Exploring the feasibility of on-site earthquake early warning using close-in records of the 2007 Noto Hanto earthquake

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In view of the remarkable success of the Japan Meteorological Agency earthquake early warning system (developed jointly with the National Research Institute for Earth Science and Disaster Prevention) during the 2007 Noto Hanto earthquake, we explore the use of an on-site early warning method with the hope of eventually enhancing the existing system for more robust and faster warning. We determined two early warning parameters τ_c and *Pd* using the K-NET and KiK-net data for the 2007 Noto Hanto earthquake as well as 20 large earthquakes in Japan. An extended method suggests a possibility of using the initial displacement amplitude data for faster warning. For the two nearby sites at the epicentral distances of 7 and 19 km of the 2007 Noto Hanto earthquake, an early warning can be ideally issued at 2.27 and 5.46 s, respectively, before the peak ground motion velocity occurs at the site.
Key words: Earthquake early warning, magnitude, seismic hazard mitigation, *P*-waves.

1. Introduction

Several earthquake early warning methods have been recently developed, and some of them have been already implemented either experimentally or for actual operation. 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) (Tsukada *et al*., 2004) were integrated in June, 2005. JMA started official distribution of early warning information to a limited number of organizations in August, 2006, and plans to distribute it to the public in the fall of 2007. This system includes on-site warning capability using the amplitude and the temporal variation of acceleration at a single station. 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. This information reached the sites further than about 30 km from the epicenter as "early" warning (i.e., information arrived before shaking started at the site). This is a remarkable performance of the system for inland (or close to the shore) damaging earthquakes and gave promise of an early warning system as a practical means for earthquake damage mitigation. Although the warning did not reach close-in sites in time (i.e., the information arrived after shaking began) within about 30 km from the epicenter where such warnings are most needed, this is inevitable with the current density and configuration of the network. If the network is made denser in the future, the warning can be issued more rapidly and the information will be more useful and practical.

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 on-site early warning methods to increase the speed and reliability of the warning system. In on-site 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. This method was initially developed for the Japanese Railway's Urgent Earthquake Detection and Alarm System (UrEDAS) (Nakamura, 1984, 1988) and, with some modifications, has been tested in Taiwan (Wu and Kanamori, 2005a) and southern California (Allen and Kanamori, 2003; Wu *et al*., 2007).

2. Method

Since the method has been described in detail elsewhere (Kanamori, 2005; Wu and Kanamori, 2005a), we only briefly summarize it below. We use high-pass (0.075 Hz) filtered vertical component ground-motion displacement records to compute two parameters τ_c and *Pd* from a short record with a duration t_0 (usually 3 s) after the arrival of *P* wave. Parameter τ_c characterizes the period of ground motion during the initial t_0 sec after the *P* arrival, and *Pd* is the maximum displacement amplitude during the same time interval. The high-pass filter is applied to remove the drift of the displacement records after double integration of the accelerograms (e.g., Kanamori *et al*., 1999). As shown in Appendix 1 (Fig. A.1), the high-pass filter tends to reduce *Pd*, especially for large events. Thus, the relationships involving these parameters depend on the specific filter used, and it is important to use the same filter consistently.

Table 1. Parameters of the twenty events used in this study.

Name of event	Origin time	Lat. (N)	Long. (E)	Depth (km)	M_w	τ_c (s)
Hyuganada	1996/12/02 22:18:06	31.783	131.633	35	6.7	2.151±0.418
Kagoshima	1997/03/26 08:31:53	31.983	130.367	8	6.1	1.619±0.396
Kagoshima	1997/05/13 05:38:32	31.950	130.300	8	6.0	1.075±0.458
Nii-jima-Kozu-shima	2000/07/15 01:30:35	34.423	139.253	5	6.0	1.392±0.423
Western-Tottori	2000/10/06 04:30:25	35.275	133.348	11	6.7	1.462±0.515
Geiyo	2001/03/24 06:28:02	34.123	132.705	51	6.8	1.785±0.818
Miyagi-Oki	2003/05/26 09:24:39	38.808	141.678	71	7.0	2.438±0.909
Tokachi-Oki	2003/09/25 19:50:38	41.778	144.078	42	8.3	4.399±1.198
Tokachi-Oki (aftershock)	2003/09/25 21:08:19	41.707	143.695	21	7.3	2.912±1.104
Kii-Hanto-Oki	2004/09/05 10:07:16	33.028	136.800	38	7.2	3.343±0.409
Kii-Hanto-Oki	2004/09/05 14:57:43	33.143	137.142	44	7.4	3.107±0.908
Chuetsu	2004/10/23 08:56:05	37.288	138.870	13	6.6	2.738±1.112
Chuetsu (aftershock)	2004/10/23 09:03:16	37.350	138.985	9	6.1	1.985±0.556
Chuetsu (aftershock)	2004/10/23 09:34:10	37.303	138.932	14	6.3	1.622±0.795
Kushiro-Oki	2004/11/28 18:32:19	42.943	145.278	48	7.0	3.480±0.638
Fukuoka-Oki	2005/03/20 01:53:47	33.735	130.177	9	6.6	1.134±0.508
Miyagi-Oki	2005/08/16 02:46:40	38.147	142.282	42	7.2	2.143±0.638
Oita	2006/06/11 20:01:31	33.133	131.407	146	6.4	1.453±0.673
Noto-Hanto-Oki	2007/03/25 00:41:57	37.221	136.686	11	6.7	2.331±1.382
Chuetsu-Oki	2007/07/16 01:13:30	37.557	138.608	17	6.6	2.243±0.307

The period parameter τ_c is computed by

$$\tau_c = 2\pi \Big/ \sqrt{\left[\int_0^{t_0} \dot{u}^2(t)dt\right] \Big/ \left[\int_0^{t_0} u^2(t)dt\right]},$$

where u is the high-pass filtered displacement of the vertical component ground motion. τ_c approximately represents the P wave pulse width which increases with the magnitude and can be used to estimate the event magnitude. Wu and Kanamori (2005b) showed that Pd can be used to estimate the peak ground motion velocity (PGV) at the same site. τ_c and Pd are the two basic parameters used in on-site warning.

3. Analysis

Wu and Kanamori (2005b) and Wu *et al.* (2007) showed that τ_c and Pd are useful for estimating the magnitude and peak ground motion, respectively, for earthquakes in Taiwan and southern California.

Since no systematic analysis of τ_c and Pd has been made for large Japanese earthquakes, we first present general relationships between τ_c and magnitude, and Pd and peak ground-motion velocities, PGV, determined with the data from K-NET and KiK-net of NIED. Table 1 lists the 20 events we studied. The 2007 Noto Hanto and the 2007 Niigata Chuetsu-Oki earthquakes are included. These relationships provide a basic framework for on-site early warning. Then, in an effort to explore the feasibility of very rapid warning, we will investigate the use of Pd in more detail for the Noto Hanto earthquake.

4. τ_c vs. M and PGV vs. Pd Relationships

The results for τ_c are summarized in Table 1 and Fig. 1, and the results for Pd are shown in Fig. 2(a). Three events deeper than 50 km are also included. The peak ground motion velocities are computed from the horizontal components of K-NET data and from the surface stations of KiK-net. The larger of the two horizontal components is used to determine PGV. In general, the results are consistent with those determined earlier for Taiwan and southern California. Rydelek and Horiuchi (2006) determined a period-parameter similar to τ_c for large Japanese events with a magnitude range $6 \leq M \leq 8$ using the Hi-net data. Since the period-parameter they used and the method are different from those we used, our results cannot be directly compared with theirs. However, as shown in Appendix 2, if we apply our method to their data set the results from the two studies are compatible.

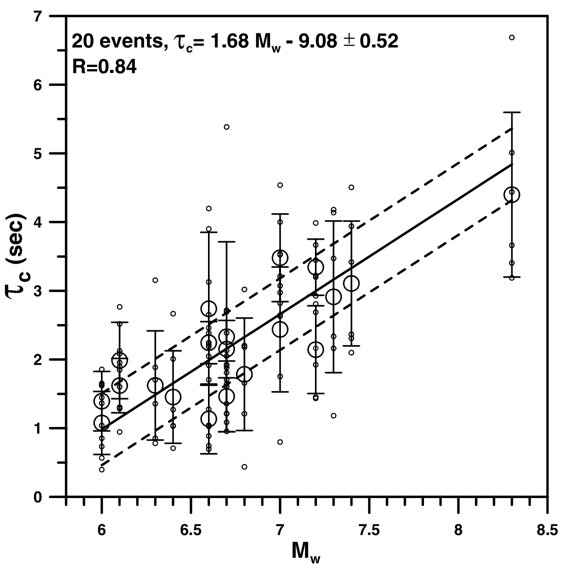

Fig. 1. τ_c estimates for 20 events using the nearest 6 stations of K-NET and KiK-net. Small open circles show single-record results and large circles show the event-average. Solid line shows the least squares fit and the two dashed lines show the range of one standard deviation.

The Pd values for Japanese earthquakes are on the same trend as those for earthquakes in Taiwan and southern California, but the scatter for the Japanese data is considerably large. We noticed that $Pd3$ values (the last digit indicates the duration over which Pd is measured) for some events

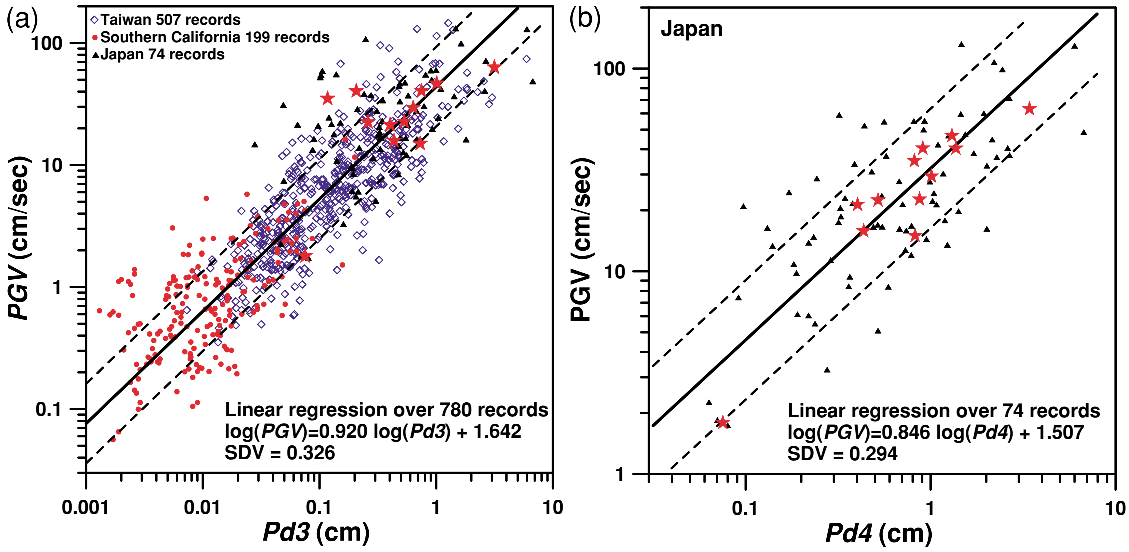

Fig. 2. (a) Relationship between peak initial three-second displacement amplitude ($Pd3$) and peak ground velocity (PGV) for 780 records with the epicentral distances less than 30 km for Japan (black triangles), southern California (red solid circles) and Taiwan (blue diamonds). Red stars indicate the event-average of the Japanese data. Solid line indicates the least squares fit and the two dashed lines show the range of one standard deviation. (b) Relationship between peak initial four-second displacement amplitude ($Pd4$) and PGV. Red stars indicate the event-average of the Japanese data. Solid line indicates the least squares fit and the two dashed lines show the range of one standard deviation.

Table 2. Parameters of station locations, τ_c, Pd, PGA and PGV measurements of the 2007 Noto Hanto earthquake.

Station	Distance (km)	τ_c (s)	$Pd3$ (cm)	$Pd4$ (cm)	$t\_Pd \geq 0.5$ (s)	PGV (cm/s)	$t_$PGV (s)	PGA (cm/s^2)	$t_$PGA (s)
ISK006	7	5.39	6.73	6.73	0.54	48.56	2.81	848.99	3.53
ISK005	19	1.88	1.63	2.45	0.64	98.96	6.10	780.42	6.38
ISK003	27	1.61	1.10	1.10	2.57	42.14	6.82	519.06	5.07
ISK007	32	2.05	0.40	0.40	—	31.48	7.67	202.56	7.59
ISKH02	35	1.71	0.22	0.38	—	28.55	6.58	359.34	7.82
ISK008	37	1.36	0.22	0.37	—	20.83	18.76	381.17	7.88

with relatively large PGV are very small. Inspection of the seismograms revealed that for these records the initial P-wave amplitude is very small, but increases rapidly after that. Thus, if we increase the time window from 3 to 4 sec, the scatter of the PGV vs. $Pd4$ diagram is significantly reduced as shown in Fig. 2(b), and the trend for the Japanese data is similar to that of the Taiwan data. A similar sensitivity of magnitude vs. Pd scaling to the duration of the time window is reported by Zollo *et al.* (2007). This observation seems to reflect the complexity of the nucleation process of earthquakes: the growth rate of the initial rupture seems to vary considerably for different events. This complexity is inherent to earthquake rupture pattern and some uncertainties are inevitable. The large scatter can be also due to site response. If we take the event average, the overall trend is approximately the same as that for the Taiwan data (Fig. 2(b)).

5. The 2007 Noto Hanto Earthquake

We now discuss the result for the 2007 Noto Hanto earthquake in detail. This earthquake ($M_{\rm w} = 6.7$) occurred at 09:41 a.m., March 25, 2007 (local time) (00:41 a.m. UT), and is located at 37.221°E, 136.686°E, and depth=10.7 km. Table 2 lists the stations used and the measured values of τ_c, Pd and PGV at each station. Except for the nearest ($\Delta = 7$ km) station, ISK006, the values of τ_c are generally consistent. As shown in Fig. 3, the near-field displacement dominated at the station ISK006. Because of the ramp-like displacement of the near-field, it yielded an anomalously large τ_c. This would result in an anomalously large estimate of magnitude. We did not encounter this problem for any other records from the events listed in Table 1. Thus, the occurrence of this problem is considered very rare. Nevertheless, this can cause a problem if we are to use the specific value of magnitude estimated from each station for early warning. However, as shown in Table 2, since the τ_c values estimated from other stations are normal, if we take the median of the τ_c values as a representative value of magnitude for the group of stations, or if we introduce a scheme to remove outliers, this problem can be alleviated. Also, if the warning is to be issued as a threshold warning (i.e. a warning with a minimum magnitude) as discussed in Kanamori (2005) and Wu *et al.* (2007), this will not cause a serious problem. In any case, this is the problem we encountered and should be borne in mind in using onsite warning methods. The effect of the near-field displacement is also evident in Pd. Again, we can take the same procedure as we discussed above for τ_c to alleviate the problem.

6. Extension of the Method for Faster Warning

In the method we discussed above we used a record with a duration of 3 s (i.e., $t_0 = 3$ s) after the P-wave arrival,

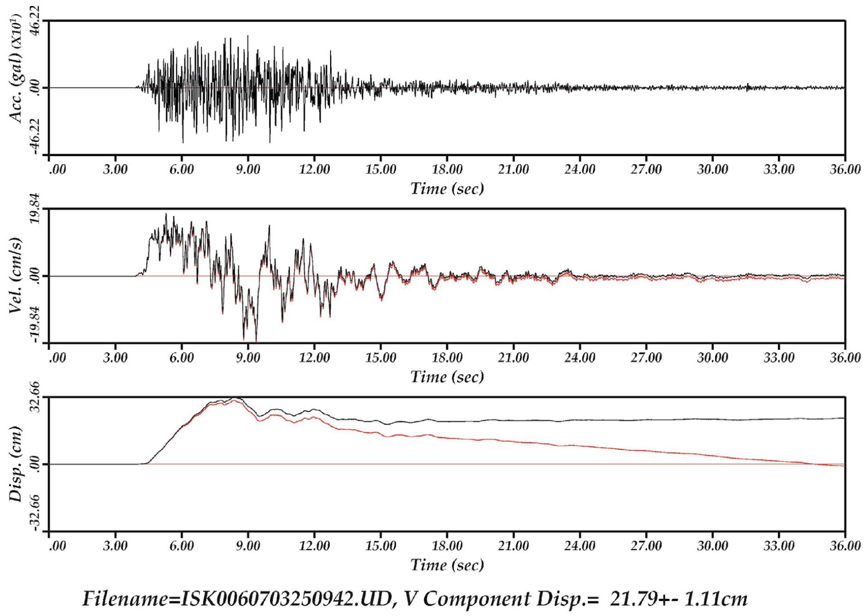

Fig. 3. Acceleration, velocity, and displacement (unfiltered) at station ISK006 ($\Delta = 7$ km). Note a ramp-like velocity waveform caused by near-field displacement. Red and black lines show raw and corrected traces, respectively.

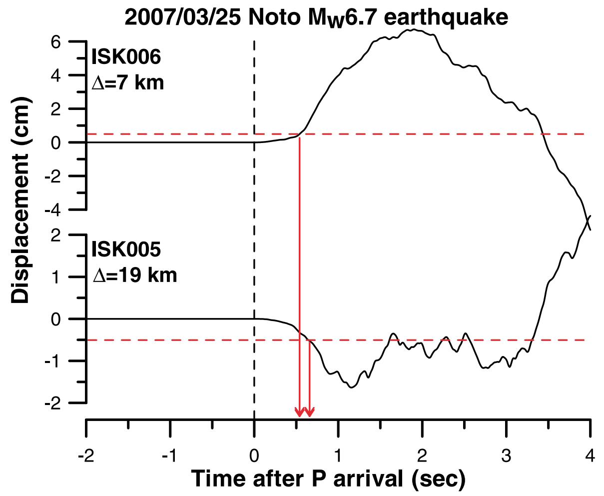

Fig. 4. Filtered displacement seismograms of the two nearest K-Net stations. Horizontal dashed lines are drawn at the threshold value of $Pd = 0.5$ cm. Vertical arrows indicate the time when the threshold is reached. If a warning is issued at this time, the warning can be issued at about 0.54 and 0.64 s after the P arrival time at stations ISK006 and ISK005, respectively.

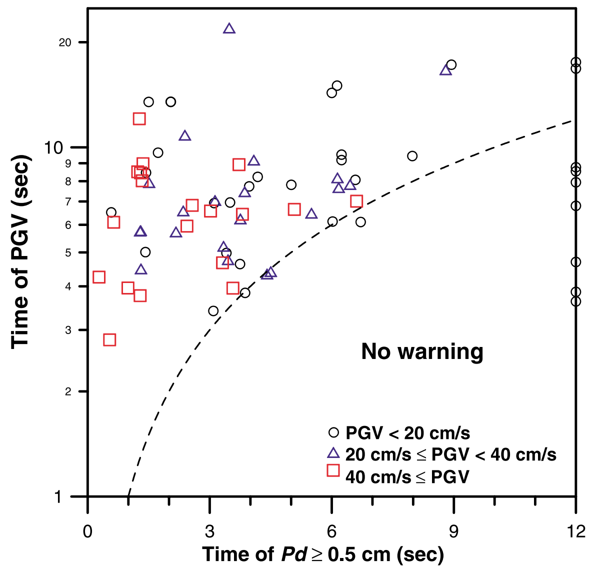

Fig. 5. Illustration of an on-site early warning scheme. The time (after P arrival) when Pd exceeds 0.5 cm (denoted by $t\_Pd \geq 0.5$ in the text) is on the horizontal axis, and the time (after P arrival) when PGV occurs (denoted by t_PGV in the text) is on the vertical axis. The open circles plotted at $t\_Pd \geq 0.5 = 12$ s indicates the events for which Pd never reached the threshold value, 0.5 cm.

which means that it will take at least 3 s after the arrival of P wave before we can issue a warning. Since the present JMA system can perform nearly as fast, the on-site method described here itself does not have advantage over the JMA system as far as the warning time is concerned. However, the on-site method described here provides redundancy desirable for any warning system.

One possible approach toward issuing faster warning is to monitor the high-pass filtered ground motion displacement, and issue a warning as soon as it has exceeded a threshold value. From our experience with the 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. As shown in Fig. 4, for the 2007 Noto Hanto earthquake, at the two nearest stations, ISK006 ($\Delta = 7$ km) and ISK005 ($\Delta = 19$ km), the threshold value of $Pd = 0.5$ cm was reached at 0.54 s, and 0.64 s, respectively, from the arrival of P wave. If we are to issue an onsite warning at a threshold of $Pd \geq 0.5$ cm, then at the site ISK006 and ISK005, an warning will be issued at 0.54 s and 0.64 s after the P arrival, respectively, which are 2.27 s and 5.46 s before PGA occurs at the respective sites (Table 2) and the early warning system becomes effective even at close-in sites where warnings are most needed. So far we have experienced only a very few cases in which *Pd* exceeded 0.5 cm within 3 sec after *P* arrival, and we need to accumulate more data to be able to determine the best threshold value for *Pd*.

We tested this approach with other events. In this method, we monitor the filtered displacement after a *P* trigger. When *Pd* exceeds a threshold value (e.g., 0.5 cm), an alarm is issued. If this alarm is followed by a large PGV (e.g., $\geq$ 20 cm/s), then the alarm is successful; otherwise it is a false alarm. Then an important parameter is the difference between the time when $Pd = 0.5$ cm is detected (denoted by $t\_Pd \geq 0.5$), and PGV is detected (denoted by t_PGV). Figure 5 shows the result for the 74 records at distances shorter than 30 km of the events listed in Table 1. For the case in which t_PGV is large (e.g., > 7 sec), we will have enough time to examine the data from other stations to update the warning. Figure 5 indicates that for t_PGV$\leq$7 s, the alarms with $t\_Pd \geq 0.5$ s are successful (i.e., PGV$\geq$20 cm/s) 70 to 80% of the time. Considering the difficulty in issuing useful alarms at short distances, this success rate is satisfactory. For practical applications, we may have to modify the thresholds and method, but we hope that this approach will provide additional capability for short-distance warning.

7. Conclusion

We used the NIED K-NET and KiK-net data to determine two on-site earthquake early warning parameters τ_c and *Pd* for 20 large earthquakes in Japan. The results are overall consistent with those obtained earlier for earthquakes in Taiwan and southern California and demonstrate that τ_c and *Pd* are useful parameters for early warning in Japan. We explored extension of the method for faster threshold warning by monitoring the high-pass filtered ground motion amplitudes of the 2007 Noto Hanto earthquake. For the two nearby sites at epicentral distances of 7 and 19 km, a warning can be issued before the peak ground motion velocity occurrs there. Thus, useful early warning can be issued to the epicentral area where such warning is most needed; this is an advantage of on-site warning, and the method will provide additional capability to the existing JMA system.

At present, the data from K-NET and KiK-net are not available real-time for early warning purposes. However, if the method illustrated in this paper proved useful, two options can be considered. One is to implement real-time telemetry for these networks and the other is to install a simple software to perform the onsite analysis at the station processor and send only warning information. In view of the remarkable success of the JMA system, 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.

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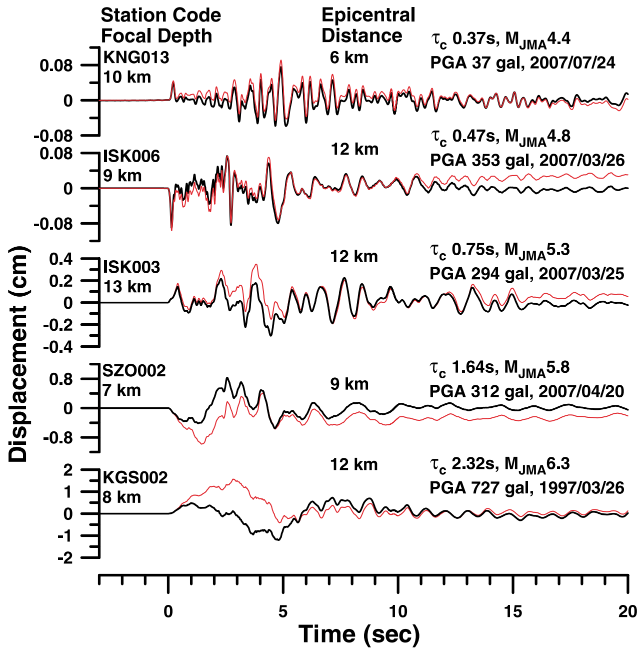

Fig. A.1. Comparison of the raw (red) and high-pass filtered (black) records.

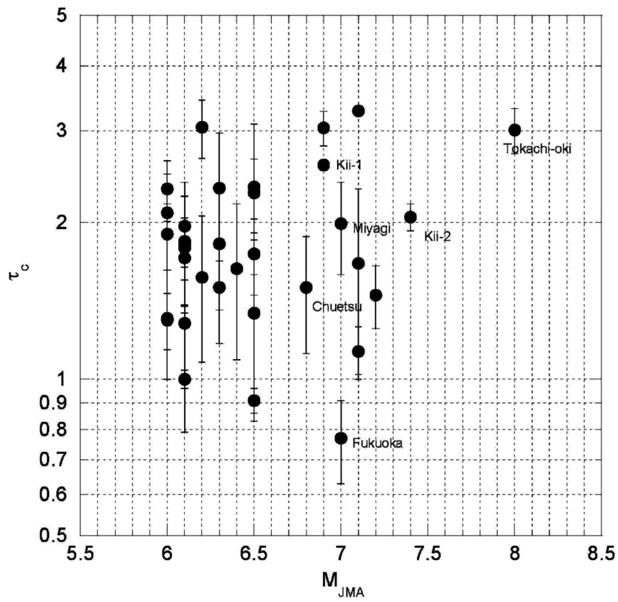

Fig. A.2. τ_c from Hi-net data computed with the method used in this paper.

Appendix 1. The effect of high-pass filter on the displacement records

The noise in the strong motion data at long period is always a critical issue. The noise level depends on the particular instrument type as well as the site condition. In our paper, we used a one-pass (i.e., causal) high-pass Butterworth filter which removes essentially everything below 0.075 Hz (about 13 s). In this paper we used the method of applying a causal filter to on-line data discussed in Kanamori *et al.* (1999). Thus, the regression relations and the scaling relations used in this paper depend on the particular filter and the cut-off frequency used. A lower cut-off frequency is more desirable for larger earthquakes, but effect of the

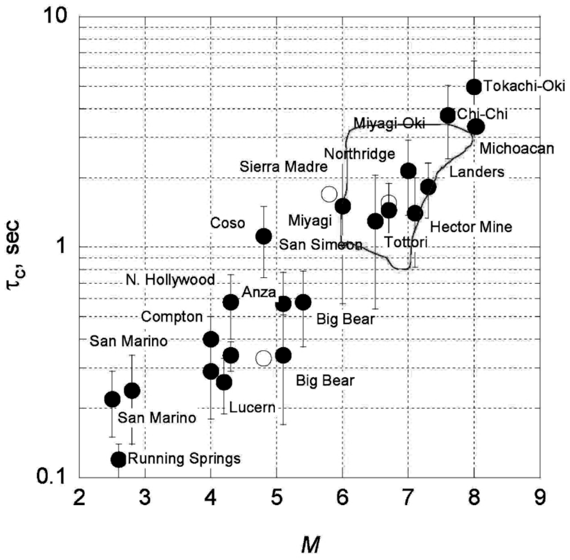

Fig. A.3. Comparison of the overall trend of the Hi-net results shown by red curve with the results obtained from earthquakes over a large magnitude range.

long-period noise increases. Considering this trade-off we empirically chose the cut-off frequency at 0.075 Hz. Figure A.1 compares the filtered and raw displacement records.

Appendix 2. Comparison with the results of Rydelek and Horiuchi (2006)

Rydelek and Horiuchi (2006) determined a period-parameter similar to τ_c for large Japanese events with a magnitude range $6 \leq M \leq 8$ using the Hi-net data. Since the period-parameter they used and the method are different from those we used, we cannot directly compare the results by the two studies.

The methods used in this paper and Rydelek and Horiuch (2006) (hereafter 260 referred to as RH) differ in two respects. 1) We use a fixed 3-sec window while RH used a sliding window originally used by Nakamura (1988). 2) As discussed in Kanamori (2005), we used $\dot{u}$-u pairs while RH used $\ddot{u}$-$\dot{u}$ pairs to compute the period parameters. Furthermore, if we use Hi-net data directly for $\ddot{u}$ and $\dot{u}$, as was presumably done by RH, the meaning of τ_c becomes different. As discussed in Kanamori (2005), our τ_c is determined by the average of f^2 weighted by the square of the modulus of the displacement spectrum, while the period parameter used by RH is defined by the average of f^2 weighted by the square of the modulus of the (velocity spectrum)*(Hi-net response). Since the Hi-net response falls off very rapidly at frequencies below 1 Hz, the combined effect of the velocity spectrum and the Hi-net response results in the period parameter used by RH being weighted much more strongly by shorter period waves than our τ_c. For this reason, as the period increases with magnitude, the period parameter tends to saturate. Thus, the relation between our τ_c and magnitude cannot be directly compared with that by RH. For comparison, we computed τ_c from Hi-net data after deconvolving the instrument response, and using our method (Fig. A.2).

For this small magnitude range, the dependence of τ_c on magnitude is not apparent, as pointed out by RH, but as shown in Fig. A.3, if we compare the Hi-net results as a whole with those from other events (Kanamori, 2005), the over all trend determined from the Hi-net data is essentially consistent with the general trend. Thus, the correlation between τ_c and magnitude is ambiguous over a magnitude range from 6 to 8, but we found no fundamental difference between our results obtained from KiK-net and K-net and that from Hi-net.

References

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

Horiuchi, S., H. Negishi, K. Abe, A. Kamimura, and Y. Fujinawa, An Automatic Processing System for Broadcasting Earthquake Alarms, *Bull. Seism. Soc. Am.*, **95**, 708–718, 2005.

Kanamori, H., Real-time seismology and earthquake damage mitigation, *Annual Review of Earth and Planetary Sciences*, **33**, 195–214, doi:10.1146/annurev.earth.33.092203.122626, 2005.

Kanamori, H., E. Hauksson, and P. Maechling, Continuous monitoring of ground motion parameters, *Bull. Seism. Soc. Am.*, **89**, 311–316, 1999.

Nakamura, Y., Development of the earthquake early-warning system for the Shinkansen, some recent earthquake engineering research and practical in Japan, *The Japanese National Committee of the International Association for Earthquake Engineering*, 224–238, 1984.

Nakamura, Y., On the urgent earthquake detection and alarm system (UrEDAS), *Proceeding of 9^{th} world conference on earthquake engineering*, Tokyo-Kyoto, Japan, 1988.

Rydelek, P. and S. Horiuchi, Is earthquake rupture deterministic?, *Nature*, **442**, E5–E6, 2006.

Tsukada, S., T. Odaka, K. Ashiya, K. Ohtake, and D. Zozaka, Analysis of the envelope waveform of the initial part of P-waves and its application to quickly estimating the epicentral distance and magnitude, *Zisin*, **56**, 351–361, 2004.

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

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

Wu, Y. M., H. Kanamori, R. Allen, and E. Hauksson, Determination of earthquake early warning parameters, τ_c and *Pd*, for southern California, *Geophys. J. Int.*, **170**, 711–225, doi:10.1111/j.1365-246X.2007.03430.x, 2007.

Zollo, A., M. Lancieri, and S. Nielsen, Peak ground displacement and earthquake magnitude: Reply, *Geophys. Res. Lett.*, doi:10.1029/2007GL030560, 2007 (in press).

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