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Parametric Criteria in Onsite Earthquake Early Warning System

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Abstract

In recent years, rapid estimation of Peak Ground Motion (PGM) and Modified Mercalli Intensity (MMI) based on a few seconds of the initial portion of P wave has been studied as the most important part of the onsite Earthquake Early Warning (EEW) systems studies. To establish an onsite EEW, we need the empirical relationship between earthquake size, PGM and epicentral distance in real-time mode. In some EEWs, the epicentral distance is estimated from the amplitude growth rate of a few seconds of P waves. Many studies have empirically confirmed that the growth rate becomes smaller as epicentral distance becomes far. This relation is true regardless of the earthquake size. In the current study, five parametric criteria including A, B, $B * P_a$, $B * P_v$ and $B * P_d$ are proposed for quick detection of destructive oncoming strong motions at a specific target based on ground motions of the first 4 seconds of Japan event waveforms where A and B parameters represent the characteristics of P wave envelope curve in a simple function with the form of $Bt.\exp(-At)$. In this study, B parameter is inversely proportional to epicentral distance which can be readily estimated within a given short time after P waves' arrival. P_a, P_v and P_d are the initial peak ground acceleration, velocity and displacement, respectively. The current study represent five thresholds parameters including A, B, $B * P_a$, $B * P_v$ and $B * P_d$ in order to warn a Peak Ground Velocity (PGV) greater than about 10 cm/sec which are clustered in strong shaking with Modified Mercalli Intensity (MMI) larger than VI. Therefore, destructive earthquakes can be detected form the maximum amplitudes and growth rate of few seconds of P waves by using mentioned parametric criteria.

Keywords: Onsite earthquake early warnings, KiK-net, P wave, PGV, Parametric criteria

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1 Introduction

EEW system operates based on the concept that the initial portion of P wave contains significant information of earthquake magnitude, epicentral distances and accordingly oncoming peak ground motions including peak ground acceleration (PGA), PGV and peak ground distance (PGD) at the specific targets. In recent years, EEW systems have been established and studied in many countries such as Southern California of the United States (Allen et al., 2009a, b; Bose et al., 2009), Japan (Nakamura, 1984, 1988; Odaka et al., 2003: Horiuchi et al., 2005), Mexico (Espinosa-Aranda et al., 2009), Taiwan (Wu and Teng, 2002; Wu and Zhao, 2006), Italy (Zollo et al., 2009; Satriano et al., 2011; Zollo et al., 2013), China (Peng et al., 2011) and Turkey (Alcik et al., 2009). One of the main types of EEW systems is onsite warning system through which the oncoming higher amplitudes (i.e. S and surface waves) at the target area can be estimated by using the real-time signals of ground motions from a single accelerometer and/or seismometer installed in the same area. Regional warning system is another type of EEW system which includes a number of acceleration and/or velocity sensors installed in the fault zone to provide warning time for distant targets. Therefore, rapid estimation of magnitude and epicentral distance is the main feature of the regional EEW system. However, onsite EEW system does not require measuring source parameters (i.e. magnitude and location). In onsite EEW systems, rapid estimation of peak ground motion including PGA, PGV and PGD and also intensity is enough to issue an alert. Therefore, Wu and Kanamori (2005a, b) suggested a good identifier for destructive earthquakes as $\tau_c * P_d$, showing an appropriate threshold for huge incoming ground motions, where τ_c is the characteristic period suggested by *Kanamori* (2005) as follows:

$$\tau_c = 2\pi\sqrt{\int_{t0}^{t0+dt} u^2 / \int_{t0}^{t0+dt} v^2} \qquad (1)$$

where u and v denote ground displacement and velocity, respectively. τ_c represents the frequency content of the initial ground motion and is correlated with the earthquake magnitude (Kanamori, 2005; Wu and Kanamori, 2005a, b). This study tries to gain parametric thresholds utilized in onsite EEW systems in an attempt to identify destructive earthquakes in Japan. Author choses Japan for study area because of the high quality acceleration waveforms from various earthquakes with different magnitude and the recorded epicentral distance .

Odaka et al. (2003) fitted a simple function as $\mathrm{Bt.exp}(-\mathrm{At})$ to the few seconds of early part of acceleration waveforms (P wave) and calculated $A\,(\frac{1}{sec})$ and $B\,(\frac{gal}{sec})$ parameters using the least-squares method. The origin of time t is measured since P-phase arrival time. Odaka et al. (2003) showed an inverse relationship between $log(B)$ and $log(\Delta)$, where Δ denotes epicentral distance in km. According to Odaka et al. (2003) while the amplitude of large earthquake arises exponentially with time t, A values would be less than zero and vice versa for small to moderate earthquakes. The fitting curve executes as a low-pass filter on the time series and then two key parameters, A and B, are not strongly affected by high frequency noise. In order to avoid the noise level preceding the P wave arrivals, the logarithm of the ground motion is used for fitting curve (Odaka et al. 2003). Heidari (2016) showed that P wave picking is a sensitive process and small error in P-phase arrival time can lead to significant errors in the estimation of A and B parameters. Moreover, Wu et al.

(2007) and Wu and Kanamori (2008 a, b) indicated that the initial displacement amplitude, P_d, is well correlated with PGV. This study investigates the combination of initial displacement amplitude, P_d, velocity, P_v, and acceleration, P_a, with two parameters A and B and makes a rapid identification of destructive earthquakes. In other words, multiplication of P wave amplitudes by a parameter associated with distance (B) is studied in this paper.

2 Data

The used catalog including events occurred within 1998-2015 is closely similar to the one used by Huang et al. (2015). The dataset contains high quality strong motion waveforms (SNR>10) which are recorded at KiK-net acceleration borehole and surface sensors in Japan with sampling frequency of 100 and 200 Hz (see Figure 1). KiK-net is a broad-band strong-motion seismograph network, which consists of pairs of seismographs installed in a borehole together at approximately 700 locations. The used instrumentation is a V403 or V404 tri-axial force-balance accelerometer with a natural frequency of 450 Hz and a damping factor of 0.707 with the typical sensor gain of 3 *V/g* (*0.306 V/m/s^2*).

Finally, more than 6480 vertical-component accelerograms of 120 in-land events occurred in Japan, with magnitude $5.0 < M_{\text{JMA}} < 7.3$, epicentral distances of 15-80 km and depth less than 50 km are being studied. P-phase arrival times are manually triggered and then the first 4 seconds of the waveforms are extracted after P-phase incoming time (see Figure 2). A %5 cosine taper is applied on two cutting edges. In order to obtain P_v, and P_d, first and second integration of each accelerograms is taken, respectively. Velocity and displacement seismograms are high-pass filtered using a causal two-pole Butterworth filer with a cut-off frequency at 0.075 Hz to remove low-frequencies artifact generated by the integration.

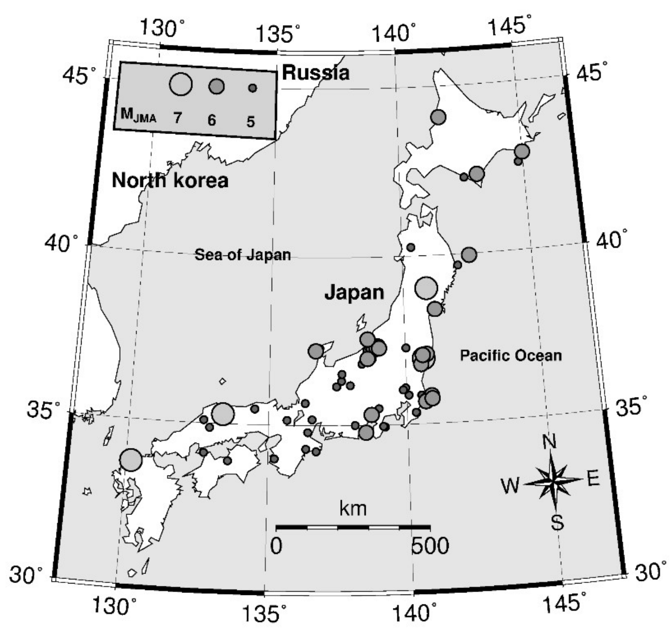

Figure 1. Epicenter map of the studied events in Japan. Radius and color of the circles indicate the earthquake magnitude.

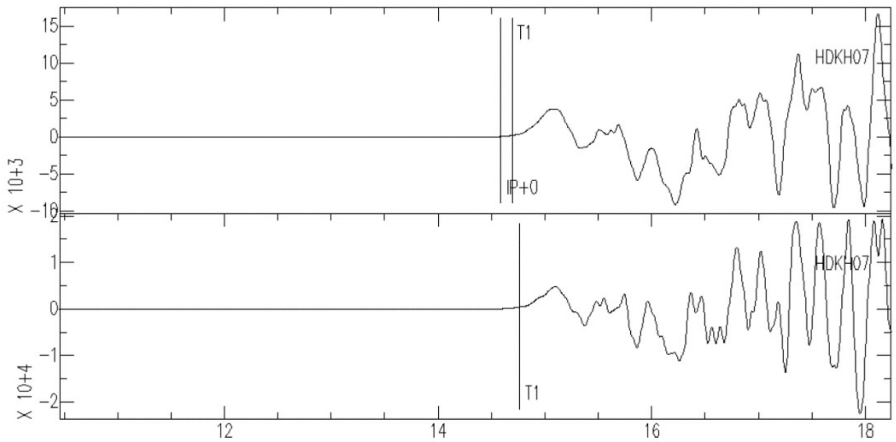

Figure 2. Example of surface and borehole waveforms an earthquake. The P-wave trigger time is shown by the vertical line.

3 Methods and analyses

A two-pole band-pass Butterworth filter in the frequency band of 10-20 Hz is applied to the acceleration waveforms in order to calculate A and B parameters (Odaka et al., 2003). The mentioned frequency band have been selected based on the fact that the if radiation pattern of high frequencies ground motion can be isotropic (Okamoto and Tsuno., 2015). Finally, five parameters including A, B, P_a, P_v and P_d are calculated for each record. Parameters A and B are determined using the least-squares approach. Time windows of 4 s from the initial part of the P wave are extracted, and the function of $y = Bt.\exp(-At)$ is fitted to them. For this purpose, the logarithm of this function is used as ln(y)=ln(Bt)−At. In this way, parameters A and ln(B) can be easily calculated using the least-squares method. Whereas, the amplitude of P_d from the vertical components in the first portion of P-phase, as a function of distance and magnitude, is well correlated with the PGV (Kanamori, 2005; Zollo et al., 2006; Wu and Kanamori, 2005a, 2005b; Wu et al., 2007; Wu and Kanamori, 2008a, 2008b), and A and B values are controlled by the earthquake size and epicentral distances respectively (Odaka et al., 2003). The idea of this study is that A and B parameters as well as their combination with P wave amplitudes (i.e. P_a, P_v and P_d) would be properly correlated with PGV. Figure 3 illustrates the scattering between A and B parameter measurements. Figure 3 shows the clear thresholds of A and B

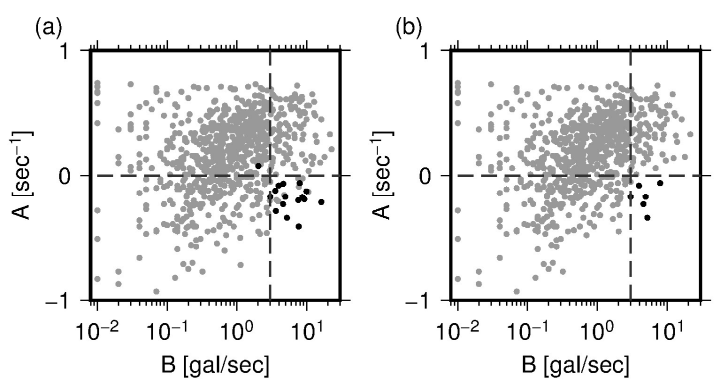

Figure 3. The scatter plot of A and B measurements of (a) both borehole and surface and (b) only borehole records. Values corresponding to PGV $>$ 10 cm/sec are indicated by black circles.

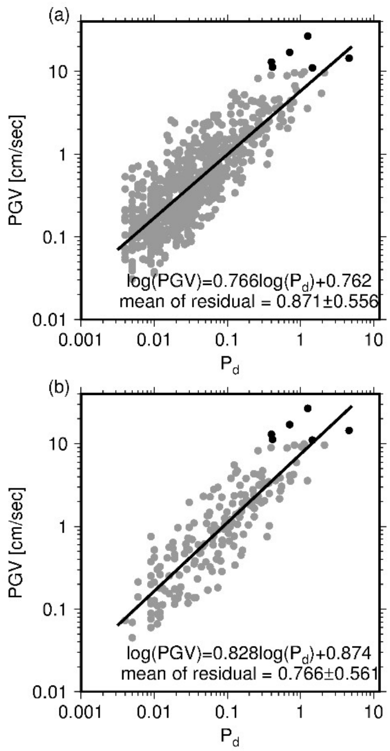

Figure 4. The relationship between P_d and PGV for (a) all A values and (b) $A < 0$, respectively based on borehole sensor records. Six pairs with PGV > 10 cm/sec are indicated by black circles.

parameters at PGV values greater than about 10 cm/sec (corresponding to strong shaking), especially for only borehole sensor records. This, in its turn, leads to MMI intensity larger than VI (Wald et al., 1999) providing good thresholds for detecting a destructive earthquake. Figures 4a and 4b indicate scattering and best-fitting relationships between P_d and PGV of only borehole sensor records for all values of A (Equation 2) and for values of A less than zero (Equation 3), respectively as follows:

$$\log(PGV) = 0.766 \log(P_d) + 0.762 \quad (2)$$
$$\log(PGV) = 0.828 \log(P_d) + 0.874 \quad (3)$$

The residual, i.e. mean of catalog minus the estimated $\log(P_d)$, and its standard deviation for equations (2) and (3) is 0.87±0.55 and 0.76±0.56, respectively. It means that the scaling correlation between P_d and PGV for large earthquakes ($A < 0$) presents more reliable and robust results. Therefore, given the reasons described in Figures 3 and 4, it is assumed that A values are negative for destructive earthquakes.

Additional regression of $B * P_a$, $B * P_v$ and $B * P_d$ and PGV are evaluated for different values of A parameter. It is concluded that for A less than 0, small hypocentral distances (or large value of B) and large amount of the initial amplitude of P-pahse P_a, P_v and P_d, the large value of PGV will be expected. Figures 5a, 5b and 5c show scatter plot between $B * P_a$, $B * P_v$ and $B * P_d$ and PGV, respectively (for all A values), and Figures 5d, 5e and 5f illustrate the same diagrams for only negative value of A. Figure 5 and 6 show that for many measurements, when PGV > 10 cm/sec, there are also good separator criteria for $B * P_a$, $B * P_v$ and $B * P_d$, especially for only borehole records.

Results in Figure 3a show that when $A < 0$ (1/sec) and $B > 3$ (gal/sec), the PGVs are greater than 10 for 68% of the main database waveforms. In addition, except for one case the waveforms with PGV>10 have $A < 0$ (1/sec) and $B > 3$ (gal/sec) (see Figure 3a). The reliability of this combined threshold is surprisingly increased for only borehole records which are recorded on the bedrock (Figure 3b) due to the small noise and lake of surface effects.

In order to provide more criteria parameters, additional regressions of $B * P_a$, $B * P_v$ and $B * P_d$ measurements and PGVs are evaluated once for all waveforms in the main database and once again for the records with a negative values of A parameter.

Figures 5a, 5b and 5c show scatter plot between $B * P_a$, $B * P_v$ and $B * P_d$ and PGV, respectively for all of the records; and Figures 5d, 5e and 5f illustrate the same diagrams for only negative value of A. Although Figure 5 (a, b and c) represents a good relation between $B * P_{a,v,d}$ and PGV for main database records, results indicate that if condition of A<0 would be combined with $B * P_{a,v,d}$, it could provide more accurate and reliable parameters for assessing the potential damage. As shown, when $A < 0$ and $B * P_a > 100$, 15 out of 27 waveforms (58%) have PGV greater than 10 cm/sec, and the earthquake is likely damaging. This amount reaches more than 63% of measurements (14 out of 22 waveforms) when $A < 0$ and $B * P_d > 1.5$ and 68% (15 out of 22) when $A < 0$ and $B * P_v > 4$.

Although the number of borehole records is very low, their results (on bedrock) are very interesting (see Figure 6). When $A < 0$ and $B * P_a > 100$ (and/or $B * P_v > 4$ and/or $B * P_d > 1.5$), the whole data (6 out of 6) have PGV>10 cm/sec and the earthquake is most likely destructive. Generally, Figures 5 and 6 show that for most of the measurements, when PGV>10 cm/sec, there are good separator criteria for four sets of combination of $A, B, B * P_a$, $B * P_v$ and $B * P_d$ parameters, especially for only borehole records.

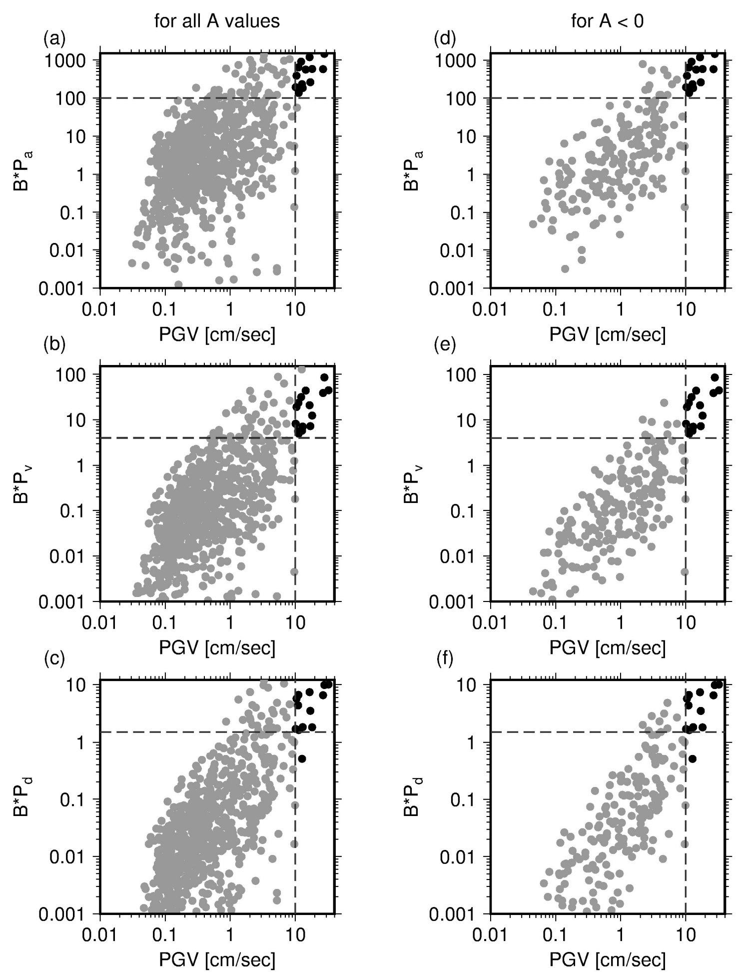

Figure 5. (a), (b) and (c) show the scatter plot between P_a, P_v and P_d and PGV for all values of A and based on both borehole and surface records. (d), (e) and (f) show the same illustrations for $A < 0$. PGVs greater than 10 cm/sec are indicated by black circles.

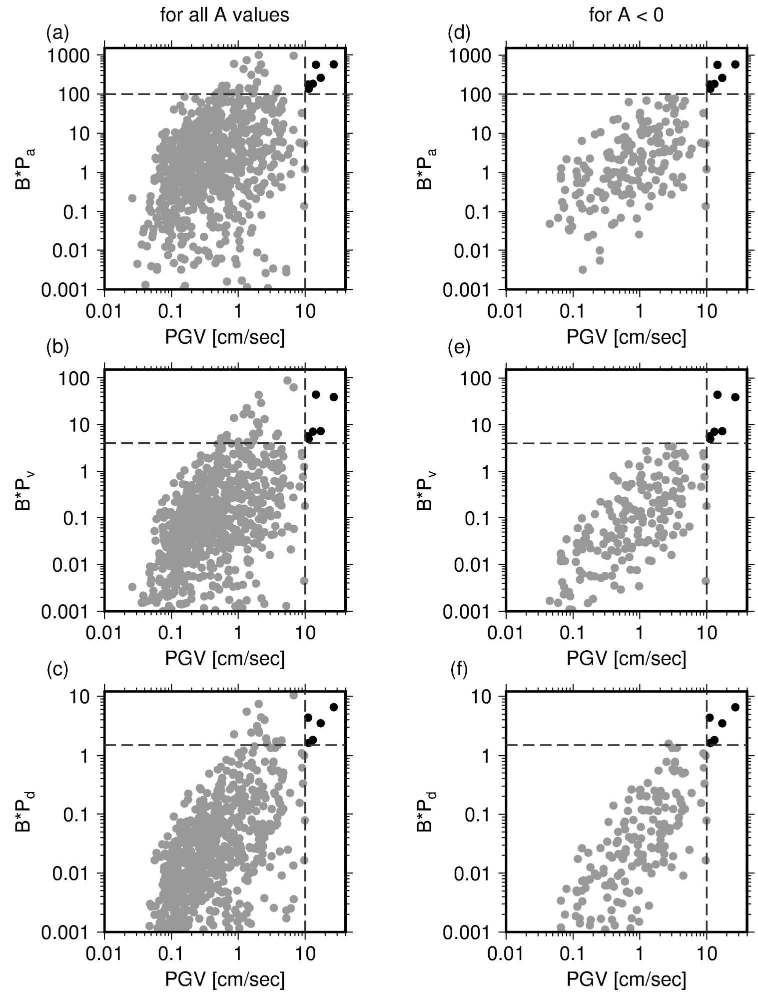

Figure 6. (a), (b) and (c) show the scatter plot between P_a, P_v and P_d and PGV for all values of A and based on only borehole records. (d), (e) and (f) show the same illustrations for $A < 0$. PGVs greater than 10 cm/sec are indicated by black circles.

4 Discussions and conclusions

Large events in populated regions are potentially destructive. For a successful and operational alert system in the populated areas, it is very important to use the approaches that allow us to detect the destructive earthquake rapidly using empirical criteria parameters between initial parameters of P wave and peak ground motion PGA, PGV and PGD. An onsite EEW system issues warning for areas close to the same station by using a single seismic sensor (or array). In the current study, five different parametric criteria have been explored for quick identification of destructive earthquakes based on the characteristics of the initial portion of P-phase envelope and amplitude which are used in onsite EEW systems. These approaches are tested based on the KiK-net data during 1998-2015 which consist of the acceleration waveforms of earthquakes with epicentral distances between 15-80 km and M_{JMA} between 5.0 and 7.3 in Japan.

In this study, practical approaches to EEW systems have been presented in order to detect PGV larger than 10 cm/sec with the use of a slope rate of ground motion period growth parameter A and B

and also P wave amplitudes P_d, P_v and P_a from the initial 4 sec of the waveforms. The results indicate thresholds for five parameters including A, B, $B * P_a$, $B * P_v$ and $B * P_d$ for quick recognition of the oncoming strong shaking, especially for borehole sensor records. When the amplitude of P waves decreases by propagating through the earth, the ground motions growth rate of the initial portion of the oncoming P-waves decreases, which is independent of the earthquake magnitude. Therefore, the B parameter is used to consider the effects of the distance on the estimation of peak ground motions.

The A, B, $B * P_a$, $B * P_v$ and $B * P_d$ parameters in EEW systems can estimate strong ground velocity larger than 10 cm/sec with a time window of 4 s before the arrival of the destructive S-wave part of the strong ground motion.

The parametric criteria provide an opportunity for automatic shut-off devices and emergency reactions. Even a few second of preceding warning time will be useful for emergency actions, such as high-speed trains to avoid potential derailment. It will be also beneficial to shutoff gas pipelines to minimize fire hazards. So, it can be noticed that a massive ground motion and consequently noticeable intensity ($MMI > VI$) is foreseeable based on P-wave envelope parameters and amplitudes. Furthermore, the values of $\tau_c * P_d$ are calculated and plotted against PGV values for all used data (Figure 7a) and for borehole sensor data (Figure 7b) separately. Wu and Kanamori (2005) suggested that the value of $\tau_c * P_d = 1$ cm-sec is a good threshold for detecting a destructive earthquake in Taiwan. In comparison to $\tau_c * P_d$ approach which is multiplication of the amplitude by a frequency-estimator for magnitude (Kanamori, 2005), it seems that the proposed criteria parameters can be more accurate and reliable for identifying destructive earthquake in the studied area. Besides, more studies are needed based on a greater variety of data in different tectonic environments and with wider range of earthquake sizes and epicentral distances.

Although the saturation may leads to underestimation of EWS parameters within few seconds of P-wave arrivals (Kanamori, 2005; Rydelek and Horichi, 2006; Rydelek et al., 2007; Zollo et al., 2007; Colombelli et al., 2012), Allen and Kanamori (2003) showed that the earthquake magnitude can be estimated only during the first 4 seconds of wave based on the events with $M < 7.3$. In this study, results indicate that the proposed parameters work well for rapid detection of damaging earthquakes (PGV>10 cm/sec) within a quite short time of the initial portion of P wave (4 seconds). However, more investigations and studies is required for earthquake with a complicated source rupture history, earthquake which was recorded in various tectonically environment and near earthquakes.

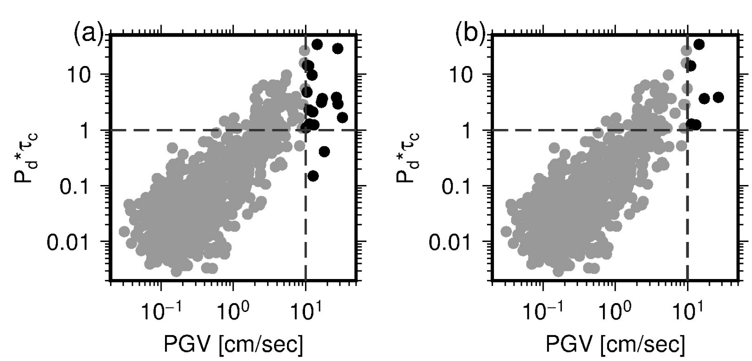

Figure 7. The scattering plot of $\tau_c * P_d$ and PGV for (a) all A values and (b) $A < 0$.

Generally, onsite EWSs are applied for the targets located near the fault in order to generate a rapid warning time. Therefore, rapid estimation of peak ground motion and intensity is adequate in real-time processing. There are not robust algorithms for real-time estimation of the magnitude and location in onsite warning systems. The proposed methodology in this study evaluates thresholds for rapid detection of destructive earthquake regardless the event magnitude and location. Additionally, results are obtained based on the waveforms which are picked (onset of P wave) in offline mode. However, in real-time applications, P-phase picking uncertainties (and others processing procedures such as real-time filtering) may affect the reliability performance and may leads to false and missed alarms.

5 Data and resources

The understudy time series data are obtained from Kyoshin Network (KiK-NET; http://www.kik.bosai.go.jp) of National Research Institute for Earth Science and Disaster Prevention (NIED). All of the figures in this study were plotted using Generic Mapping Tools (*Wessel and Smith, 1998*). Data processing is performed using Seismic Analysis Code (http://ds.iris.edu/ds/nodes/dmc/software/downloads/sac, last accessed May 2014).

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