

# Major Earthquakes around Taipei and a Seismic Hazard Assessment with Monte Carlo Simulation

J. P. Wang<sup>1</sup>; Yih-Min Wu<sup>2</sup>; and Duruo Huang<sup>3</sup>

**Abstract:** The region around Taiwan is known for high seismicity. Under the circumstances, seismic hazard assessments and proper earthquake-resistant designs are essential to the region. From a well-studied earthquake catalog, this paper presents the statistics of major earthquakes (i.e., moment magnitude  $M_w \geq 5.5$  and distance  $\leq 200$  km) around the most important city in Taiwan (i.e., Taipei). The analysis shows that the mean annual rate of the major earthquakes is 2.79 around the city, with mean magnitude and SD equal to  $M_w$  6.12 and 0.68, respectively, and mean source-to-site distance and SD equal to 129 and 39 km, respectively. With the earthquake statistics and local ground motion models, a seismic hazard assessment was conducted with Monte Carlo simulations (MCSs). The analysis shows the mean rate for peak ground acceleration  $\geq 0.23g$  (where  $g$  is gravitational acceleration) should be around 0.013 per year, indicating that the current design peak ground acceleration in Taipei. From this paper, the current seismic design in Taipei might not be as conservative as expected, and a review and revision could be needed for assuring the city's seismic safety against high seismicity in the region. DOI: [10.1061/\(ASCE\)NH.1527-6996.0000176](https://doi.org/10.1061/(ASCE)NH.1527-6996.0000176). © 2015 American Society of Civil Engineers.

**Author keywords:** Statistics of major earthquakes; Monte Carlo simulation; Seismic hazard assessment; Taipei.

## Introduction

The region around Taiwan is known for high seismicity. On average, around the region there are about 2,000 earthquakes every year and catastrophic events, such as the 1999 Chi-Chi earthquake, could recur in decades. However, earthquake prediction nowadays is still controversial and unsuccessful (Geller et al. 1997), so that the alternatives such as earthquake early warning and seismic hazard analysis are considered more practical to earthquake hazard mitigation (e.g., Campbell et al. 2002; Cheng et al. 2007; Wu and Kanamori 2008; Hsiao et al. 2011; Wang et al. 2012b).

Taipei, the most important city in Taiwan, is therefore under an earthquake threat. For the seismic safety of the city, a few studies focusing on investigating earthquake potentials and seismic hazards were reported. For example, by examining the sediments of the Taipei basin, Huang et al. (2007) considered that a few large earthquakes should have occurred in the past 10,000 years (or in the Holocene). In addition, Wang et al. (2013) conducted a probabilistic seismic hazard analysis (PSHA) for the city, including seismic hazard deaggregation and suggestions of earthquake time histories for seismic design.

From a different perspective, the key scope of this paper is to review the major earthquakes around Taipei (i.e., moment magnitude  $M_w \geq 5.5$  and hypocentral distance  $\leq 200$  km) based on a well-studied earthquake catalog. Accordingly, Monte Carlo simulations (MCSs) were performed to estimate seismic hazard in the city. From the seismic hazard study to benchmark technical

references, it was found that the current seismic design in Taipei might not be as conservative as expected, and a review or revision on the local technical reference could be needed with new investigations and analyses.

## Statistics of Major Earthquakes around Taipei

### Geological Setting in Northern Taiwan

The region around Taiwan is on the boundary of two tectonic plates. It is believed that the Philippine Sea plate is moving underneath (or subducting) the Eurasian plate in eastern Taiwan and that the Eurasian plate is moving underneath the Philippine Sea plate in southern Taiwan. Such tectonic activities are the cause of high seismicity in the region, also resulting in a unique topography and geologic setting in Taiwan.

As shown in Fig. 1, the geologic setting on the island mainly consists of the Western Foothills, Hsueshan Range, Central Range, Coastal Range, and Hengchun Peninsula, with the Western Foothills and Hsueshan Range predominant in northern Taiwan (Ho 1999). Besides, volcanic activities were active in northern Taiwan around 0.5–2 million years ago, resulting in the Tatun Volcano Group present in north of the Taipei basin now.

### Earthquake Catalog

Fig. 2 shows the locations of more than 55,000 earthquakes around Taiwan from years 1900–2009. The catalog was compiled with the data from the Central Weather Bureau Taiwan that is responsible for earthquake monitoring in Taiwan. The foreshocks and aftershocks were removed from the catalog with a double-link algorithm, on the use of time and distance windows of 3 days and 5 km usually employed in the declustering of earthquake data in Taiwan (Wu and Chiao 2006; Wu and Chen 2007; Wu et al. 2008b).

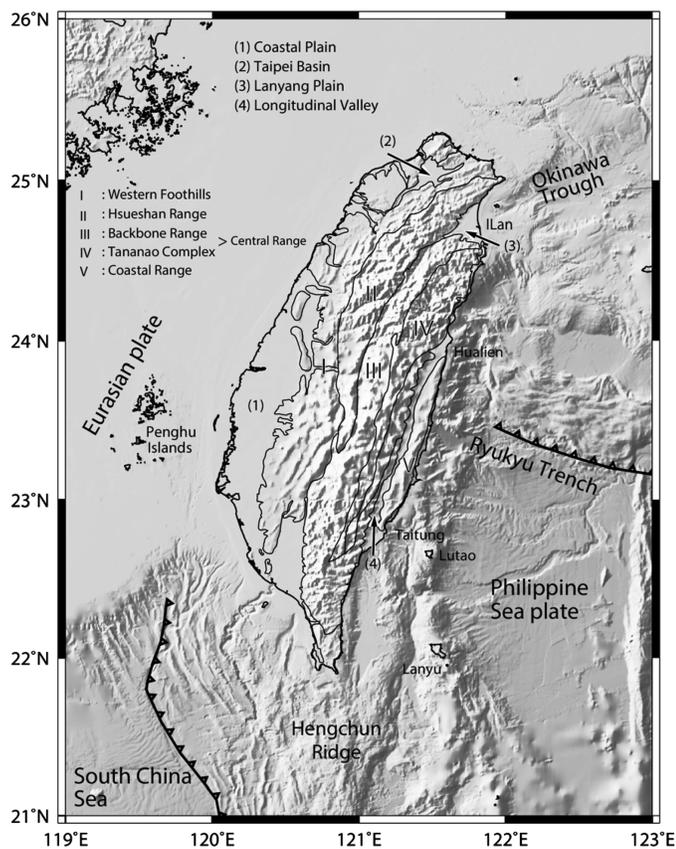
Although a few earthquake catalogs for Taiwan were reported in the literature (Chen and Tsai 2008; Wu et al. 2008a), they were not analyzed and used as extensively as the catalog of the research

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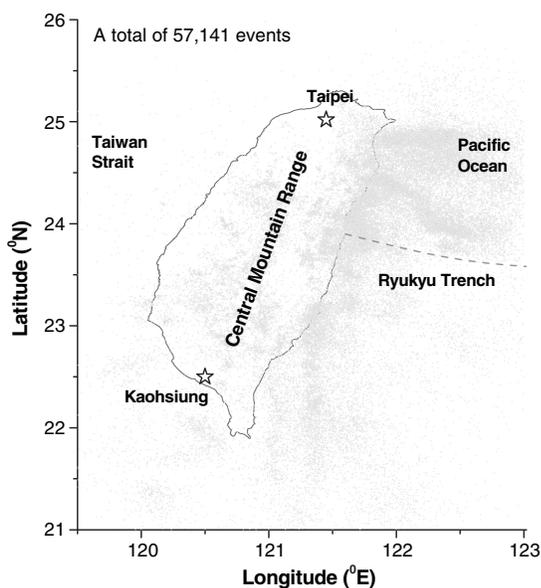
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**Fig. 1.** Geologic setting around the region of Taiwan (data from Ho 1999; Central Geological Survey Taiwan 2010)

reported in this paper. For example, based on the earthquake catalog, a statistical study found that annual maximum earthquake magnitudes around Taiwan should be in accordance with a Gamma distribution (Wang et al. 2011). In addition, on the basis of the same catalog, a recent study examining whether earthquake occurrence



**Fig. 2.** Spatial distribution of the seismicity around Taiwan from years 1900–2009

should be in accordance with the Poisson distribution provided quantitative evidence that the hypothesis should not be rejected for major earthquakes with magnitude greater than 5.0; otherwise it should be rejected (Wang et al. 2014).

Like the recent earthquake statistics studies, the other reason of using the earthquake catalog is because the data are more complete than those given in other earthquake catalogs (Chen and Tsai 2008; Wu et al. 2008a).

### Local Empirical Model for Magnitude Conversion

As mentioned previously, the earthquake magnitude used in the catalog was in local magnitude  $M_L$ , rather than in moment magnitude  $M_w$  that is usually used in ground motion models. As a result, an empirical relationship is needed to convert  $M_L$  to  $M_w$  prior to seismic hazard calculations. In the research reported in this paper, the relationship developed with local earthquake data was used (Wu et al. 2001)

$$M_L = 4.53 \times \ln(M_w) - 2.09 \quad (1)$$

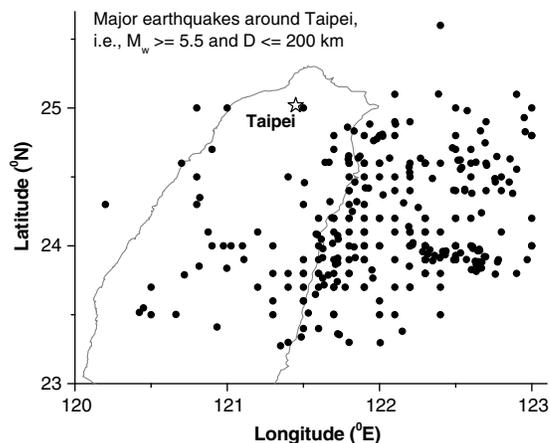
Therefore, the earthquake statistics given in the subsequent sections are in  $M_w$  after the conversion, so that the data can be used in the subsequent seismic hazard calculations with  $M_w$  used in both magnitude probability functions and ground motion models.

### Statistics

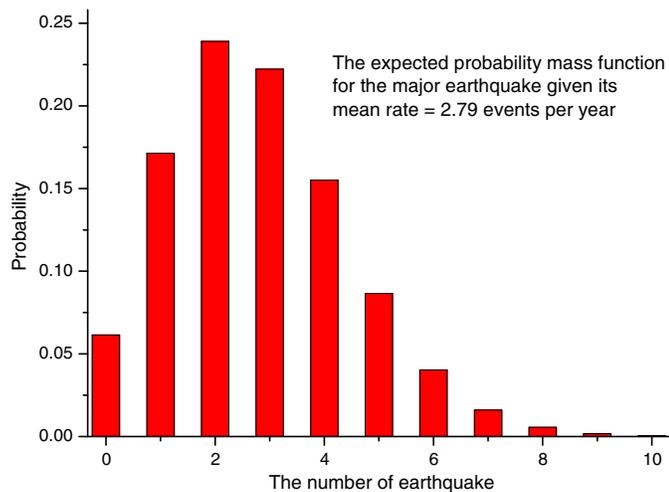
From the earthquake catalog, Fig. 3 shows the locations of 307 major earthquakes around the geographical center of Taipei. In other words, the mean annual rate of such earthquakes is about 2.79 based on the records in the past 110 years. As suggested (e.g., Ang and Tang 2007; Wang et al. 2014), it was assumed that the frequency of major earthquakes is a random variable in accordance with the Poisson distribution, so that the expected earthquake frequency, as shown in Fig. 4, can be developed with the model's probability (Pr) mass function (e.g., Ang and Tang 2007)

$$\Pr(X = x|v) = \frac{v^x e^{-v}}{x!} \quad (2)$$

where  $X$  (a symbol) or  $x$  (a number) = number of earthquake;  $v$  = mean annual rate of earthquakes with at least  $M_w$  5.5, which is equal to 2.79 in this paper. As a result, based on the probability



**Fig. 3.** Locations of the 307 major earthquakes around Taipei from years 1900–2009



**Fig. 4.** Expected probability mass function (Poisson distribution) for the frequency of major earthquakes around Taipei with a mean annual rate of 2.79

model given model parameter  $\nu = 2.79$ , there is, for example, a 17% probability for one earthquake to occur in 1 year.

From the 307 major earthquakes, Fig. 5 shows the histograms for earthquake magnitudes and source-to-site distances. Fig. 5 indicates that the majority of the earthquake magnitudes are below  $M_w$  6.5, with mean and SD equal to  $M_w$  6.12 and 0.68, respectively. As for source-to-site distance, the majority of them were occurring within a distance of 100–200 km from Taipei, with mean and SD equal to 129 and 39 km, respectively. The histograms shown in Fig. 5 can be easily converted to probability mass functions, with the data in the histograms divided by the total number of observations (i.e., 307 events).

In order to examine the correlation between the (1) magnitude and (2) distance of the 307 events, the data was plotted in Fig. 6. The result shows that the two variables are rather independent, with the coefficient of determination  $R^2$  as low as 0.005 from the regression analysis. Therefore, in the subsequent seismic hazard analysis it was considered that the two variables were independent, like most seismic hazard studies (e.g., Cheng et al. 2007).

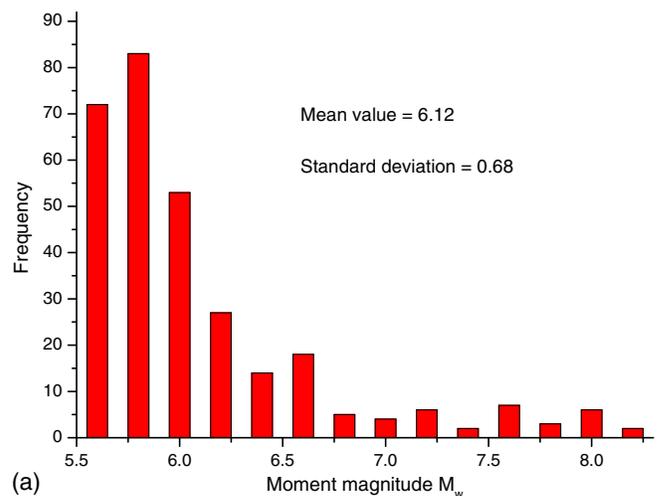
However, the statistics of major earthquakes are not as relevant as seismic hazards to earthquake-resistant designs. As a result, another key scope of this paper is to evaluate seismic hazard with Monte Carlo simulation, based on the earthquake statistics in the past 110 years. The methodology of the MCS-based seismic hazard analysis is detailed in the subsequent sections.

Like others, the seismic hazard study is subject to some best engineering judgment, which includes the thresholds of earthquake magnitude and source-to-site distance for an earthquake that could possibly cause damage to modern structures. In this paper, the writers specifically used magnitude and distance thresholds as  $M_w$  5.5 and 200 km, respectively, similarly to those employed by several seismic hazard studies (e.g., Fernandez and Fatehi 2013; Wang et al. 2012a, 2013).

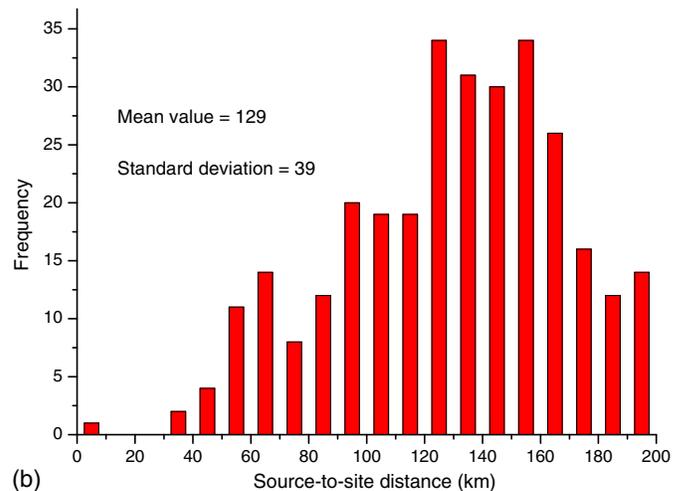
## Seismic Hazard Assessment with Monte Carlo Simulation

### Overview of Monte Carlo Simulation

Monte Carlo simulation is commonly used for probabilistic analyses (e.g., Melchers 1989; Cramer et al. 1996; Proppe et al. 2003). In

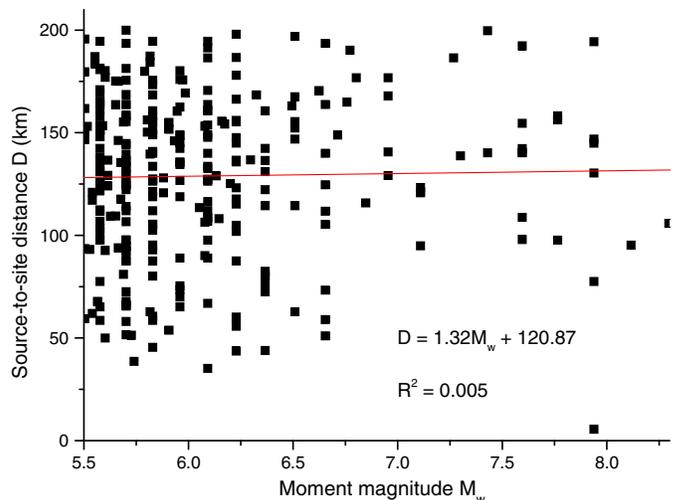


(a)



(b)

**Fig. 5.** Statistics of the 307 major earthquakes around Taipei: (a) magnitude distribution; (b) distance distribution



**Fig. 6.** Relationship between magnitude and distance of the 307 major earthquakes

short, MCS repeats a number of randomizations to estimate the probability of an event. For example, in order to find the probability of  $X = 1$  while tossing a dice, the MCS is to generate a number of (uniformly distributed) values from 1 to 6, and the probability

of  $X = 1$  is equal to the number of trials with  $X = 1$ , divided by the total number of trials.

One of the keys to a reliable MCS is the sample size (i.e., the number of trials). The larger the size, the more accountable a MCS estimate will be. As a result, the research reported in this paper employed a sample size of 100,000 in the subsequent MCS to ensure the reliability of the seismic hazard calculations.

### Seismic Hazard Analysis

Seismic hazard refers to the annual rate of an earthquake motion [e.g., peak ground acceleration (PGA)  $\geq 0.5g$ ], but not casualty or economic loss associated with earthquakes as the word hazard might imply.

Regardless of methodology, seismic hazard analysis is on the basis of a ground motion model, which is an empirical relationship for predicting earthquake ground motion depending on earthquake magnitude and source-to-site distance. Based on local earthquake data, Cheng et al. (2007) proposed two PGA models for soil sites in Taiwan, and used them in their probabilistic seismic hazard analysis (PSHA)

$$\ln \text{PGA} = -2.85 + 0.975M_w - 1.593 \\ \times \ln[D + 0.206 \times \exp(0.612M_w)] \pm 0.554 \quad (3)$$

$$\ln \text{PGA} = -2.80 + 0.955M_w - 1.583 \\ \times \ln[D + 0.176 \times \exp(0.603M_w)] \pm 0.555 \quad (4)$$

where  $D$  = source-to-site hypocentral distance (km). The terms  $\pm 0.554$  and  $\pm 0.555$  are model errors, or the SD of model error  $\varepsilon$  of a regression, which is a random variable in accordance with the normal distribution with mean = 0 (Ang and Tang 2007). Therefore, for a regression model  $\ln Y = f(X_i, s) + \varepsilon$  like the attenuation relationships,  $\ln Y$  is in accordance with the normal distribution as  $\varepsilon$  does, or  $Y$  is in accordance with the so-called lognormal distribution.

The reasons of adopting the two models in this study are as follows: (1) they were developed with local earthquake data; (2) most areas in the Taipei Basin are soil sites; and (3) like most seismic hazard assessments (e.g., Cheng et al. 2007; Fernandez and Fatehi 2013; Wang et al. 2013), multiple models were adopted to account for the epistemic uncertainty, given the two local relationships are equally suitable for the study region and the analysis.

The seismic hazards presented in this paper are not associated with the so-called characteristic earthquake model related to a specific active fault (e.g., Kramer 1996). Instead, the estimates are a result of analyzing the earthquake statistics in the past 110 years. Therefore, the descriptions on active faults in Taiwan were not given in this paper but are available in the literature, such as the reports of the Central Geological Survey Taiwan (Lin et al. 2008, 2009).

### Monte Carlo Simulation–Based Seismic Hazard Analysis

The ground motion model shown in Eq. (3) or Eq. (4) is the governing equation of the probabilistic analysis to estimate the annual rate of earthquake ground motions (or seismic hazard). As a result, the probabilistic analysis is governed by three random variables [i.e., (1)  $M$ , (2)  $D$ , and (3)  $\varepsilon$ ] as they appear in the ground motion model.

In addition to the three variables, the seismic hazard study is governed by two more variables [(1)  $R$ , and (2)  $K$ ].  $R$  is a binary

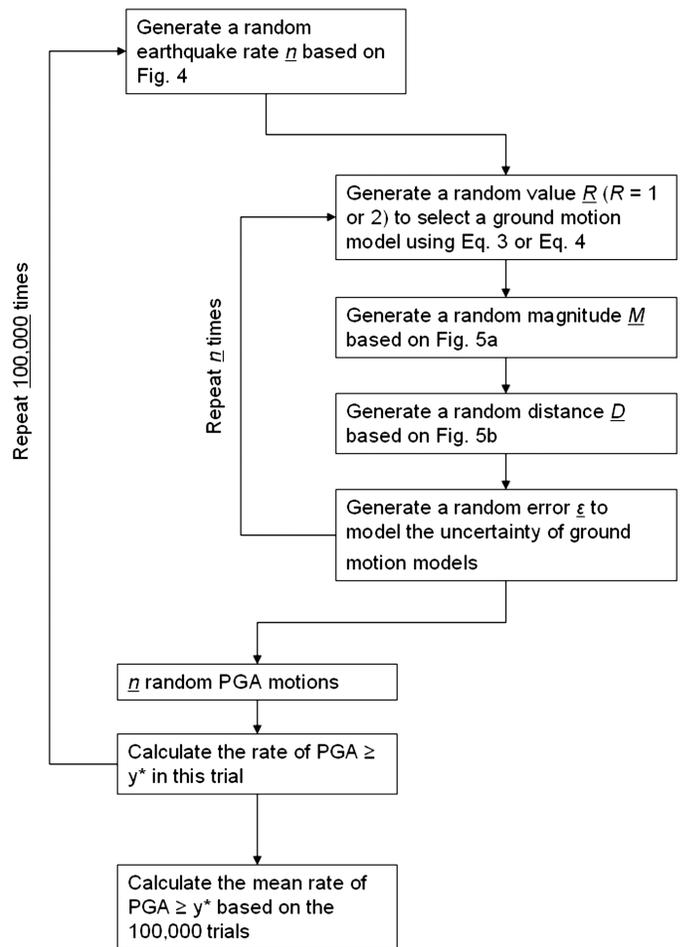


Fig. 7. Flowchart summarizing the Monte Carlo simulation of this paper

variable (e.g., 1 or 2 with equal probability), used for selecting a ground motion model among the two. When  $R = 1$ , Eq. (3) will be used; otherwise, Eq. (4) will be selected. By contrast,  $K$  is the random earthquake frequency (i.e., an integer) based on the expected earthquake frequency probabilities shown in Fig. 4.

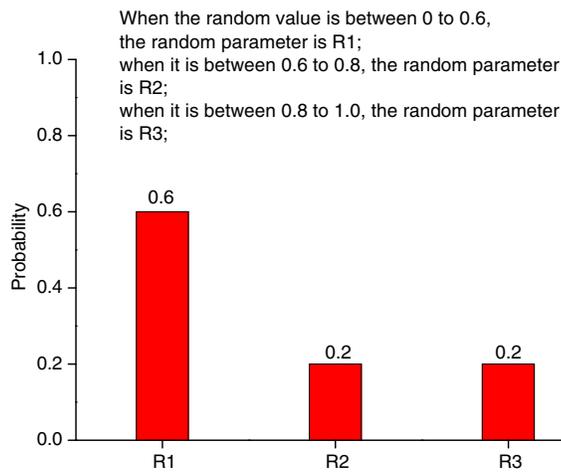
Fig. 7 shows the flowchart summarizing the procedure of the MCS. The first step is to generate a random earthquake frequency, say  $K = 2$ , in the simulation. As a result, two random PGAs will be generated based on two sets of random parameters that were substituted into the ground motion model selected (depending on  $R = 1$  or 2). For example, if two random PGAs are (1)  $0.1g$  and (2)  $0.2g$ , the rate for  $\text{PGA} \geq 0.3g$  is then equal to zero from this trial. Therefore, with the randomization repeated for a number of trials, the annual rate for PGA greater than a given motion  $y^*$  can be estimated

$$\lambda(\text{PGA} \geq y^*) = \frac{\sum_{i=1}^n \lambda_i(\text{PGA} \geq y^*)}{n} \quad (5)$$

where  $\lambda_i(\text{PGA} > y^*)$  = random rate of the  $i$ th trial; and  $n$  = sample size of the MCS study of the research reported in this paper, which is 100,000 as mentioned previously.

### Randomizations and Verifications

This section shows the randomizations with the random number generator (function name is RAND) in Excel that can generate a (uniformly distributed) random number from 0 to 1. Fig. 8 shows



**Fig. 8.** Schematic diagram illustrating how the in-house algorithm can generate discrete random parameters based on their probability mass function

a schematic diagram illustrating how the writers used an in-house algorithm for parameter randomizations based on the probability mass functions shown in Figs. 4 and 5, with random values from 0–1 from Excel.

Verification was performed to make sure the in-house algorithm is robust before use. The verification is to randomize, for example, earthquake magnitude for 10,000 times based on its probability function (i.e., Fig. 5), and next calculating the probability mass function from the 10,000 randomizations and comparing it to the observed distributions. When the two are in good agreement, the algorithm is considered robust.

Fig. 9 shows the result of the verification on the randomization algorithm. Fig. 9 shows that the expected and observed distributions are in good agreement, so the in-house algorithm was ready for use in the Monte Carlo simulation.

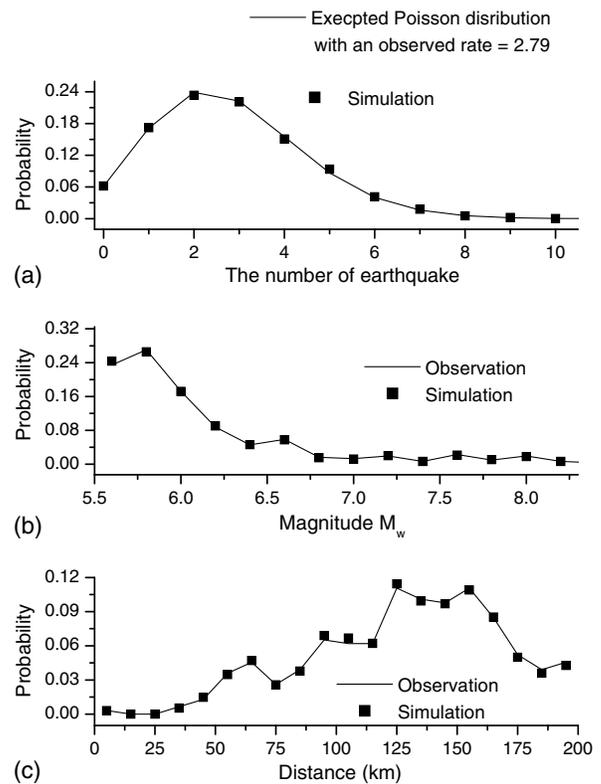
As for  $R$  (i.e., 1 or 2) and  $\varepsilon$  (i.e., a Gaussian variate), their randomizations are relatively straightforward given several well-established algorithms that are available. Therefore, the randomization and verification are not detailed in this paper.

### Demonstration to the MCS

This section shows a demonstration to the MCS-based seismic hazard analysis with a sample size of 5. As summarized in Table 1, the random earthquake numbers are 3, 2, 7, 4, and 5 for each trial. Therefore, the same numbers of random PGA motions were then generated with MCS. Accordingly (Table 1), the annual rate for  $\text{PGA} \geq 0.03g$  is equal to one from Trials 1, 3, and 4, and zero from Trials 2 and 5. Therefore, with a sample size of 5, the mean annual rate of  $\text{PGA} \geq 0.03g$  was determined as 0.6 ( $= 3/5$ ) from this MCS.

### Results and Discussion

With the statistics of major earthquakes, local ground motion models, and Monte Carlo simulation, Fig. 10 shows the relationships between PGA of exceedance and its annual rate. For example, the rate of  $\text{PGA} \geq 0.23g$  is estimated at 0.013 events per year, corresponding to a return period of around 77 years ( $= 1/0.013$ ). By contrast, the annual rate of  $\text{PGA} \geq 1.43g$  is about 0.0001 events per year, corresponding to a return period of 10,000 years. The annual rate for  $\text{PGA} \geq 0$  from Fig. 10 was found equal to that of the



**Fig. 9.** Expected and observed distributions that are in good agreement from the writers' verification

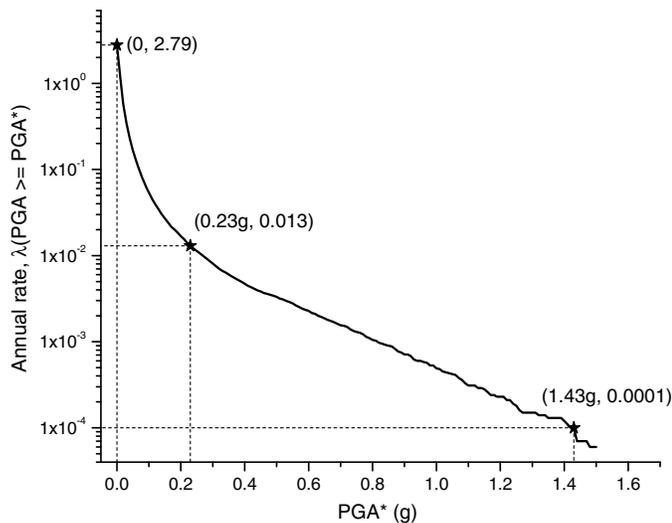
major earthquake ( $= 2.79$  events per year), proving that the MCS analysis is robust because any earthquake must induce a ground motion no matter how small it is.

The seismic hazard analysis was on the basis of two local, soil-site ground motion models, considering most sites in the Taipei

**Table 1.** Demonstration Example to the MCS-Based Seismic Hazard Analysis with a Sample Size of 5, on the Basis of the Earthquake Statistics Shown in Figs. 4 and 5

Trial	Magnitude $M_w$	Distance (km)	$\varepsilon$	PGA ( $g$ )	Rate of $\text{PGA} \geq 0.03g$
1	6.4	85	0.934	<b>0.035</b>	<b>1</b>
	5.6	165	-1.075	0.002	
	5.6	55	0.618	0.027	
2	6.2	155	1.096	0.013	<b>0</b>
	6	155	-1.302	0.003	
3	6.4	155	-0.141	0.008	<b>1</b>
	5.8	185	-0.769	0.002	
	5.6	65	0.868	0.025	
	8.0	95	-0.887	<b>0.041</b>	
	5.6	135	1.864	0.014	
4	5.8	155	0.042	0.005	<b>1</b>
	5.6	95	-0.678	0.006	
	6.4	115	1.904	<b>0.039</b>	
	6.8	125	0.749	0.026	
5	5.8	45	-1.317	0.015	<b>0</b>
	5.6	105	0.980	0.013	
	5.8	115	-0.128	0.007	
	6.8	145	0.249	0.016	
	7.6	135	-0.084	0.029	
	5.6	115	0.171	0.007	
	6.2	125	0.982	0.017	

Note: The terms in bold fonts specify they exceed a given hazard level in the analysis.

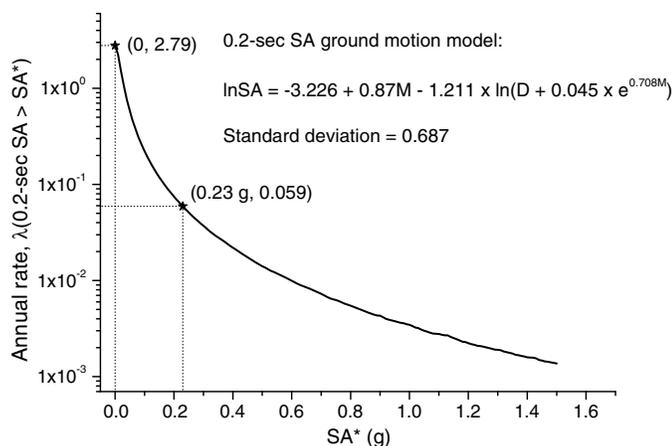


**Fig. 10.** Peak ground acceleration hazard curve from the MCS-based seismic hazard analysis based on the statistics of major earthquakes

Basin are sitting on thick soil deposits. Nevertheless, the analysis can be further evaluated with a more sophisticated ground motion model including  $V_{s30}$  (average shear-wave velocity down to 30 m from the ground) in the attenuation, even though it is not a local one, to better incorporate site condition into the seismic hazard assessment.

Depending on structure types and some other considerations, sometimes a specific spectral acceleration (SA; e.g., 0.2-s SA) is of more interest than PGA in earthquake-resistant designs. Nevertheless, the MCS-based seismic hazard study is applicable to evaluating seismic hazard in terms of spectral acceleration, with the same earthquake statistics but with a new ground motion model.

For example, with the local ground motion model for 0.2-s SA shown on Fig. 11 (Lin et al. 2011), another MCS analysis was performed to calculate the hazard curve for 0.2-s SA, with the same analytical procedure and the same earthquake statistics. The calculation suggests that the mean annual rate for 0.2-s SA  $\geq 0.23g$  in Taipei should be around 0.059, higher than 0.013 per year for PGA  $> 0.23g$ . The analysis can be repeated for other earthquake motions in different periods (e.g., 0.5 s, 1.0 s, and so on), in order to develop design response spectra from a series of hazard curves.



**Fig. 11.** Hazard curve, 0.2-s SA, from the MCS-based seismic hazard analysis based on the statistics of major earthquakes

According to the local technical reference (Republic of China Construction and Planning Agency 2005), the current design PGA in Taipei is  $0.23g$ , with its return period around 475 years. Although the methodology and input data were not detailed in the technical reference, the design criteria should be determined with some seismic hazard assessment conducted around the time when the guideline was developed.

However, from a different perspective based on the record of major earthquakes in the past 110 years, this paper provided some evidence that the design PGA in Taipei might not be as conservative as expected, or the design motion's return period could be less than 475 years that is expected. More importantly, the finding was similar to other seismic hazard assessments for Taiwan, such as the PSHA studies by Cheng et al. (2007) and Wang et al. (2013) both reporting that for a 475-year return period, PGA of exceedance should be around  $0.3g$  in Taipei, greater than  $0.23g$  reported in the guideline.

In contrast to seismic designs in Taiwan, the USGS (2013) developed a tool for engineers to look up site-specific design values prescribed by different technical references, such as ASCE/SEI Standard 7 (ASCE 2013), International Building Code (IBC), and AASHTO (2011) guide specifications for load and resistance factor design (LRFD) seismic bridge design. For example, the parameters on the design map for the AASHTO code were determined on the basis of a return period of 1,000 years. By contrast, the IBC specifies risk-targeted design ground motions that approximately have a 2,500-year mean recurrence interval. From the two benchmark technical references, it seems that the local guideline is less conservative owing to a shorter design return period prescribed.

As a result, from recent seismic hazard studies to the benchmark technical references, the current earthquake-resistant design in Taipei might not be as conservative as expected. Therefore, a review or revision on the technical reference is suggested with new investigations and analyses in near future, making sure the seismic design for the city is satisfactory and safe.

## Conclusion and Summary

From a well-studied earthquake catalog, this paper presented the statistics of major earthquakes with  $M_w \geq 5.5$  and distance  $\leq 200$  km around Taipei in the past 110 years. The analysis shows that the mean annual rate of the major earthquakes is 2.79, with mean magnitude and SD equal to  $M_w$  6.12 and 0.68, respectively, and mean source-to-site distance and SD equal to 129 and 39 km, respectively.

With the earthquake statistics and local ground motion models, a seismic hazard analysis was conducted using Monte Carlo simulation. The result shows that the mean annual rate of PGA  $\geq 0.23g$  (i.e., the current design PGA in Taipei) is around 0.013, corresponding to a return period of only 77 years.

From recent seismic hazard assessments to benchmark technical references, the current seismic design in Taipei might not be as conservative as expected, and a review and revision on the technical reference should be worth conducting in near future for assuring the seismic safety of the city located in a high-seismicity region.

## Acknowledgments

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## References

- AASHTO. (2011). "AASHTO guide specifications for LRFD seismic bridge design, 2nd Ed." Washington, DC.
- Ang, A., and Tang, W. (2007). *Probability concepts in engineering: Emphasis on applications to civil and environmental engineering*, Wiley, Hoboken, NJ.
- ASCE. (2013). "ASCE 7: Minimum design loads for buildings and other structures." *49 CFR 193.2013*, Office of the Federal Register, Washington, DC.
- Campbell, K. W., Thenhaus, P. C., Barnhard, T. P., and Hampson, D. B. (2002). "Seismic hazard model for loss estimation and risk management in Taiwan." *Soil Dyn. Earthq. Eng.*, 22(9–12), 743–754.
- Central Geological Survey Taiwan. (2010). "Digital data of Taiwan topography maps." (<http://cgsweb.moeacgs.gov.tw/Result/Lib/Index.asp>) (Oct. 15, 2014).
- Chen, K. P., and Tsai, Y. B. (2008). "A catalog of Taiwan earthquakes (1900–2006) with homogenized Mw magnitudes." *Bull. Seismol. Soc. Am.*, 98(1), 483–489.
- Cheng, C. T., Chiou, S. J., Lee, C. T., and Tsai, Y. B. (2007). "Study on probabilistic seismic hazard maps of Taiwan after Chi-Chi earthquake." *J. GeoEng.*, 2(1), 19–28.
- Cramer, C. H., Petersen, M. D., and Reichle, M. S. (1996). "A Monte Carlo approach estimating uncertainty for a seismic hazard assessment of Los Angeles, Ventura, and Orange Counties, California." *Bull. Seism. Soc. Am.*, 86(6), 1681–1691.
- Fernandez, A., and Fatehi, A. (2013). "Development of probabilistic seismic hazard analysis for international sites, challenges and guidelines." *Nucl. Eng. Des.*, 259, 222–229.
- Geller, R. J., Jackson, D. D., Kagan, Y. Y., and Mulargia, F. (1997). "Earthquake cannot be predicted." *Science*, 275(5306), 1616–1617.
- Ho, C. S. (1999). *An introduction to the geology of Taiwan*, Central Geology Survey Taiwan, Taipei, Taiwan.
- Hsiao, N. C., et al. (2011). "A new prototype system for earthquake early warning in Taiwan." *Soil Dyn. Earthq. Eng.*, 31(2), 201–208.
- Huang, S., Robin, C. M., Chen, Y., and Liu, H. (2007). "Prehistoric earthquakes along the Shanchiao Fault, Taipei basin, northern Taiwan." *J. Asian Earth Sci.*, 31(3), 265–276.
- Kramer, S. L. (1996). *Geotechnical earthquake engineering*, Prentice Hall, Upper Saddle River, NJ.
- Lin, C. W., Chen, W. S., Liu, Y. C., and Chen, P. T. (2008). *Active faults of central Taiwan*, Central Geology Survey Taiwan, Taipei, Taiwan (in Chinese with English abstract).
- Lin, C. W., Chen, W. S., Liu, Y. C., and Chen, P. T. (2009). *Active faults of eastern and southern Taiwan*, Central Geology Survey Taiwan, Taipei, Taiwan (in Chinese with English abstract).
- Lin, P. S., Lee, C. T., Cheng, C. Y., and Sung, C. H. (2011). "Response spectral attenuation relations for shallow crustal earthquakes in Taiwan." *Eng. Geol.*, 121(3–4), 150–164.
- Melchers, R. E. (1989). "Importance sampling in structural systems." *Struct. Saf.*, 6(1), 3–10.
- Propepe, C., Pradlwarter, H. J., and Schueller, G. I. (2003). "Equivalent linearization and Monte Carlo simulation in stochastic dynamics." *Probab. Eng. Mech.*, 18(1), 1–15.
- Republic of China Construction and Planning Agency. (2005). *Seismic design code for buildings in Taiwan*, 29–30.
- USGS. (2013). "Seismic design map & tools." (<http://earthquake.usgs.gov/hazards/designmaps/>) (Jan. 13, 2015).
- Wang, J. P., Brant, L., Wu, Y. M., and Taheri, H. (2012a). "Probability-based PGA estimations using the double-lognormal distribution: Including site-specific seismic hazard analysis for four sites in Taiwan." *Soil Dyn. Earthq. Eng.*, 42, 177–183.
- Wang, J. P., Chan, C. H., and Wu, Y. M. (2011). "The distribution of annual maximum earthquake magnitude around Taiwan and its application in the estimation of catastrophic earthquake recurrence probability." *Nat. Hazards*, 59(1), 553–570.
- Wang, J. P., Huang, D., Chang, S. C., and Wu, Y. M. (2014). "New evidence and perspective to the Poisson process and earthquake temporal distribution from 55,000 events around Taiwan since 1900." *Nat. Hazards Rev.*, 15(1), 38–47.
- Wang, J. P., Huang, D., Cheng, C. T., Shao, K. S., Wu, Y. C., and Chang, C. W. (2013). "Seismic hazard analysis for Taipei City including deaggregation, design spectra, and time history with Excel applications." *Comput. Geosci.*, 52, 146–154.
- Wang, J. P., Huang, D., and Yang, Z. (2012b). "The deterministic seismic hazard map for Taiwan developed using an in-house Excel-based program." *Comput. Geosci.*, 48, 111–116.
- Wu, Y. M., Chang, C. H., Zhao, L., Teng, T. L., and Nakamura, M. (2008a). "A comprehensive relocation of earthquakes in Taiwan from 1991 to 2005." *Bull. Seism. Soc. Am.*, 98(3), 1471–1481.
- Wu, Y. M., and Chen, C. C. (2007). "Seismic reversal pattern for the 1999 Chi-Chi, Taiwan, Mw 7.6 earthquake." *Tectonophysics*, 429(1–2), 125–132.
- Wu, Y. M., Chen, C. C., Zhao, L., and Chang, C. H. (2008b). "Seismicity characteristics before the 2003 Chengkung, Taiwan Mw6.8 earthquake." *Tectonophysics*, 457(3–4), 177–182.
- Wu, Y. M., and Chiao, L. Y. (2006). "Seismic quiescence before the 1999 Chi-Chi, Taiwan Mw7.6 earthquake." *Bull. Seism. Soc. Am.* 96(1), 321–327.
- Wu, Y. M., and Kanamori, H. (2008). "Development of an earthquake early warning system using real-time strong motion signals." *Sensors*, 8(1), 1–9.
- Wu, Y. M., Shin, T. C., and Chang, C. H. (2001). "Near real-time mapping of peak ground acceleration and peak ground velocity following a strong earthquake." *Bull. Seismol. Soc. Am.*, 91(5), 1218–1228.