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Faster Short-Distance Earthquake Early Warning Using Continued Monitoring of Filtered Vertical Displacement: A Case Study for the 2010 Jiasian, Taiwan, Earthquake

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Abstract We collected the strong-motion accelerograms from the 2010 Jiasian earthquake (M 6.4) that struck southern Taiwan recorded by the Taiwan Strong-Motion Instrumentation Program (TSMIP) stations to perform an off-line test for our proposed short-distance earthquake early-warning (EEW) approach. The 2010 Jiasian earthquake demonstrates the vital need for the short-distance EEW. The tested short-distance EEW method is a threshold-based approach relying on the amplitude of the filtered vertical displacement. Our result shows that the EEW lead times by the tested method are significantly improved compared to those of the current EEW systems (EEWS) in Taiwan for short-distance warning. For sites located at the epicentral distances of about 25 km the EEW lead times are of 2 to 4 s, ahead of the arrival of the strong ground acceleration. We propose that this threshold-based EEW method might be used for target areas and objects of those in the vicinity of seismogenic zones around the world where warnings are most needed.

Introduction

The Jiasian earthquake (M_w 6.0 and M_L 6.4), which occurred on 4 March 2010, was the largest inland earthquake to strike southern Taiwan in the nearly 50 years since the 1964 Paiho earthquake (M_L 6.3). The epicenter of the 2010 Jiasian earthquake is located at latitude 22.97° N and longitude 120.71° E with a focal depth of about 23 km given by the Central Weather Bureau (CWB) (Fig. 1). The fault mechanisms given by Broadband Array in Taiwan for Seismology (BATS), CWB, United States Geological Survey (USGS), and Global Centroid Moment Tensor (CMT) solutions all suggest a thrust mechanism with the fault plane most likely striking in the northwest-southeast direction and dipping about 30°–40° to the northeast direction, interpreted from the aftershock and ground-shaking intensity distributions (Fig. 1).

According to the damage report of the 2010 Jiasian earthquake released by the Taiwan National Fire Agency, there were 96 people injured, but thankfully, no deaths. However, over hundreds of buildings including school buildings were required to be evaluated immediately for their structural safety. One train of the Taiwan High Speed Rail (THSR) went off the rails during the occurrence of the Jiasian mainshock, although the earthquake monitoring and warning system of THSR had issued an earthquake alert and the train had automatically applied an emergency stop. Apparently, the early-warning lead time (i.e., the time interval between the warning notification and the arrival of the destructing waves, usually S waves) for the earthquake early warning systems (EEWS) in THSR might be too short for an earthquake occurring about 50 km away from the rail, in case of the Jiasian mainshock. The basic operation procedure for the EEWS in THSR is to continuously monitor ground acceleration and issue a warning once it exceeds the threshold value (set for $40g$ in the present operation, $1g = 1.0\ \text{cm/s}^2 = 1.0 \times 10^{-3}g$). Figure 2 shows the accelerograms recorded by three Taiwan Strong-Motion Instrumentation Program (TSMIP) stations near the rail of THSR and indicates that the warning threshold values of $40g$ were not detected in the lower amplitude P-wave portion but rather in the higher amplitude S-wave portion. As a consequence, the time difference between when the acceleration exceeded $40g$ and the peak ground acceleration (PGA) was recorded might be too short to apply the emergency procedures.

When a large earthquake occurs, an EEWS aims to provide timely alerts to populated areas, sensitive facilities, or public transportations and earthquake early warning (EEW) is a practical, effective approach to seismic risk mitigation on a short time-scale (Kanamori *et al.*, 1997; Teng *et al.*, 1997; Wu and Teng, 2002; Allen and Kanamori, 2003; Kanamori, 2005). The two most common approaches to EEWS at present are either regional or onsite warning systems. In the regional approach, the seismograms recorded by seismic

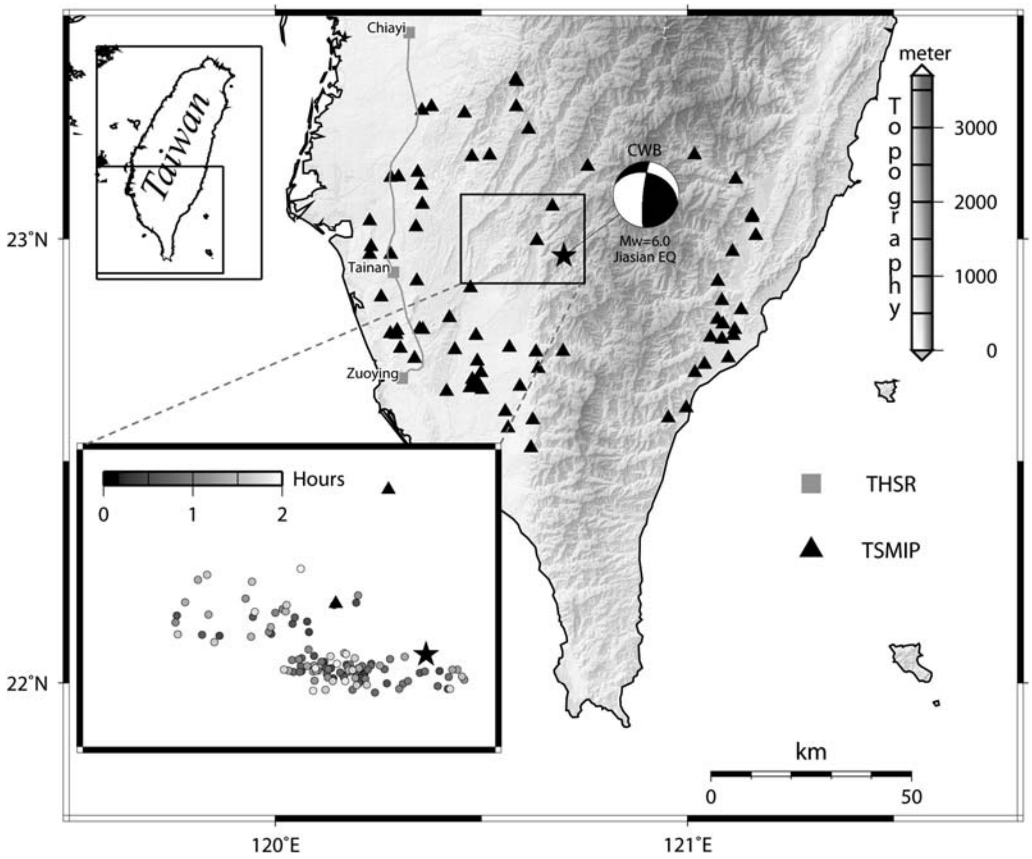

Figure 1. Locations of seismic stations (triangles) of the TSMIP seismic network and the epicenter of the 2010 Jiasian earthquake (star). The inset also shows the distribution of the aftershocks within two hours following the 2010 Jiasian mainshock. The TSMIP stations are limited in the high-relief mountain ranges. The route of THSR between Zuoying and Chiayi is shown as the line and is about 50 km away from the 2010 Jiasian mainshock. Three THSR train stations are shown by the solid squares.

stations closer to the earthquake are used to estimate the earthquake location and magnitude, and to predict the ground motions at more distant target areas. In the onsite approach, the initial P-wave motion at a target site is used to predict the ground motions of the later S and surface waves (which commonly have higher amplitudes or destructive energy than that of the initial P-wave motion) at the same site. Generally, the onsite EEW is faster but less accurate than the regional EEW (Wu and Kanamori, 2005a, 2005b).

The EEWS in Taiwan implemented by CWB nowadays integrates both the regional (virtual subnetwork, VSN method) and onsite (P-wave method:τ_c, $\tau_p^{\max}$, and Pd) techniques operating in a parallel scheme. The VSN method based on the regional EEW approach has been in operation for practical real-time earthquake monitoring since 2001 in Taiwan (Wu and Teng, 2002; Hsiao *et al.*, 2009). The autoconfigured, event-dependent VSN is a subset of the Rapid Earthquake Information Release System operated by CWB. The fundamental argument behind the VSN method is that empirically the determinations of event location and magnitude with a practically sufficient accuracy in rapid reporting are mostly dominated by the stations close to the epicenter (less than 60 km). The VSN method has a blind zone with a radius of 70 km around the epicenter, in which warnings cannot be issued in a timely manner (Hsiao *et al.*, 2009).

Based on the initial 3-s window of the first P-wave arrival on the high-pass (0.075 Hz) filtered vertical displacement seismogram, the average period (τ_c, Kanamori, 2005; Wu and Kanamori, 2005a; Wu *et al.*, 2007; Wu and Kanamori, 2008a, 2008b) and the dominant period ($\tau_p^{\max}$, Nakamura, 1988; Allen and Kanamori, 2003) are used to estimate earthquake magnitude in the current EEWS design in CWB (Hsiao *et al.*, 2009).

Wu and Kanamori (2005b, 2008a) and Wu *et al.* (2007) showed that the peak vertical displacement amplitude, Pd, usually from the first 3 s of the P wave, correlates well with the peak ground-motion velocity (PGV) observed at the same site, using the strong-motion data from Taiwan and southern California, respectively. Wu and Kanamori (2008b) also explored the feasibility of using Pd to correlate with PGV for 20 large earthquakes in Japan, and found a consistent relation as those for earthquakes in Taiwan and southern California. Compared with the VSN approach, the P-wave method using τ_c , $\tau_p^{\max}$, and Pd is more oriented to onsite use.

Figure 3 shows the flow chart of the current EEWS implementation by CWB (Hsiao *et al.*, 2009). Once the

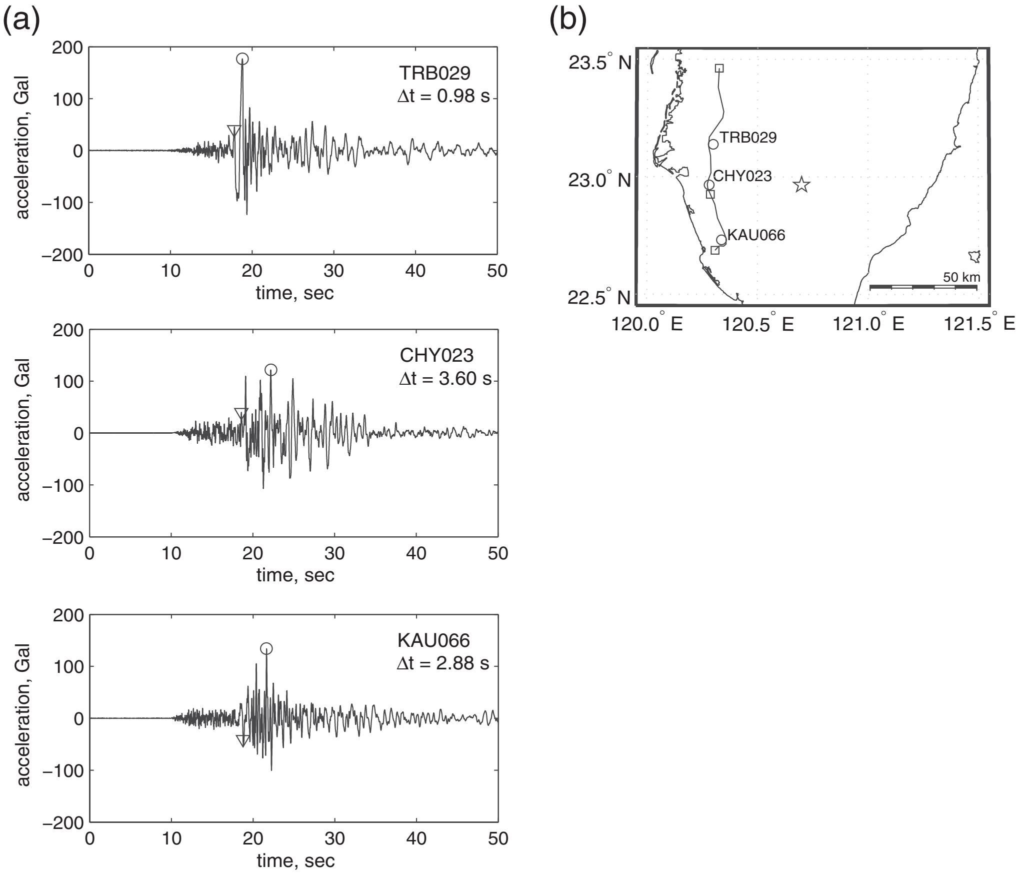

Figure 2. (a) The accelerograms recorded by three TSMIP stations near the rail of THSR. The triangles and circles indicate when the acceleration first exceeded $40g$ and the PGA was recorded, respectively. Δt represents the time difference between the recording times indicated by the triangle and circle. (b) The map shows three TSMIP stations (circles), three THSR stations (squares), and the epicenter of the 2010 Jiasian earthquake (star).

EEWS in CWB is triggered, both the *P*-wave and VSN methods are activated. The VSN method, based on the traditional seismological methods, will give the information on the event location and magnitude (M_{L10}, Wu *et al.*, 1998). For the *P*-wave method, τ_c and $\tau_p^{\max}$ are used to estimate the event magnitude as M_τ, mean of the magnitudes given by τ_c and $\tau_p^{\max}$, when an averaged P*d* obtained from the five nearest stations is larger than 0.1 cm. For an event with both M_{L10} and M_τ exceeding 6.0, a shake map (i.e., maximum expected ground-motion) is generated for the EEW and earthquake rapid reporting. A new prototype under development in Taiwan by EEWS (Hsiao *et al.*, 2010), based on the Central Weather Bureau Seismographic Network (CWBSN), proposes using the P*d* attenuation relationship with hypocentral distance ($M_{\mathrm{P}d}$, Wu and Zhao, 2006), along with the current VSN system, in magnitude determination. This new EEWS prototype can report earthquake information (i.e., location and magnitude) in 18.8 ± 4.1 s on average after the earthquake occurrence and provide timely warning for areas located 70 km away from the epicenter before the arrival of the *S* wave (Hsiao *et al.*, 2010).

The hypocenter of the 2010 Jiasian earthquake is shallow and located near the populated areas with distances less than a couple of tens of kilometers. Besides, the rupture direction of the Jiasian event mainly pointed to the populated areas in its western direction. Inevitably, these conditions reduce the early-warning lead time in nature. These conditions emphasize the importance and urgent demand of a faster onsite EEW system. In the current operating (Hsiao *et al.*, 2009; Wen *et al.*, 2009) and prototype (Hsiao *et al.*, 2010) EEWS in Taiwan by CWB, timely earthquake warning is not available for sites located within 70 km away from the epicenter owing to the limitation of the regional EEW approach. The magnitude and EEW processing time of the 2010 Jiasian estimated by the VSN method are of 6.33 ± 0.60 and 27 s, respectively. Apparently, the VSN method is not a favorable warning system with respect to its processing

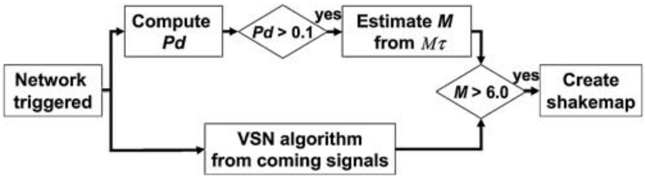

Figure 3. Flow chart illustrating the current EEWS operation in Taiwan as presented in Hsiao *et al.* (2009).

time for the populated areas with the epicentral distances less than 50–60 km, as was the case of the 2010 Jiasian earthquake. For the new prototype EEWS (Hsiao *et al.*, 2010) using the P*d* attenuation relationship (Wu and Zhao, 2006) in magnitude estimation, the estimated magnitude and processing time after the 2010 Jiasian mainshock origin time are 7.01 and 13.65 s, respectively.

Our study tests an experimental concept originally proposed by Wu and Kanamori (2005b, 2008a, 2008b) to reduce the EEW processing time, which is critically needed for short-distance warning within a couple of tens of kilometers. They suggested one approach toward faster warning by monitoring the filtered vertical displacement; once the amplitude exceeds a threshold value (0.5 cm in their study), an alarm is issued. We find that this tested EEW approach provided sufficient early-warning lead time in the case of the Jiasian earthquake with the target areas about 50 km away from the earthquake.

Seismic Data and Strong Ground Motion

In this study we collected the strong ground-motion data of the 2010 Jiasian mainshock recorded by the TSMIP stations. A total of 74 TSMIP acceleration records are used in this study. The TSMIP (Liu *et al.*, 1999), operated by CWB, consists of over 800 free-field stations densely distributed throughout the Taiwan island as of 2008 (Fig. 1). The TSMIP has a station spacing of about 5 km throughout most

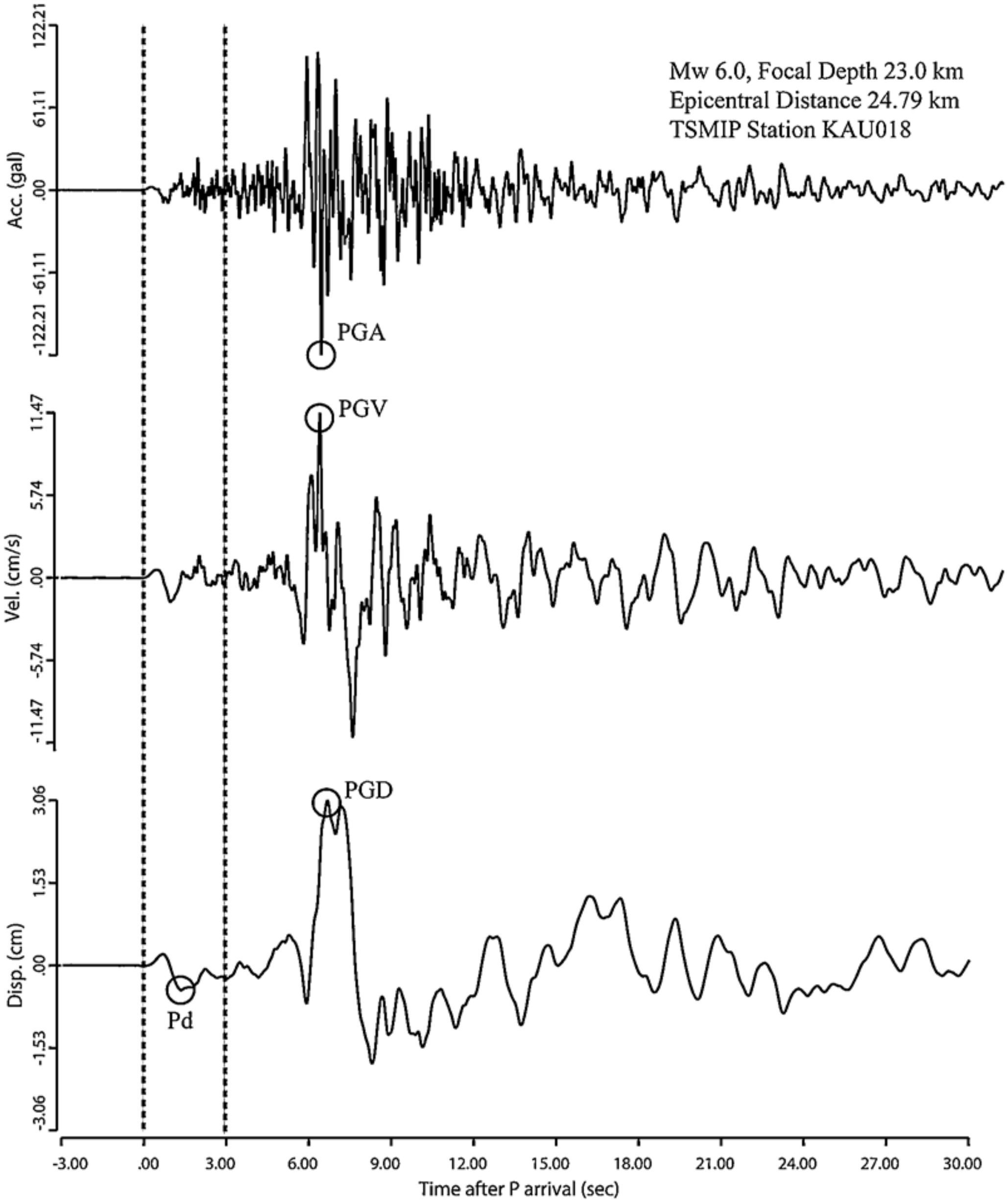

Figure 4. The raw acceleration waveform recorded on one TSMIP accelerometer and its integrations to velocity and displacement waveforms. The first 3 s after *P*-wave arrival is indicated by two dashed lines.

populated areas except for the higher relief mountain ranges. Each TSMIP station is equipped with a three-component, force-balance accelerometer with a sampling rate of 200 Hz or higher.

The original accelerations were integrated to find velocity and displacement, and the double-integrated displacements were filtered using a high-pass recursive Butterworth filter with a corner at 0.075 Hz as empirically suggested by Kanamori (2005) and Wu and Kanamori (2005a, 2005b, 2008a, 2008b). Figure 4 displays an example of the TSMIP acceleration record and its corresponding velocity and displacement waveforms. Peak ground acceleration (PGA), peak ground velocity (PGV), and peak ground disablement (PGD) are picked as the largest amplitudes among three components, and P*d* is defined on the filtered vertical displacement. The first arrivals were automatically detected from the vertical acceleration records by a *P*-wave picker described by Allen (1978).

Figures 5 and 6 summarize the PGA, PGV, and P*d* readings of the 2010 Jiasian earthquake and show the relationship between P*d* and PGV, respectively. Overall, the distributions of the high-value PGA and PGV reflect the fault plane rupture toward the northwestern direction and the layout of the TSMIP stations. Because the focal depth of the 2010 Jiasian earthquake is shallow and its epicenter is close to the populated areas (Kaohsiung and Tainan Counties), most of the regional populated areas including the route of THSR are covered by high PGA $(\sim\ 80g = 0.08\,g)$ and PGV values (Fig. 5) with the epicentral distances less than 50 km.

P*d* values perceivably show a clear attenuation relationship with the earthquake distances inferred by the elliptical-shaped contour in Figure 5. Wu and Zhao (2006) used the

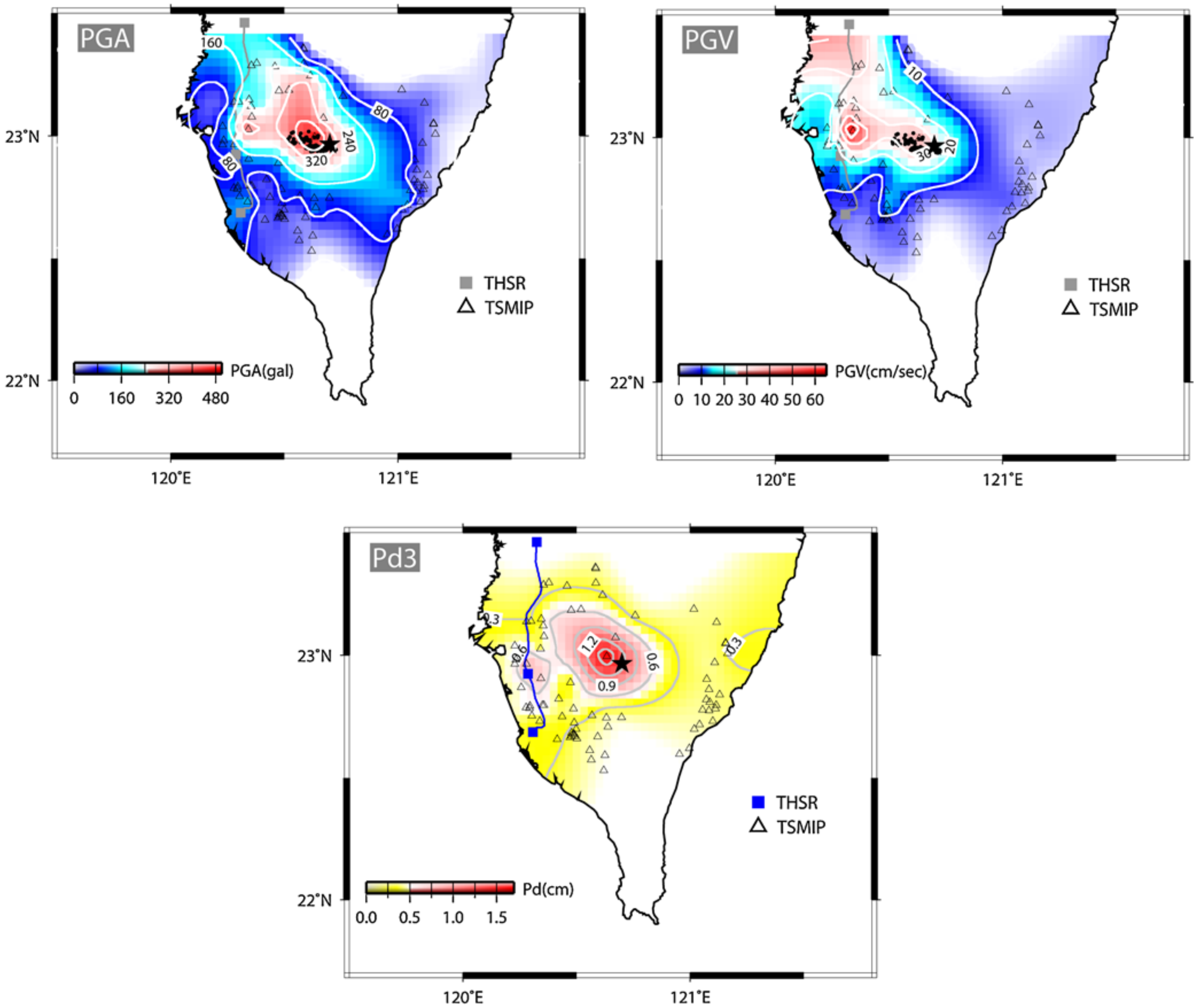

Figure 5. Distributions of the PGA, PGV, and P*d* readings of the 2010 Jiasian earthquake in southern Taiwan. The color version of this figure is available only in the electronic edition.

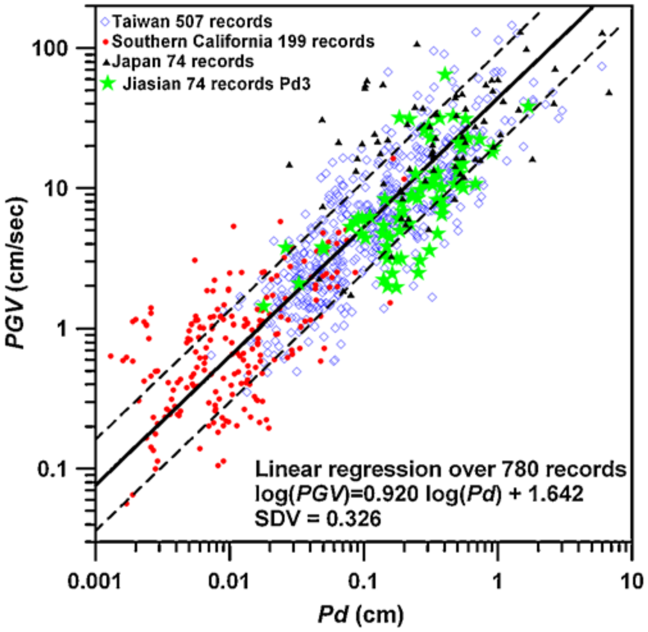

Figure 6. The relationship between peak amplitude of initial 3-s displacement (P*d*) and PGV. Solid line indicates the least squares fit for 780 records from Japan, southern California, and Taiwan, excluding the reading of the 2010 Jiasian earthquake. Two dashed lines show the range of on standard deviation. The color version of this figure is available only in the electronic edition.

attenuation of P*d* with the hypocentral distance in southern California to estimate the earthquake magnitude. The relationship between P*d* and PGV for the Jiasian earthquake (Fig. 6) generally follows the same trend as those for earthquakes in Taiwan, Japan, and southern California (Wu and Kanamori, 2005b; Wu *et al.*, 2007; Wu and Kanamori, 2008a, 2008b).

Faster Onsite Warning

Timely EEW to the near-source populated areas, sensitive facilities, or public transportation is most needed for earthquake hazard mitigation. Onsite EEWS under development in Taiwan and southern California use a 3-s time window after the *P*-wave arrival for peak ground-motion prediction in terms of PGV and magnitude estimations. One possible way to improve the processing time of near-distance EEW is to monitor the high-pass (0.075 Hz) vertical displacement, and issue a warning accordingly once it exceeds a threshold value. For the 2007 Niigata Chuetsu-Oki earthquake, Wu and Kanamori (2008a) found that, at the nearest station (epicentral distance = 14 km), P*d* = 0.5 cm was reached at 1.36 s after the arrival of the *P* wave. Wu and Kanamori (2008b) also observed that, for two stations at the epicentral distances of 7 and 19 km from the epicenter of the 2007 Noto Hanto earthquake, P*d* = 0.5 cm was detected at 0.54 and 0.64 s, respectively. From their experience with the Taiwan, southern California, and Japan data, if P*d* exceeds 0.5 cm the PGV most likely exceeds the damaging level, that is, 20 cm/s. These examples suggest that a commonly adopted 3-s time window after the arrival of the *P* wave for computing warning parameters might be too long for identifying a damaging earthquake for near-source sites.

Figure 7a reveals the relationship between the filtered vertical displacement and PGA, and shows that for all the TSMIP stations with the displacement (using a 5-s window after initial *P* wave arrival) larger than 0.35 cm, 76% of those stations have PGA values larger than 80*g*. PGA is closely related to the level of strong surface shaking that is the most concerned factor in evaluating the earthquake damage potential. A PGA value larger than 80-*g* corresponds to a CWB intensity scale of V (80–250*g*) in Taiwan (Wu *et al.*, 2003), or to a Modified Mercalli intensity scale (Wald *et al.*, 1999) value of VI (92–180*g*). Based on the empirical relationships between P*d* and PGV [$\log(\mathrm{PGV}) = 0.920\log(\mathrm{P}d) + 1.642$ in Wu and Kanamori, 2008a], and one between PGV and PGA [$\log(\mathrm{PGA}) = 0.595 + 1.069\log(\mathrm{PGV})$ in Wu *et al.*, 2003], a seismic receiver with P*d* of 0.35 cm will have a PGA value of about 80-*g*. In this study, we test a threshold value of 0.35 cm for the filtered vertical displacement and define the early-warning lead time at one station as the time difference between when the filtered vertical displacement exceeds the threshold value (0.35 cm) and the ground acceleration reaches 80*g*. Note that for a station if the time, the filtered vertical displacement exceeding the 0.35 cm threshold value, is later than 5 s after the initial *P* wave, it is not included as a triggered station even though it recorded the acceleration reaching 80*g* later than the time the displacement exceeded the warning threshold value. Because the tested short-distance EEW method is based on the onsite approach, the actual online warning releasing time should be a fraction of a second later than the time while exceeding the threshold value.

Figures 7b and 7c analyze the failed and missed alarm rates if using 0.35 cm as the threshold value for the filtered vertical displacement. The failed and missed alarms occur when the filtered vertical displacement exceeds or does not exceed 0.35 cm, and the acceleration reaches or does not reach 80*g*, respectively. The failed and missed alarm rates are 24% and 29%, respectively. The geographic positions of the four largest PGA recorded by the missed-alarm stations are shown in Figure 7d. These missed-alarm stations are in-line to the fault plane with a strike of 313° (Huang *et al.*, 2011) implying the effects of the radiation pattern on the displacements. We consider that the threshold value for the filtered vertical displacement of 0.35 cm is not quite sensitive to seismic sources other than earthquakes. We have installed several tens of Micro Electro Mechanical Systems (MEMS) accelerometers in Hualien, one of the most seismically active zones in Taiwan, and found that the filtered vertical displacement seldom exceeds 0.05 cm most of the time, unless earthquakes occur. For instance, an averaged P*d* of 0.1 cm obtained from the five nearest recording stations is used as the threshold value to confirm an occurrence of earthquakes in the current EEWS of CWB in Taiwan (Hsiao *et al.*, 2009).

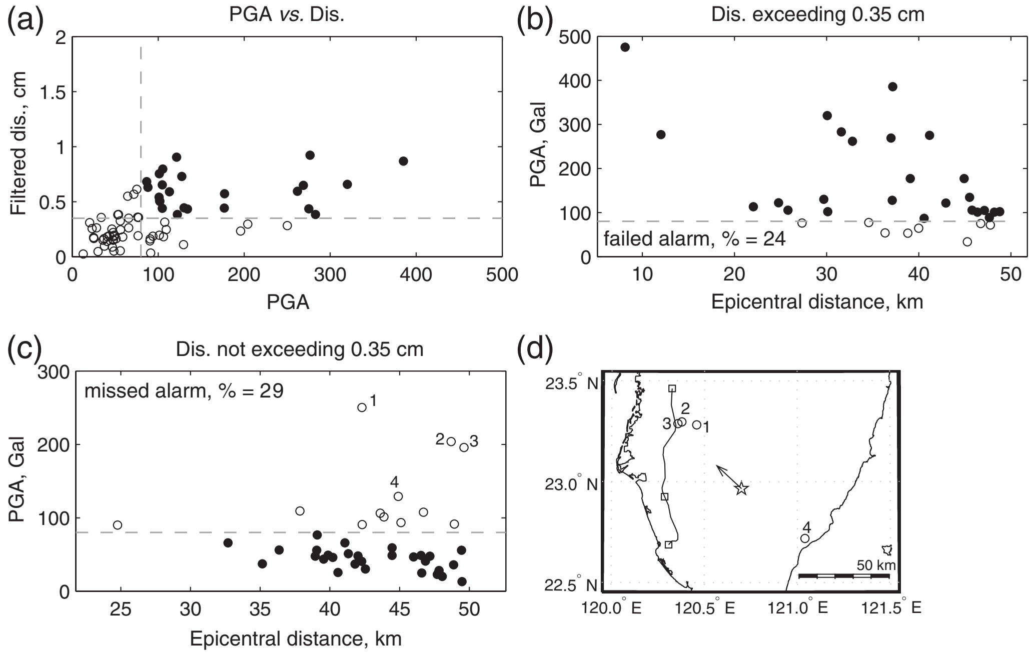

Figure 7. (a) The scatter plot between the filtered vertical displacement and PGA. The horizontal and vertical dashed lines indicate the values of 0.35 cm and 80g, respectively. The solid circles show the TSMIP stations with displacement (using a 5-s window after initial P wave arrival) larger than 0.35 cm and PGA larger than 80g. The failed and missed alarm rates are analyzed in (b) and (c), respectively, if using 0.35 cm as the threshold value for the filtered vertical displacement. The dashed lines in (b) and (c) indicate the acceleration of 80g. The open circles in (b) and (c) represent the failed- and missed-alarm TSMIP stations, respectively. (d) Location map showing the four missed-alarm TSMIP stations (open circles) with high PGA indicated in (c), three THSR stations (squares), and the epicenter of the 2010 Jiasian earthquake (star). The arrow points to the striking direction (313°) of the fault plane given in Huang *et al.* (2011).

Figure 8 displays the resulting early-warning lead time defined in our study. For sites located at the epicentral distances of about 25 and 50 km the EEW lead times are 2 to 4 s and 6 to 8 s, respectively, ahead of the arrival of the ground acceleration reaching 80g. It is a prominent improvement toward a faster EEWS. For example, the route of THSR where the train went off the rails during the occurrence of the Jiasian mainshock has the lead time of 6 to 8 s; undoubtedly, it is a quite sufficient amount of time for a preprogrammed EEWS to take emergent safety responses. As shown in Figure 2a, the time differences between when the acceleration exceeded 40g, the acceleration threshold value for the EEWS in THSR, and the PGA are recorded ranging from 1.0 to 3.6 s. The early-warning lead time and minimum warning distance are significantly improved compared with the current VSN method in Taiwan, which cannot provide a timely warning for sites located 70 km away from the epicenter.

Discussion and Conclusion

The 2010 Jiasian earthquake demonstrates the vital need for the short-distance EEW. Our proposed method successfully shows a much better performance in short-distance EEW than the currently operating VSN system in Taiwan. Moreover, 80% of the stations with the filtered vertical displacement exceeding 0.35 cm are less than 3 s after the first P-wave arrival, the commonly used duration for the calculations of Pd and τ_c. We believe that this proposed method will be particularly useful for EEW target areas and objects of those in the vicinity of the seismogenic zone. Of course, the practical implementation of the proposed method still has to be validated through more earthquakes to build a more stable statistical base observation. The displacement threshold

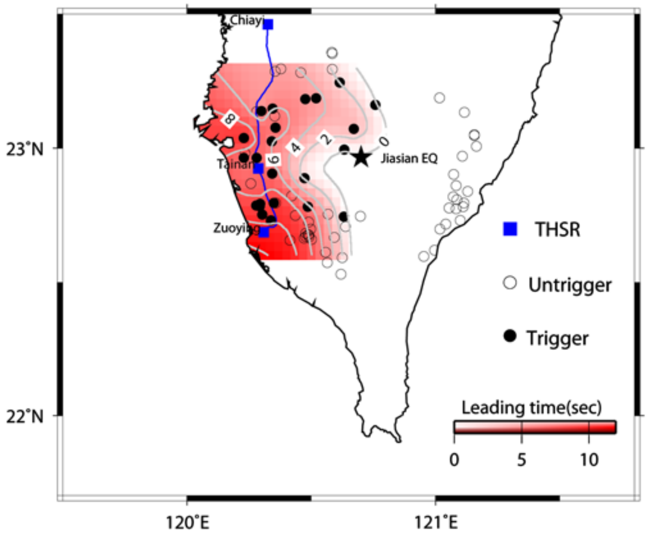

Figure 8. The contour of the resulting early-warning lead time defined in this study. The triggered stations are defined as those recording a filtered vertical displacement larger than 0.35 cm and earlier than the PGA reading time. The color version of this figure is available only in the electronic edition.

value of the onsite warning might be modified depending on the strength tolerance of target-to-ground shaking and the expense of the failed alarm.

Surely, one may argue the applicability of this method to larger magnitude earthquakes since the magnitude of the 2010 Jiasian earthquake is 6.3. Zollo *et al.* (2007) observed that peak displacement amplitudes in the 2-s and 4-s windows after the *P*-wave arrival show an excellent correlation with magnitude up to about *M* 6.5 and *M* 7.1, respectively, consistent with observations from southern California, Taiwan, and the Mediterranean. Therefore, at least our proposed method is expected to apply for earthquakes with magnitude up to 6.5. Even an earthquake with a magnitude of 6.0 occurring in the shallow depth and being adjacent to a protective EEW target is capable of causing severe earthquake damage.

In real application, a dense seismic network or array is always desirable for EEW implementation, both for the onsite and for the regional approaches. Our proposed short-distance EEW method relies on the wide dynamic range of the accelerometer. The MEMS accelerometer that has been recently introduced into seismic applications (Holland, 2003) is suitable to record near-field, high-frequency unsaturated waveforms at very short epicentral distances, and is miniature and cost-saving. Extensive installation of MEMS accelerometers at an onsite EEW target is expected to boost the signal-to-noise ratio by averaging scheme and reducing the odds of false and missed alarms.

The EEW information is not yet publicly distributed in the present EEWS of CWB in Taiwan, except (for experimental purposes) to organizations such as railway administration, rapid transit companies, and disaster prevention agencies . A collaborative effort that will involve government ministries, research institutions, and private sectors may be established to promote a publicly available EEWS in the near future in Taiwan. Before planning such a publicly based EEWS, we should make more of an effort to educate or train emergency response managers, earthquake engineers, and the general public to use the EEW information more effectively and understand the limitations/uncertainties of EEW.

Data and Resources

Raw accelerograms can be accessed by making a request to the Taiwan Central Weather Bureau or to author C.-H. Chang.

Acknowledgments

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References

Allen, R. V. (1978). Automatic earthquake recognition and timing from single traces, *Bull. Seismol. Soc. Am.* **68,** 1521–1532.

Allen, R. M., and H. Kanamori (2003). The potential for earthquake early warning in Southern California, *Science* **300,** 786–789.

Holland, A. (2003). Earthquake data recorded by the MEMS accelerometer, *Seismol. Res. Lett.* **74,** 20–26.

Hsiao, N. C., Y. M. Wu, T. C. Shin, L. Zhao, and T. L. Teng (2009). Development of earthquake early warning system in Taiwan, *Geophys. Res. Lett.* **36,** L00B02, doi 10.1029/2008GL036596.

Hsiao, N. C., Y. M. Wu, L. Zhao, D. Y. Chen, W. T. Huang, K. H. Kuo, T. C. Shin, and P. L. Leu (2010). A new prototype system for earthquake early warning in Taiwan, *Soil Dyn. Earthquake Eng.* **31,** 201–208, doi 10.1016/j.soildyn.2010.01.008.

Huang, H. H., Y. M. Wu, T. L. Lin, W. A. Chao, J. B. H. Shyu, C. H. Chan, and C. H. Chang (2011). The preliminary study of the 4 March 2010 M_w 6.3 Jiasian, Taiwan, earthquake sequence, *Terr. Atmos. Ocean. Sci.*, accepted for publication.

Kanamori, H. (2005). Real-time seismology and earthquake damage mitigation, *Ann. Rev. Earth Planet. Sci.* **33,** 195–214, doi 10.1146/annurev.earth.33.092203.122626.

Kanamori, H., E. Hauksson, and T. Heaton (1997). Real-time seismology and earthquake hazard mitigation, *Nature* **390,** 461–464.

Liu, K. S., T. C. Shin, and Y. B. Tsai (1999). A free-field strong motion network in Taiwan: TSMIP, *Terr. Atmos. Ocean. Sci.* **10,** 377–396.

Nakamura, Y. (1988). On the urgent earthquake detection and alarm system (UrEDAS), *Proceeding of the 9th World Conference on Earthquake Engineering*, Tokyo–Kyoto, Japan.

Teng, T. L., Y. M. Wu, T. C. Shin, Y. B. Tsai, and W. H. K. Lee (1997). One minute after: Strong-motion map, effective epicenter, and effective magnitude, *Bull. Seismol. Soc. Am.* **87,** 1209–1219.

Wald, D. J., V. Quitoriano, T. H. Heaton, and H. Kanamori (1999). Relationships between peak ground acceleration, peak ground velocity, and Modified Mercalli Intensity in California, *Earthquake Spectra* **15,** 557–564.

Wen, K. L., T. C. Shin, Y. M. Wu, N. C. Hsiao, and B. R. Wu (2009). Earthquake early warning technology progress in Taiwan, *J. Disaster Res.* **4,** 202–210.

Wessel, P., and W. H. F. Smith (1998). New, improved version of Generic Mapping Tools released, *Eos Trans. AGU* **79,** 579.

Wu, Y. M., and H. Kanamori (2005a). Experiment on an onsite early warning method for the Taiwan early warning system, *Bull. Seismol. Soc. Am.* **95,** 347–353.

Wu, Y. M., and H. Kanamori (2005b). Rapid assessment of damaging potential of earthquakes in Taiwan from the beginning of *P* waves, *Bull. Seismol. Soc. Am.* **95,** 1181–1185.

Wu, Y. M., and H. Kanamori (2008a). Development of an earthquake early warning system using real-time strong motion signals, *Sensors* **8,** 1–9.

Wu, Y. M., and H. Kanamori (2008b). Exploring the feasibility of on-site earthquake early warning using close-in records of the 2007 Noto Hanto earthquake, *Earth Planets and Space* **60,** 155–160.

Wu, Y. M., and T. L. Teng (2002). A virtual sub-network approach to earthquake early warning, *Bull. Seismol. Soc. Am.* **92,** 2008–2018.

Wu, Y. M., and L. Zhao (2006). Magnitude estimation using the first three seconds *P*-wave amplitude in earthquake early warning, *Geophys. Res. Lett.* **33,** L16312, doi 10.1029/2006GL026871.

Wu, Y. M., T. L. Teng, T. C. Shin, and N. C. Hsiao (2003). Relationship between peak ground acceleration, peak ground velocity, and intensity in Taiwan, *Bull. Seismol. Soc. Am.* **93,** 386–396.

Wu, Y. M., H. Kanamori, R. Allen, and E. Hauksson (2007). Determination of earthquake early warning parameters, τ_c and P_d, for southern California, *Geophys. J. Int.* **170,** 711–717, doi 10.1111/j.1365-246X.2007.03430.x.

Zollo, A., M. Lancieri, and S. Nielsen (2007). Reply to comment by P. Rydelek *et al.* on "Earthquake magnitude estimation from peak amplitudes of very early seismic signals on strong motion records", *Geophys. Res Lett.* **34,** L20303, doi 10.1029/2007GL030560.

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