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Rapid Assessment of Damage Potential of Earthquakes in Taiwan from the Beginning of *P* Waves

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Abstract To rapidly assess the potential for damage of an earthquake for purposes of earthquake early warning in Taiwan, we used the peak displacement and velocity amplitudes of the first 3 sec of the *P* wave. The vertical-component records, high-pass filtered at 0.075 Hz, are used. We found that the peak initial-displacement amplitude (Pd) correlates well with the peak ground-motion displacement (PGD) and the peak ground-motion velocity (PGV) at the same site. When Pd $>$ 0.5 cm, the event is most likely damaging. If Pd is combined with the period parameter τ_c, determined in an earlier study, then $\tau_c \times$ Pd provides an even more robust parameter for assessing the potential for damage.

Introduction

For timely seismic emergency response, rapid and accurate determination of the potential for damage of an earthquake is an important issue, especially in the operation of a seismic early-warning system (Nakamura, 1988; Kanamori *et al.*, 1997; Teng *et al.*, 1997; Wu and Teng, 2002; Allen and Kanamori, 2003; Wu and Kanamori, 2005). The potential for damage depends on many parameters, such as the earthquake magnitude, location, intensity, proximity to population in the area, frequency content of ground motions in relation to important structures, and others. With a small area and a population of 23 million, Taiwan ranks among the top in population density in the world. Any on-land large and shallow earthquake is likely to be a damaging earthquake. A similar situation applies equally to many earthquake-prone and populous areas in the world.

Many researchers investigated the relationships between seismic losses and the peak ground motion amplitude, such as peak ground-motion acceleration (PGA) and peak ground-motion velocity (PGV) (Tsai *et al.*, 2001; Wu *et al.*, 2002, 2003, 2004). However, for seismic early-warning purposes, we need to identify the areas that are most likely to sustain damage as early as possible before the peak motion occurs.

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 a good determination of the earthquake size from the *P* wave provides information about the strength of shaking being brought by the following *S* wave. In this study we investigate the possibility of estimating PGA and PGV at a site from the very beginning of the record at the same site as a follow-up of our previous work (Wu and Kanamori, 2005).

Data and Analysis

Large and shallow earthquakes often cause the most serious damage. We selected 26 events in Taiwan for this study (Table 1). The selection criteria are $M_w > 5.0$ and focal depth $<$ 35 km listed in both the Central Weather Bureau (CWB) and the Harvard catalogs. All the events were well recorded by the Taiwan Strong Motion Instrumentation Program (TSMIP) network. These events occurred from 1993 to 2003 and were widely felt in Taiwan. With about 650 modern digital accelerographs installed at free-field sites (Fig. 1), the TSMIP station signals are digitized at 200 samples per second or higher with 16-bit resolution. Most accelerographs have a dynamic range of $\pm 2g$.

A total of 208 TSMIP records are used for this study. The vertical-component records of the closest eight stations with an epicentral distance of less than 30 km are used for quick assessment.

The acceleration signals are integrated to velocity and displacement. We apply a 0.075-Hz high-pass recursive Butterworth filter to remove the low-frequency drift after the last integration. An automatic *P* picker described by Allen (1978) is used to detect the *P* arrival from the vertical-acceleration records.

We use the peak values of acceleration (Pa), velocity (Pv), and filtered displacement (Pd) determined from the beginning of the *P* wave. An obvious trade-off exists between the duration of the initial motion and the reliability. For reliable estimation of PGA, PGV, and peak ground-motion dis-

Table 1
The List of 26 Events Used in This Study

Origin time (UT) (yyyy/mm/dd)		Lat. (N)	Long. (E)	Depth (km)	M_w	No. of Houses Damaged*
1993/12/15	21:49:43.10	23.213	120.524	12.50	5.4	0
1994/06/05	01:09:30.09	24.462	121.838	5.30	6.3	25
1995/01/10	07:55:19.56	23.680	121.432	3.81	5.1	0
1995/02/23	05:19:02.78	24.204	121.687	21.69	6.2	0
1995/05/27	18:11:11.12	23.008	121.465	19.73	5.7	0
1995/12/18	16:17:54.53	24.018	121.692	22.06	5.2	0
1996/11/26	08:22:23.71	24.164	121.695	26.18	5.2	0
1998/01/18	19:56:51.71	22.725	121.089	3.28	5.2	0
1998/07/17	04:51:14.96	23.503	120.663	2.80	5.7	183
1998/11/17	22:27:32.52	22.832	120.790	16.49	5.3	0
1999/09/20	17:47:15.85	23.855	120.816	8.00	7.6	106,685
1999/10/22	02:18:56.90	23.517	120.423	16.59	5.8	69
1999/10/22	03:10:17.46	23.533	120.431	16.74	5.5	0
1999/10/30	08:27:49.50	24.017	121.319	14.36	5.4	0
2000/02/15	21:33:18.15	23.316	120.740	14.71	5.2	0
2000/07/14	00:07:32.46	24.048	121.728	7.19	5.4	0
2000/08/23	00:49:16.58	23.636	121.635	27.48	5.3	0
2000/09/10	08:54:46.53	24.085	121.584	17.74	5.8	0
2001/06/14	02:35:25.78	24.419	121.928	17.29	5.9	0
2001/06/19	05:16:15.46	23.177	121.077	6.58	5.3	0
2001/06/19	05:43:39.17	23.197	121.098	11.70	5.1	0
2002/02/12	03:27:25.00	23.741	121.723	29.98	5.7	0
2002/04/03	18:06:10.79	24.322	121.868	12.87	5.3	0
2002/05/15	03:46:05.91	24.651	121.872	8.52	6.1	0
2003/06/16	18:33:38.85	23.543	121.654	28.26	5.5	0
2003/12/10	04:38:13.52	23.067	121.398	17.73	6.8	†

*Data from Central Weather Bureau (2003).
†Damage under investigation.

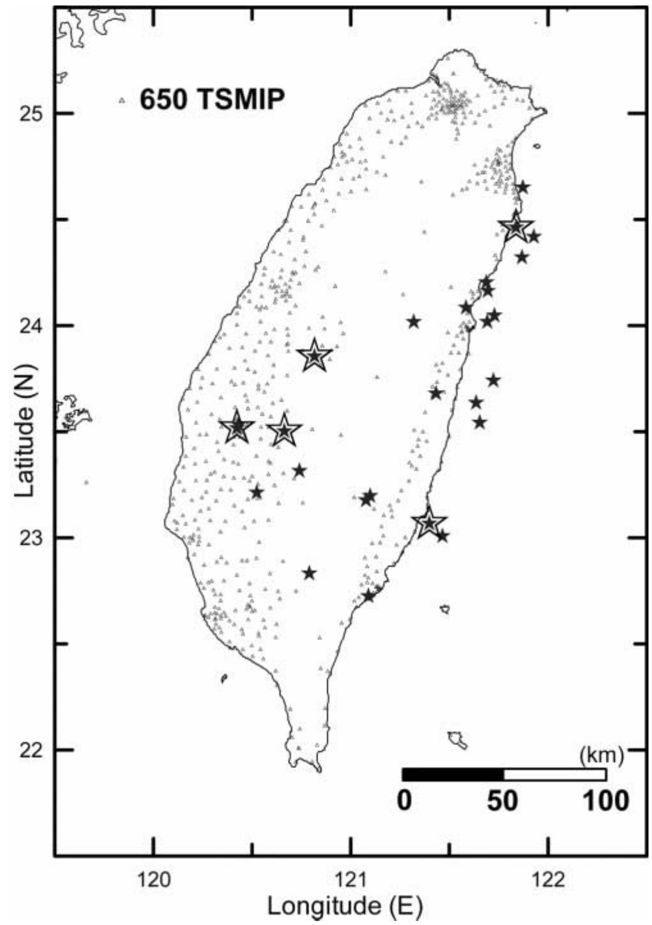

Figure 1. Distribution of stations of the TSMIP and the epicenters of 26 events (stars) used in this study. The larger open stars are the five damaging earthquakes.

placement (PGD), the longer the duration the better. However, too long a duration compromises the ability for early warning. Following the analysis of Wu and Kanamori (2005) for Taiwan, we use a duration of 3 sec for estimation of the initial amplitude.

Results

In general, the ground-motion amplitudes correlate with the amplitude of the initial motions such as Pa, Pv, and Pd, especially when the averages of the eight stations are taken. However, the correlation is poor if Pa is used as the amplitude parameter for the initial motion. For a nearby small event, Pa can be large but the PGA and PGV are small. Pa is determined by a very-high-frequency wave with short duration which does not have a high-damage potential. In contrast, Pv and Pd contain more long-period energy than Pa and correlate well with PGA and PGV. In particular, Pd correlates well with the peak amplitude parameters. (The peak amplitudes, PGA, PGV, and PGD are determined from the largest amplitude of the three components.) Figure 2 compares Pd with the high-pass-filtered PGD for all the records. Except for the Chi-Chi earthquake, the filtered PGD values increase with Pd approximately linearly. As indicated by the large filled star symbols in Figure 2, all the damaging events have the filtered PGD larger than 4 cm. Figure 2 demonstrates that if Pd is larger than 0.5 cm, it indicates that the event is damaging.

Figure 3 presents a similar plot showing the relation between PGV and Pd for the same data set. The filled symbols indicate the average for each event. For the average values, we obtain a regression relation

$$\log(\mathrm{PGV}) = 0.832 \log(\mathrm{Pd}) + 1.481, \tag{1}$$

where PGV is in centimeters per second and Pd is in centimeters.

Wu *et al.* (2003) obtained the following relation between the Taiwan Intensity I_t and PGV.

$$I_t = 2.138 \log(\mathrm{PGV}) + 1.890. \tag{2}$$

Combining (1) and (2), we can estimate I_t from Pd as

$$I_t = 1.779 \log(\mathrm{Pd}) + 5.056, \tag{3}$$

where Pd is in centimeters.

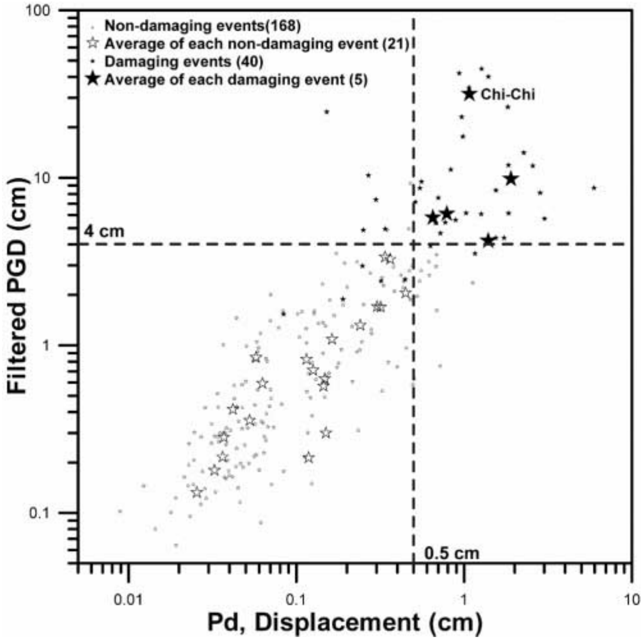

Figure 2. Relationship between peak initial displacement amplitude (Pd) and 0.075 Hz high-pass-filtered peak ground displacement (PGD) for the 26 events.

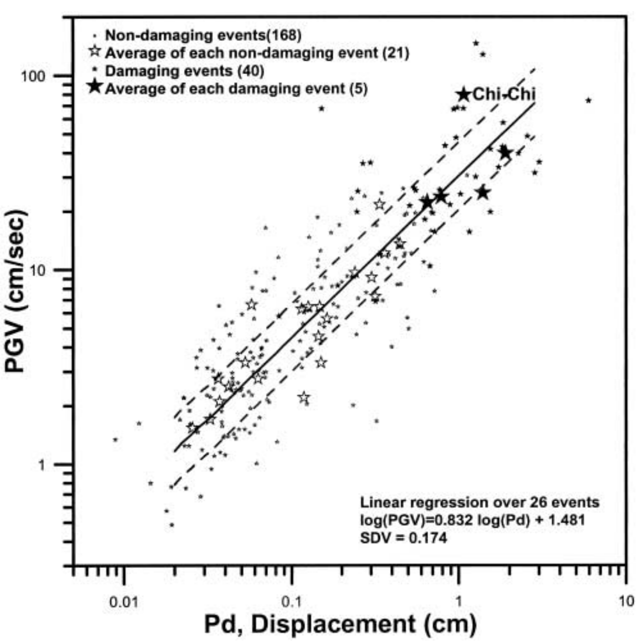

Figure 3. Relationship between peak initial displacement amplitude (Pd) measurements and peak ground velocity (PGV) for the 26 events. Solid line shows the least-squares fit and two dashed lines show the range of one standard deviation.

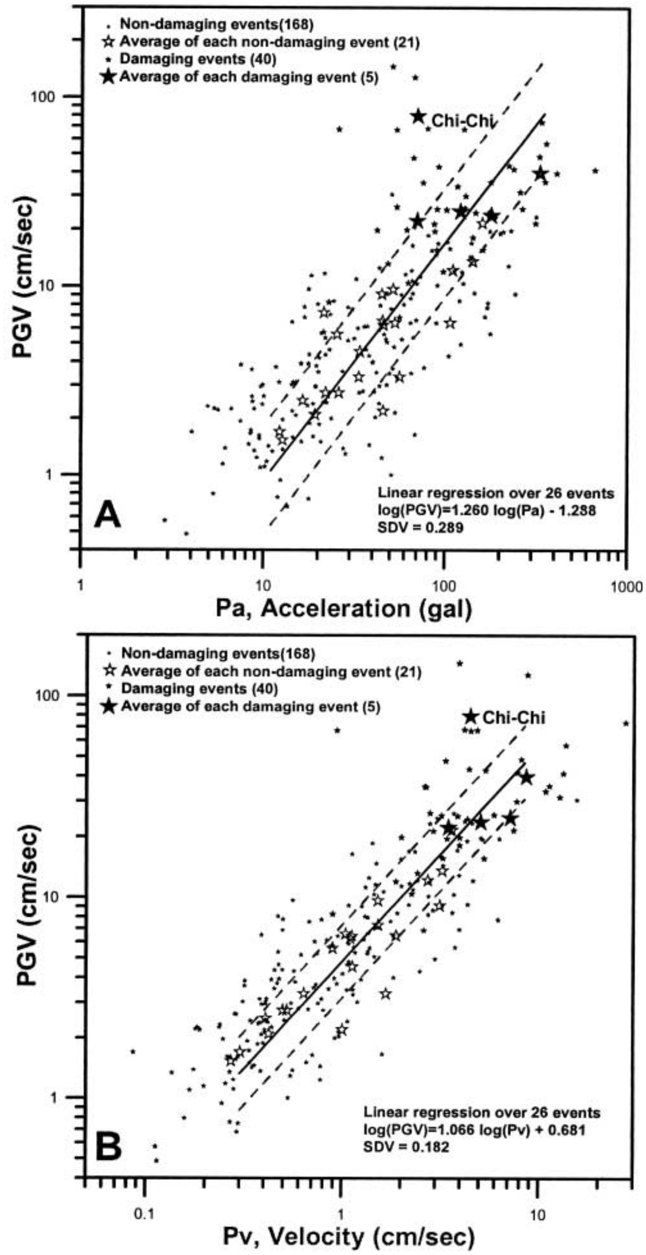

Figure 4. (A) Relationship between peak initial acceleration amplitude (Pa) measurements and peak ground velocity (PGV) for the 26 events. (B) Peak initial velocity amplitude (Pv) measurements and PGV for the 26 events. Solid line shows the least-squares fit and two dashed lines show the range of one standard deviation.

Figure 4 presents two similar plots showing the relations between Pa, Pv, and PGV for the same data set. As mentioned previously, Pv and Pd contain more long-period energy than Pa and correlate better with PGV.

Wu and Kanamori (2005) determined a period parameter τ_c for the same data set used here by using a method modified from Nakamura (1988). The parameter τ_c is determined from the ratio of integrals of the velocity squared to

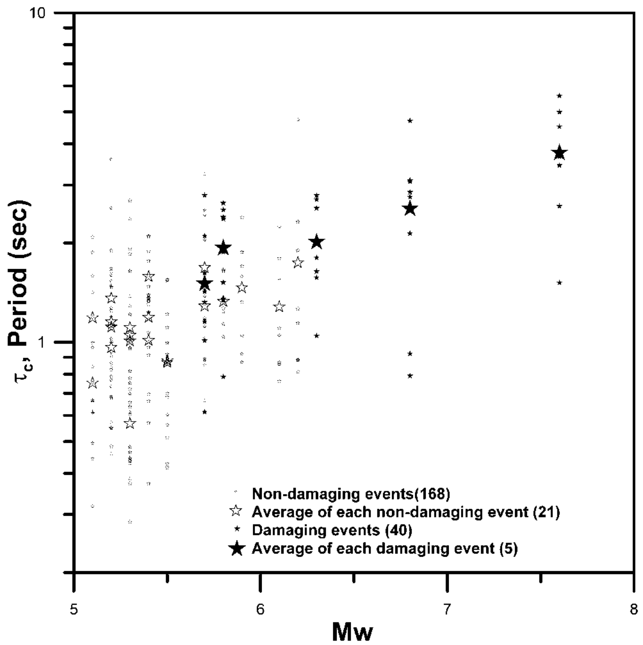

Figure 5. Relationship between period parameter (τ_c) for the 26 events and moment magnitude (M_w).

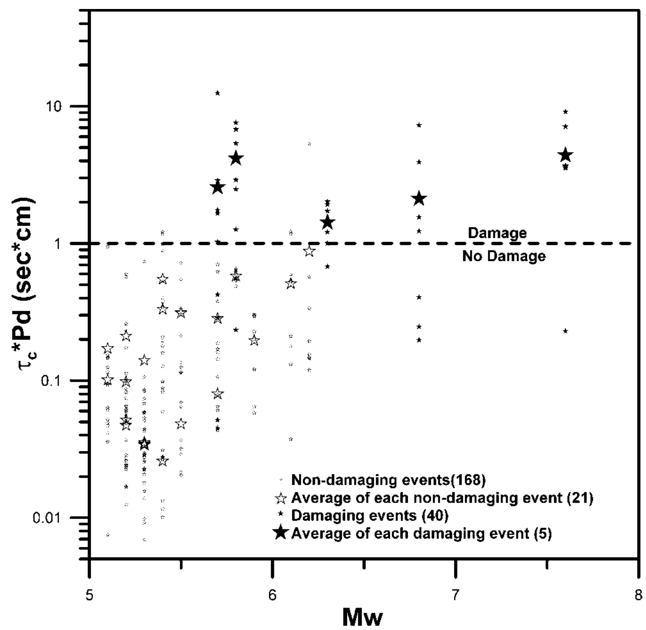

Figure 6. Relationship between $\tau_c \times$ Pd and M_w for the 26 events, where τ_c is the period parameter and Pd is the peak initial displacement amplitude.

that of the displacement squared and, in principle, is independent of the distance at least to the first order. Figure 5 shows τ_c for all the events (open symbols) and the average τ_c (filled symbols) as a function of M_w. In general, the τ_c values increase with M_w and are useful for magnitude determinations (Kanamori, 2005; Wu and Kanamori, 2005). Damaging events are indicated by star symbols.

We combine these two parameters as a single indicator to improve reliability. Figure 6 shows τ_c*Pd values for all the events (open symbols) and their average (filled symbols) as a function of M_w. Damaging events are indicated by star symbols. The product τ_c*Pd gives a clearer indicator for discriminating damaging events from nondamaging events. The value τ_c*Pd $= 1.0$ sec-cm is a good threshold for identifying damaging earthquakes.

Note that because Pd depends not only on the magnitude but also on the distance, we do not generally expect a unique relationship between the amplitudes and M_w. For the Taiwan data set we used here, the average epicenter-station distance is approximately 20 km for all the events. Thus, Figure 6 with the threshold of τ_c*Pd $= 1.0$ sec-cm should be used only for the station-epicenter geometry of Taiwan.

In other areas where the station distribution is not as dense and uniform as in Taiwan, we may use τ_c and Pd independently. If both τ_c and Pd are measured at a station or at a group of stations, then four combinations are possible: (1) Pd > 0.5 cm and $\tau_c > 1.0$ sec; (2) Pd < 0.5 cm and $\tau_c > 1.0$ sec; (3) Pd < 0.5 cm and $\tau_c < 1.0$ sec; and (4) Pd > 0.5 cm and τ_c, < 1.0 sec. Corresponding warnings are: (1) the event is most likely damaging in the station area as well as a larger area; (2) the event is not damaging in the station area, but it can be damaging in other areas; (3) the event is not damaging; (4) the event is damaging only in the limited area around the station.

Discussions and Conclusions

Large earthquakes in populated areas are potentially damaging. The high population density of Taiwan and the dense distribution of the TSMIP stations in the populated areas allow us to investigate the correlation between the damage and ground-motion parameters and to develop a method for reliable and early assessment of damaging earthquakes.

The method described here has a wide application. These days, almost every populated area has internet connection, and modern strong-motion instruments are equipped with an internet-networking function; all the processes discussed in this study can be carried out in automatic and real-time operation mode. The software to compute τ_c and Pd can be easily installed on site. Once a P arrival produces a trigger, only the P arrival, τ_c, and Pd values (instead of the entire waveforms) are sent to the control center. By using the averaged values from the first eight stations as indicators, a quick identification of a damaging earthquake can be achieved within 8 sec of the earthquake origin time. Also, P arrivals, τ_c, and Pd measurements can jointly be used to determine the hypocenter, magnitude, and the source-region intensity, respectively.

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