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Full Research Paper

Development of an Earthquake Early Warning System Using Real-Time Strong Motion Signals

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Abstract: As urbanization progresses worldwide, earthquakes pose serious threat to lives and properties for urban areas near major active faults on land or subduction zones offshore. Earthquake Early Warning (EEW) can be a useful tool for reducing earthquake hazards, if the spatial relation between cities and earthquake sources is favorable for such warning and their citizens are properly trained to respond to earthquake warning messages. An EEW system forewarns an urban area of forthcoming strong shaking, normally with a few sec to a few tens of sec of warning time, i.e., before the arrival of the destructive S-wave part of the strong ground motion. Even a few second of advanced warning time will be useful for pre-programmed emergency measures for various critical facilities, such as rapid-transit vehicles and high-speed trains to avoid potential derailment; it will be also useful for orderly shutoff of gas pipelines to minimize fire hazards, controlled shutdown of high-technological manufacturing operations to reduce potential losses, and safe-guarding of computer facilities to avoid loss of vital databases. We explored a practical approach to EEW with the use of a ground-motion period parameter τ_c and a high-pass filtered vertical displacement amplitude parameter Pd from the initial 3 sec of the P waveforms. At a given site, an earthquake magnitude could be determined from τ_c and the peak ground-motion velocity (PGV) could be estimated from Pd. In this method, incoming strong motion

acceleration signals are recursively converted to ground velocity and displacement. A P-wave trigger is constantly monitored. When a trigger occurs, τ_c and *Pd* are computed. The earthquake magnitude and the on-site ground-motion intensity could be estimated and the warning could be issued. In an ideal situation, such warnings would be available within 10 sec of the origin time of a large earthquake whose subsequent ground motion may last for tens of seconds.

Keywords: earthquake, early warning system, seismic hazard mitigation.

1. Introduction

Because of the extreme complexity involved in the earthquake processes, reliable earthquake prediction is not currently possible (Kanamori et al., 1997). Present technological advances in seismic instrumentation and in digital communication and processing permit the implementation of a real-time earthquake monitoring system. From the point of view of seismic hazards mitigation, earthquake early warning (EEW) is becoming a practical tool to reduce the loss caused by a damaging earthquake (Kanamori et al., 1997; Teng et al., 1997; Wu and Teng, 2002; Allen and Kanamori, 2003).

The idea of an earthquake early warning system was proposed more than one hundred years ago by Cooper (1868) for San Francisco, California. About a hundred years later, Japan Railways Company designed an EEW system in 1965 and started operation in the following year (Nakamura, 1988). In the past decade, progress has been made towards implementation of earthquake early warning in Japan, Taiwan, Mexico, Southern California, Italy, and Romania (e.g., Nakamura, 1988; Odaka et al. 2003; Allen and Kanamori, 2003; Horiuchi et al, 2005; Wu et al., 1998, 1999, 2006, 2007; Wu and Teng, 2002; Wu and Zhao, 2006; Espinosa-Aranda et al., 1995; Zollo et al, 2006; Böse et al., 2007). In particular, the systems developed at the National Research Institute for Earth Science and Disaster Prevention (NIED) (Horiuchi et al., 2005) and the Japan Meteorological Agency (JMA) (Kamigaichi, 2004; Tsukada et al., 2004) were integrated in June, 2005. The system was successfully activated during the 2007 Noto Hanto (Peninsula) and the 2007 Niigata Chuetsu-Oki earthquakes, and provided accurate information regarding the source location, magnitude and intensity at about 3.8 s after the arrival of *P* wave at nearby stations. Thus, it provided early warning before arrival of strong shaking. Currently, there are many seismic networks using real-time strong motion signals for earthquake monitoring (Wu et al., 1997, 2000, 2001; Hauksson et al., 2001). In this paper, we describe the τ_c and *Pd* methods developed for earthquake early warning purposes.

2. τ_c and P_d method

Determinations of magnitude and the strength of shaking from the initial P wave are two important elements for earthquake early warning. Strength of shaking can practically be represented by peak gound acceleration (PGA), peak ground velocity (PGV), and peak ground displacement (PGD). Figure 1 shows a strong motion record of a $M_w6.6$ earthquake in Japan. Generally, strong motion signal represents acceleration, and after once and twice integration the signal can be coverted to velocity and

displacement. PGA, PGV, and PGD are the peak values of the three components. In real-time operation, velocities and displacements are recursively filtered with a one-way Butterworth high-pass filter with a cutoff frequency of 0.075 Hz for removing the low frequency drift during the first integration process.
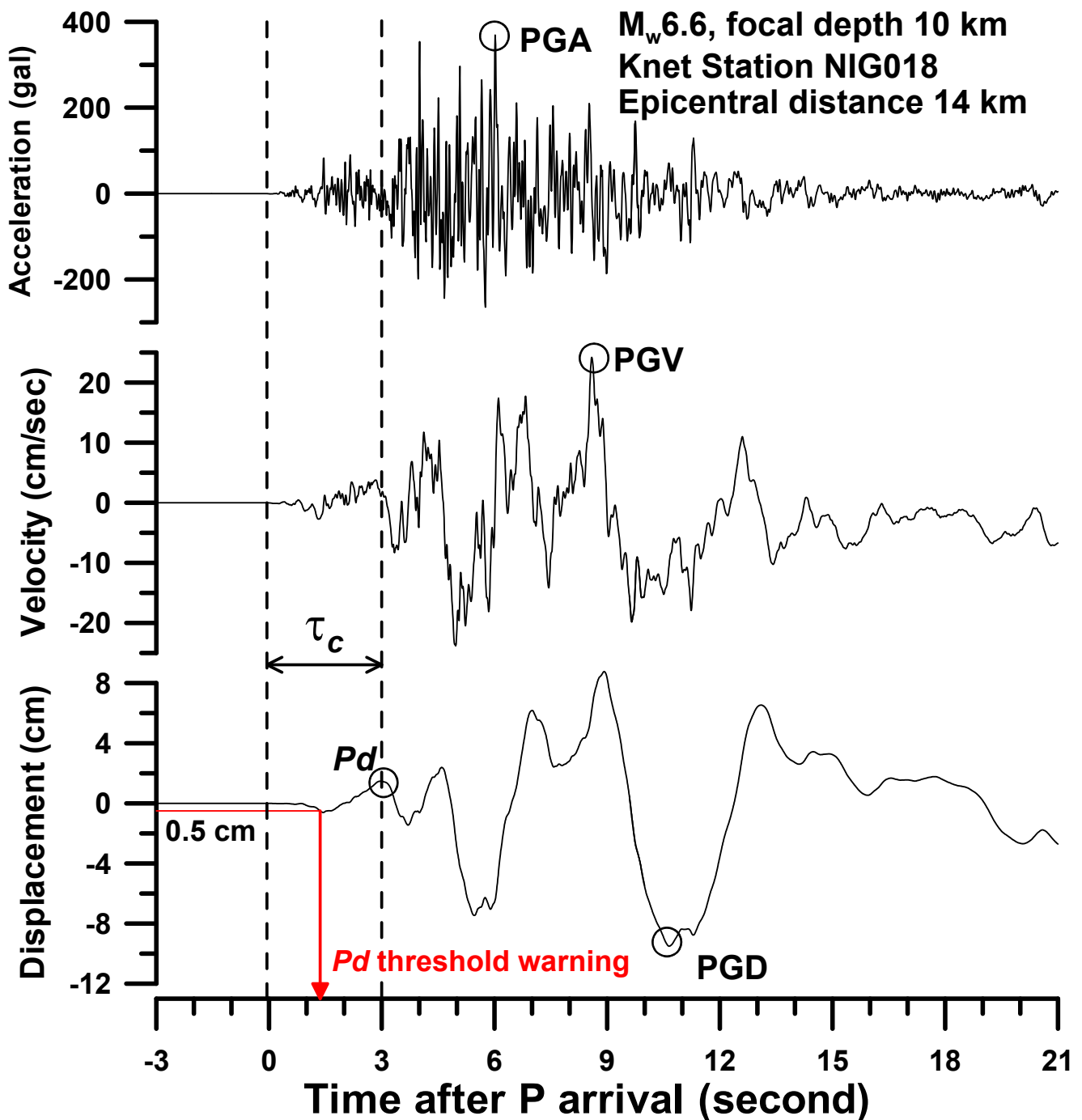

Figure 1. Vertical component acceleration, velocity and displacement seismograms for the 2007 Niigata Chuetsu-Oki earthquake, at the nearest stations, NIG018 (Δ=14 km). A ground-motion period parameter τ_c and a high-pass filtered displacement amplitude parameter P_d are determined from the initial 3 sec of the P waveforms.

An earthquake excites both P and S waves. The S wave carries the major destructive energy, and the smaller amplitude P wave precedes the S wave by the time equal to the 70% of the P-wave travel time to the station. The initial portion of the P wave, despite its small and nondestructive amplitude, carries the information of the earthquake size, and estimation of the earthquake size from the P wave provides information about the strength of shaking to be brought by the following S wave. Using *P* wave information to estimate the strength of S wave destructive shaking is a principal concept of EEW.

One of the major elements of EEW is to determine the earthquake magnitude rapidly and reliably. To determine the size of an earthquake, it is important to determine whether the earthquake rupture has stopped or keeps growing which is generally reflected in the period of the initial motion. Small and large events generally cause short and long period initial motions, respectively. The method developed by Nakamura (1988) attempts to use the period averaged over some time window. Kanamori (2005) used the following procedure which is modified from the method used by Nakamura (1988). The ground-motion displacement, $u(t)$, and velocity, $\dot{u}(t)$, from the vertical component record are used to compute the following ratio *r* by

$$r = \frac{\int_0^{\tau_0} \dot{u}^2(t)dt}{\int_0^{\tau_0} u^2(t)dt} \tag{1}$$

where the integration is taken over the time interval $(0, \tau_0)$ after the onset of P wave. In a series of previous studies (Wu and Kananmori, 2005a, 2005b, 2007; Wu et al., 2006; 2007), τ_0 is set at 3 s. Using Parseval's theorem,

$$r = \frac{4\pi^2 \int_0^\infty f^2 \left| \hat{u}(f) \right|^2 df}{\int_0^\infty \left| \hat{u}(f) \right|^2 df} = 4\pi^2 \left\langle f^2 \right\rangle \tag{2}$$

where $\hat{u}(f)$ is the frequency spectrum of $u(t)$, and $\left\langle f^2 \right\rangle$ is the average of f^2 weighted by $\left| \hat{u}(f) \right|^2$. Thus,

$$\tau_c = \frac{1}{\sqrt{\left\langle f^2 \right\rangle}} = \frac{2\pi}{\sqrt{r}} \tag{3}$$

can be used as a parameter representing the average period of the initial portion of the P wave. τ_c approximately represents the P wave pulse width which increases with the magnitude and can be used to estimate the event magnitude.

Another important element of EEW is to estimate the strength of S wave shaking at a site from the initial P waves at the same site. Wu and Kanamori (2005a) showed that the maximum amplitude of a high-pass filtered vertical displacement during the initial 3 sec of the P wave, *Pd* can be used to

estimate the PGV at the same site. When $Pd \geq 0.5$ cm, the event is most likely damaging. τ_c and Pd are the two basic parameters used for EEW in this approach.

Wu and Kanamori (2005a, 2005b, 2007), and Wu et al. (2006, 2007) applied this method to EEW in southern California, Taiwan, and Japan by determining τ_c and Pd. Figure 2 shows a good linear trend between τ_c and M_w determined from the Japan, Taiwan, and southern California records. τ_c values of 54 events for which at least four measurements are available for each event are shown in this figure. The potentially damaging earthquakes with $M_w > 6$ all have $\tau_c > 1$ sec. The regression with errors in both coordinates of M_w and τ_c results in relationships

$$\log \tau_c = 0.296 M_w - 1.462 \pm 0.122 \text{ and}$$
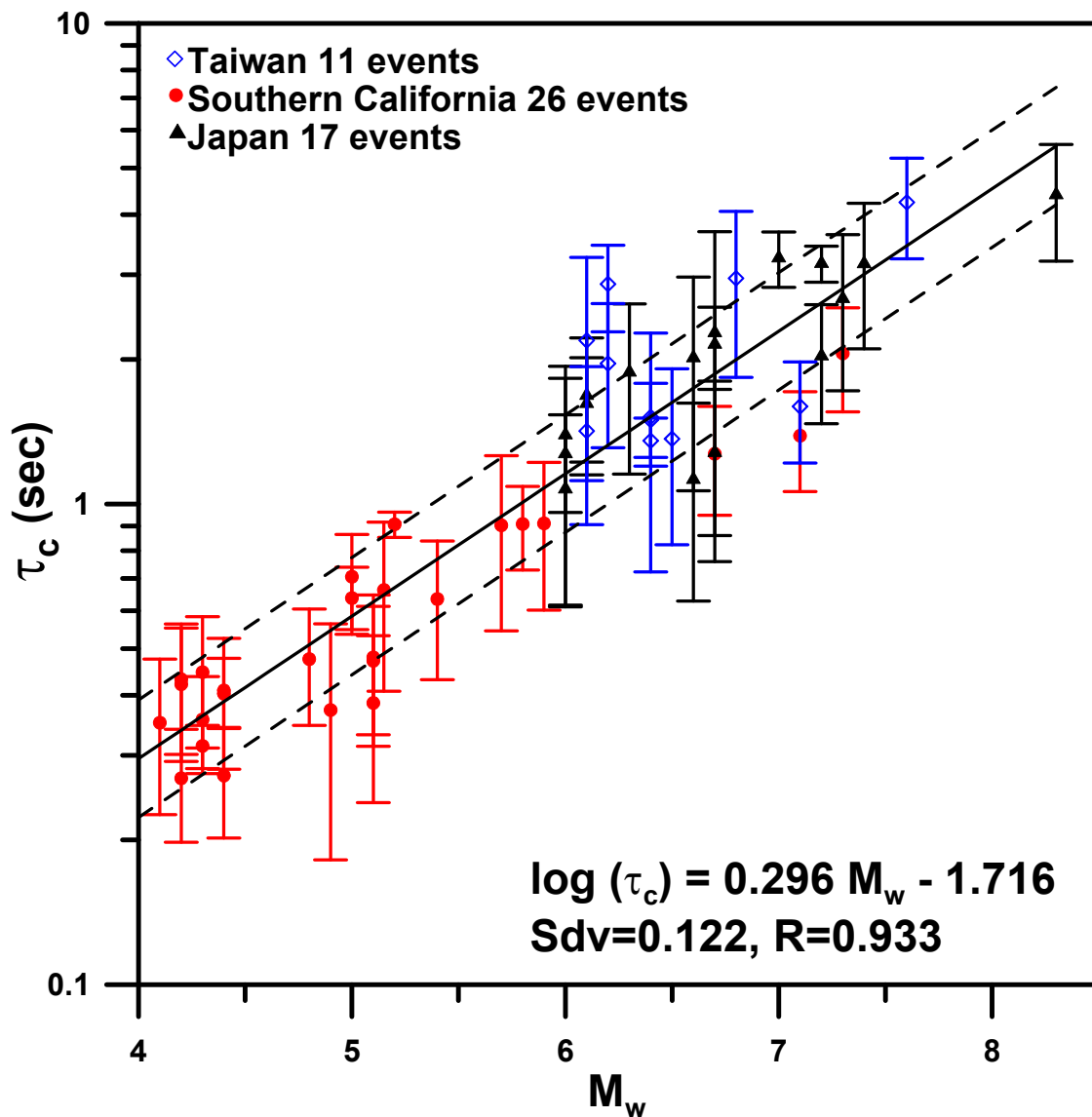$$M_w = 3.373 \log \tau_c + 5.787 \pm 0.412 \tag{4}$$

Figure 2. τ_c estimates for 54 events using the nearest stations for Japan (black triangles), southern California (red solid circles) and Taiwan (blue diamonds). Symbols show the event-average with standard deviation. Solid line shows the least squares fit and the two dashed lines show the range of one standard deviation.

The standard deviation of the estimate of M_w is 0.41 for all the events. This regression is based on the average τ_c for each event with at least four measurements.

Figure 3 shows the relationship between *Pd* and *PGV* for the 780 records with epicentral distances less than 30 km from Japan, Taiwan and southern California. We obtained a regression relation

$$\log(PGV) = 0.920 \log(Pd) + 1.642 \pm 0.326 \ (PGV \text{ in cm/sec and } Pd \text{ in cm}) \tag{5}$$
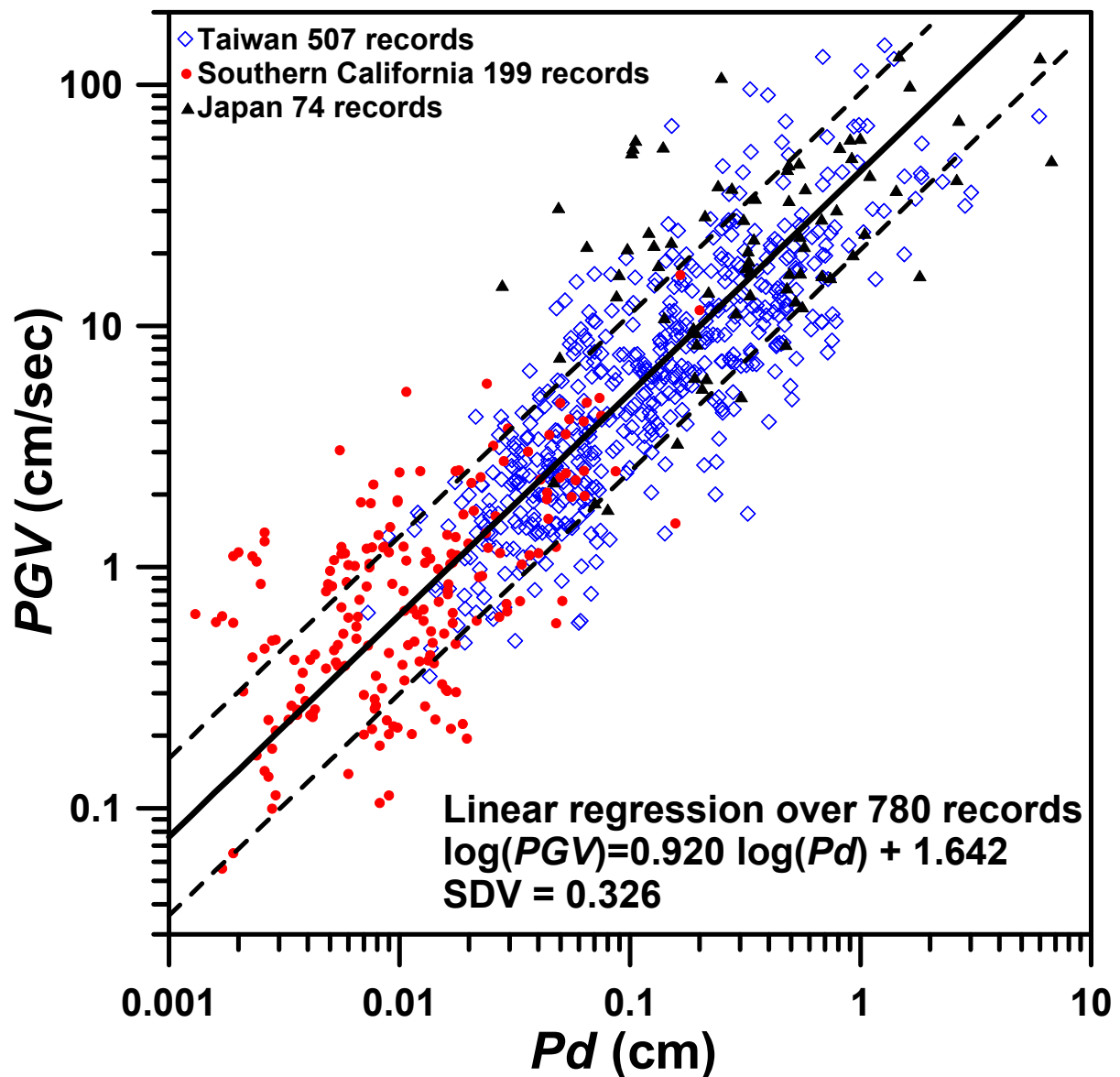

Figure 3. Relationship between peak initial three-second displacement amplitude (*Pd*) and peak ground velocity (*PGV*) for 780 records with the epicentral distances less than 30 km for Japan (black triangles), southern California (red solid circles) and Taiwan (blue diamonds). Solid line indicates the least squares fit and the two dashed lines show the range of one standard deviation.

Instrumental intensity scale for large events is defined with respect to *PGV* (Wald et al., 1999a, 1999b; Wu et al., 2003). Using these relationships, the shaking intensity can be estimated from a single station with a standard deviation of 1.0 unit of MMI scale or 0.6 unit of Japan and Taiwan intensity

scale. Thus, the magnitude and shaking intensity can be estimated for EEW purposes 3 sec after the P arrival is detected (Allen, 1978). If $\tau_c > 1$ sec and *Pd*>0.5 cm at a site, then the potential of a damaging earthquake striking this site is high (Wu and Kanamori, 2005a, 2005b, 2007; Wu et al., 2007).

3. Discussion and conclusions

From our experience with the Japan, Taiwan and southern California data, if *Pd* exceeds 0.5 cm, the PGV at the site most likely exceeds the damaging level, i.e., 20 cm/s. One possible approach for faster warning is to monitor *Pd*, and issue a warning as soon as it has exceeded 0.5 cm. As shown in Figure 1, for the 2007 Niigata Chuetsu-Oki earthquake, at the nearest stations, NIG018 (Δ=14 km), the threshold value of *Pd*=0.5 cm was reached at 1.36 s from the arrival of P wave. If we issue a warning at a threshold of *Pd* $\geq$ 0.5 cm, a warning will be issued at 1.36 s after the P arrival and several seconds before the occurrences of PGA and PGV. This type of early warning approach will become effective especially for close-in sites where warnings are most needed.

For any warning system, reliability is always important and it is desirable to have redundancy built in the system to make it more robust. In this paper, we explore the feasibility of using several early warning methods to increase the speed and reliability of early warning. In these methods, the information from the initial part (up to a few seconds) of P wave is used to estimate the magnitude and the strength of the impending ground motion at the same site. In view of the success of the Japan, Taiwan, and Mexico warning systems, we believe that further enhancement of the system like the one described here is worthwhile to make the overall system faster, more reliable, and robust.

Currently, MEMS (Micro Electro Mechanical Systems) acceleration sensors are well developed for a wide range of applications from air bag systems, detecting industrial vibrations, and strong motion recording (Holland, 2003). MEMS sensors are miniature sensors made in wafer fabrication facilities similar to semiconductor foundries. Many types of commercial MEMS accelerometers exist and they are inexpensive. Those accelerometers could be used for EEW purposes with the concept described in this paper and are useful for future seismic hazard mitigation.

Acknowledgements

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