first floor of a school building, on a concrete foundation with a depth of 2 meters, and in a downhole with a depth of 40 meters. This paper discusses the performance of the EEW system for these three sensor locations.

II. Prediction Methods for On-Site EEW Systems

A. Support Vector Regression Method

Recently, a new method for the estimation of seismic intensity using support vector regression (SVR) was developed [2]. Estimating the predicted peak ground acceleration (PGA) based on the SVR method is achieved by two steps. The first step extracts six P-wave features from the first three seconds of the vertical ground acceleration after the arrival of the P-wave. The second step predicts the PGA using a regression model established by supervised learning with the P-wave features as the inputs. The six P-wave features are the predominant period (TauC), peak acceleration (Pa), peak velocity (Pv), peak displacement (Pd), cumulative absolute velocity (CAV), and the integral of the squared velocity (IV2). The peak values, Pa, Pv, and Pd are defined as the maximum values of absolute acceleration, absolute velocity, and absolute displacement, respectively. The other related formulae are summarized as:

$$\mathrm{TauC} = 2\pi/\gamma, \gamma = \int_0^3 \dot{u}^2(t)dt / \int_0^3 u^2(t)dt \quad (1)$$

$$\mathrm{CAV} = \int_0^3 |\ddot{u}(t)| dt \quad (2)$$

$$IV2 = \int_0^3 \dot{u}^2(t)dt \quad (3)$$

B. TauC-Pd-Attenuation Method

There are three steps in predicting the PGA via the TauC-Pd-Attenuation (TPA) method. First, TauC and Pd are calculated from the first three seconds of the vertical ground acceleration after the arrival of the P-wave. Second, the earthquake magnitude (M) and the hypocenter distance (R) are inferred through the following formulae [3]:

$$M = 3.09 \times \log(TauC) + 5.3 \quad (4)$$

$$\log(Pd) = -3.801 + 0.722 \times M - 1.444 \times \log(R) \quad (5)$$

Finally, the PGA is estimated according to the attenuation law in Taiwan [4] as:

$$PGA = 0.00284 \times e^{1.73\times M} \times \left[R + 0.0999 \times e^{0.772\times M}\right]^{-2.06} \quad (6)$$

III. On-Site Data of Different Sensor Locations

NCREE has constructed several on-site EEW systems at elementary schools and junior high schools in Taiwan. In order to investigate the performance of an on-site EEW system, the system at the I-Lan elementary school was chosen because it was the only station with three sensor locations installed in three different stages. At the original stage, a seismometer was mounted on the ground of the first floor of the school building (Fig. 1). At this station, only the TPA method was implemented in the EEW system. Due to the intrinsic characteristic of the TPA method, once the system was triggered by small vibrations, there was a high likelihood of issuing a false alarm. Therefore, the seismometer was moved to the surface of a concrete foundation with a depth of 2 meters (Fig. 2) in the second stage. However, a certain ratio of false alarms was still present. Therefore, another strategy, which utilized a seismometer in a downhole with a depth of 40 meters, was employed (Fig. 3) in the third stage. The number of trigger events became infrequent; hence, almost no false alarms were anticipated. However, the cost of installation and maintenance was greatly increased. The cost of installation of the seismometers in these three stages in Taiwan is summarized in Table I.

TABLE I
Cost of Installation of Seismometers

Stage	Sensor location	Cost (USD)
I	On the ground of the first floor of a school building	100
II	On the surface of a concrete foundation with a depth of 2 meters	3,000
III/III'	In a downhole with a depth of 40 meters	20,000

To determine whether or not vibration data is caused by an earthquake event, the time of the occurrence of the recorded data is compared with the time recorded by the Central Weather Bureau Seismic Network (CWBSN), along with an examination of the acceleration signal. Since the locations of the on-site station and the CWBSN station are not the same, the separate times are compared by compensating for the time difference due to the two distances from the epicenter to the stations. If the times of occurrence of the data correspond to each other and the signal is similar to an earthquake event, the corresponding data is then regarded as "earthquake (EQ)" data. The remaining data of the on-site stations is considered as "Unknown" data.

TABLE II
Summary of Performance of Seismometers at Different Locations

Stage	STA/LTA ratio for trigger	"EQ" data per month	"Unknown" data per month	False Positive alarm due to "Unknown" data per month using TPA method	False Positive alarm due to "Unknown" data per month using SVM method
I	0.012	13.59	51.56	1.17	0
II	0.021	7.41	385.24	1.06	0.18
III	0.021	2.26	0.14	0	0
III'	0.016	0.92	661.13	330.99	0

Fig. 1 A seismometer was mounted on the ground of the first floor of the school building in the first stage

Fig. 2 A seismometer was mounted on the concrete foundation with a depth of 2 meters in the second stage

Fig. 3 A seismometer was installed in the downhole with a depth of 40 meters in the third stage.

IV. Performance of the EEW System for Different Sensor Locations

During the first stage from 28th March 2011 to 5th August 2011, 278 data values were triggered and recorded within 128 days, or approximately four months. The number of EQ data and Unknown data were 58 and 220, respectively. The average number of Unknown data per day was approximately 1.72. The criterion for triggering the seismometers was based on the ratio of the short-term average over the long-term average (STA/LTA) of the signal. The predicted PGA using the TPA method and the corresponding measured PGA are plotted in Fig. 4. In all the figures, the triangles represent the earthquake data that correlated to the CWBSN data, while the circles represent the Unknown data. The red solid triangles and the black circles are used to emphasize the estimated PGAs that were located in the false positive area. The regions enclosed by the blue lines and the red lines are within a zero- and one-level difference of the seismic intensity (SI) scale of Taiwan for reference, respectively. In general, the EEW system triggers an alarm when $SI_{predicted} \geq 4$ at on-site stations. Therefore, in this study, only earthquake data with $SI_{predicted} \geq 4$ is of concern, especially for the Unknown data. The prediction outcome is defined as a false positive alarm when $SI_{predicted} \geq 4$ and $SI_{predicted} - SI_{measured} \geq 2$. In addition, the corresponding region is defined as a false positive area, which is the upper left area enclosed by the black dashed lines in Fig. 4.

It can be observed in Fig. 4 that there are five Unknown data values that lie in the false positive area. This means that on average, more than one false positive alarm could be issued every month if the threshold for earthquake emergency action is set to be $SI_{predicted} \geq 4$. This could be problematic as the school schedule could be adversely affected. On the other hand, if the SVM method is employed during stage one, the predicted PGA using the SVM method can also be calculated off-line with almost no error [5]. The predicted PGA using the SVM method and the corresponding measured PGA are plotted in Fig. 5. As can be observed in Fig. 5, no Unknown data lies in the false positive area. However, the SVM has not been developed during that period.

During the second stage, the seismometer was moved to the surface of a concrete foundation with a depth of 2 meters. From 15th November 2011 to 5th April 2012, 2,225 data values were triggered and recorded within 170 days, or approximately six months. The numbers of EQ data and Unknown data were 42 and 2,183, respectively. The average number of Unknown data per day was approximately 12.84, which was much higher than the first stage, even though the STA/LTA trigger threshold was higher than during the first stage. The predicted PGA using the TPA method and the corresponding measured PGA are plotted in Fig. 6. It can be observed in Fig. 6 that there are six Unknown data values that lie in the false positive area. Similar to the one in the first stage, on average about one false positive alarm could be issued every month if the threshold for earthquake emergency action is set to be $SI_{predicted} \geq 4$. The likelihood of issuing false alarms does not vary significantly. The predicted PGA using the SVM method and the corresponding measured PGA are plotted in Fig. 7. There is only one Unknown data value that lies in the false positive area, and it is very close to the boundary. Nevertheless, the likelihood of false alarms was much smaller using the SVM method when the seismometer was mounted on the surface of a concrete foundation with a depth of 2 meters.

During the third stage, the seismometer was installed in a downhole with a depth of 40 meters. From 30th November 2012 to 30th June 2013, only 17 data values were triggered and recorded within 212 days, or approximately seven months. The numbers of EQ data and Unknown data were 16 and 1, respectively. The average data per day was less than 0.01, which is much lower than that in the first stage. The predicted PGA using the TPA method and the corresponding measured PGA are both plotted in Fig. 8. It can be observed in Fig. 8 that there are no Unknown data values that lie in the false positive area. The likelihood of issuing false alarms is almost eliminated. Both the predicted PGA using the SVM method and the corresponding measured PGA are plotted in Fig. 9. As expected, no Unknown data values lie in the false positive area. It seems that the likelihood of issuing false alarms is almost zero while the ability to issue early warnings for an earthquake remains functional.

As shown in Table II, the largest number of earthquakes is triggered by the seismometer on the ground. This may be because the STA/LTA trigger threshold is the smallest one. Note that the number of earthquakes triggered by the downhole seismometer is much less than the number triggered by the other two stages. It can also be noted that most of the SI of the earthquakes triggered by the downhole seismometer was greater than 1, which means that many earthquakes with SI=1 are not recorded when the downhole seismometer is used, as shown in Fig. 8. In order to improve the sensitivity of the EEW system to earthquakes, the STA/LTA trigger threshold was decreased to 0.016 in stage III' from 1st July 2013 to 28th July 2014. However, this did not increase the number of triggered EQ data values but the number of Unknown data and the likelihood of issuing false alarms greatly increased.

Comparison of the predicted PGA using the TPA method in Fig. 10 with those in Fig. 4 and Fig. 6 shows that the predicted PGA is even higher when the seismometer was installed in the downhole with a depth of 40 meters in stage III'. This high likelihood of false alarms is undesirable and should be avoided. On the other hand, the predicted PGA using the SVM method and the corresponding measured PGA are plotted in Fig. 11. As expected, no Unknown data value lies in the false positive area even when a large amount of Unknown data was triggered in stage III.

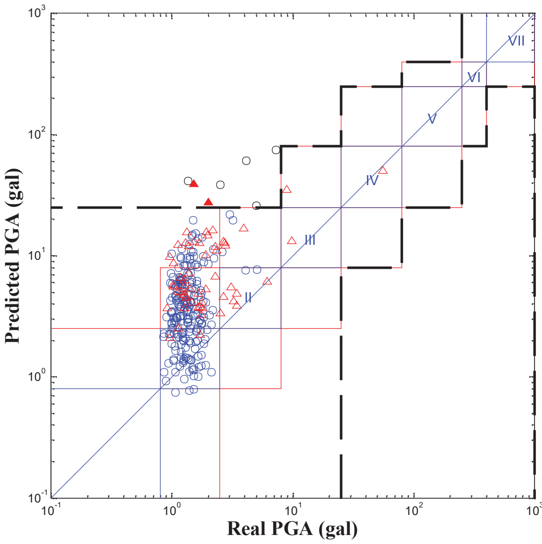

Fig. 4 Measured PGA and predicted PGA values using the **TPA** method when the seismometer was mounted on the ground in the first stage

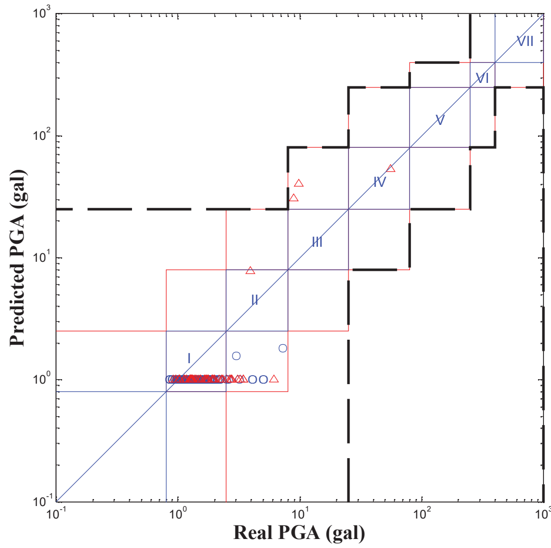

Fig. 5 Measured PGA and predicted PGA values using the **SVM** method when the seismometer was mounted on the ground in the first stage

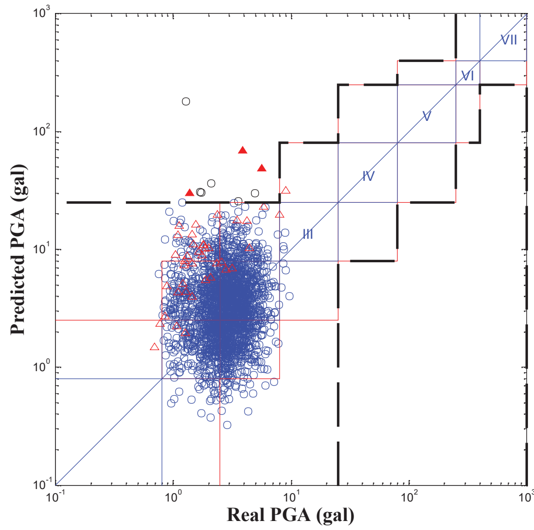

Fig. 6 Measured PGA and predicted PGA values using the **TPA** method when the seismometer was installed at a depth of 2 meters in the second stage

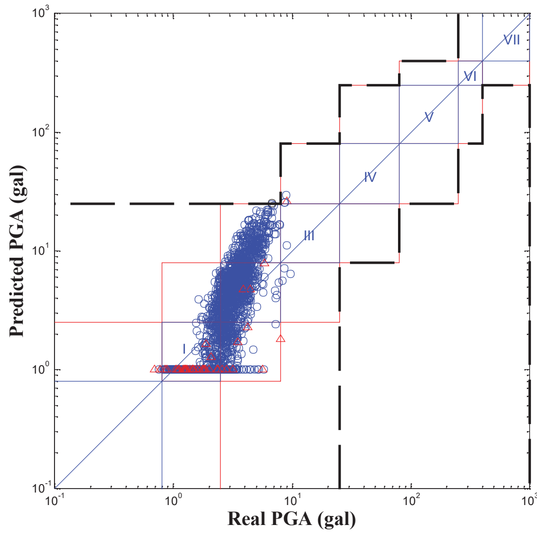

Fig. 7 Measured PGA and predicted PGA values using the **SVM** method when the seismometer was installed at a depth of 2 meters in the second stage

V. Conclusion

In order to reduce the possibility of false positive alarms of EEW systems, the National Center for Research on Earthquake Engineering (NCREE) in Taiwan has tried to install seismometers at three different locations in an on-site EEW station. The results show that if the TauC-Pd-Attenuation (TPA) method is employed to predict the PGA in the on-site EEW system, the likelihood of false positive alarms can be suppressed when a seismometer is installed in a downhole with a depth of 40 meters with an adequate STA/LTA trigger threshold. However, the cost of installation of the seismometer in the downhole with a depth of 40 meters is very high. Surprisingly, if the SVM method to predict PGA is employed in the on-site EEW system, the likelihood of false positive alarms is almost zero when the seismometer is installed at any of the three locations. Of course, the ability to issue early warnings for earthquakes remains functional. These findings imply that the seismometer can be installed just on the ground of the first floor of a school building with less cost and effort if the SVM method is employed. We plan to prove these findings further by establishing three EEW systems with three seismometers installed at these three different locations respectively at the same on-site EEW station in the near future. The adequate STA/LTA trigger threshold for these three EEW systems will be chosen individually to improve the performance of the EEW systems.

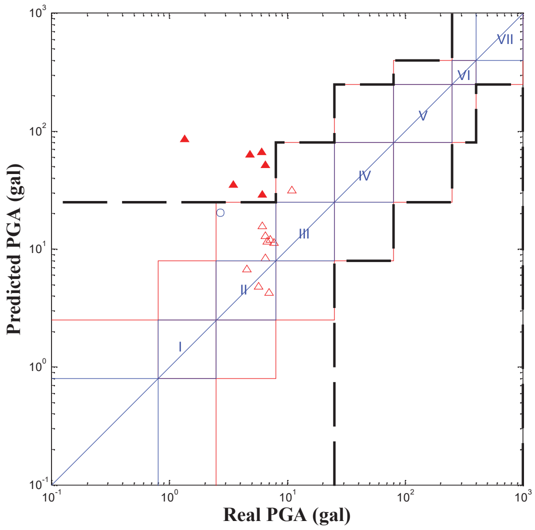

Fig. 8 Measured PGA and predicted PGA values using the **TPA** method when the seismometer was installed at a depth of 40 meters in the third stage

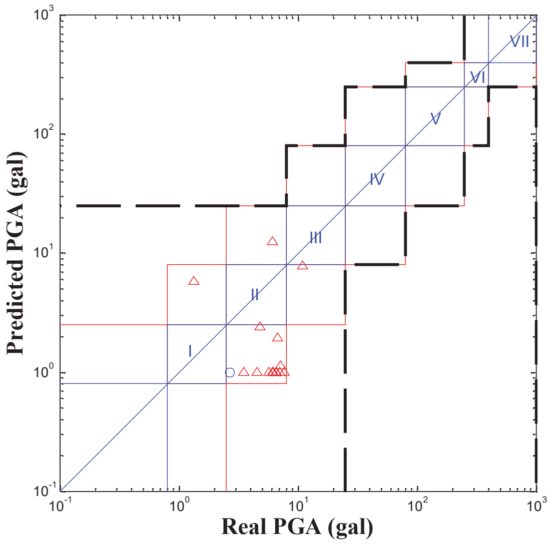

Fig. 9 Measured PGA and predicted PGA values using the **SVM** method when the seismometer was installed at a depth of 40 meters in the third stage

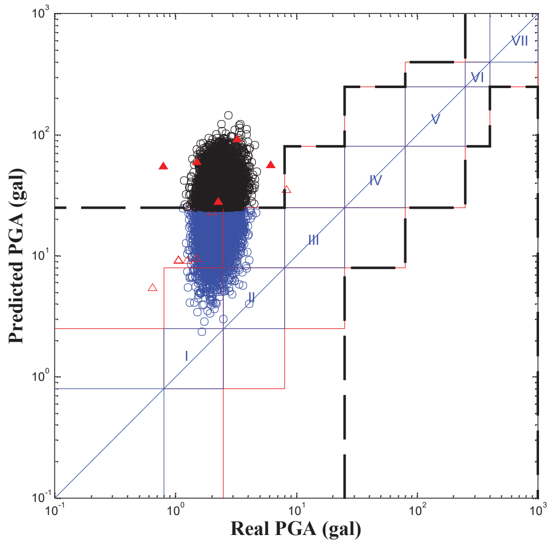

Fig. 10 Measured PGA and predicted PGA values using the **TPA** method when the seismometer was installed at a depth of 40 meters in the third stage with a smaller trigger threshold

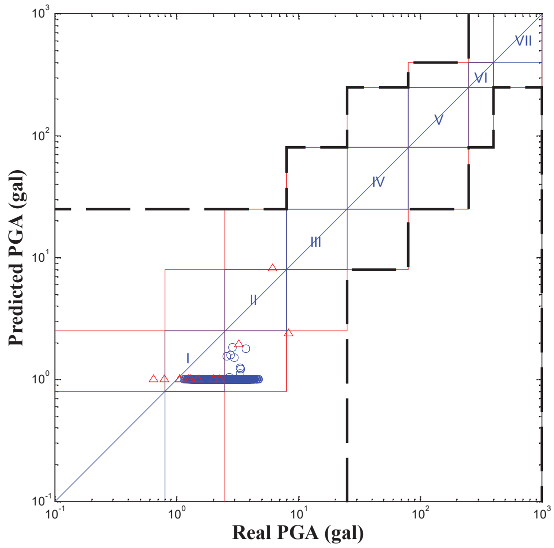

Fig. 11 Measured PGA and predicted PGA values using the **SVM** method when the seismometer was installed at a depth of 40 meters in the third stage with a smaller trigger threshold

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