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Reliability assessment on earthquake early warning: A case study from Taiwan

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ABSTRACT

Earthquake early warning (EEW) has been implemented in several regions around the world. However, because of natural randomness and uncertainty, false alarm and missed alarm can be expected in EEW. The key scope of this study is to evaluate the reliability of an on-site EEW in Taiwan, by testing the system's algorithm with 17,836 earthquake data from 1999 to 2013. The analysis shows that the on-site EEW system, empirically speaking, should have a false-alarm probability of 2.5%, and a missed-alarm probability of 14.1%. Considering missed alarm should be more critical to EEW, a new algorithm that could reduce the system's missed-alarm occurrences to 6% is also discussed in this paper.

1. Introduction

The region around Taiwan is known for high seismicity. As a result, a variety of earthquake studies were conducted for the region, including earthquake early warning [1–5]. Understandably, the working principle of earthquake early warning (EEW) is to send out warning messages to the public a few seconds before the arrival of peak ground shaking, utilizing the nature that radio waves can travel much faster than seismic waves [6]. Nowadays, EEW has been established in several regions around the world, including Taiwan, Japan, California, Mexico, Romania, and Turkey [7–16].

For example, Japan Railways first developed an alarm system along the tracks in the 1960 s to stop/deaccelerate moving trains immediately as long as the precursor threshold was exceeded by early earthquake motions [7]. By the current EEW characterizations, such a system is within the scope of on-site EEW, which relies on the precursor information detected at one site for EEW decision-making for the same site. On the other hand, the Japan Meteorological Agency (JMA) developed a different EEW approach by deploying a number of instrumentations along the east coast of Japan in an attempt to "dissect" occurring earthquakes in the offshore areas as early as possible (i.e., interpreting its magnitude and location). Then if the system judges a big earthquake is occurring, the information will be immediately sent out to high-speed trains with immediate deceleration in order to lower derailing likelihood as peak motions arrive [11]. But unlike the previous on-site system, the JMA system is referred to as a regional EEW by today's standard, utilizing ground motions that have been received by multiple stations closer to the earthquake to determine its magnitude and location as early as possible for EEW decision-making.

Like the JMA system, a similar EEW is now in operation in Mexico, by installing a number of instrumentations along the Guerrero Coast in an attempt to detect earthquakes in the offshore area as early as possible. Similarly, if a big earthquake is detected, early warning messages will be immediately sent out to the public of Mexico City for immediate responses and actions [13]. More recently, the CISN (California Integrated Seismic Network) EEW system in California is under testing, which is a new, hybrid system that integrates the essences of both on-site and regional systems into such a newly developed EEW approach [16].

Although earthquake early warning is considered a practical solution to earthquake hazard mitigation e.g., [13,17–21], its reliability is another research topic because not an EEW system can claim perfect accuracy without false/missed alarm. Therefore, in addition to methodology, the studies of EEW reliability have also been reported e.g., [22–27]. For example, Iervoline et al. (2009) [22] pointed out that ground motion prediction equations should play a more critical role than real-time estimations on earthquake magnitude and location, as far as regional EEW is concerned .

On the other hand, with the data from the PEER ground motion database (Pacific Earthquake Engineering Research Center), Wang et al. (2013) considered that using multiple precursors can predict

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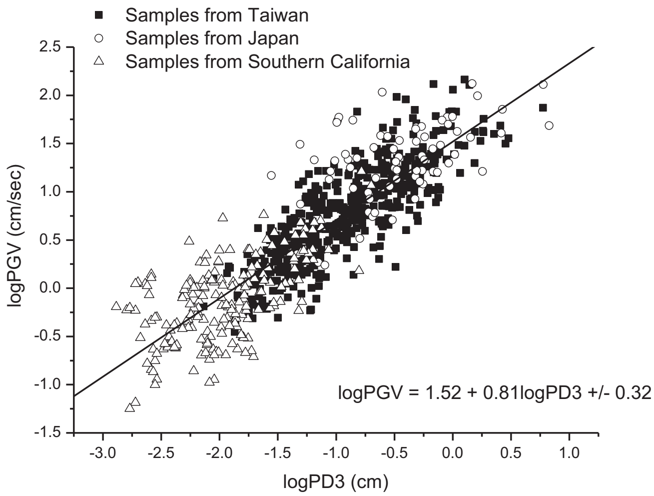

Fig. 1. A regression model between PGV and PD3 for on-site earthquake early warning (after Wu and Kanamori [29]).

earthquake peak motions more accurately, then increasing the reliability of an on-site system [23]. Note that such an approach and suggestion are similar to the study of Böse et al. (2009), pointing out that the false triggers can be substantially reduced by utilizing multiple precursors in the calculations [24]. Instead of focusing on improving the real-time estimation's accuracy, Wang et al. (2012) adopted a different approach in an attempt to improve the decision-making reliability of EEW from the perspective of risk reduction, which not only considers false-alarm and missed-alarm probabilities, but also the consequences of the two errors [25]. Other studies relevant to EEW reliability include the developments of the automated EEW decision-making for engineering purpose in particular [26], as well as the epistemic uncertainty issues, such as which empirical relationship should be used in the algorithm, that could also affect the reliability of EEW [27].

Different from those EEW reliability studies, the scope of this study is to evaluate the reliability of an on-site EEW system in Taiwan. In short, the methodology of the study is to test the system with historical data, then counting how many false alarms and missed alarms will be occurring among the 17,836 tests. The result shows that among the 17,836 tests, 437 false alarms and 2516 missed alarms would be occurring with the current algorithms, in corresponding to a false-alarm probability of 2.5%, and a missed-alarm probability of 14.1% from an empirical point of view.

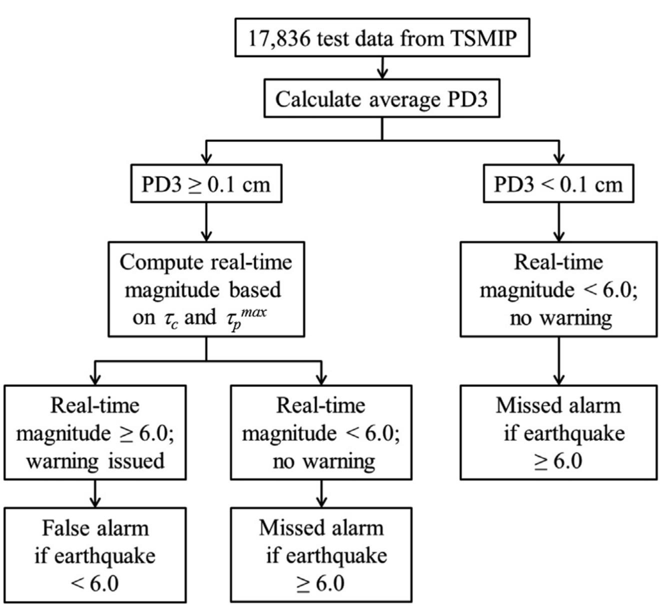

Fig. 2. The on-site EEW decision-making and the methodology of the reliability assessment.

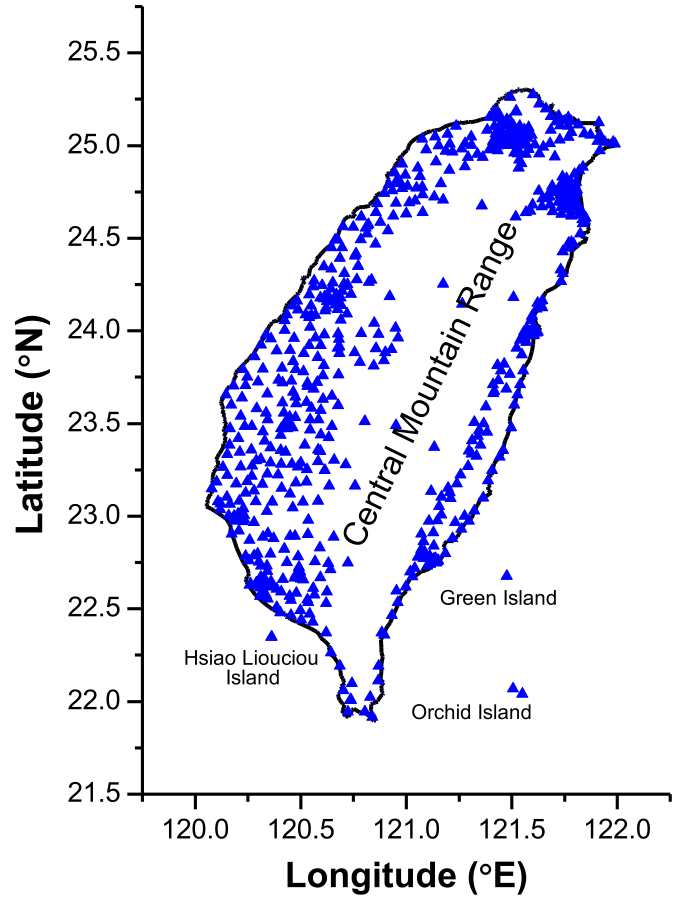

Fig. 3. Locations of 700 earthquake stations of the Taiwan Strong Motion Instrumentation Program (TSMIP).

2. The on-site EEW system in Taiwan

2.1. Overview of EEW methodology and algorithms

Earthquake early warning can be mainly categorized into two types: regional and on-site. Generally speaking, a regional EEW system is to utilize information from multiple stations close to the earthquake for estimating its magnitude and location (i.e., hypocenter/epicenter) as early as possible, then using the real-time information for EEW decision-making for farther sites utilizing the nature that radio waves (for data transmitting) can travel much faster than seismic waves. By contrast, an on-site system is based on the estimate of earthquake magnitude or peak motion at a target site, which is predicted based on the precursor or early motion that has been received/detected at the same site. Note that because such a system is mainly utilizing earthquake information from one site (also referred to as the target site), the

Table 1
Summary of the 17,836 data used for the EEW reliability assessment.

	$M_L < 6.0$	$M_L \geq 6.0$	Total
No. of earthquakes	253	41	294
No. of waveforms	14,150	3,686	17,836

system is called on-site EEW. More recently, the so-called hybrid EEW system was also developed, and it is basically to install both on-site and regional EEW systems for a target site.

On the other hand, it should be understood that regional EEW is more "time-consuming" than on-site EEW since the former needs to process more data from multiple stations. For example, the average report time of a regional EEW system in Taiwan is 22 s, about the time that seismic waves could have travelled 70 km from epicenters [3]. As a result, the areas within 70 km from epicenters are considered as the "blind zone" of the regional EEW in Taiwan. Therefore, the development of on-site EEW in Taiwan is to make up the limitation of the regional EEW with a quicker processing time based on initial information from one seismic station, also in an attempt to deliver earthquake early warning for the same site within 70 km from epicenters [3].

Understandably, another important task in EEW is to locate earthquake sources (i.e., hypocenter) for estimating hypocentral/epicentral distance, and we summarized three commonly used algorithms as follows: i) With *P*-wave detected from one station, epicentral distance can be approximated based on the slope of initial (acceleration) time history with an empirical relationship [28], ii) the azimuth and depth of earthquake source can be inferred from the motions in three different directions (i.e., one vertical and two horizontal), and iii) when the data from three or more stations are detected/received, the earthquake source will be located through optimization by minimizing the differences between the recorded traveling time (of seismic waves) and the theoretical calculations [7].

2.2. On-site EEW in Taiwan

As mentioned previously, on-site EEW only uses the precursor information from one site for predicting earthquake magnitude and/or peak shaking at the same site, and therefore the relationship using early motions to obtain the real-time estimates is essential to on-site EEW. For example, based on 780 samples from Taiwan, Japan, and Southern California, Wu and Kanamori [29] developed an empirical relationship between PGV (i.e., peak ground velocity) and PD3 (i.e., the

Table 2
Summary of the false-alarm evaluation for the M_L 5.62 earthquake on April 30, 2005; note that the first five PD3 highlighted are those closest to the epicenter for calculating average PD3; also note that "1" in the last column denotes false alarm was occurring during this event, while "0" denotes the system was inactivated correctly (i.e., no false alarm).

Station	Distance (km)	PD3 (cm)	τ_c	Real-time magnitude from τ_c	τ_p^{max}	Real-time magnitude from τ_p^{max}	Average of two real-time estimates	False alarm
HWA028	2.41	**0.407**	1.032	5.07	1.347	6.83	5.95	0
HWA027	4.05	**0.418**	1.137	5.16	1.293	6.76	5.96	0
HWA009	4.13	**0.453**	2.470	5.88	1.778	7.33	6.61	1
HWA007	4.68	**0.413**	2.731	5.97	1.791	7.35	6.66	1
HWA011	5.12	**0.262**	1.152	5.17	1.853	7.41	6.29	1
HWA008	5.22	0.458	1.854	5.61	1.626	7.17	6.39	1
HWA048	5.31	0.420	1.086	5.12	1.356	6.84	5.98	0
HWA050	5.76	0.320	1.247	5.25	1.597	7.14	6.19	1
HWA010	5.87	0.381	2.109	5.73	1.585	7.13	6.43	1
HWA023	6.07	0.275	2.181	5.76	1.496	7.02	6.39	1
MND016	6.07	0.408	2.497	5.89	1.626	7.17	6.53	1
HWA019	6.09	0.307	1.881	5.63	1.529	7.06	6.34	1
HWA013	6.49	0.282	1.650	5.51	1.552	7.09	6.30	1
HWA014	6.69	0.406	2.147	5.75	1.494	7.02	6.38	1
HWA049	7.40	0.303	0.879	4.92	1.109	6.48	5.70	0
HWA015	9.08	0.227	0.945	4.99	1.408	6.91	5.95	0
HWA016	9.45	0.203	0.875	4.92	1.439	6.95	5.93	0
HWA026	9.90	0.153	0.815	4.85	1.549	7.08	5.97	0
HWA047	11.00	0.147	1.296	5.28	2.620	8.03	6.66	1
HWA029	11.52	0.125	0.865	4.91	1.442	6.95	5.93	0
HWA017	12.12	0.189	0.722	4.74	1.531	7.06	5.90	0
HWA046	13.23	0.180	0.903	4.95	1.099	6.46	5.71	0
HWA025	15.01	0.215	1.396	5.35	1.178	6.59	5.97	0
HWA018	16.95	0.085	0.806	4.84	1.330	6.81	5.83	0
HWA051	19.24	0.052	0.847	4.89	1.634	7.18	6.03	1
HWA056	20.18	0.053	1.191	5.20	1.072	6.42	5.81	0
HWA001	28.03	0.041	1.113	5.14	1.248	6.69	5.92	0
HWA052	28.13	0.019	0.809	4.85	1.199	6.62	5.73	0
HWA020	30.63	0.018	0.835	4.88	0.978	6.25	5.56	0
HWA031	32.21	0.018	0.720	4.74	1.215	6.64	5.69	0
HWA045	33.47	0.021	1.197	5.21	1.259	6.71	5.96	0
HWA043	36.61	0.013	0.956	5.00	1.877	7.43	6.22	1
HWA035	38.05	0.017	1.019	5.06	1.331	6.81	5.93	0
HWA033	40.89	0.016	1.099	5.13	1.196	6.62	5.87	0
HWA032	41.30	0.013	0.607	4.58	0.869	6.04	5.31	0
HWA044	42.87	0.016	1.638	5.50	1.140	6.53	6.01	1
HWA006	44.74	0.009	0.828	4.87	1.099	6.46	5.67	0
ILA050	45.92	0.012	0.554	4.50	0.932	6.17	5.33	0
HWA005	46.07	0.011	1.204	5.21	0.990	6.27	5.74	0
HWA002	48.95	0.010	1.105	5.13	2.391	7.87	6.50	1
TCU088	51.43	0.010	1.067	5.10	0.790	5.87	5.48	0
HWA034	54.72	0.022	2.424	5.86	0.861	6.02	5.94	0
ILA068	65.69	0.010	1.756	5.56	1.783	7.34	6.45	1
ILA031	66.99	0.018	3.344	6.16	1.386	6.88	6.52	1
ILA010	67.49	0.014	1.458	5.39	1.673	7.22	6.31	1
ILA043	67.62	0.012	0.961	5.01	1.338	6.82	5.91	0
ILA025	68.05	0.014	1.736	5.55	0.814	5.92	5.74	0
HWA037	68.40	0.019	1.833	5.60	0.966	6.23	5.92	0
ILA052	68.44	0.014	4.250	6.38	1.547	7.08	6.73	1

maximum ground displacement up to the first three seconds since the arrival of *P*-wave) for on-site earthquake early warning [29]. But as the data shown in Fig. 1, the 780 samples did not present a perfect trend because of natural randomness, and as discussed in the literature, such data scattering/randomness is the main source affecting the reliability of on-site EEW [25,27].

The development of on-site EEW in Taiwan has started since the 1990 s [30]. Nowadays, many elementary schools in Taiwan are equipped with on-site EEW. Note that a more detailed introduction to the on-site EEW in Taiwan was given by Wen et al. [5], with the key specifications of the system summarized in the following. Based on historical data from 596 major earthquakes in Taiwan, the researchers found the likelihood was relatively low for PD3 < 0.1 cm and $M_L > 6$ to be happening simultaneously. As a result, PD3=0.1 cm was then adopted as the precursor threshold for the on-site EEW in Taiwan, above which EEW will be activated since the earthquake magnitude will be most likely greater than $M_L > 6.0$, the pre-setup warning magnitude. However, it is worth noting that such an interpretation from the historical data is somehow a best engineering judgment, rather than a result from mathematically robust calculations.

Second, as the calculation shows PD3 is greater than 0.1 cm, it will go on to compute the so-called τ_c and τ_p^{max} (see the Appendix for their definition) of the first three seconds of the *P*-wave at a given site. Then based on the τ_c and τ_p^{max} calculated, the real-time earthquake magnitude is estimated as the average from the two empirical relationships [5,31]:

$$\log \tau_c = 0.47 \times M_L - 2.37 \tag{1}$$

$$\log \tau_p^{\max} = 0.24 \times M_L - 1.51 \tag{2}$$

As a result, when the (real-time) magnitude estimate is larger than M_L 6.0, the on-site EEW system will be activated at the site; otherwise it will not. Note that such an EEW system in Taiwan facilitated with a less complicated algorithm as above is mainly based on the early information from one site for providing early warning for the same site, and therefore the EEW discussed in this paper is an on-site system (rather than regional or hybrid systems) by the general EEW characterizations as mentioned previously. Also note that since the on-site system is mainly based on the early motions received at a target site to obtain the real-time estimates (e.g., peak motion) at the same site for EEW decision-making, the earthquake location or epicentral distance is not needed by such an on-site EEW.

2.3. False alarm and missed alarm

The general idea and definition of false alarm and missed alarm could be perceived as follows: i) false alarm is an error that a warning system should not have been activated while it has; and ii) missed alarm is an error that a warning system should have been activated while it has not. As a result, for this on-site EEW using M_L 6.0 as warning magnitude, a false alarm will be occurring as the (real-time) magnitude estimate is larger than M_L 6.0 while the true magnitude revealed later is less than M_L 6.0. By contrast, a missed alarm will be occurring as the (real-time) magnitude estimate is less than M_L 6.0 while the true magnitude is larger. Therefore, a logical and scientific approach to evaluate the system's reliability is to test it with a rich set of earthquake data. Then if the errors occur 100 times out of 1000 tests, the reliability of the system should be around 90% from an empirical point of view.

To sum up, the working principle and algorithm of the on-site EEW in Taiwan are shown in Fig. 2, as well as the present methodology to perform a reliability assessment on the system. Understandably, a prior task to such a study is earthquake data mining, and in total we collected 17,836 earthquake data for this study, thanks to the Taiwan Strong Motion Instrumentation Program detailed in the following [32,33].

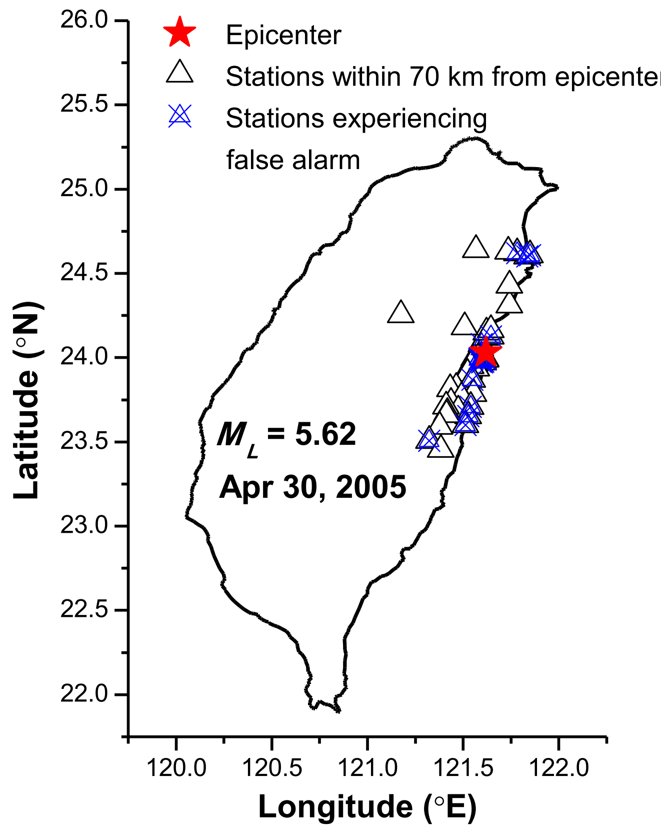

Fig. 4. An example of false-alarm evaluation based on the data of the M_L 5.62 earthquake on April 30, 2005; a false-alarm probability is around 41% for this particular event.

3. The earthquake instrumentation network in Taiwan

In order to collect earthquake data around Taiwan, the Taiwan Strong Motion Instrumentation Program (TSMIP) was established in the 1990s [32,33]. As shown in Fig. 3, the network consists of around 700 free-field earthquake stations, and about 100 of them are equipped with automatic data transmitting that can immediately send the data back to the Central Weather Bureau Taiwan for real-time earthquake analyses.

Undoubtedly, TSMIP is valuable to a variety of earthquake studies. For example, Lin et al. (2011) used the TSMIP database to develop a series of local ground motion models for the region around Taiwan [1], essential to local seismic hazard assessments conducted later [2]. Besides, basin effects and site effects in Taiwan were also studied with the TSMIP strong-motion database, in an attempt to develop proper earthquake-resistant designs for several major cities in Taiwan [34,35].

4. The analysis

4.1. The data mining

Similarly, we also utilized the TSMIP database for this study. As mentioned previously, a total of 17,836 earthquake time histories associated with 294 major earthquakes from 1999 to 2013 around Taiwan were collected. The magnitudes of the 294 earthquakes are in a range from M_L 5.0 to 7.3, which allows us to evaluate the probability of false alarm with the data from $M_L < 6.0$ events, and to estimate missed alarms with the data from $M_L \geq 6.0$ earthquakes.

For a quick understanding of the 17,836 data (i.e., earthquake time histories), the key statistics are summarized in Table 1. Accordingly, a total of 14,150 data are associated with 253 earthquakes with $M_L < 6.0$, while 3,686 samples are from 41 earthquakes with $M_L \geq 6.0$. Note that

Table 3
Summary of false-alarm evaluation with the data from the M_L 5.18 earthquake on December 10, 2003; similarly, the first five data of PD3 highlighted are those closest to the epicenter for average-PD3 calculation; and since the average is less than 0.1 cm, the system will be inactivated correctly for each site, without any false alarm for the sites within 70 km from the epicenter.

Station	Distance (km)	PD3 (cm)	τ_c	Real-time magnitude from τ_c	τ_p^{max}	Real-time magnitude from τ_p^{max}	Average of two real-time estimates	False alarm
TTN034	11.36	**0.071**	0.506	4.41	1.099	6.46	(5.44)[a]	0
TTN002	12.77	**0.056**	1.164	5.18	1.291	6.75	(5.97)	0
TTN046	16.12	**0.043**	0.692	4.70	1.131	6.51	(5.61)	0
TTN042	16.37	**0.045**	0.833	4.87	1.226	6.66	(5.77)	0
TTN043	17.79	**0.057**	0.794	4.83	1.273	6.73	(5.78)	0
TTN036	18.57	0.019	1.394	5.35	1.387	6.88	(6.12)	0
TTN047	22.69	0.022	1.282	5.27	1.574	7.11	(6.19)	0
TTN004	23.07	0.021	0.407	4.21	1.061	6.40	(5.31)	0
TTN008	23.70	0.014	2.148	5.75	1.332	6.81	(6.28)	0
TTN007	24.22	0.014	1.843	5.61	1.392	6.89	(6.25)	0
TTN044	24.23	0.038	0.483	4.37	1.168	6.57	(5.47)	0
TTN006	24.31	0.027	1.421	5.37	1.325	6.80	(6.08)	0
TTN015	24.48	0.011	1.133	5.16	1.060	6.40	(5.78)	0
TTN005	24.92	0.018	1.913	5.64	1.305	6.77	(6.21)	0
TTN009	25.04	0.010	1.210	5.22	1.142	6.53	(5.88)	0
TTN013	25.42	0.010	0.807	4.84	1.117	6.49	(5.67)	0
TTN014	25.51	0.033	0.886	4.93	1.276	6.73	(5.83)	0
TTN011	26.29	0.013	0.807	4.84	1.374	6.87	(5.86)	0
TTN024	27.30	0.016	0.568	4.52	1.185	6.60	(5.56)	0
TTN026	27.37	0.009	0.599	4.57	1.054	6.39	(5.48)	0
TTN027	27.92	0.010	0.689	4.70	1.038	6.36	(5.53)	0
TTN010	28.18	0.012	0.615	4.59	1.066	6.41	(5.5)	0
TTN025	28.74	0.019	0.866	4.91	1.150	6.54	(5.73)	0
TTN022	28.98	0.028	0.756	4.78	1.246	6.69	(5.74)	0
TTN018	29.00	0.011	0.778	4.81	0.905	6.11	(5.46)	0
TTN048	29.41	0.007	0.460	4.33	1.144	6.53	(5.43)	0
TTN049	29.87	0.009	0.637	4.63	1.303	6.77	(5.7)	0
TTN028	31.98	0.011	0.406	4.21	0.885	6.07	(5.14)	0
TTN020	32.15	0.028	0.762	4.79	1.276	6.73	(5.76)	0
TTN040	34.90	0.017	0.512	4.42	1.269	6.72	(5.57)	0
HWA004	35.60	0.026	1.512	5.42	1.460	6.98	(6.2)	0
TTN029	35.90	0.009	0.621	4.60	0.976	6.25	(5.43)	0
TTN033	36.13	0.014	0.875	4.92	1.193	6.61	(5.77)	0
TTN041	37.76	0.021	0.282	3.87	1.273	6.73	(5.3)	0
TTN030	38.93	0.004	0.715	4.73	1.057	6.39	(5.56)	0
TTN050	39.47	0.010	0.755	4.78	1.029	6.34	(5.56)	0
HWA042	40.26	0.020	1.937	5.65	1.766	7.32	(6.49)	0
TTN032	42.20	0.007	0.473	4.35	1.190	6.61	(5.48)	0
HWA041	44.62	0.016	0.750	4.78	1.278	6.74	(5.76)	0
TTN003	45.70	0.004	0.783	4.82	1.100	6.46	(5.64)	0
TTN001	50.72	0.004	0.627	4.61	1.583	7.12	(5.87)	0
HWA040	52.10	0.013	1.134	5.16	1.845	7.40	(6.28)	0
TTN037	54.74	0.003	1.197	5.21	1.094	6.45	(5.83)	0
TTN031	55.20	0.011	1.066	5.10	1.513	7.04	(6.07)	0
HWA037	65.03	0.008	0.979	5.02	1.769	7.32	(6.17)	0
KAU077	65.71	0.008	1.459	5.39	1.192	6.61	(6)	0
KAU050	68.88	0.005	1.037	5.08	1.268	6.72	(5.9)	0

[a] Real-time magnitude estimation is not necessary for this EEW decision-making for each site, because the average PD3 from the five closest stations to the epicenter was less than 0.1 cm, and the system would not be activated regardless.

although the sample sizes of the two groups are quite different, the sample size of the smaller group is still as many as 3,686, which is considered a relatively large sample size for any statistical analysis. Besides, it must be noted that the 17,836 time histories were all collected from stations within 70 km from epicenters on purpose, in accordance with the prerequisite that this on-site EEW system in Taiwan is targeting on those sites/areas within 70 km from the earthquake.

4.2. PD3, τ_c, and τ_p^{max} calculations

Since the raw data collected from the strong-motion TSMIP database are in earthquake time history, the first task of the study is to calculate PD3, τ_c, and τ_p^{max} for each of the 17,836 time-history data, followed by real-time magnitude estimations using Eqs. (1) and (2). Taking the M_L 5.62 earthquake on April 30 in 2005 for example, Table 2 summarizes the calculations for this event, and in total there were 49 time-history data within 70 km from the epicenter were collected and processed.

4.3. Examples for false-alarm probability assessment

To better explain this EEW reliability assessment, we demonstrated two calculations in the following. The first is based on the data collected from the M_L 5.62 earthquake on April 30, 2005. From the data and calculations summarized in Table 2, 20 of the 49 stations (Fig. 4) could experience a false alarm, given the (real-time) magnitude estimate is greater than the warning magnitude of M_L 6.0. Therefore, as far as this particular event is concerned, the system should have a false-alarm probability around 41% (=20/49).

Summarized in Table 3, the second demonstration is based on the M_L 5.18 earthquake on December 10, 2003. Given the average PD3 of

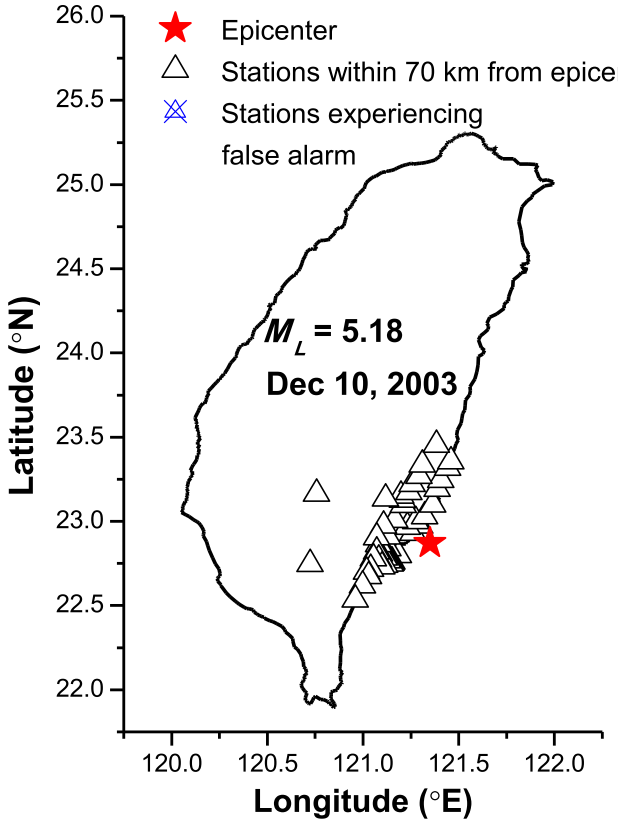

Fig. 5. Another example of false-alarm evaluation based on the data from the M_L 5.18 earthquake on December 10, 2003; EEW would not be activated given the average PD3 calculated from the five closest stations is smaller than 0.1 cm, and therefore no false alarm would be registered for this event.

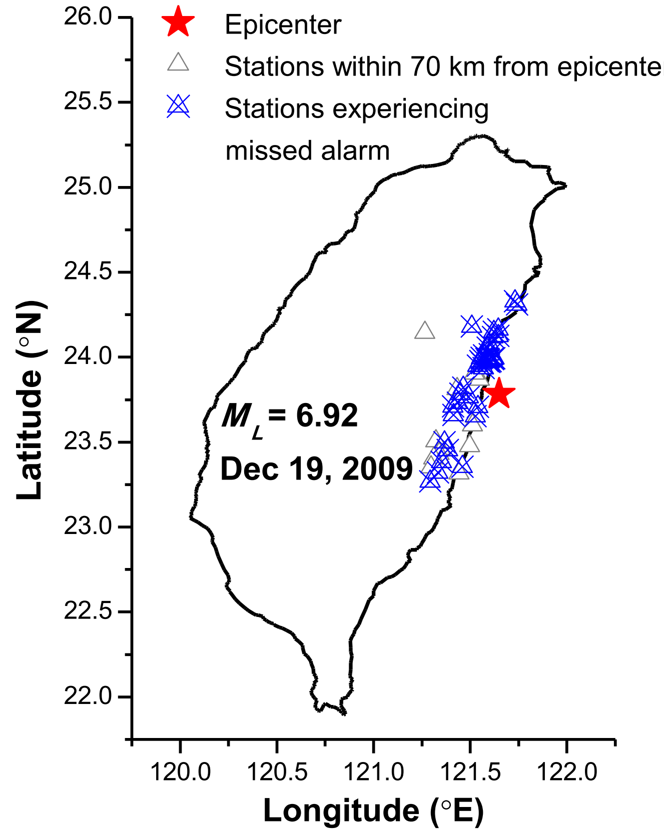

Fig. 6. An example of missed-alarm evaluation based on the data of the M_L 6.92 earthquake on December 19, 2009; the missed-alarm probability is around 78% for this event.

the five closest stations is smaller than 0.1 cm, EEW would not be activated (in this case real-time magnitude estimation will not be conducted at any sites), and therefore the false-alarm probability is zero for this event. Fig. 5 shows the 41 test stations where false alarms were not occurring during the event.

4.4. Examples for missed-alarm probability assessment

By contrast, we would like to demonstrate another two examples to evaluate the system's missed-alarm probability with $M_L \geq 6.0$ data. The first is based on the M_L 6.92 earthquake on December 19, 2009. Fig. 6 shows the 52 stations within 70 km from the epicenter where data were collected. As summarized in Table 4, the analysis shows that 40 of the 52 stations would experience a missed alarm, given the (real-time) magnitude estimate is lower than M_L 6.0, resulting in a missed-alarm probability of 78% as far as this event is concerned.

Similarly, the second example is based on the data from the M_L 6.07 earthquake on September 20, 1999. As summarized in Table 5, only 5 of the 72 stations would experience a missed alarm (Fig. 7), resulting in a missed-alarm probability as low as 7% for the particular event.

4.5. The EEW reliability assessment

Similar to the four demonstrated calculations, we went on performing the same analysis for the rest of the data. Based on the analyses, we found that 437 false alarms and 2,516 missed alarms could be occurring out of the total 17,836 tests. Accordingly, our best estimates on the system's false-alarm and missed-alarm probabilities are about 2.5% and 14.1%, respectively. Therefore, empirically speaking, the on-site EEW system in Taiwan should have a reliability about 85% (≈1−2.5% −14.1%), the scope and the key finding of this study.

5. Discussions

5.1. Real false alarm and false alarm

By definition, false alarm refers to a situation that EEW is activated for $M_L < 6.0$ events given their magnitudes are misjudged to be greater than the warning magnitude of M_L 6.0. However, as far as the public is concerned, such a false alarm is not really a mistake (or the so-called real false alarm in this paper), because from the perception of the public, a real false alarm should refer to a situation that EEW is activated but no earthquake or very small ground shaking is felt by the public.

To further explain the difference between the false alarm and the real false alarm, we used the M_L 5.62 event (summarized in Table 2) as an example: Despite the fact that several sites would experience a false alarm (i.e., true magnitude=M_L 5.62 while real-time magnitude estimate≥M_L 6.0), ground motions at those false-alarm sites should be strong enough for the public to consider the system is correctly activated by default, instead of being activated by mistake. As a result, the false alarm discussed in this paper is not a real false alarm as far as the public is concerned, because moderate/strong ground shaking can be still felt by the public, even though the magnitude is somewhat lower than the warning magnitude of M_L 6.0.

On the other hand, when the EEW system is not activated for an $M_L \geq 6.0$ event, it is not only a missed alarm by default, but the public will also respond to it as a system mistake/malfunction, owing to the fact that we do feel a moderate/strong earthquake while the system is not activated as it should. Therefore, from the perception and the concern of the public, missed alarm is more important than false alarm when it comes to improving the credibility of EEW, because missed alarm is realized as a mistake by the public, while false alarm might not.

5.2. Sensitivity analysis

Given missed alarm is more important to EEW than false alarm, we proposed two approaches in this section that could lower the missed-alarm probability for the on-site EEW system in Taiwan. The detailed methodology and analysis are given in the following.

From the current algorithm shown in Fig. 2, we can understand the precursor threshold as PD3=0.1 cm employed currently is a key parameter to the EEW, and different levels of false alarm and missed alarm can be expected when a different value is used. As a result, a logical method to examine this issue is to repeat the analyses with new, different PD3 thresholds, developing the relationship between PD3 thresholds and missed/false alarms based on the same pool of the 17,836 data.

With an interval of 0.001 cm used in the sensitivity analysis, we literately repeated a total of 501 calculations using PD3 from 0 to 0.5 cm. From the analyses, Fig. 8 shows the relationship between PD3 thresholds and false/missed alarms, indicating the probability of false alarm is decreasing with PD3 thresholds, while the trend is opposite for missed alarm.

Such a result from the sensitivity study can be expected, as we could explain it with the extreme case of PD3=0, which is an equivalent measure of removing the PD3 threshold from the current decision-making. Under the condition, the EEW system will be activated much more frequently even though the PD3 or the earthquake is small, hence lowering the chance of missed alarm substantially. However, the cost of the action is that many of the alarms are not necessary because the

Table 4
Summary of the missed-alarm evaluation with the data from the M_L 6.92 earthquake on December 19, 2009; note that "1" denotes missed alarm was occurring, while "0" denotes the system was activated corrected (no missed alarm).

Station	Distance (km)	PD3 (cm)	τ_c	Real-time magnitude from τ_c	τ_p^{max}	Real-time magnitude from τ_p^{max}	Average of two real-time estimates	Missed alarm
HWA043	13.70	**0.129**	0.804	4.84	1.404	6.91	5.87	1
HWA051	14.42	**0.269**	0.827	4.87	1.616	7.16	6.01	0
HWA031	16.16	**0.243**	0.737	4.76	1.147	6.54	5.65	1
HWA044	18.79	**0.164**	0.727	4.75	0.965	6.23	5.49	1
HWA018	19.06	**0.340**	0.612	4.59	8.831	10.23	7.41	0
HWA029	19.26	0.170	0.894	4.94	1.212	6.64	5.79	1
HWA052	19.46	0.246	0.855	4.90	1.073	6.42	5.66	1
HWA030	20.46	0.191	1.068	5.10	1.143	6.53	5.82	1
HWA017	22.02	0.251	0.596	4.56	1.033	6.35	5.46	1
HWA014	22.08	0.239	1.165	5.18	1.019	6.33	5.75	1
HWA019	22.38	0.275	1.437	5.38	1.103	6.47	5.92	1
HWA020	22.40	0.226	1.356	5.32	1.600	7.14	6.23	0
HWA035	22.42	0.149	1.484	5.41	1.170	6.58	5.99	1
HWA016	22.51	0.220	0.774	4.81	1.213	6.64	5.72	1
HWA013	22.82	0.196	0.714	4.73	1.557	7.09	5.91	1
HWA010	23.12	0.243	0.994	5.04	1.151	6.55	5.79	1
HWA007	23.37	0.166	1.509	5.42	1.149	6.54	5.98	1
HWA012	23.84	0.166	1.152	5.17	1.059	6.40	5.78	1
HWA008	23.90	0.229	0.809	4.85	1.358	6.85	5.85	1
HWA009	23.92	0.176	1.222	5.23	1.217	6.65	5.94	1
HWA015	23.92	0.171	0.858	4.90	1.121	6.50	5.70	1
HWA050	24.30	0.191	0.689	4.70	1.266	6.72	5.71	1
HWA002	24.36	0.108	1.518	5.43	1.530	7.06	6.24	0
HWA011	24.88	0.192	0.688	4.70	1.260	6.71	5.70	1
HWA032	25.41	0.224	1.084	5.12	1.174	6.58	5.85	1
HWA049	25.67	0.170	0.766	4.80	1.093	6.45	5.62	1
HWA028	26.82	0.169	0.697	4.71	1.215	6.64	5.68	1
HWA048	26.88	0.218	0.744	4.77	1.154	6.55	5.66	1
HWA005	27.43	0.211	1.187	5.20	1.299	6.77	5.98	1
HWA027	31.16	0.152	0.537	4.47	0.894	6.09	5.28	1
HWA023	33.81	0.252	1.372	5.33	0.996	6.28	5.81	1
HWA003	37.12	0.110	1.415	5.36	1.379	6.87	6.12	0
HWA026	37.84	0.110	0.417	4.23	0.870	6.04	5.14	1
HWA047	38.48	0.186	0.795	4.83	0.992	6.28	5.55	1
HWA046	41.14	0.087	0.335	4.03	1.150	6.55	5.29	1
HWA036	42.43	0.122	1.060	5.10	1.273	6.73	5.91	1
HWA025	42.59	0.100	1.060	5.10	1.273	6.73	5.91	1
HWA021	45.22	0.076	1.675	5.52	1.238	6.68	6.10	0
HWA037	45.26	0.160	0.852	4.89	1.183	6.60	5.75	1
HWA056	46.76	0.089	0.937	4.98	1.308	6.78	5.88	1
HWA038	47.07	0.079	2.103	5.73	1.512	7.04	6.38	0
HWA054	49.95	0.123	3.874	6.29	1.496	7.02	6.66	0
TTN031	50.97	0.121	0.671	4.67	1.101	6.47	5.57	1
HWA039	53.40	0.071	0.703	4.72	1.172	6.58	5.65	1
HWA053	53.91	0.037	1.527	5.43	1.506	7.03	6.23	0
TTN001	55.54	0.067	1.294	5.28	1.284	6.74	6.01	0
TCU130	56.37	0.205	1.729	5.55	1.208	6.63	6.09	0
HWA045	59.65	0.079	0.566	4.52	0.978	6.25	5.38	1
HWA024	59.66	0.025	1.395	5.35	1.600	7.14	6.25	0
HWA055	60.27	0.083	0.912	4.96	1.110	6.48	5.72	1
ILA053	61.71	0.056	0.497	4.40	0.892	6.09	5.24	1
HWA041	67.52	0.039	0.982	5.03	1.313	6.78	5.91	1

Table 5
Summary of the missed-alarm evaluation with the data from the M_L 6.07 earthquake on September 20, 1999; similarly to Table 4, "1" refers to the situation that missed alarm was occurring, while "0" is for the system activated correctly (no missed alarm).

Station	Distance (km)	PD3 (cm)	τ_c	Real-time magnitude from τ_c	τ_p^{max}	Real-time magnitude from τ_p^{max}	Average of two real-time estimates	Missed alarm
TCU071	3.71	**0.481**	1.773	5.57	1.162	6.56	6.07	0
TCU089	8.25	**0.167**	2.050	5.71	1.132	6.52	6.11	0
TCU072	8.43	**0.218**	1.940	5.65	1.283	6.74	6.20	0
TCU084	12.64	**0.122**	2.102	5.73	0.965	6.23	5.98	1
TCU073	13.99	**0.145**	2.521	5.90	1.006	6.30	6.10	0
TCU074	14.46	0.264	4.254	6.38	1.165	6.57	6.47	0
TCU075	14.50	0.165	1.618	5.49	1.522	7.05	6.27	0
TCU076	16.18	0.245	2.272	5.80	1.458	6.97	6.39	0
TCU079	16.30	0.106	1.857	5.61	1.041	6.36	5.99	1
TCU065	16.42	0.610	4.804	6.49	2.452	7.91	7.20	0
TCU067	16.86	0.188	4.137	6.35	0.956	6.21	6.28	0
TCU129	17.20	0.077	1.449	5.39	0.981	6.26	5.82	1
TCU078	17.77	0.075	1.819	5.60	1.356	6.84	6.22	0
TCU120	21.06	0.495	3.066	6.08	1.692	7.24	6.66	0
TCU055	24.58	0.241	6.732	6.80	1.599	7.14	6.97	0
TCU082	24.61	0.412	8.698	7.04	2.261	7.77	7.40	0
TCU063	25.78	0.316	2.928	6.04	2.164	7.69	6.86	0
TCU054	25.84	0.591	5.773	6.66	2.057	7.60	7.13	0
TCU052	26.65	0.154	4.807	6.49	4.444	8.99	7.74	0
TCU049	26.73	0.425	9.358	7.11	2.334	7.83	7.47	0
TCU051	27.15	0.193	3.262	6.14	1.338	6.82	6.48	0
TCU116	27.44	0.183	4.948	6.52	1.394	6.89	6.71	0
TCU122	27.58	0.400	8.117	6.98	3.061	8.32	7.65	0
TCU109	28.34	0.231	1.681	5.52	1.000	6.29	5.91	1
TCU123	28.56	0.112	1.137	5.16	1.046	6.37	5.77	1
TCU056	28.94	0.318	4.090	6.34	2.628	8.04	7.19	0
TCU053	29.25	0.492	4.095	6.35	1.857	7.41	6.88	0
TCU106	29.98	0.243	3.713	6.25	1.189	6.60	6.43	0
TCU050	30.20	0.150	4.425	6.42	1.070	6.41	6.42	0
TCU107	30.66	0.440	4.953	6.52	1.253	6.70	6.61	0
TCU057	30.98	0.366	4.733	6.48	1.778	7.33	6.91	0
TCU100	31.78	0.209	4.467	6.43	1.528	7.06	6.74	0
CHY024	32.16	0.280	2.989	6.05	3.627	8.62	7.34	0
TCU102	32.61	0.263	4.106	6.35	3.358	8.48	7.42	0
TCU048	32.66	0.260	5.946	6.69	1.492	7.02	6.85	0
TCU061	33.13	0.344	4.849	6.50	1.797	7.35	6.93	0
TCU060	33.51	0.252	4.649	6.46	2.668	8.07	7.26	0
TCU068	34.57	0.198	3.947	6.31	5.073	9.23	7.77	0
TCU115	35.68	0.188	3.311	6.15	2.471	7.93	7.04	0
TCU136	36.48	0.239	4.089	6.34	1.001	6.29	6.32	0
TCU111	37.42	0.548	6.167	6.72	5.302	9.31	8.02	0
CHY025	37.61	0.285	3.431	6.18	2.983	8.27	7.23	0
TCU104	37.83	0.631	5.522	6.62	4.164	8.87	7.75	0
TCU070	37.94	0.467	4.917	6.51	1.280	6.74	6.63	0
TCU103	39.51	0.396	5.429	6.61	4.654	9.07	7.84	0
TCU105	39.96	0.155	2.679	5.95	2.496	7.95	6.95	0
TCU118	40.40	0.403	4.257	6.38	4.011	8.81	7.59	0
TCU117	40.85	0.384	6.966	6.84	3.963	8.78	7.81	0
CHY101	41.06	0.529	5.443	6.61	4.169	8.88	7.74	0
TCU112	41.34	0.177	3.847	6.29	2.155	7.68	6.98	0
TCU059	42.19	0.352	7.082	6.85	2.248	7.76	7.30	0
TCU087	42.30	0.259	9.463	7.12	2.104	7.64	7.38	0
CHY080	43.92	0.176	6.697	6.80	1.741	7.29	7.05	0
TCU113	44.83	0.303	4.027	6.33	3.808	8.71	7.52	0
CHY026	45.73	0.493	3.448	6.19	3.824	8.72	7.45	0
TCU064	46.93	0.295	5.515	6.62	3.641	8.63	7.63	0
TCU128	49.95	0.208	8.130	6.98	1.710	7.26	7.12	0
CHY074	51.17	0.032	3.066	6.08	1.305	6.77	6.43	0
TCU119	51.88	0.986	4.741	6.48	4.599	9.05	7.77	0
CHY036	53.23	0.175	6.567	6.78	2.582	8.01	7.39	0
CHY035	55.50	0.288	4.005	6.32	4.288	8.93	7.63	0
WTC	55.99	0.102	3.810	6.28	2.594	8.02	7.15	0
CHY082	59.72	0.810	4.658	6.46	4.856	9.15	7.81	0
TCU038	60.08	0.223	10.11	7.18	2.760	8.13	7.65	0
CHY027	63.11	1.067	4.647	6.46	6.120	9.57	8.02	0
CHY041	63.30	0.086	2.316	5.82	1.530	7.06	6.44	0
TCU042	64.95	0.141	3.740	6.26	3.760	8.69	7.47	0
CHY046	65.77	0.386	5.693	6.65	4.571	9.04	7.85	0
CHY073	66.11	0.293	3.407	6.18	3.944	8.77	7.47	0
HWA032	66.74	0.063	3.280	6.14	1.626	7.17	6.66	0
CHY032	69.13	0.519	4.906	6.51	4.660	9.08	7.79	0
CHY039	69.57	0.241	4.898	6.51	2.717	8.10	7.31	0

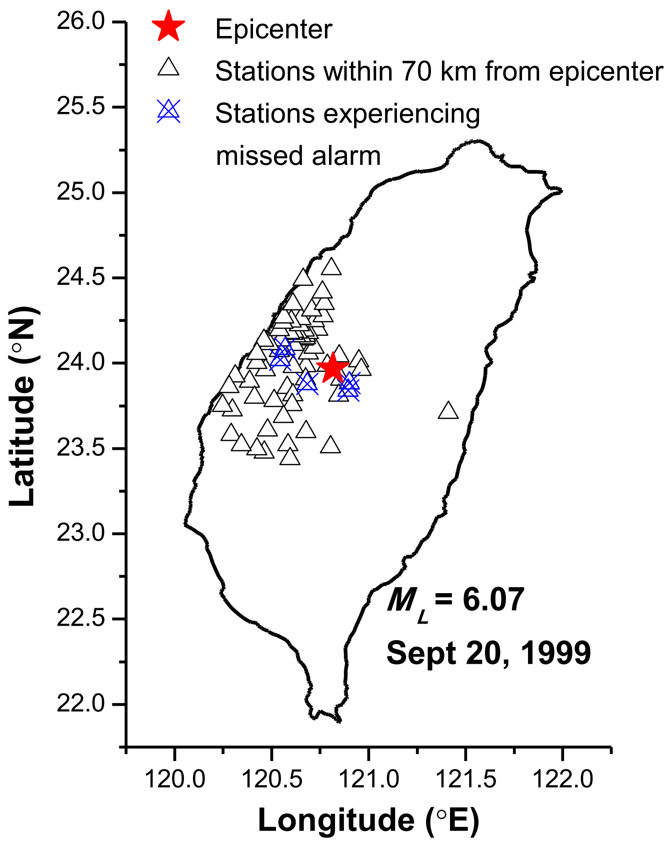

Fig. 7. Another example of missed-alarm evaluation based on the data of the M_L 6.07 earthquake on September 20, 1999; the probability of missed alarm is as low as 7% for this particular event.

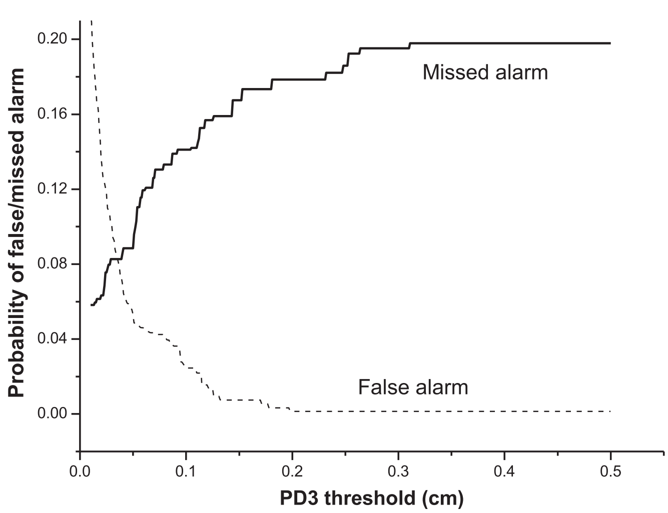

Fig. 8. The relationships between PD3 thresholds and false/missed alarms, on the basis of the same 17,836 data used for the previous reliability assessment on the on-site EEW in Taiwan.

earthquakes are too small, increasing the chances of false alarm substantially.

5.3. New EEW decision-making

According to the sensitivity analysis, we then proposed two new approaches for the on-site EEW system in Taiwan. First, from the perspective of minimizing missed alarm, we suggest the removal of the PD3 threshold (or PD3=0) from the current framework, which could reduce the probability of missed alarm to 5.8%, a significant improvement over the current algorithm (using PD3=0.1 cm) with 14% missed alarm. However, it must be noted that the cost of the alternative is that the probability of false alarm could be increasing to more than 20% from the current 2.5%, although the false alarms are not necessarily as a mistake from the perception of the public as explained previously.

Second, in order to achieve a more balanced distribution in false alarm and missed alarm, we also suggest PD3=0.022 cm as a new PD3 threshold for the on-site EEW. That is, with the new parameter, the probability of missed alarm could be reduced to 6.3% from the current 14.1%, and that the probability of false alarm can be controlled at around 10% rather than 20% in comparison to the first method. Note that this recommendation is a result of optimization calculations by trying different PD3 values, on the condition (our best judgment) that a missed alarm is five times as important as a false alarm to the system's credibility during the calculations.

Nevertheless, from the principle of decision-making depending on different objectives [25], it is normal that different decisions could be made for a given target problem as our two suggestions presented above. Specifically speaking, the first measure is to lower the system's missed alarm as much as possible to improve the credibility of the EEW, because the missed alarm will be immediately realized as a system mistake/malfunction by the public. By contrast, the second is to achieve a more balanced distribution in missed alarm and false alarm, with the missed alarm reduced substantially while the false alarm is still under control.

Although the false alarm is not a mistake to the public, it should be also important to EEW from a different consideration/objective, such as minimizing economic loss. For example, given an operation will be shut down after the warning is received, too many false alarms will accumulate huge economic losses owing to the frequent, unnecessary interruptions. But in order to quantify the consequence of false alarm and incorporate it into decision-making, much more information is needed to entertain this new objective, which is another important EEW study in the future, but beyond the scope of the study.

5.4. The cause to missed alarm and false alarm

No matter what kind of objective or decision-making is employed in EEW, false alarm and missed alarm cannot be eliminated completely, owing to natural randomness or the uncertainties in earthquake motion attenuation, site effect, machine reliability, etc. Besides, another inevitable cause to an imperfect EEW system is our imperfect understandings of the subjects, or the “true behaviors” of earthquake.

6. Conclusion and summary

Earthquake early warning is considered a more practical approach to earthquake hazard mitigation. Different from EEW methodology and applications, the scope of this study is to evaluate the reliability of an on-site system in Taiwan, by carrying out a total of 17,836 tests with historical data. The result shows that among the 17,836 tests, the system will be correctly activated/inactivated in about 85% of the times. Moreover, new decision-making algorithms for this on-site EEW were also discussed in this paper, which should be able to lower the system's missed alarm substantially, given missed alarm is more critical to the reliability/credibility of earthquake early warning from the perception and concern of the public.

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Appendix. : Definitions of τ_c and τ_p^{max}

- Average period parameter [3]:

$$\tau_c = \frac{2\pi}{\sqrt{r}} \quad (A.1)$$

$$with\ r = \frac{\int_0^{\tau_0} \dot{u}^2(t)dt}{\int_0^{\tau_0} u^2(t)dt} \quad (A.2)$$

where $u(t)$ is the high-pass-filtered ground motion displacement of the vertical component, $\dot{u}(t)$ is the velocity differentiated from $u(t)$, and τ_0 is set at 3 s for earthquake early warning.

- Maximum predominant period parameter within 3 s of *P*-wave arrival:

$$\tau_p^{\max} = \max\,[(\tau_p)_1,\ (\tau_p)_2,\ (\tau_p)_3] \quad (A.3)$$

where $(\tau_p)_i$ is the dominant period parameter, calculated as follows [21]:

$$(\tau_p)_i = 2\pi\sqrt{\frac{X_i}{D_i}} \quad (A.4)$$

where

$$X_i = \alpha X_{i-1} + x_i^2 \quad (A.5)$$

$$D_i = \alpha D_{i-1} + (dx/dt)_i^2 \quad (A.6)$$

where x_i is the velocity signal to which both high- and low-pass filters have been applied, X_i is the smoothed ground velocity squared, D_i is the smoothed velocity derivative squared, and α is the smoothing constant, usually as 0.99 [31].

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