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

Yih-Min Wu[1] and Hiroo Kanamori[2]

1. Department of Geosciences, National Taiwan University, Taipei, Taiwan
2. Seismological Laboratory, California Institute of Technology, Pasadena, CA, USA.

Correspondence to: Yih-Min Wu
Address: No. 1, Sec. 4th, Roosevelt Rd., Dept. of Geosciences, National Taiwan Univ., Taipei, Taiwan
Tel: 886-2-3366-2942
Fax: 886-2-23644625
E-mail: drymwu@ntu.edu.tw, yihmin.wu@gmail.com
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Abstract

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 P_d using the K-NET and KiK-net data for the 2007 Noto Hanto earthquake as well as 15 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 issued within about 4 s after the origin time.

Keywords: 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 February, 2004, and JMA started test distribution of early warning information to a limited number of organizations. This system was successfully activated during the 2007 Noto Hanto (Peninsular) earthquake, and provided accurate information regarding the source location, magnitude and intensity about 5 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 an inland (or close to the shore) damaging earthquake 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 the 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 (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 low-pass (0.075 Hz) filtered vertical component ground-motion displacement records to compute two parameters τ_c and P_d 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 P_d is the maximum displacement amplitude during the same time interval. The period parameter τ_c is computed by

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

where u is the 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 P_d can be used to estimate the peak ground motion velocity (PGV) at the same site. τ_c and P_d 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 P_d are useful for estimating the magnitude and peak ground motion, respectively, for earthquakes in Taiwan and southern California. However, no systematic analysis has been made for large Japanese earthquakes. To establish the basic relationships for Japanese earthquakes we determined τ_c and P_d for large Japanese earthquakes including the 2007 Noto Hanto earthquake listed in Table 1 using the data from K-NET and KiK-net of NIED; the results for τ_c are summarized in Table 1 and Figure 1, and the results for P_d are shown in Figure 2. 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. The P_d values for Japanese earthquakes are on the same trend as those for earthquakes in Taiwan and southern California, but the scatter within the data for Japan is considerably large. This large scatter can be due to the site response. If the effect of the site response is removed and an average for a group of stations is used, the scatter is expected to decrease.

4. The 2007 Noto Hanto earthquake

We now discuss the result for the 2007 Noto Hanto earthquake in detail. This earthquake (M_w=6.7) occurred at 09:41 a.m., March 25, 2007 (local time), 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, P_d and PGV at each station. Except for the nearest (Δ=7 km) station, ISK006, the values of τ_c are generally consistent. As shown in Figure 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 P_d. Again, we can take the same procedure as we discussed above for τ_c to alleviate the problem.

The median values of τ_c and P_d are 1.8 s and 0.6 cm respectively, which are comparable to the threshold values for warning established in Taiwan and southern California.

5. 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, 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 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 P_d exceeds 0.5 cm, the PGV at the site most likely exceeds the damaging level, i.e., 20 cm/s. As shown in Figure 4, for the 2007 Noto Hanto earthquake, at the two nearest stations, ISK006 (Δ=7 km) and ISK005 (Δ=19 km), the threshold value of P_d=0.5 cm was reached at 0.63 s, and 0.74 s, respectively, from the arrival of P wave. This translates to 2.8 and 4.2 s, respectively, after the origin time. Thus, if a warning is issued at this time, it will reach most of the sites before ground shaking starts, and the early warning system becomes effective even at close-in sites where warnings are most needed. Of course, trade-off exists between speed and reliability, and exactly how this faster warning method should be implemented would require further tests. Nevertheless, we believe that this is an advantage of on-site warning, and the method will provide additional capability to the existing JMA system.

6. Conclusion

We used the NIED K-NET and KiK-net data to determine two on-site earthquake early warning parameters τ_c and P_d for 16 large earthquakes in Japan including the 2007 Noto Hanto earthquake. The results are overall consistent with those obtained earlier for earthquakes in Taiwan and southern California and demonstrate that τ_c and P_d are also 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 an epicentral distances of 7 and 19 km, a warning can be issued within about 4 s after the origin time which will enable useful early warning for the epicentral area where such warning is most needed. 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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Table 1 Parameters of the sixteen events used in this study.

Origin Time	Lat. (N)	Long. (E)	Depth (km)	M_w	τ_c (s)
1996/12/02 22:18:06	31.783	131.633	35	6.7	2.151+-0.418
1997/03/26 08:31:53	31.983	130.367	8	6.1	1.619+-0.396
1997/05/13 05:38:32	31.950	130.300	8	6.0	1.075+-0.458
2000/07/15 01:30:35	34.423	139.253	5	6.0	1.392+-0.423
2000/10/06 04:30:25	35.275	133.348	11	6.7	1.462+-0.515
2003/09/25 19:50:38	41.778	144.078	42	8.3	4.399+-1.198
2003/09/25 21:08:19	41.707	143.695	21	7.3	2.912+-1.104
2004/09/05 10:07:16	33.028	136.800	38	7.2	3.343+-0.409
2004/09/05 14:57:43	33.143	137.142	44	7.4	3.107+-0.908
2004/10/23 08:56:05	37.288	138.870	13	6.6	2.738+-1.112
2004/10/23 09:03:16	37.350	138.985	9	6.1	1.985+-0.556
2004/10/23 09:34:10	37.303	138.932	14	6.3	1.622+-0.795
2004/11/28 18:32:19	42.943	145.278	48	7.0	3.480+-0.638
2005/03/20 01:53:47	33.735	130.177	9	6.6	1.134+-0.508
2005/08/16 02:46:40	38.147	142.282	42	7.2	2.143+-0.638
2007/03/25 00:41:57	37.221	136.686	11	6.7	2.331+-1.382

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

Station	Distance (km)	τ_c (s)	P_d (cm)	PGV (cm/s)	PGA (cm/s/s)
ISK006	7	5.39	3.87	20.15	462.18
ISK005	19	1.88	1.01	22.89	555.72
ISK003	27	1.61	0.80	13.20	141.46
ISK007	32	2.05	0.41	7.51	167.49
ISKH02	35	1.71	0.22	19.53	203.96
ISK008	37	1.36	0.19	7.91	298.23

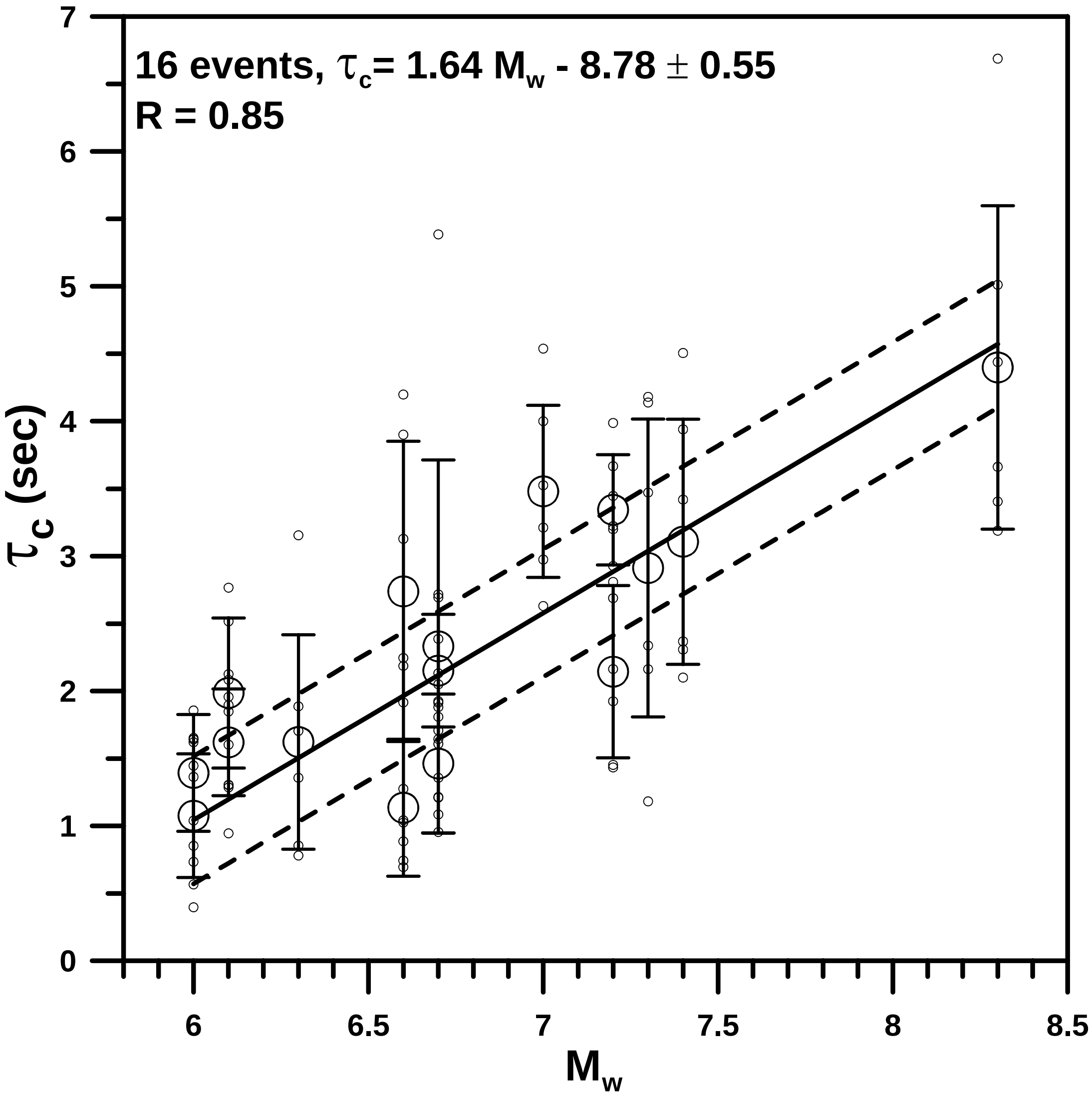

Figure 1. τ_c estimates from 16 events using the nearest 6 stations of K-NET and KiK-net. Small open circles show single-record results and large circles show the event-average. Solid line shows the least squares fit and the two dashed lines show the range of one standard deviation.

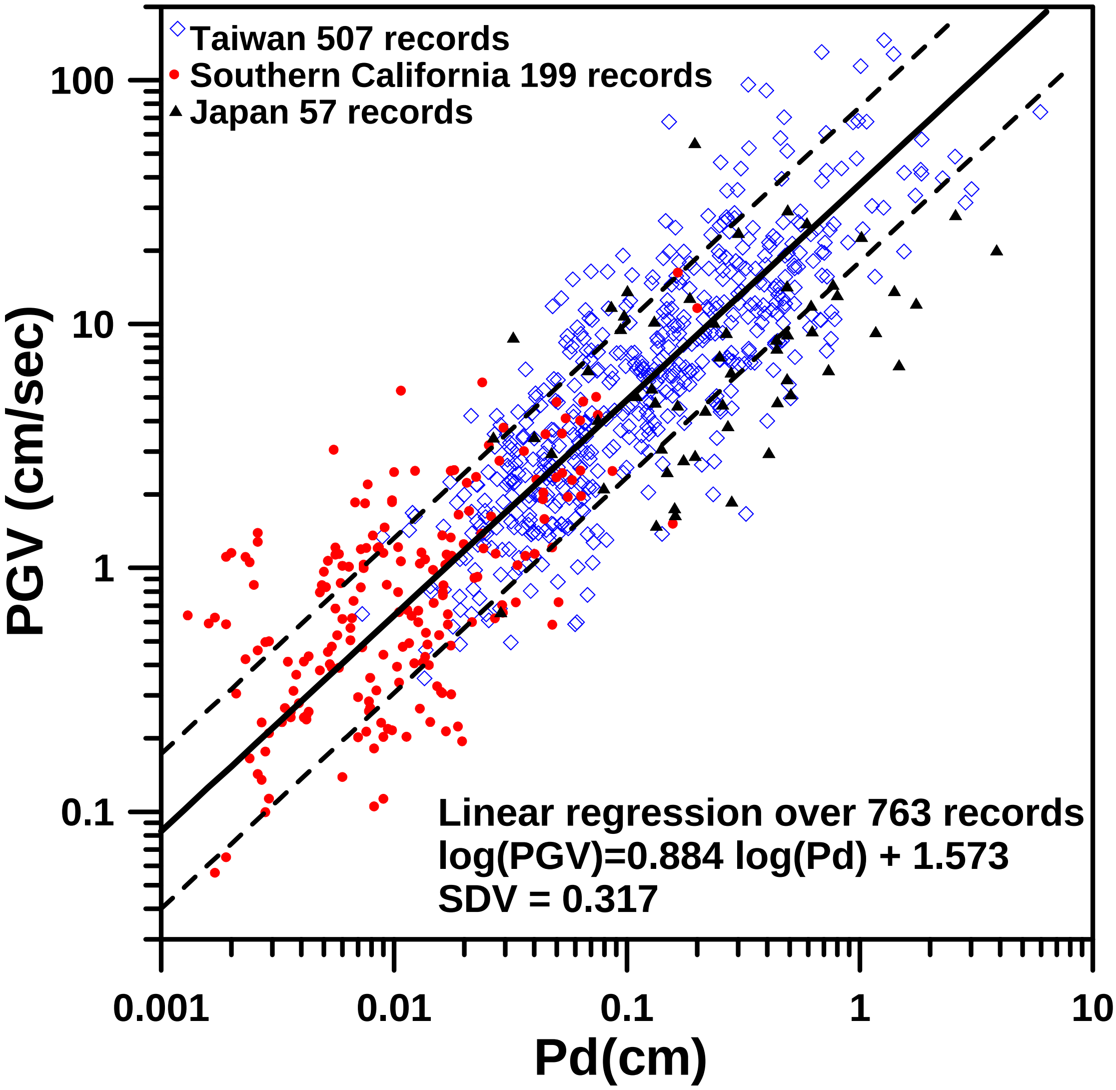

Figure 2. Relationship between peak initial displacement amplitude (*Pd*) measurements and peak ground velocity (*PGV*) for 763 records with the epicentral distances less than 30 km for Japan (black triangles), southern California (red solid circles) and Taiwan (blue diamonds). Solid line indicates the least squares fit and the two dashed lines show the range of one standard deviation.

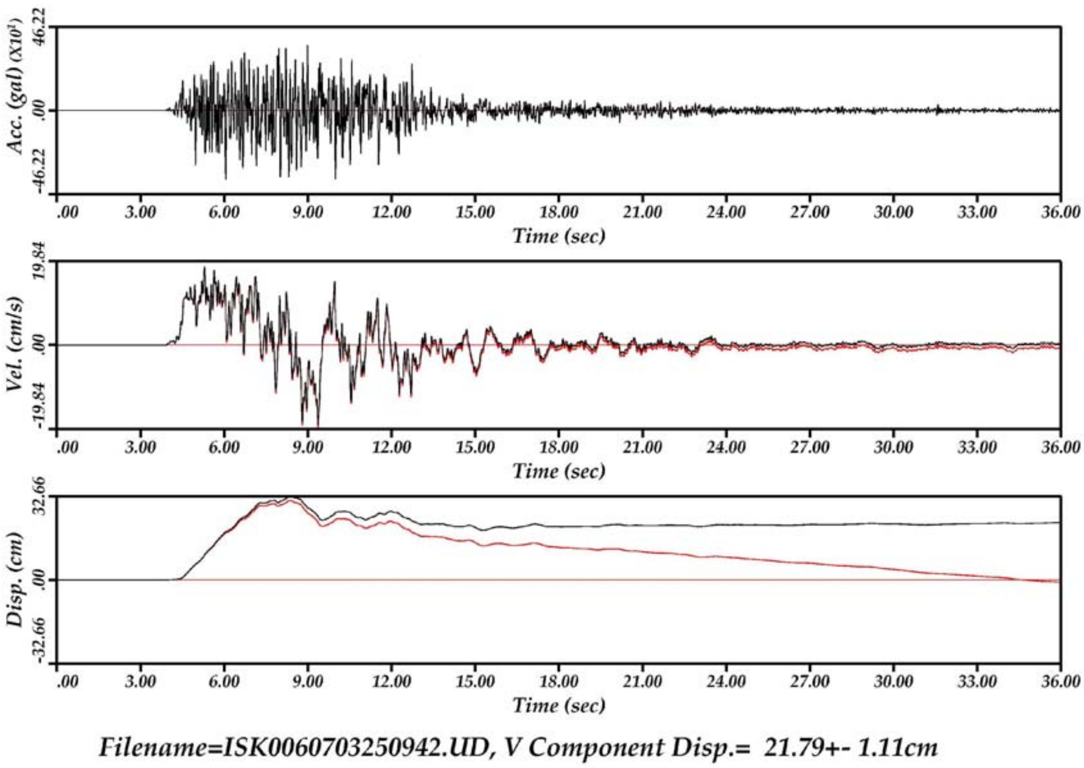

Figure 3. Acceleration, velocity, and displacement at station ISK006 (Δ=7 km). Note a ramp-like velocity waveform caused by near-field displacement. Red and black lines show raw and corrected traces, respectively.

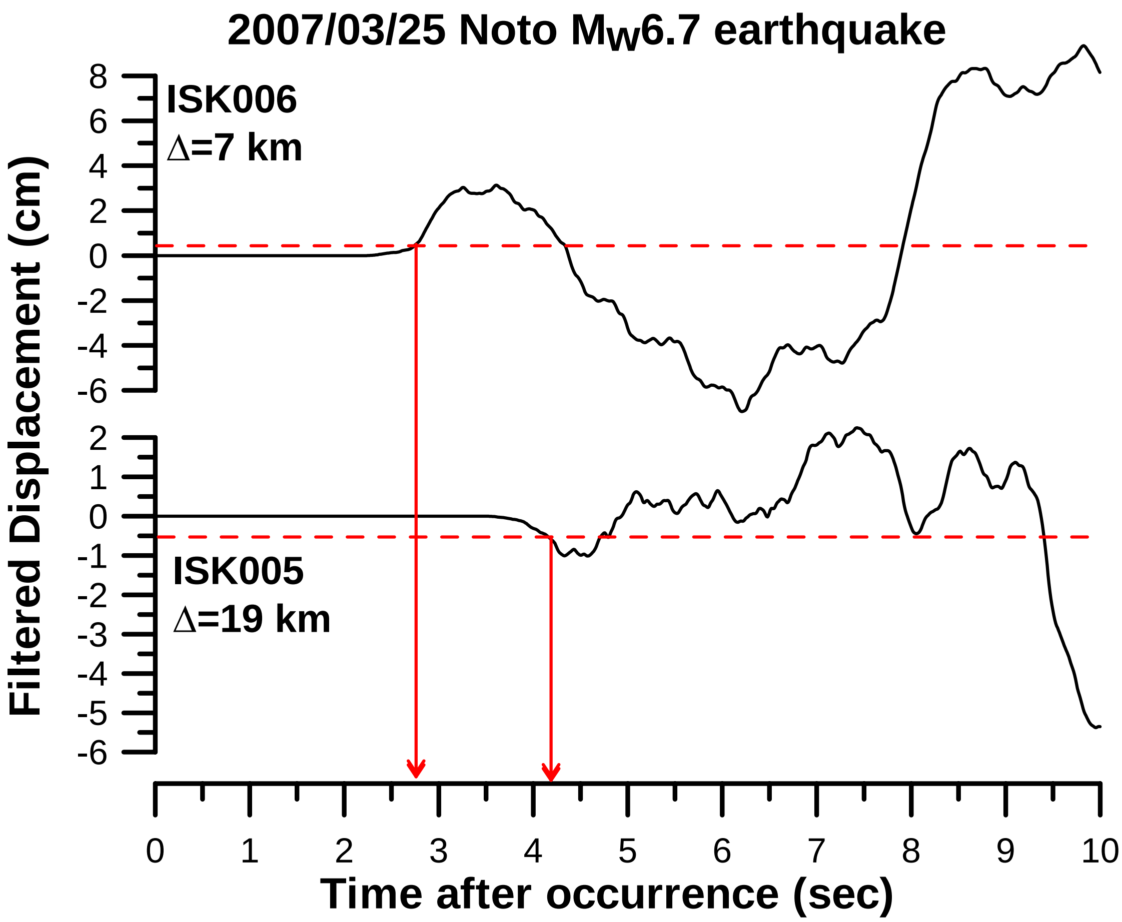

Figure 4. Filtered displacement seismograms of the three nearest K-Net stations. Horizontal dashed lines are drawn at the threshold value of P_d =0.5 cm. Vertical arrows indicate the time when the threshold is reached. If a warning is issued at this time, the warning can be issued at about 2.8 and 4.2 s after the origin time at stations ISK006 and ISK005, respectively.