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Estimated Seismic Intensity Distributions for Earthquakes in Taiwan from 1900 to 2008

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Abstract In this study we recreated peak ground accelerations (PGA) and peak ground velocity (PGV) distributions for Taiwan by applying the attenuation relations of Liu and Tsai (2005) to calculate the PGA and PGV values for 1989 $M_w \geq 5.0$ earthquakes in a catalog of earthquakes from 1900 to 2008 with homogenized magnitude (M_w) (Chen and Tsai, 2008). We further combined the PGA and PGV values to obtain corresponding modified Mercalli intensity (MMI) values (Wald, Quitoriano, Heaton, Kanamori, *et al.*, 1999) and their spatial distributions and recurrence intervals. We adopted a logarithmic functional form analogous to the Gutenberg–Richter relation for seismicity to represent the annual frequency of seismic intensity parameters: $\log_{10}(N) = a - b\log_{10}(\mathrm{PGA})$, $\log_{10}(N) = a - b\log_{10}(\mathrm{PGV})$, and $\log_{10}(N) = a - bI$. The regions with high PGA and PGV values are often associated with low b values in these equations. As it is well known that the M_w 7.45 Chi-Chi earthquake of 21 September 1999 had produced high PGA values (in excess of $0.9g$) and PGV values (in excess of 300 cm/s), we used these relations to estimate the Poisson probability distributions in Taiwan for MMI ≥ VIII (i.e., PGA ≥ $485g$) for recurrence intervals of 30, 50, and 100 years. The results show a wide range of differences in the Poisson probability of MMI ≥ VIII among different areas of Taiwan. For example, for a 50-year interval, this probability at 10 major cities in Taiwan is as follows: Taipei 0.67%, Hsinchu 2.15%, Taichung 5.24%, Chiayi 24.35%, Tainan 1.61%, Kaohsiung 0.04%, Hengchun 4.94%, Ilan 17.67%, Hualien 37.04%, and Taitung 9.82%. These estimates should be of interest to city planners, especially for earthquake preparedness planning.

Online Material: Time, hypocentral location, and magnitude of Taiwan earthquakes with $M_w \geq 5.0$ from 1900 to 2008.

Introduction

Taiwan is at the juncture of the Philippine Sea plate and Eurasian plate. Earthquakes occur very frequently, particularly along Taiwan's eastern margins. This frequent seismic activity along the east coast provides ample seismic data. This constant seismic energy release may also lessen the possibility of an extreme earthquake event occurring. On the other hand, earthquakes occur less often in western than eastern Taiwan but can be of great intensity. In addition, much of Taiwan's industry and population are located in the western regions. A few major past earthquakes occurred in western Taiwan and resulted in great disasters. They included the 1906 M_w 7.06 Meishan earthquake, 1935 M_w 7.06 Hsinchu-Taichung earthquake, and 1999 M_w 7.45 Chi-Chi earthquake. Omori (1907) described the 1906 M_w 7.06 Meishan earthquake by depicting only the isoseismal lines in accordance with motion conditions; however, the actual seismic intensity is still unknown.

This study uses data based on Chen and Tsai's (2008) study that converted the original magnitudes of Taiwan's earthquake catalog 1900–2006 into homogenized M_w magnitudes. For this study, the catalog has been updated to include earthquakes up to 2008 and to add supplementary data found in the literature for the time period 1900–1935. There were 1989 $M_w \geq 5.0$ crustal earthquakes over the study period as shown in Figure 1a. This figure shows that most of these earthquakes were located in eastern Taiwan and its offshore regions. A plot of annual frequency of earthquakes versus magnitude (Fig. 1b) shows a sudden change of slope at M_w 5.0, indicating completeness of the catalog for $M_w \geq 5.0$. For this reason and because events with smaller

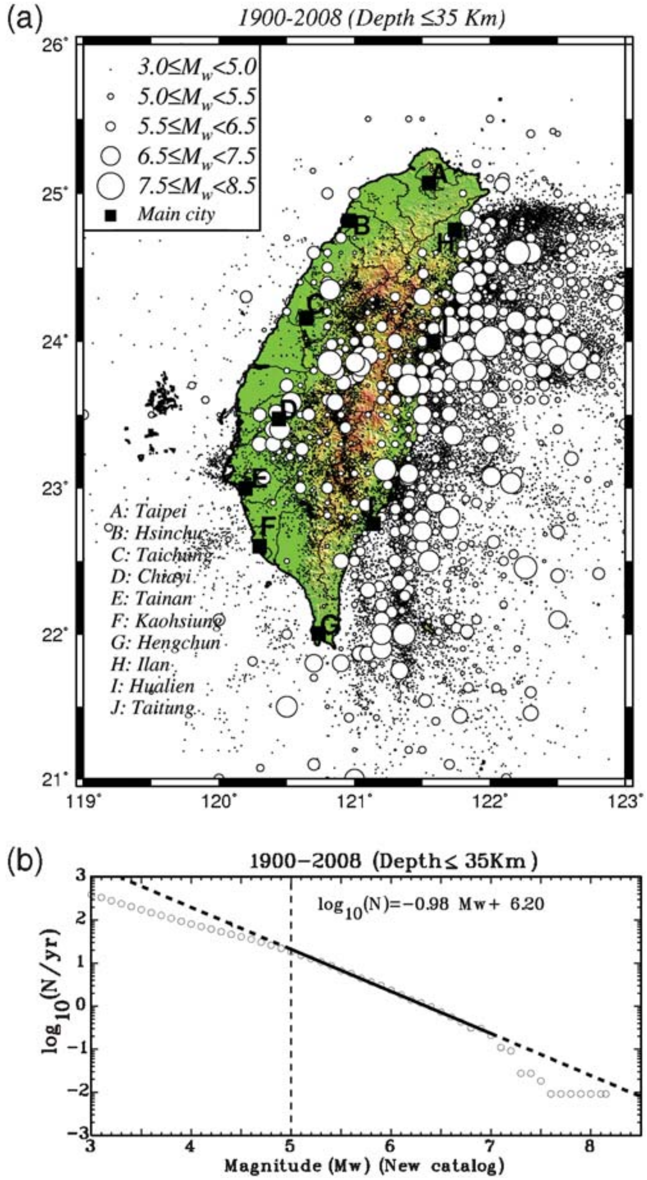

Figure 1. (a) Distribution of epicenters of 1989 $M_w \geq 5.0$ crustal earthquakes from 1900 to 2008 and the locations of 10 major cities in Taiwan considered in this study. (b) Determination of the lower cutoff threshold on magnitude for this study. A clear change in the slope at magnitude M_w 5.0 indicates our earthquake catalog is complete above this magnitude. Earthquakes smaller than this magnitude will present only minor seismic hazards. Solid line, regression range; dash lines, extrapolation.

magnitude are likely to present minimal seismic hazards only, we choose this point (M_w 5.0) as the lower cutoff threshold of magnitude in our study. Besides, events with smaller magnitude are likely to present minimal seismic hazards only.

We first divide the Taiwan region into 391 grids, with a grid interval of 0.1° between grids. We next apply the new acceleration and velocity attenuation relationships for Taiwan (Liu and Tsai, 2005) to calculate the peak ground acceleration (PGA) and velocity (PGV) for each of the 1989 $M_W \geq 5.0$ crustal earthquakes at each grid. In accordance with the attenuation relationships, the hypocentral distance is used in our calculations. We further adopt the following logarithmic equations: $\log_{10}(N) = a - b\log_{10}(\mathrm{PGA})$, $\log_{10}(N) = a - b\log_{10}(\mathrm{PGV})$, and $\log_{10}(N) = a - bI$ to evaluate respective a and b values. The modified Mercalli intensity (MMI), I, is computed from PGA and PGV according to Wald, Quitoriano, Heaton, Kanamori, *et al.* (1999) and Wald, Quitoriano, Heaton, and Kanamori (1999).

Wald, Quitoriano, Heaton, Kanamori, *et al.* (1999) and Wald, Quitoriano, Heaton, and Kanamori (1999) pointed out that the lower (MMI ≤ VI) intensities are generally assigned based on felt accounts, while higher intensities are based on the level of damage, the onset of damage being at about intensity MMI VI or VII. In Taiwan, the 21 September 1999 M_w 7.45 Chi-Chi earthquake produced maximum horizontal peak ground accelerations in excess of $0.9g$. Therefore, we also made estimates on the probability of higher peak ground acceleration (i.e., MMI ≥ VIII, or PGA ≥ $485g$). After application of the various approaches described thus far in this article, we find that regions with low b values and higher probabilities for MMI ≥ VIII are present along a zone extending from Hsinchu southward to Taichung, Chiayi, and Tainan in western Taiwan and a zone extending from Ilan southward to Hualian and Taitung in eastern Taiwan. These zones also coincide with the trends of high PGA.

Data Processing and Interpretation

In this study, we first divide the Taiwan region into 391 grids at a grid spacing of 0.1°. Then we use an earthquake catalog of homogenized M_w magnitudes developed by Chen and Tsai (2008) originally for earthquakes from 1900 to 2006. This catalog is subsequently updated to include events up to 2008 and to incorporate available supplementary data for the period 1900–1935 up to a total of 1989 $M_w \geq 5.0$ crustal earthquakes for the Taiwan region.

Previously, Liu and Tsai (2005) derived new attenuation relationships for horizontal peak ground acceleration and velocity for crustal earthquakes on Taiwan, using a large amount of strong-motion data obtained by the Taiwan Strong Motion Instrumentation Program. We apply these attenuation relationships to calculate the values of peak ground acceleration and velocity for each of the 1989 earthquakes at each grid. In recognition of the uniqueness of the large set of recorded PGA and PGV data from the Chi-Chi earthquake of 21 September 1999, we use the real data of this event to combine with the calculated PGA and PGV values from all other events for our subsequent analysis.

From these calculated data, we can obtain the maximum PGA, PGV, and MMI values of each grid (see Fig. 2). Figure 2 shows that PGA values in Taipei and Kaohsiung cities in northern and southern Taiwan, respectively, are relatively low. On the other hand, PGA values are high over a zone in western Taiwan starting from Hsinchu southward through Taichung, Nantou, and Chiayi to Tainan. PGA values are also

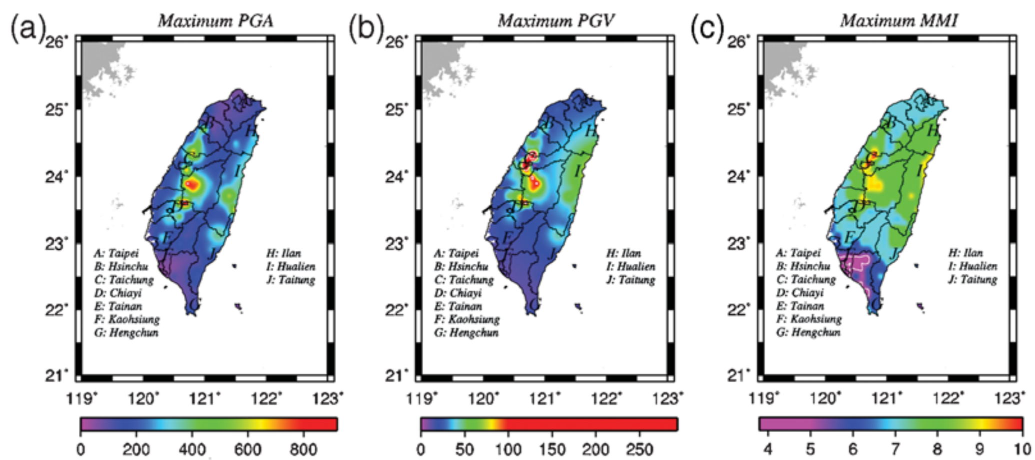

Figure 2. Contour of estimated maximum PGA, maximum PGV. and maximum MMI for earthquakes in Taiwan from 1900 to 2008.

high in Hualien area in eastern Taiwan. Likewise, PGV values in Kaohsiung and Hengchun areas in southern Taiwan are low, while the highest PGV value is in the Chi-Chi earthquake area. The patterns for MMI are quite similar. Apparently, the high intensity values in western Taiwan can be attributed to several strong earthquakes, including the 21 September 1999 Chi-Chi earthquake.

Next, we examine the annual frequencies of PGA and PGV at each grid. We find that they closely follow a log versus log trend. Accordingly, we use $\log_{10}(N) = a - b\log_{10}(\mathrm{PGA})$ and $\log_{10}(N) = a - b\log_{10}(\mathrm{PGV})$ to represent the data and evaluate their respective a and b values. In the process, we adopt equal intervals in logarithmic scale on the horizontal axis (PGA or PGV axis) in order to avoid excessive weighting of higher PGA and PGV values in determining the regression parameters. Likewise, we also use $\log_{10}(N) = a - bI$ in the evaluation of the a and b values for each grid.

Because we are most concerned about the seismic hazards of the 10 major cities, they are selected to demonstrate example results. Figure 3 and Figure 4 show the data on annual frequency of PGA and PGV, together with their regression equations for the 10 cities. The regression parameters a and b, together with the maximum PGA, PGV, and MMI values are listed in Table 1. From the table we can see that, during 1900 to 2008, Hualien and Ilan in eastern Taiwan and Chiayi in western Taiwan had experienced strong shaking reaching MMI IX and VIII, respectively. On the other hand, Tainan, Kaohsiung, and Hengchun in southern Taiwan had experienced only minor shaking up to MMI V and VI. The remaining four cities had experienced moderate shaking up to MMI VII. Cheng *et al.* (2007) recently incorporated active fault data to assess probabilistic seismic hazards for Taiwan. They provided the PGA values for various recurrence intervals. Here we make a rough comparison between our estimates and their results for the 10 major cities for a recurrence interval of 475 years. We obtain our estimates by extrapolating the regression lines for the 10 major cities in Figure 3 to an annual frequency of 0.002 (i.e., a recurrence interval of 500 years). For low intensity areas, such as Tainan and Kaohsiung, our PGA values are lower than their results, suggesting the importance of incorporating active fault information in the assessments of long-term seismic hazards, On the other hand, in high intensity areas, such as Chiayi and Hualien, our PGA values are higher than their results. This suggests that our estimates from a relatively complete earthquake catalog may provide a valuable check on short-term estimates by probabilistic seismic hazards assessment.

Figure 5 shows the spatial distributions of a and b for PGA, PGV, and MMI for Taiwan in its entirety. It is evident that low b values appear over western Taiwan's high PGA and PGV areas. This pattern suggests that these areas can expect future strong shaking (Wyss and Stefansson, 2006). The a values of PGA and MMI have similar trends, but they are somewhat different for PGV, probably due to the difference between the attenuation relationships for PGA and PGV. Because western Taiwan is densely populated and contains much of Taiwan's industrial infrastructure, the region deserves attention in terms of future seismic hazard mitigation efforts.

Comparison of Our Estimated Seismic Intensity with Available Felt Intensity Data

The first seismograph was installed on Taiwan in 1897, launching the era of instrumental observations. In the past, seismographic stations were usually colocated with meteorological observatories. The staffs on duty at these observatories were required to take note on the timing of earthquakes and the shaking intensity they felt personally according to the Central Weather Bureau's (CWB) intensity scale, as shown in Table 2. We have found such felt intensity data available at six observatories from 1954 to 1983, as shown in Figure 6.

In order to compare our estimates with the CWB felt intensity data, we convert the PGA values calculated for all crustal earthquakes (i.e., earthquakes with focal depth less than or equal to 35 km and $M_w \geq 5.0$ data) during 1900–2008 at the six meteorological observatories into

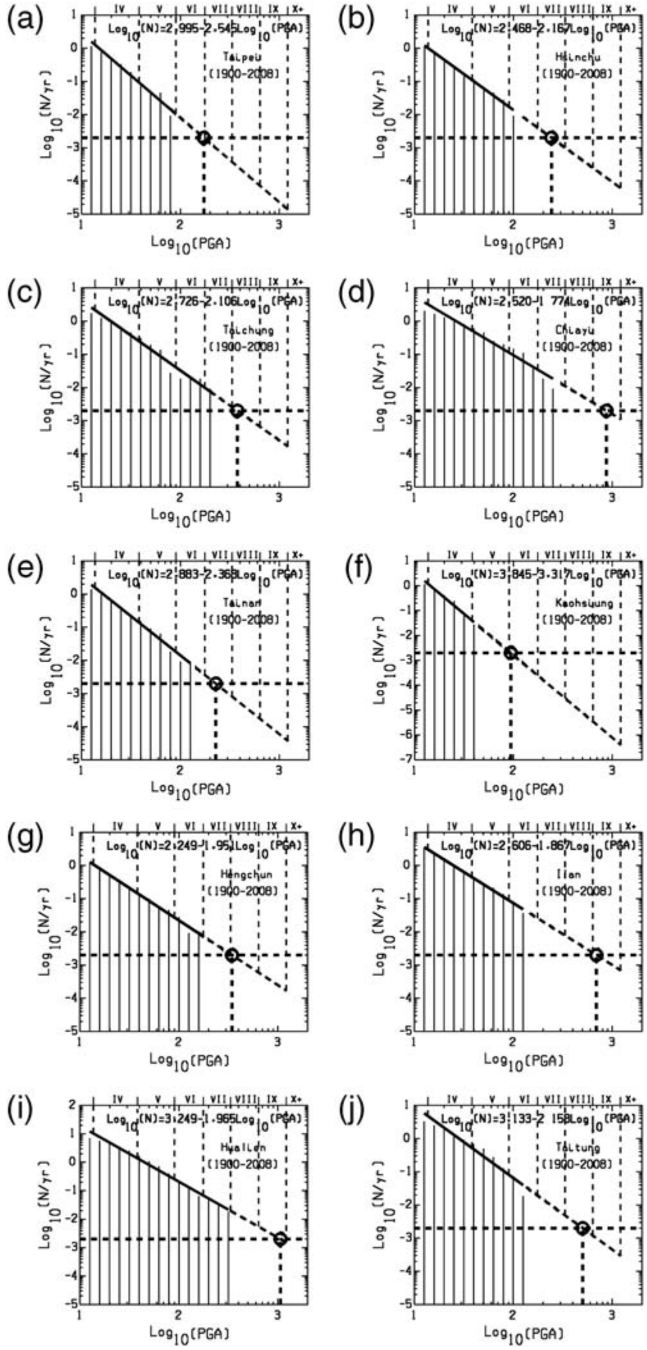

Figure 3. Estimated intensity data and their regressions in the form of $\log_{10}(N) = a - b\log_{10}(\mathrm{PGA})$ for the 10 major cities in Taiwan. The open circle marks the PGA value for a recurrence interval of 500 years.

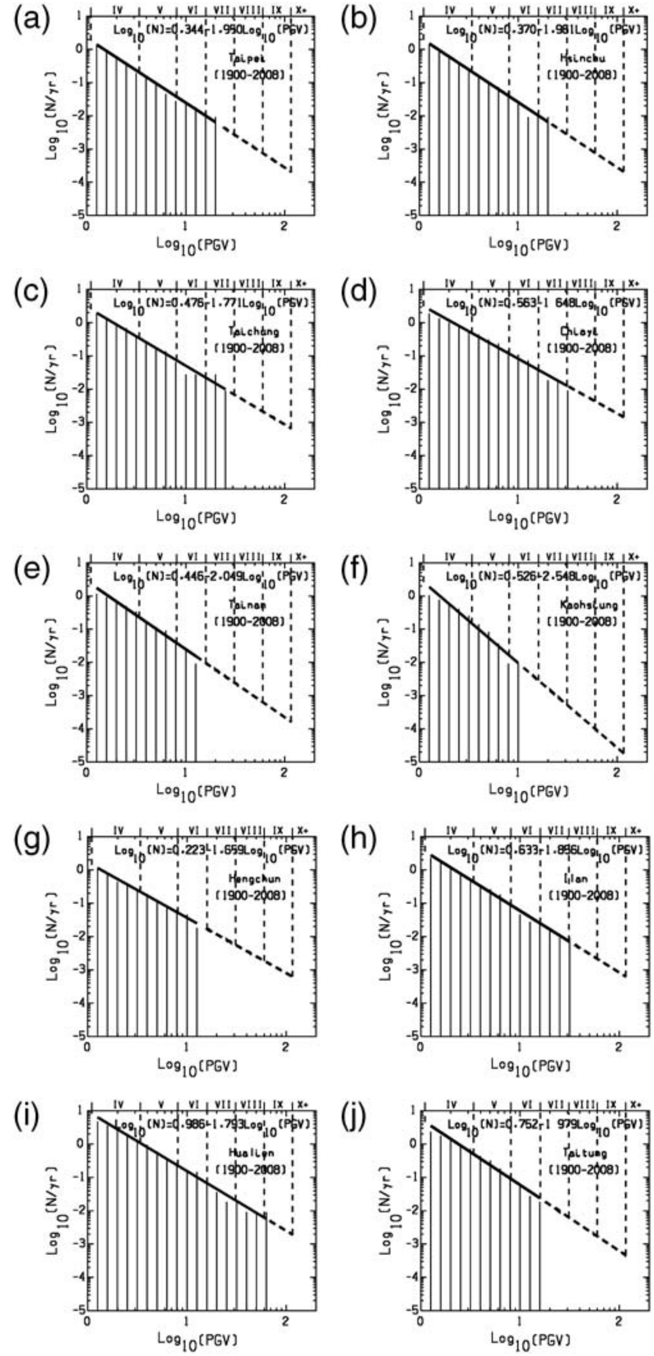

Figure 4. Estimated intensity data and their regressions in the form of $\log_{10}(N) = a - b\log_{10}(\mathrm{PGV})$ for the 10 major cities in Taiwan.

CWB intensity values. The results are also shown in Figure 6 for comparison. This figure shows that both sets of data follow similar trends. However, the annual frequency of felt intensity is apparently less than that calculated from the catalog, in particular at low seismicity areas, such as Taichung and Tainan. This suggests that some of the earthquakes were missed by the station operators. Nevertheless, this comparison provides valuable support for our approach for seismic intensity estimation.

Probabilities of Devastating Intensity (MMI ≥ VIII) for 10 Major Cities

The Taiwan Strong Motion Instrumentation Program (TSMIP) (Shin, 1993) installed more than 600 free-field strong-motion stations in 10 metropolitan areas of Taiwan, as well as on the offshore islands of Penghu. Epicenter distribution data of earthquakes that have occurred in the Taiwan area (21°–26° N, 119°–123° E) show Penghu to be

Table 1
Maximum, *a*, and *b* Values for PGA, PGV, and MMI at 10 Major Cities in Taiwan from Earthquakes, 1900–2008

City	PGA (cm/s^2)			PGV (cm/s^2)			MMI		
	Maximum	*a*	*b*	Maximum	*a*	*b*	Maximum	*a*	*b*
Taipei	79.7	2.995	2.545	24.14	0.344	1.950	VII	3.5120	0.8612
Hsinchu	124.8	2.468	2.167	21.88	0.370	1.961	VII	3.3119	0.7895
Taichung	199.9	2.726	2.106	28.45	0.476	1.771	VII	3.2592	0.7391
Chiayi	304.1	2.520	1.774	32.66	0.563	1.648	VIII	2.9244	0.6221
Tainan	143.1	2.883	2.368	12.72	0.446	2.049	VI	3.8536	0.9289
Kaohsiung	44.9	3.845	3.317	11.42	0.526	2.548	V	4.8180	1.2400
Hengchun	159.5	2.249	1.951	15.73	0.223	1.659	VI	3.3855	0.8319
Ilan	147.8	2.606	1.867	35.70	0.633	1.856	VIII	3.0514	0.6497
Hualien	334.4	3.249	1.965	68.51	0.986	1.793	IX	3.0619	0.5822
Taitung	135.9	3.133	2.158	18.10	0.752	1.979	VII	3.4033	0.7260

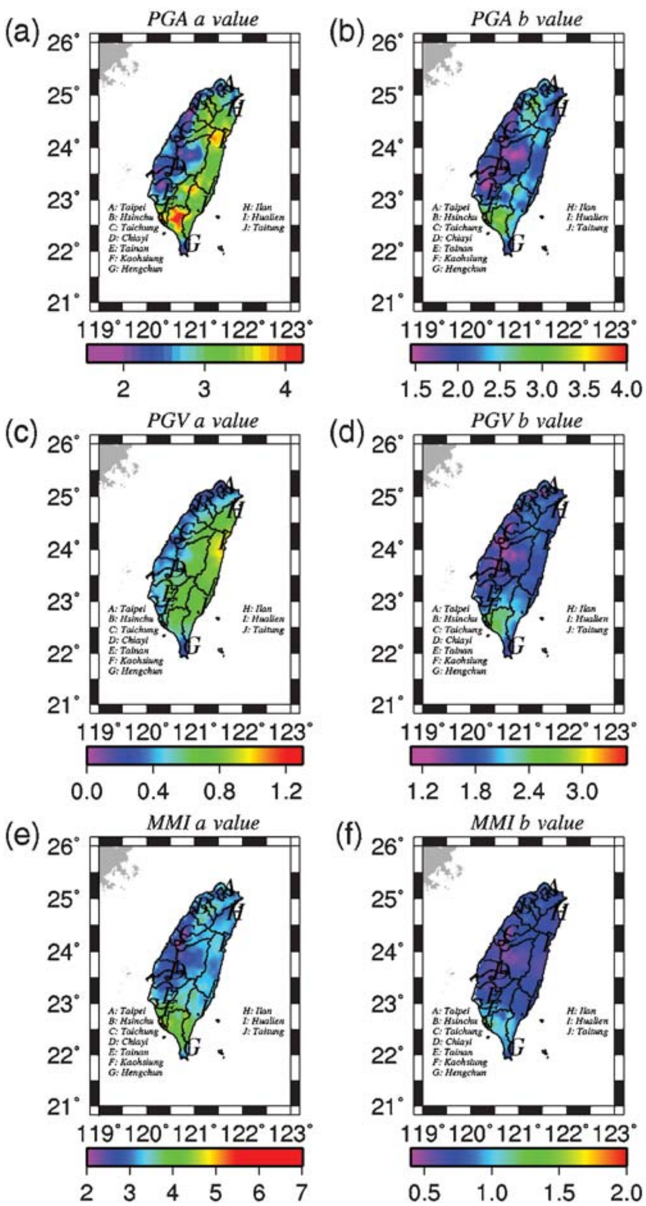

Figure 5. The contour of respective *a* and *b* values for PGA, PGV, and MMI. Areas of low *b* values tend to coincide with areas of high PGA and PGV values.

relatively free of earthquakes. On the other hand, the 10 metropolitan areas all have experienced some seismic activities in the past. Among them, Taipei is Taiwan's capital, Hsinchu hosts much of Taiwan's high-tech industries, Kaohsiung is the most important port city in southern Taiwan, Nuclear Power Plant No. 3 is located near Hengchun, and Ilan, Hualien, and Taitung are all located along the east coast of Taiwan close to the suture zone of the Eurasian plate and Philippines Sea plate. Earthquakes occur very frequently in eastern Taiwan. They also occur inland in western Taiwan, sometimes with devastating intensity. They include the 1906 M_w 7.06 Meishan earthquake, 1935 M_w 7.06 Hsinchu-Taichung earthquake, and the 21 September 1999 M_w 7.45 Chi-Chi earthquake. The Chi-Chi earthquake produced a maximum horizontal acceleration in excess of $0.9g$, so it is of great interest to estimate the probability of devastating intensity (i.e., peak ground acceleration $\geq 485g$, or MMI ≥ VIII) for the 10 major cities.

As described previously, we used the new attenuation relationship (Liu and Tsai, 2005) to calculate PGA values at the 10 cities from the 1989 $M_w \geq 5.0$ crustal earthquakes. Here we use these data to estimate the Poisson probabilities of MMI ≥ VIII for 30-year, 50-year, and 100-year intervals (see Fig. 7). The results are listed in Table 3. From this table, we can see that the probabilities of MMI ≥ VIII vary significantly among the 10 major cities. As expected, Hualien in eastern Taiwan and Chiayi in western Taiwan have the highest probabilities, whereas Taipei and Kaohsiung are relatively low. Even so, their seismic hazards are still of concern because they are the largest metropolitan regions in north and south Taiwan, respectively.

Figure 8 shows the probability of MMI ≥ VIII as a function of recurrence interval for the 10 major cities. It clearly shows that the probabilities of strong shaking are high for Hualien, Ilan, and Taitung in eastern Taiwan. In the meantime, Chiayi in western Taiwan has the second highest probabilities; as we have seen in the past, inland earthquakes along the west side of Taiwan can be very devastating (e.g., the 1906 M_w 7.06 Meishan earthquake). Noting that western Taiwan is marked by low *b* values, we should pay attention

Table 2
Seismic Intensity Scale of the Central Weather Bureau of Taiwan

Perceived Shaking	Not felt	Microshaking	Light	Weak	Moderate	Strong	Violent
Potential Damage	none	none	none	none	very light	light	heavy
Peak Acceleration (g)	<0.8	0.8–2.5	2.5–8	8.0–25	25–80	80–250	>250
Instrumental Intensity	0	I	II	III	IV	V	VI

to high seismic hazards in western Taiwan. For example, the Poisson probability of MMI ≥ VIII in a 50-year interval reaches 24.35% for Chiayi and 5.24% for Taichung. The devastating M_w 7.06 Hsinchu-Taichung earthquake of 1935 was a vivid reminder. Finally, we estimate the 30-year, 50-year, and 100-year Poisson probabilities of MMI ≥ VIII

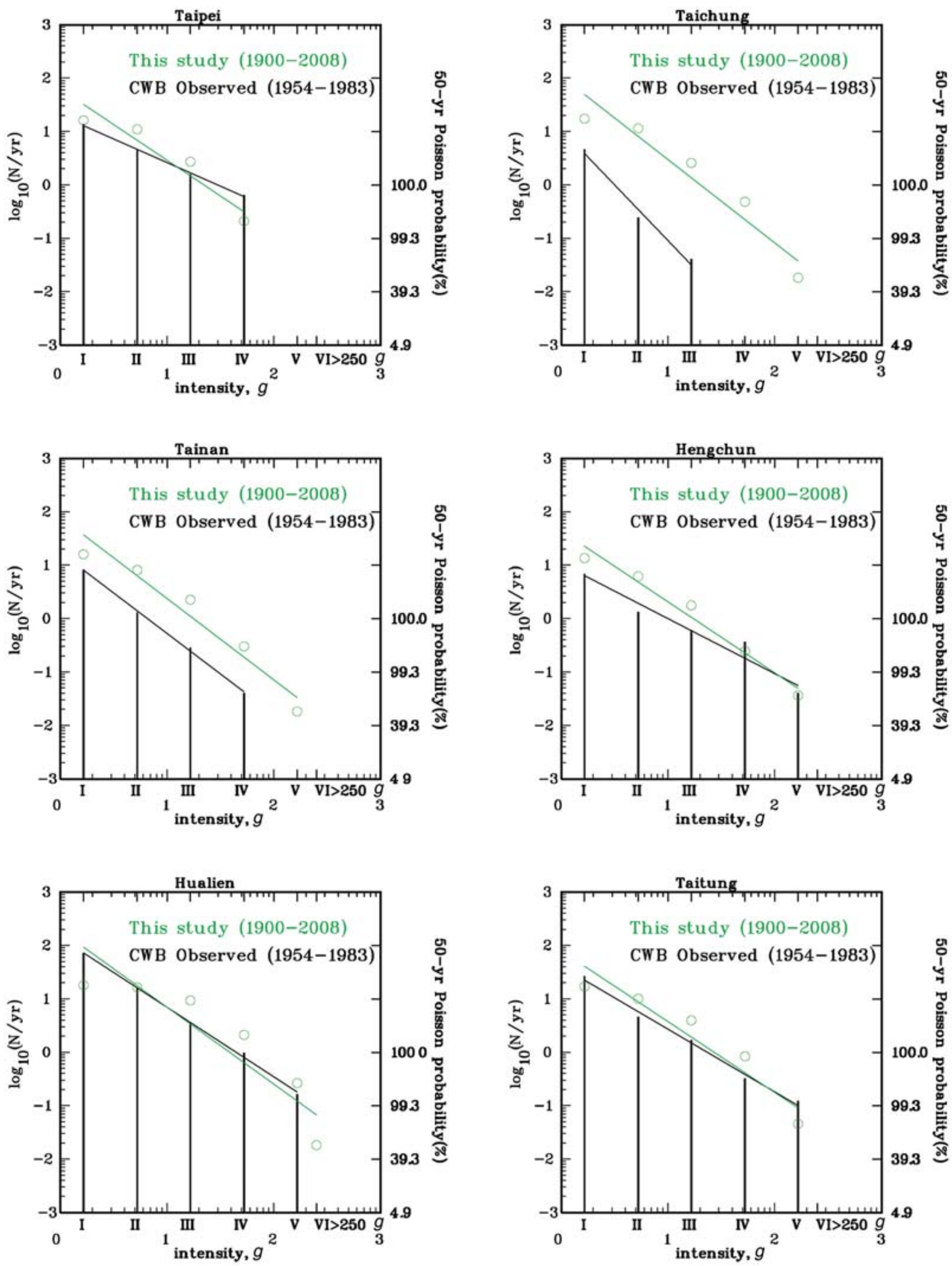

Figure 6. Comparison between our estimated intensity with available felt intensity data at six meteorological observatories in Taiwan, according to the Central Weather Bureau's seismic intensity scale.

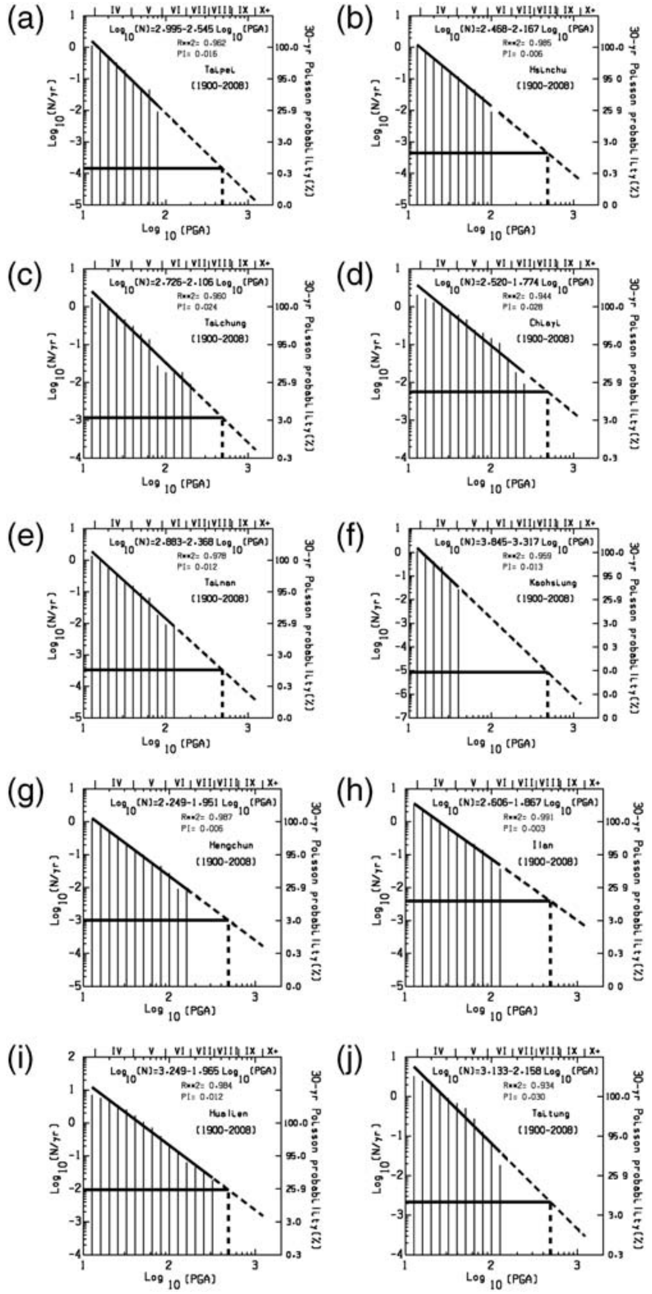

Figure 7. Estimation on 30-year Poisson probability of MMI ≥ VIII (or PGA ≥ 485*g*) for the 10 major cities in Taiwan.

for all Taiwan, as shown in Figure 9. It is evident that the high-probability zones also coincide with the low *b* value and high peak ground acceleration zones.

Discussion and Conclusions

Recently, probabilistic seismic hazard maps using various approaches have been produced for many regions of the world to assess future probable ground motions (e.g., Frankel *et al.*, 1996; Global Seismic Hazard Assessment Program, 1999; Headquarters for Earthquake Research Promotion, 2005). Bozkurt *et al.* (2007) used historical intensity data to forecast probabilistic seismic shaking. Miyazawa and Mori (2009) used historical intensity data over 500 years to test the seismic hazard map in Japan. Stirling and Petersen (2006) also made use of historical earthquake hazard data to examine the seismic hazard models in the United States. These studies all provided valuable comparison with probabilistic seismic hazard assessment. Recently, Cheng *et al.* (2007) incorporated active fault data to estimate the probabilistic seismic hazards in Taiwan.

In this study, we use a relatively complete earthquake catalog from 1900 to 2008 to recreate seismic shaking intensities in Taiwan and to estimate the probabilities of strong shaking (MMI ≥ VIII) for its 10 major cities. We accomplish these tasks by applying the new attenuation relationships based on a large set of recorded strong motion data obtained

Table 3
Estimated Percent Probabilities of MMI ≥ VIII (PGA ≥ 485*g*) over Three Recurrence Intervals for 10 Major Cities in Taiwan

City	30 Years (%)	50 Years (%)	100 Years (%)
Taipei	0.40	0.67	1.33
Hsinchu	1.30	2.15	4.26
Taichung	3.17	5.24	10.20
Chiayi	15.42	24.35	42.77
Tainan	0.97	1.61	3.19
Kaohsiung	0.03	0.04	0.09
Hengchun	2.99	4.94	9.63
Ilan	11.01	17.67	32.21
Hualien	24.24	37.04	60.36
Taitung	6.01	9.82	18.68

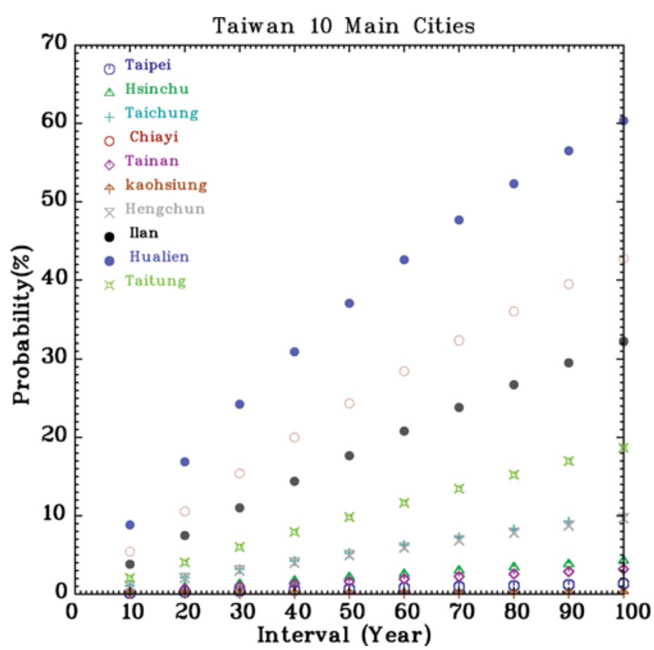

Figure 8. Plots of the probability of MMI ≥ VIII (or PGA ≥ 485*g*) versus recurrence interval for the 10 major cities in Taiwan.

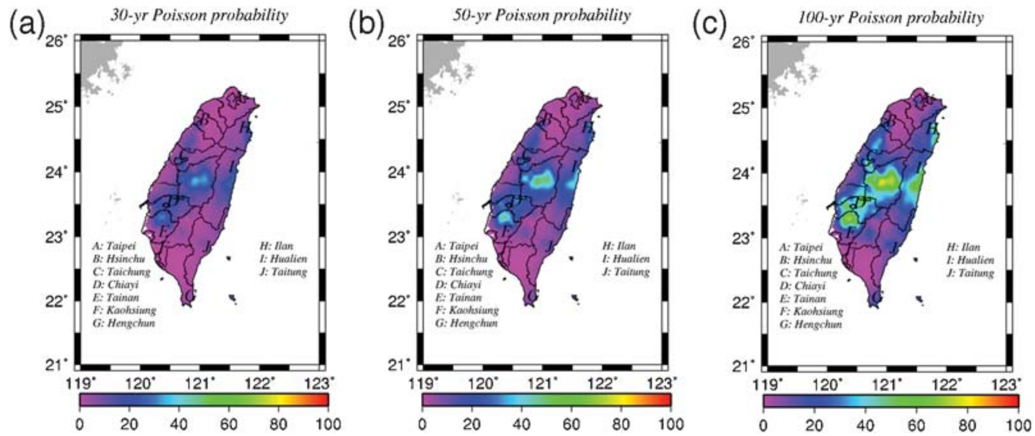

Figure 9. Contours of the probability of PGA $\geq 485g$ (or MMI > VIII) over Taiwan for recurrence intervals of 30 years, 50 years, and 100 years. We can see that high-probability zones tend to coincide with low b-value zones.

by the TSMIP (Liu and Tsai, 2005) to calculate PGA and PGV values from 1989 $M_w \geq 5.0$ crustal earthquakes in the catalog (Chen and Tsai, 2008) for all of Taiwan at a grid interval of 0.1°. We then use the resulting data to study the spatial distribution patterns of seismic intensity in Taiwan over the past 109 years, with a focus on 10 major cities.

Taiwan is a densely populated island, especially along the west coast. Our data show that, for all regions of Taiwan covered by the TSMIP, the probabilities of strong earthquake shaking are generally high, except for the Penghu Islands. Among the cities studied, Taipei is the capital of Taiwan. It is densely populated and houses many high-rise buildings, such as the Hsinkuang and Taipei 101 buildings. Hsinchu is home to much of Taiwan's high-tech industry and is close to the Hsincheng fault. Taichung is another large city in western Taiwan close to the Chelongpu fault. The region has experienced devastating earthquakes in the past, including the M_w 7.06 Hsinchu-Taichung earthquake of 1935. Our study shows that Chiayi has the second highest probability of strong shaking (MMI ≥ VIII), with a 50-year Poisson probability of 24.35%. The area has also experienced large devastating earthquakes in the past such as the 1906 M_w 7.06 Meishan earthquake. Tainan is an important cultural city and has a long history of destructive earthquakes as documented by Omori (1907): such earthquakes occurred in 1655, 1660, 1720, 1721, 1736, and 1862. Hengchun is not far from Nuclear Power Plant No. 3. Finally, the east coast cities of Ilan, Hualien, and Taitung are all close to the suture zone of the Philippines Sea plate and the Eurasian plate and consequently are subject to frequent seismic activity.

This study takes a new approach in the estimation of seismic intensity by using the following logarithmic relations for relevant intensity data types: $\log_{10}(N) = a - b\log_{10}(\mathrm{PGA})$, $\log_{10}(N) = a - b\log_{10}(\mathrm{PGV})$, and $\log_{10}(N) = a - bI$ are used to calculate their respective a and b values. Our estimation of b values shows consistent correlation with PGA, PGV, and MMI values. According to Wyss and Stefansson (2006), future mainshocks can be expected along zones characterized by low b values. In this study, lower b values (see Fig. 5) are found in regions with higher PGA, PGV, and MMI values (Fig. 2). The areas exhibiting these features include Hsinchu, Taichung, Nantou, and from Chiayi to northern Tainan in western Taiwan and Hualien, Ilan, and Taitung in eastern Taiwan. Even though Taipei has a low PGA value and Kaohsiung has both the lowest PGA and the lowest PGV value, we still need to pay attention to the seismic hazards of these cities, as they are the major population centers in Taiwan. The results of this study should be of use to city planners, especially for earthquake preparedness planning. For example, Table 1 provides good empirical evidence on probable maximum seismic intensity experienced at the 10 major cities since 1900. Table 3 and Figure 9 give estimates on the probabilities of damaging intensity (MMI ≥ VIII) for different time intervals. They also show that the seismic hazards vary greatly among the 10 major cities around Taiwan.

Data and Resources

In this study we used a total of 1989 crustal earthquakes with focal depth ≤35 km and $M_w \geq 5.0$ from 1900 to 2008 to estimate the seismic intensity distributions in Taiwan. These earthquakes are listed in Ⓔ Table S1 in the electronic supplement to this paper. The information given in the table includes the origin time, latitude and longitude of epicenter, focal depth, and M_w magnitude of each of these earthquakes. Their locations are shown in Figure 1a. All other data were taken from published works listed in the References. Some plots were made using the Generic Mapping Tools version 4.3.1 (www.soest.hawaii.edu/gmt; Wessel and Smith, 1998).

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