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Magnitude estimation using the covered areas of strong ground motion in earthquake early warning

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[1] We collected the strong-motion accelerograms with peak ground acceleration (PGA) larger than 100 Gal (1 Gal = 1.0 cm/s^2) from large crustal earthquakes in Taiwan recorded by the Taiwan Strong Motion Instrumentation Program (TSMIP) stations to find an empirical relationship between the area of high PGA and the corresponding earthquake magnitude. We found that the logarithms of the areas inside the PGA contours have a linear relation to the corresponding earthquake magnitudes. We propose that this relationship might be able to rapidly define the earthquake magnitude while providing sufficient seismic station coverage and might have practical application in earthquake early warning (EEW) and rapid reporting systems. The proposed magnitude estimation method is directly related to the level of strong surface shaking and is inherently suitable for the purpose of the EEW and rapid reporting systems.

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1. Introduction

[2] Earthquake early warning aims to provide timely alerts before the strong ground shakings of a damaging earthquake to popularized areas, sensitive facilities, or public transportations. At the very least, EEW system is expected to immediately provide the rapid reporting of event location, magnitude, and the intensity map to allow rapid response after the occurrence of a large earthquake. Although the EEW time window might seem to be as short as a few seconds to a few tens of seconds, it can be extremely critical since even a few seconds are sufficient for pre-programmed EEW systems to take emergent safety responses. Therefore, EEW is a practical, effective approach to reduce seismic risk on a short time-scale [*Kanamori et al.*, 1997; *Teng et al.*, 1997; *Wu and Teng*, 2002; *Allen and Kanamori*, 2003; *Kanamori*, 2005].

[3] Two types of EEW are mostly adopted at the present time, regional and onsite warning systems. In regional warning, the ground shaking characteristics recorded by the closer-to-earthquake seismic sensors or network are used to predict the strong ground motions at more distant target areas. In onsite warning, the initial *P*-wave motion is used to predict the ground motions of later arriving *S* and surface waves that commonly have higher amplitudes or destructive energy than that of the initial *P*-wave motion at the same site or region where the onsite warning instruments are operating.

[4] Estimation of earthquake magnitude is a vital step in an EEW system, since it is directed toward the size and damage potential for an occurring earthquake. In the onsite EEW approach, an average period parameter (τ_c) from the initial 3 seconds of the *P*-wave [*Kanamori*, 2005; *Wu and Kanamori*, 2005; *Wu et al.*, 2007], originally proposed by *Nakamura* [1988] and *Allen and Kanamori* [2003], is used to predict the size of an earthquake. *Wu and Kanamori* [2008a, 2008b] showed that an earthquake magnitude (M_w) could be estimated from τ_c for strong motion data from the Japan, Taiwan, and southern California records. In the present EEW developments in Taiwan and southern California, τ_c method is proposed for magnitude determination by means of onsite warning.

[5] For regional EEW, *Wu et al.* [1998] proposed the M_{L10} method based on the first 10 sec of signal to determine earthquake magnitude that is well correlated to the local magnitude M_L using the real-time strong-motion network in Taiwan. *Wu and Zhao* [2006] showed that for earthquakes in southern California the attenuation of Pd, from the initial 3 seconds of the *P* waveforms, with the hypocentral distance is also a robust measurement for estimating the earthquake magnitudes. Similar to *Wu and Zhao* [2006], *Zollo et al.* [2006] also found that the low-pass filtered, peak amplitudes of initial *P*- and *S*-wave seismic signals recorded in the vicinity (within 50 km) of an occurring earthquake source correlates with the earthquake magnitude.

[6] *Teng et al.* [1997] introduced the experimental concept of the effective magnitude that can be derived immediately from the surface area covered by the specific high level of recording PGA contour. They found a simple empirical relationship between the source areas covered by the 100 Gal contour and their corresponding earthquake magnitudes using historical shallow damaging earthquakes around the world.

[7] Generally following the concept of the effective magnitude [*Teng et al.*, 1997], in this study we define the relationship between the areas covered by the high levels of acceleration and their corresponding earthquake magnitudes for the large shallow earthquakes in Taiwan and also extend the 100-Gal contour used by *Teng et al.* [1997] to higher PGA levels in order to reduce the time and stations needed to obtain the covered areas. We find that for the large shallow earthquakes in Taiwan the logarithms of the areas covered by the high levels of PGA contours have a definite linear relation to the corresponding earthquake magnitudes. We propose that this resulting relationship could be used to rapidly estimate earthquake magnitude once the strong

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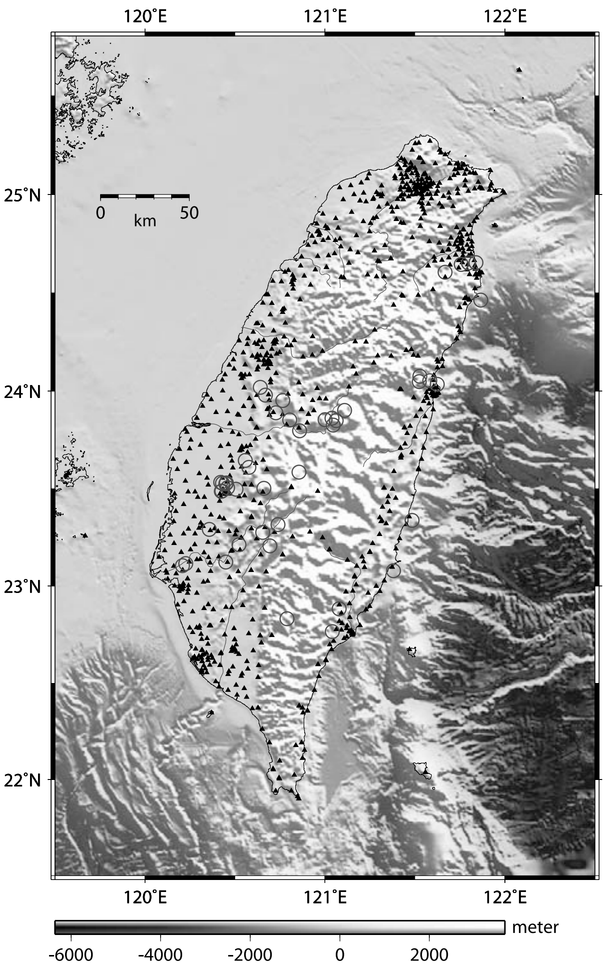

Figure 1. Locations of seismic stations (triangles) of the TSMIP seismic network. The epicenters of the 45 crustal earthquake events with PGA larger than 100 Gal recorded by the TSMIP stations are shown as the open circles. The TSMIP stations are limited in the mountain ranges.

ground motion covered areas are determined. The magnitude determination method presented in this study might be integrated into the current operating EEW and rapid reporting systems to provide additional estimation of earthquake magnitude, thus build more redundancy in the systems.

2. Strong Ground Motion Data

[8] Taiwan, located at the western portion of the Pacific Rim seismic belt, is situated in the collision boundary zone between the Philippine Sea and Eurasian continental plates. Therefore, the seismicity in Taiwan is considerably high. Considering its high population density and seismic activity, Taiwan is an area that has been prone to suffering from serious seismic hazards such as demonstrated by the catastrophic 1999 Chi-Chi earthquake.

[9] In this study we searched the shallow crustal earthquakes with PGA (largest one among three components) values larger than from 100 to 400 Gal recorded by the TSMIP stations for the time period from 1993 to 2008; since shallow inland earthquakes often cause the most serious damage, and both EEW and rapid reporting are practically applied to large damaging earthquakes. In fact, most inland or offshore (distance to shoreline <5 km) earthquakes that caused ground shaking to a maximum PGA exceeding 100 Gal have focal depths shallower than 25 km in Taiwan. A PGA value larger than 100-Gal corresponds to the CWB intensity scale of V (80–250 Gal) in Taiwan [*Wu et al.*, 2003] or the Modified Mercalli intensity scales [*Wald et al.*, 1999] of VI (92–180 Gal). Totally, there are 45 crustal earthquakes (Figure 1 and Table 1) having PGA larger than 100 Gal recorded by the TSMIP stations.

[10] The TSMIP [*Liu et al.*, 1999] operated by the Taiwan Central Weather Bureau (CWB), consists of over 800 free-field stations densely distributed throughout the Taiwan island as of 2008 (Figure 1). The TSMIP has a station spacing of about 5 km throughout the populated areas except for the higher relief mountain ranges. The spatial distribution of the recording stations was first carefully inspected to avoid unilateral sampling before computing the areas enclosed by a variety of PGA contours ranging from 100 to 400 Gal. At least 5 recording stations are required inside each PGA contour, and the PGA contours are manually examined to remove the jagged ones.

3. PGA Covered Area

[11] Figure 2 plots the resulting relationship between the covered areas and earthquake magnitudes in M_w of each specific PGA contour level from 100 to 400 Gal. Figure 2 shows that the logarithms of the covered areas have a definite linear relation to the corresponding earthquake magnitudes indicating that an earthquake with larger magnitude will affect a larger surface area enclosed by the specific PGA contour level. The increasing uncertainties in the area-magnitude relation with increasing PGA contour level (Figure 2) might be simply due to the fact that fewer earthquakes are available for generating higher PGA values (three events for PGA > 400 Gal). An empirical relationship between the area covered by the PGA contour and earthquake magnitude shown in Figure 2 can be expressed as

$$M_W = a \log A + b \tag{1}$$

where a and b are the slope and intercept of the linear relationship in Figure 2 and A (in km^2) is the area of recording PGA larger than the specific PGA value. These two parameters, a and b, are summaries in Figure 3. Figure 3 shows that the parameter a is rather independent of the value of PGA contour and the parameter b, in contrast with a, is a function of the value of PGA contour. According to Figure 3, the parameters a and b in Equation (1) can be substituted as

$$M_W = 1.95 \log A + 0.006P - 1.619 \tag{2}$$

where P is one specific PGA value describing the PGA contour for computing the enclosed area (A in Equation (1)).

[12] In the real-time EEW operation, a simple algorithm of computing the covered area inside a variety of high PGA

Table 1. Parameters of the 45 Events

Origin Date	Origin Time	Latitude (N)	Longitude (E)	Depth (km)	M_w	Number of Records
1993/12/15	21:49:43	23.213	120.524	13	5.4	20
1994/04/06	01:12:11	23.533	120.421	13	4.9	6
1995/06/25	06:59:07	24.606	121.669	40	5.9	38
1995/10/31	22:27:07	23.291	120.359	11	5.0	11
1996/05/28	21:53:22	24.054	121.583	25	4.9	17
1998/07/17	04:51:15	23.503	120.663	3	5.7	23
1998/11/17	22:27:33	22.832	120.790	16	5.3	6
1999/09/20	17:47:16	23.853	120.805	7	7.6	169
1999/09/20	18:03:42	23.797	120.861	10	6.5	21
1999/09/20	18:05:54	23.952	120.767	13	5.1	16
1999/09/20	18:11:54	23.849	121.063	3	6.6	64
1999/09/20	18:16:18	23.862	121.041	13	6.5	36
1999/09/20	21:41:23	23.610	120.579	14	5.0	5
1999/09/20	21:46:38	23.585	120.857	9	6.4	19
1999/09/22	00:14:41	23.826	121.047	16	6.4	45
1999/09/25	23:52:50	23.854	121.002	12	6.5	56
1999/09/28	05:53:50	23.980	120.671	11	4.9	8
1999/10/22	02:18:57	23.488	120.428	21	5.9	73
1999/10/22	02:43:25	23.487	120.425	19	4.6	6
1999/10/22	03:10:17	23.526	120.450	17	5.6	52
1999/10/22	08:34:15	23.530	120.454	12	4.8	10
1999/10/22	17:57:04	23.528	120.432	17	4.8	14
1999/10/23	17:08:03	23.505	120.461	12	4.9	8
1999/11/15	07:25:22	23.497	120.507	7	4.9	5
1999/11/17	07:35:10	24.019	120.643	10	5.1	5
2000/02/15	21:33:18	23.316	120.740	15	5.2	9
2000/06/10	18:23:29	23.901	121.109	16	6.4	63
2000/12/10	10:08:39	23.106	120.208	16	4.9	13
2000/12/10	19:30:44	23.116	120.226	12	5.2	16
2001/09/17	22:44:45	23.276	120.654	7	4.9	7
2002/09/06	11:02:02	23.890	120.729	29	5.1	5
2003/11/06	13:58:44	23.124	120.451	18	4.8	9
2003/12/10	04:38:14	23.078	121.383	22	6.8	45
2004/05/01	07:56:11	24.076	121.528	22	5.2	25
2005/03/05	19:06:52	24.655	121.841	6	5.7	32
2005/03/05	19:08:00	24.653	121.798	7	5.7	34
2005/03/05	19:16:26	24.645	121.759	8	4.7	7
2005/04/30	14:48:17	24.035	121.625	8	5.3	27
2006/03/09	04:07:29	23.645	120.558	10	4.9	16
2006/04/01	10:02:20	22.884	121.081	7	6.1	27
2007/09/22	06:27:05	24.464	121.867	22	4.6	8
2008/03/04	17:31:47	23.207	120.696	11	5.2	7
2008/05/13	18:27:55	22.766	121.041	7	4.9	8
2008/08/01	18:55:49	24.048	121.526	21	4.9	24
2008/12/02	03:16:54	23.338	121.486	32	5.3	5

contours can be pre-programmed in the EEW system and then, once the covered area after a large earthquake occurrence is determined the earthquake magnitude is simultaneously obtained by using Equation (2).

4. Discussion

[13] Either EEW or rapid reporting is intentionally designed and applied to damaging earthquakes. Therefore, it is desirable to have a rapid earthquake magnitude determination that is closely related to the earthquake damage potential. The method of magnitude estimation proposed in this study is directed toward, instead of concerning earthquake energy release, the level of strong surface shaking that is the most concerned factor in evaluating the earthquake damage potential. Hence, the proposed magnitude estimation method is inherently suitable for the purpose of the EEW and rapid reporting systems.

[14] Figure 4 illustrates the relationship between the area covered by the PGA contour and earthquake magnitude describing in Equation (2). For an earthquake with M_w less than 7.0, a covered area of 10000 km^2 is large enough for estimating the magnitudes by the PGA contours of between 100 and 200 Gal (Figures 2 and 4). An area of 10000 km^2 corresponds to that of a circle with 57 km in radius. Therefore, adequate amount of recording stations with epicenter distances in a few tens of kilometers are most demanded to practically implement the proposed method of earthquake magnitude estimation. Assuming a wave velocity of 3.5 km/s common for the crustal *S*-wave velocity, the travelling time over a distance of 57 km is of about 16 sec (Figure 4). Hence, the duration of about 16 sec is in theory sufficient for generating the PGA contour of between 100 and 200 Gal if providing adequate seismic station density. However, the on-line processing time for our magnitude estimation need to consider the source rupture duration since

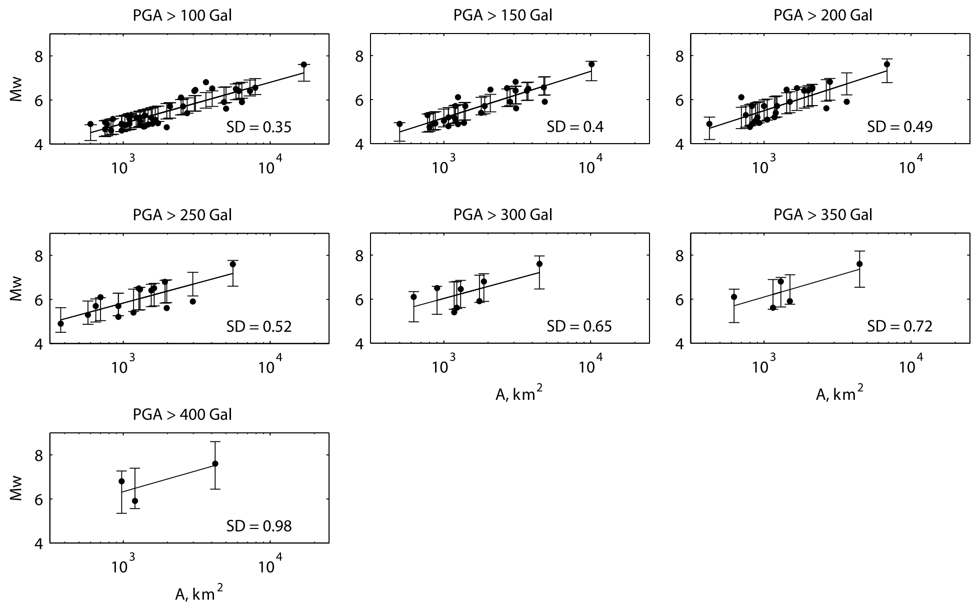

Figure 2. The resulting empirical relationship between the covered areas of each specific PGA contour level from 100 to 400 Gal and the earthquake magnitudes in M_w.

PGA is used in the estimation. According to *Wells and Coppersmith* [1994], the rupture duration for a magnitude 7 earthquake is of 20 seconds, and for an earthquake with magnitude less than 6.5 is under 10 seconds. Although, the actual rupture duration for a given magnitude event can vary by a factor of 2 or 3 [*Olson and Allen*, 2005].

[15] Currently, we have two operational systems to monitor and report earthquakes in Taiwan. One is the rapid reporting system (RRS), and the other one is the virtual sub-network (VSN) system for earthquake early warning purpose. The RRS are used to issue formal earthquake reports at present. Its average response time is about 60 seconds. The VSN was installed since 2001 on an experimental basis to test the capability of EEW. Its response time can be as short as 20 seconds [*Hsiao et al.*, 2009].

[16] Surely, for higher PGA contour the shorter collecting time is required to get the area inside the PGA contour for a given magnitude earthquake (Figure 4); however, the uncertainty of the estimated earthquake magnitude estimated by higher PGA contour becomes inevitably larger than that by lower PGA contour. This larger uncertainty is attributed to fewer recordings of higher PGA value and the influence of rupture process for stations close to the fault [*Somerville*, 2003; *Schmedes and Archuleta*, 2008]. Even so, a rapid yet rough estimation of earthquake magnitude could be available in a very short amount of time. For example, using the PGA contour of 400 Gal the acquiring time is less than 7 second for an M_w 7.0 earthquake (Figure 4). The uncertainty of the magnitude estimation decreases dynamically and progressively with acquiring more PGA reading and diluting the influence of the near-source abnormal ground motions.

[17] The accuracy of the area inside a PGA contour heavily depends on the density of seismic networks. More seismic stations with epicenter distances less than tens of kilometers will significantly improve the accuracy of the magnitude estimation. Therefore, an applicable station density will be a prerequisite to put this proposed magnitude estimation method into real-time, on-line EEW practice. Micro Electro Mechanical Systems (MEMS) acceleration sensors that recently introduced in seismic applications [*Holland*, 2003] are miniature, cost-saving, and are ideal for recording near-field, high-frequency ground motions. Our

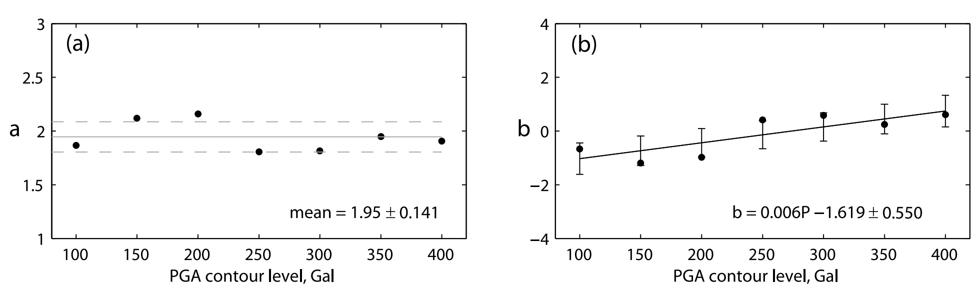

Figure 3. Summary of the (a) slope and (b) intercept of the linear relationship shown in Figure 2 of each specific PGA contour level. The labels *a* and *b* of the vertical axes are the same in Equation (1). The solid and dashed lines in (a) depict the mean and standard deviation, respectively.

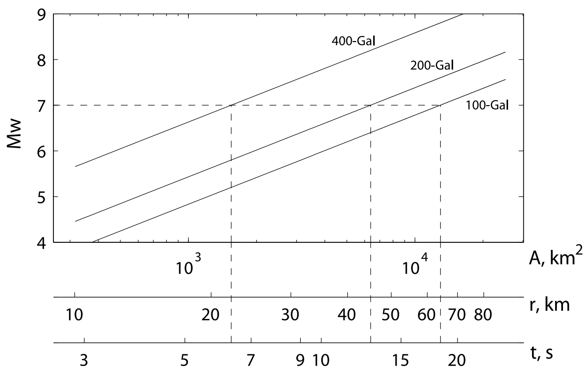

Figure 4. The relationship between the area inside the PGA contour and its earthquake magnitude describing in Equation (2). Three levels of PGA contour of 100, 200, and 400 Gal are used. The areas (A) are converted to that of the circles to obtain the radiuses (r) and travelling time (t) assuming a wave velocity of 3.5 km/s.

magnitude estimation method might be doable via extensive installation of MEMS accelerometers. MEMS accelerometer network has been successfully tested for the potential of EEW by the Quake-Catcher Network [*Cochran et al.*, 2009].

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