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Probabilistic Seismic Hazard Analysis in Thailand and Adjacent Areas by Using Regional Seismic Source Zones

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ABSTRACT

We conducted probabilistic seismic hazard analysis for Thailand and adjacent areas using a method proposed by Cornell (1968). We produced seismic hazard maps showing peak ground acceleration (PGA). Twenty-one seismic source zones covering all of Thailand and extend into adjacent areas were employed. The seismicity data used in this study was a merged data set covering 1963 - 2007 from several international earthquake catalogues and a single Thai catalogue. We selected the strong ground-motion attenuation model for this study by applying several existing attenuation models to recorded strong ground-motion data and choosing the model that best fit our data. Seismic hazard analysis was carried out for 2521 grid points on a 0.25° × 0.25° mesh within a rectangle defined by longitudes 92 - 106°E and latitudes 0° - 21°N. The resulting PGA maps for a 2% probability of exceedance for a 50-year time period suggest that ground motion of 0.3 to 0.4 g may occur in northern and western Thailand and from 0 to 0.2 g in other parts of Thailand. The seismic hazard analysis presented here is an important step toward an accurate evaluation of a seismic hazard potential in Thailand and adjacent areas. Further work is needed to refine the analysis. More observations of strong ground motion in the region are needed and further seismo-tectonic research should be encouraged.

Key words: Seismic hazard analysis, Probabilistic approach, Seismic source zone, Earthquake catalogue, Attenuation model, Thailand

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1. INTRODUCTION

On 26 December 2004, a tsunami triggered by the great Sumatra-Andaman earthquake hit coastal communities around the Indian Ocean and killed more than 283100 people (USGS 2005). Moreover, the M_w 9.0 earthquake (Martin 2005) caused ground shaking in countries surrounding its source, including Indonesia, India, Myanmar, and some parts of Thailand. The impacts of the earthquake invigorated a large number of researchers (e.g., Choy and Boatwright 2007; Dewey et al. 2007; Geist et al. 2007; Hanson et al. 2007) to recognize the need for evaluation of hazard potential in this region, particularly for tsunami and earthquake (seismic) hazards.

In this study, we applied probabilistic analysis to seismic hazards and considered the likelihood of earthquake events in Thailand and adjacent areas, their likely source locations and magnitudes, and the nature of propagation of the resulting ground shaking. We estimated ground shaking in terms of peak ground acceleration (PGA).

The first probabilistic seismic hazard map of Thailand was produced by Warnitchai and Lisantono (1996) and showed 10% probability of PGA exceedance for a 50-year time period. They applied 11 seismic source zones as defined by Nutalaya et al. (1985) and the strong ground-motion attenuation model of Esteva and Villaverde (1973). Seismic source potentials were evaluated based on the earthquake catalogue reported by Nutalaya et al. (1985). They classified northern Thailand as a moderate risk area, and western Thailand as a moderately high risk area, equivalent to the US Uniform Building Code (UBC) zones 2B and 3,

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respectively. Palasri (2006) proposed new probabilistic seismic hazard maps of Thailand using 21 seismic source zones defined by Charusiri et al. (2005) and applied the strong ground-motion attenuation model of Petersen et al. (2004) for subduction-zone earthquakes, and the model of Sadigh et al. (1997) for shallow crustal earthquakes. Seismic source potentials were evaluated based on composite earthquake catalogues reported by the US Geological Survey (USGS), International Seismological Centre (ISC), and the Thai Meteorological Department (TMD). The probabilistic seismic hazard map of Thailand that they produced for 10% probability of exceedance in a 50-year time period indicated a PGA of around 0.15 g in the west, 0.25 g in the north, and 0.02 g in Bangkok. For a 2% probability of exceedance in a 50-year time period, the PGA was up to twice that of the 10% probability of exceedance in a 50-year time period.

The probabilistic seismic hazard analysis of our study uses seismic source zones, seismicity data (earthquake catalogue), and strong ground-motion attenuation models that differ from those used by Warnitchai and Lisantono (1996) and Palasri (2006). We updated and added seismicity data and applied a different strong ground-motion attenuation model. We believe this approach can provide a more detailed and up-to-date seismic hazard assessment than that currently available. We also expect that our results will help engineers create seismic design maps in the International Building Code for improved building design and construction.

2. SEISMIC SOURCE ZONES IN THAILAND AND ADJACENT AREAS

Tectonic activity in Thailand and surrounding areas is caused by the collision of the Indian and Eurasian tectonic plates (e.g., Polachan et al. 1991; Charusiri et al. 2002). Records of earthquakes in this region indicate that seismotectonic activities are remarkable along the Andaman subduction zone, the giant strike-slip Sagiang fault (central Myanmar), and the complex shear zone at the Laos - southern China border, which includes the Red River fault zone in northwestern Vietnam. Geological evidence (e.g., hot spring locations in Thailand) suggests that Thailand is also an active seismo-tectonic region, particularly its western and northern parts (Charusiri et al. 2004). Thus, some parts of Thailand may be vulnerable to destructive earthquakes.

There have been very few published studies of seismic source zones in Thailand and adjacent areas in the past two decades. In a pioneer study, Nutalaya et al. (1985) proposed 11 seismic source zones in this area; but these zones did not cover southern peninsular Thailand and the Sumatra region. Although each of the seismic source zones of Nutalaya et al. (1985) had specific geological, geophysical, and seismological characteristics, they showed uniform earthquake potential across the various zones. Thereafter, Charusiri et al. (2005) revised the seismic source zones of Nutalaya et al. (1985) and extended the coverage to include southern peninsular Thailand and northern Sumatra. Their revision of the zoning was based on the epicentral distribution of earthquakes over the past two decades, tectonic environments, active faults, regional geomorphology, and plate boundaries, and they increased the number of seismic source zones to 21 (Fig. 1). We, therefore, used the most updated seismic source-zone model of Charusiri et al. (2005) for our probabilistic seismic hazard analysis.

3. EARTHQUAKE DATABASE

A large number of earthquake catalogues which cover the study area have been developed. These include global earthquake catalogues produced by the Incorporated Research Institutions for Seismology (IRIS), the US National Earthquake Information Center (NEIC), the global CMT catalogue (CMT), and a local catalogue produced by the Thai Meteorological Department (TMD). The various catalogues have both advantages and disadvantages in terms of the continuity and time span of their records, and the earthquake magnitude ranges they recorded. The global catalogues record large- to medium-size earthquakes continuously over a long time span, whereas the local catalogue

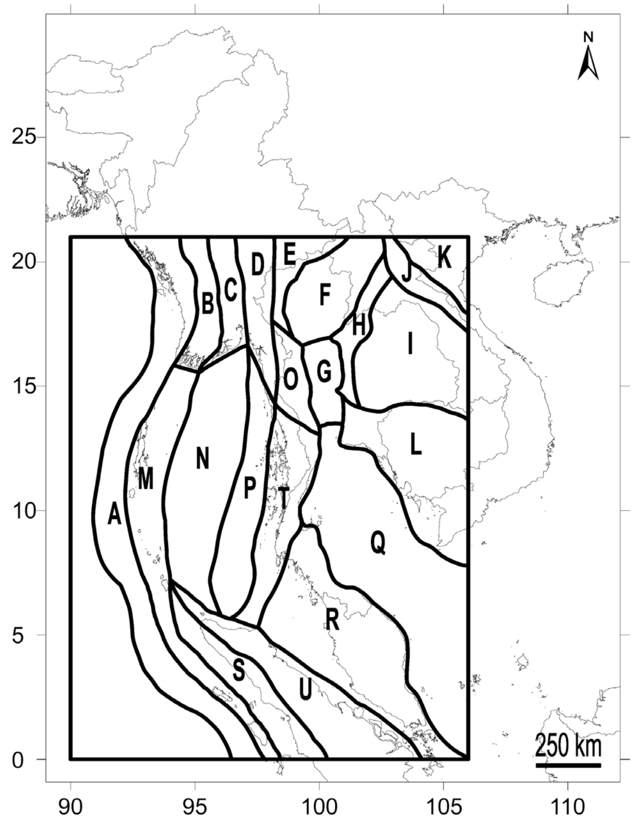


Fig. 1. Location map showing the 21 seismic source zones covering Thailand (gray shading) and adjacent areas (Charusiri et al. 2005).

records smaller earthquakes, but over a shorter time span. Hence, we prepared a new composite earthquake catalogue for this study according to the procedure suggested by Caceres and Kulhanek (2000).

3.1 Composite Earthquake Catalogue and Elimination of Overlapping Earthquakes

To improve the quantity and quality of earthquake data, we first compiled a new composite earthquake catalogue for Thailand and adjacent areas. All the existing earthquake catalogues (i.e., IRIS, NEIC, CMT, and TMD) were merged. The merged catalogue was checked for duplicate entries and, where they existed, one representative earthquake event was retained.

3.2 Earthquake Magnitude Conversion

The new merged catalogue contains a variety of earthquake magnitude scales: body wave magnitude (m_b), surface wave magnitude (M_s), local magnitude (M_L), and moment magnitude (M_w). Each of these magnitude scales is derived by a specific analytical method and has a valid but unique meaning. For seismic hazard analysis, M_w has been the standard magnitude scale used because it directly represents the physical properties of an earthquake source and avoids the "saturation phenomenon" at large seismic moments (e.g., Howell 1981; Ottemoller and Havskov 2003).

We used earthquake catalogue data from our study area to develop relationships between the different magnitude scales and thus converted m_b, M_s, and M_L to the standard M_w. The CMT catalogue provides m_b, M_s, and M_w magnitudes for individual earthquake events; we used these data to calibrate the relationship of M_w to m_b (Fig. 2a) and M_w to M_s (Fig. 2b). In this study, we used the relationships shown by the solid-line curves in Fig. 2 to convert m_b and M_s to M_w. The relationships of M_w to m_b and M_s are formulated in Eqs. (1) and (2). For M_L, we used the empirical relationship between m_b and M_L of Palasri (2006) [Eq. (3)], and then converted m_b to M_w by using our Eq. (1).

$$M_w = 0.0167\ m_b^2 + 0.8438\ m_b + 0.9071 \qquad m_b \le 6.8 \tag{1}$$

$$M_w = 0.028\ M_s^2 + 0.3364\ M_s + 3.2574 \qquad M_s \le 7.6 \tag{2}$$

$$m_b = 1.64 + 0.63\ M_L \qquad M_L \le 6.8 \tag{3}$$

The upper limits of the calibrated earthquake magnitudes are 6.8, 7.6, and 6.8 for m_b, M_s, and M_L, respectively. Therefore, earthquake events reported with magnitudes larger than m_b of 6.8, M_s of 7.6, or M_L of 6.8 are misreported (see inset of Figs. 2a and b).

3.3 Earthquake De-Clustering

A single cluster of earthquake records includes foreshocks, main shock, and aftershocks. For seismic hazard analysis, only the main shock of each independent earthquake must be considered (Cornell 1968). As for conversion of other magnitudes to M_w, earthquake records require de-clustering by filtering main shocks from foreshocks and aftershocks.

In this study, we applied the model of Gardner and Knopoff (1974) to de-cluster the earthquake events. The first step of the modeling procedure is to cluster a series of earthquake events by using windowing algorithms that identify clusters within user-specified space and time windows around each event being considered (Figs. 3a and b). The widths of both the time and space windows are in-

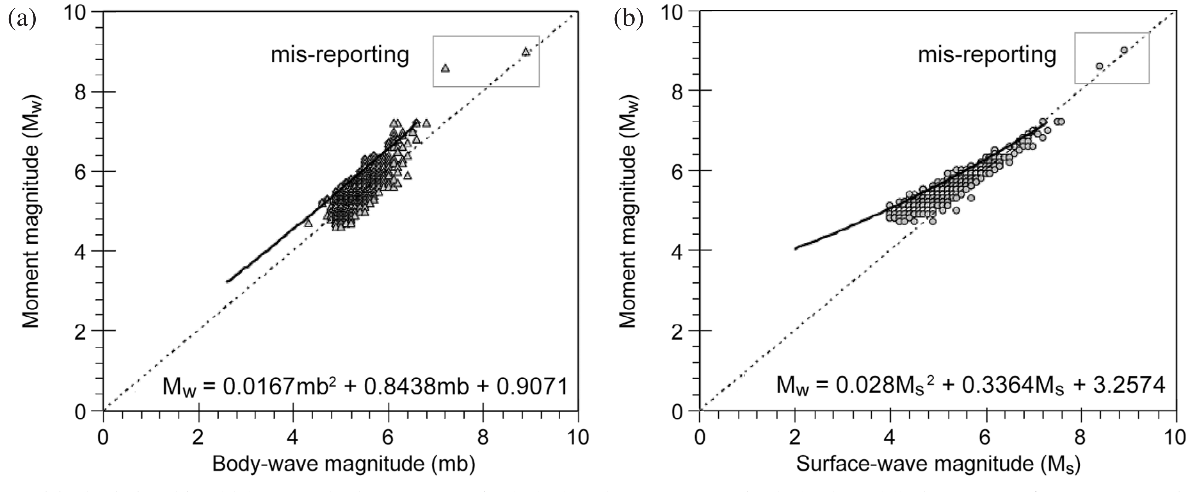


Fig. 2. Empirical relationships (a) between body wave magnitude (m_b) and moment magnitude (M_w), and (b) between surface wave magnitude (M_s) and moment magnitude (M_w). The earthquake events within the gray squares are misreported magnitudes.

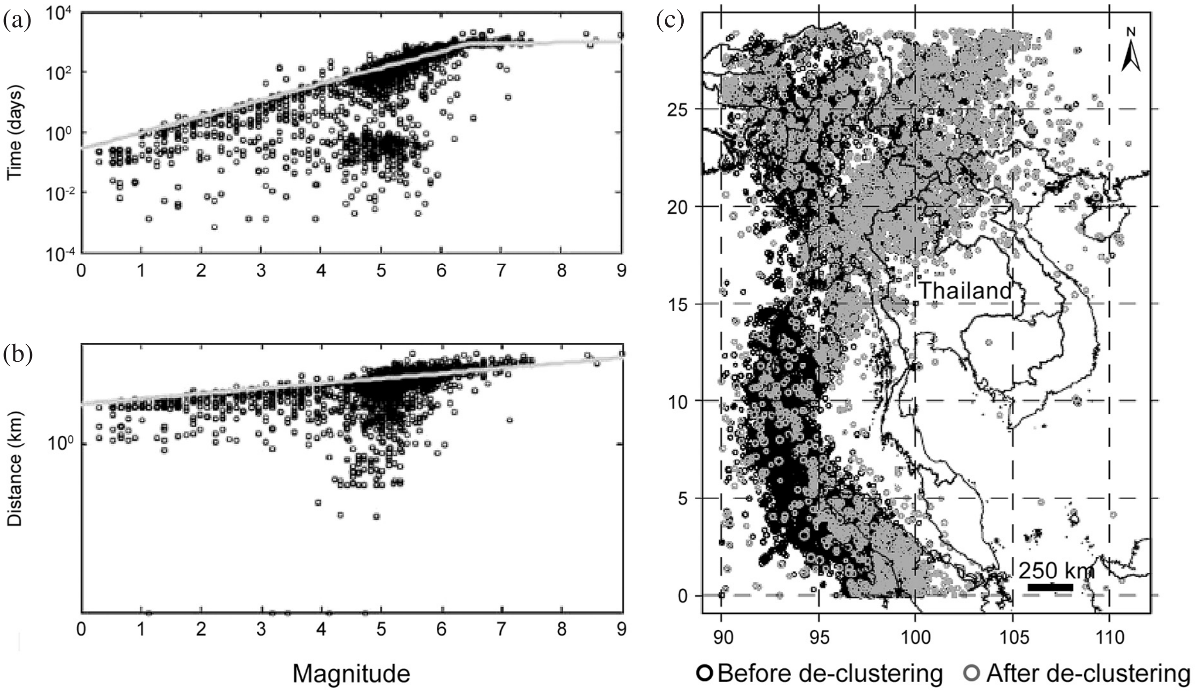


Fig. 3. (a) Time window and (b) space window of the Gardner and Knopoff (1974)'s model (grey lines) used to de-cluster and remove foreshocks and aftershocks. The earthquakes lower than the de-clustering model in both time and space windows were classified as the foreshocks or aftershocks. (c) Map of Thailand and adjacent areas showing epicentral distribution of 27775 overlapping earthquakes (black circles) and 4164 main shocks (gray circles) after de-clustering and removal of foreshocks and aftershocks.

creased with increasing earthquake magnitude. The largest earthquake event within each cluster so determined is then identified as the main shock for that cluster.

We distinguished 1605 clusters from 31939 earthquake events. Of these events, a total of 27759 events (87%) were classified as foreshocks or aftershocks and therefore were eliminated (Fig. 3c). In zone A (Andaman subduction), for instance, the 101 earthquakes with a magnitude range between 2.4 and 9.0 were de-clustered from 4014 earthquakes. The new earthquake catalogue that we derived for Thailand and surrounding areas contains 4164 main shocks; we used this catalogue to evaluate the earthquake potential in each seismic source zone as described in the next section.

4. EARTHQUAKE SOURCE PARAMETERS

Seismic hazard analysis requires assessment of earthquake source parameters in order to estimate the seismic source potential. In this study, the earthquake source parameters we considered for each seismic source zone were an expected maximum earthquake magnitude (M_{max}), earthquake activity [values *a* and *b* of the Gutenberg-Richter (G-R) relationship], and minimum earthquake magnitude (M_{min}).

M_{max} is an important parameter in seismic hazard analysis because the highest magnitude earthquakes contribute most to the analysis. We used the largest earthquake reported within an individual seismic source zones as M_{max} for that zone (Table 1). Zone A (the Andaman subduction zone) shows the highest M_{max} (i.e., M_w 9.0, 26 December 2004) among all the seismic source zones.

The earthquake activity of individual seismic source zones can be quantified using the G-R relationship [Eq. (4)] (Gutenberg and Richter 1944; Richter 1958). This relationship is a key element in estimating the probability that an earthquake with magnitude M or larger will occur within a specific time interval.

$$\log[n(M)] = a - bM \tag{4}$$

where $n(M)$ is the annual frequency of earthquakes with magnitude M or larger, and *a* and *b* are constants that represent the entire seismicity rate and seismicity potential, respectively.

For each seismic source zone, we estimated optimal values of *a* and *b* to yield the observed G-R relationship by using ZMAP software (Wiemer 2001; Fig. 4 and Table 1). The magnitude of completeness (M_c) is defined as the magnitude above which all earthquakes are considered to be fully reported (Fig. 4). Zone N (Andaman basin) revealed the highest value of *a* (i.e., 6.73) which implies the highest entire seismicity rate whereas Zone T (Tenasserim) showed the lowest *b* value (i.e., 0.25) indicating the largest proportion of large earthquakes to small ones. In contrast, there are several seismic source zones (G, L, and Q) where the total number of earthquakes is insufficient to properly evaluate earthquake activities. We excluded these zones, which the seismicity rates of them are assumed to be zero, from our seismic hazard analysis.

For all fault zone in this study, the M_{min} is taken as 4.0 (Table 1). Below this lower threshold magnitude (i.e., M_{min}) it is assumed that there is no significant earthquake hazard for engineering structures (Kramer 1996).

5. STRONG GROUND-MOTION ATTENUATION MODELS

Like earthquake source data, strong ground-motion attenuation models are essential for seismic hazard analysis.

Table 1. Summary of earthquake source parameters for the 21 seismic source zones of this study. EQ event is the number of earthquake events recorded in each seismic source zone, Tectonic setting; S means subduction zone earthquake and C for the shallow crustal earthquake. M_{max} is the expected maximum magnitude, M_{min} is the expected minimum magnitude, and *a* and *b* values are constants representing entire seismicity rate and seismicity potential, respectively, in the Gutenberg-Richter relationship.

Zone code	**Zone name**	**Tectonics setting**	**EQ event**	**M_{max}**	**M_{min}**	***a* value**	***b* value**
Zone A	Andaman subduction	S	101	9.0	4.0	4.55	0.58
Zone B	West-Central Myanmar	S	61	6.9	4.0	2.73	0.36
Zone C	East-Central Myanmar	C	87	6.5	4.0	2.72	0.35
Zone D	Mae Hong Son-Matabar	C	293	6.2	4.0	3.15	0.40
Zone E	Muang Pan-Chiang Rai	C	140	6.4	4.0	2.79	0.37
Zone F	Chiang Mai-Luang Pra Bang	C	643	6.6	4.0	2.90	0.32
Zone G	Central Thailand	C	7	5.0	4.0	-	-
Zone H	Petchabun-Wang Wiang	C	26	5.5	4.0	2.75	0.57
Zone I	Khorat Plateau	C	16	5.8	4.0	3.37	0.64
Zone J	Song Ca	C	21	5.3	4.0	2.58	0.48
Zone K	Northern Vietnam	C	17	5.8	4.0	3.05	0.58
Zone L	Eastern Thailand-Cambodia	C	3	4.6	4.0	-	-
Zone M	Andaman Arc	S	131	8.6	4.0	5.07	0.62
Zone N	Andaman Basin	C	190	6.6	4.0	6.73	0.92
Zone O	Western Thailand	C	83	6.5	4.0	2.52	0.40
Zone P	Mergui	C	36	5.7	4.0	3.62	0.60
Zone Q	Gulf of Thailand	C	4	5.4	4.0	-	-
Zone R	Malaysia-Malacca	C	33	5.6	4.0	3.44	0.60
Zone S	Aceh-Mentawai	C	210	8.4	4.0	5.04	0.60
Zone T	Tenasserim	C	14	6.2	4.0	1.68	0.25
Zone U	Sumatra Island	C	250	7.4	4.0	5.83	0.78

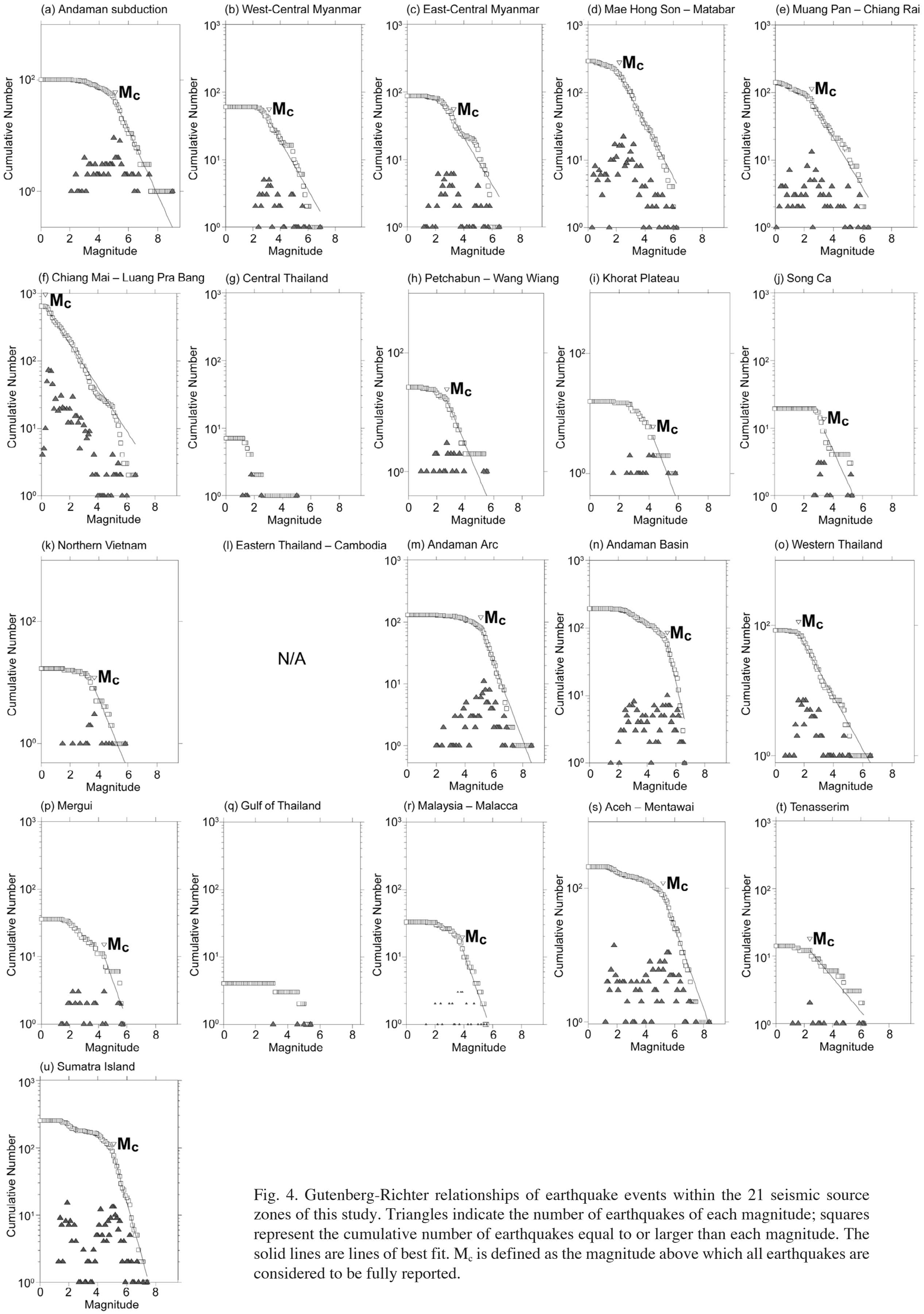


Fig. 4. Gutenberg-Richter relationships of earthquake events within the 21 seismic source zones of this study. Triangles indicate the number of earthquakes of each magnitude; squares represent the cumulative number of earthquakes equal to or larger than each magnitude. The solid lines are lines of best fit. M_c is defined as the magnitude above which all earthquakes are considered to be fully reported.

The characteristics of strong ground-motion attenuation depend on the geological framework and tectonic setting of individual seismic source zones (e.g., subduction zones, and inland active fault zone)(Gregor et al. 2002; Liu and Tsai 2005). In this study, we divided the 21 seismic source zones into two categories on the basis of tectonic setting: a subduction-related earthquake zone for the Sumatra-Andaman region (i.e., zones A, B, and M of Fig. 1), and shallow crustal earthquake zones (i.e., inland active fault zone) for the other 18 areas.

Petersen et al. (2004) collected strong ground-motion data from the Andaman subduction zone to develop an attenuation model and concluded that ground shaking in the Andaman subduction zone is consistent with the attenuation model of Youngs et al. (1997) for the rock site condition [Eq. (5)], although in the Youngs et al. (1997) model, the source-to-site distance (R) was less than 200 km.

$$\ln y_{Youngs}(M, R) = C_1^* + C_2 M + C_3^* \ln\left(R + e^{C_4^* - \frac{C_2}{C_3}M}\right) + C_5 Z_{ss} + C_8 Z_t + C_9 H \quad (5)$$

with $C_1^* = C_1 + C_3 C_4 - C_3^* C_4^*$

$C_3^* = C_3 + C_6 Z_{ss}$

$C_4^* = C_4 + C_7 Z_{ss}$

where y is peak horizontal ground acceleration (cm s^{-2}), M is moment magnitude (M_w), R is source-to-site distance (km), $C_1 = 0.2418$, $C_2 = 1.414$, $C_3 = -2.552$, $C_4 = \ln(1.7818)$, $C_8 = 0.3846$, and $C_9 = 0.00607$. Z_{ss} is zero for a rock site and one for a soil site, and Z_t is zero for plate-interface earthquakes (related to low-angle, thrust-faulting at plate interfaces), and 1 for intraslab earthquakes (related to high-angle, predominantly normal-faulting within subducting plates), and H is focal depth. The other coefficients in the equation are not necessary for the rock site condition. The standard deviation of the probability of exceedance (σ) is estimated as follows: $\sigma = 1.45 - 0.1M$.

If the source-to-site distance is equal to or greater than 200 km, the attenuation behavior of Andaman subduction-zone earthquakes is expressed as follows (Petersen et al. 2004).

$$\ln y_{Petersen}(M, R) = \ln y_{Youngs}(M, R) + \left[-0.0038 \times (R - 200)\right] \quad (6)$$

To select an appropriate attenuation model for our study, we compared four strong ground-motion attenuation models for shallow crustal earthquakes by using the data reported from Thailand by Palasri (2006) (Fig. 5). It appears that data reported by Palasri (2006) conform best to the attenuation model proposed by Kobayashi et al. (2000) for the Japan region [Eq. (7)]. Consequently, we adopted this attenuation equation for our seismic hazard analysis in Thailand and surrounding areas.

$$\log y_{Kobayashi}(M, R) = aM - bR - \log\left(R + c10^{dM}\right) + eh + S_k \quad (7)$$

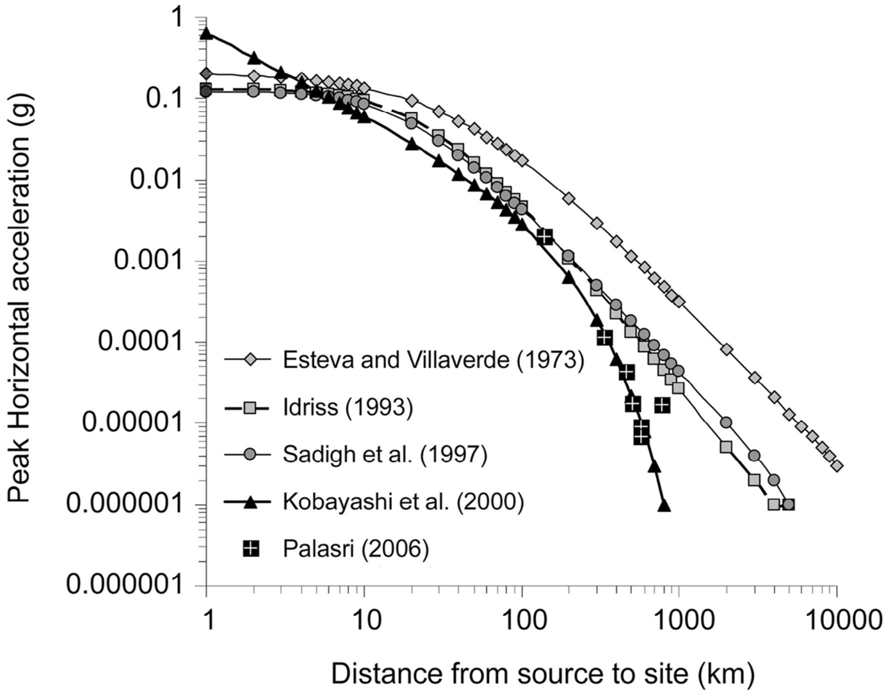


Fig. 5. Comparison of published strong ground-motion attenuation models with recorded strong ground-motion data (black squares) for a M_w 5.1 earthquake (after Palasri 2006).

where y is peak horizontal ground acceleration ($\mathrm{cm\ s^{-2}}$), M is moment magnitude (M_w), R is source-to-site distance (km), $a = 0.578$, $b = 0.00355$, $c = 0.00661$, $d = 0.00661$, $e = 0.00661$, $h = 10$, and $S_k = -0.21$ for the rock site condition. The standard deviation of the probability of exceedance (σ) is 0.213.

6. RESULTS OF PROBABILISTIC SEISMIC HAZARD ANALYSIS

The approach we used in this study is based on that of Cornell (1968). We calculated the magnitude density function by using the bounded G-R model (McGuire and Arabasz 1990). The earthquake magnitudes considered in the magnitude density function were subdivided equally into 10 portions between M_{max} and M_{min}. To investigate the probabilities of source-to-site distances, the distances considered were subdivided equally into 50 portions ranging from the shortest to the longest source-to-site distances. The minimum source-to-site distances considered in this study is 10 km. We assigned a point seismic source to each individual 0.05° × 0.05° grid cell throughout the study area. The seismic hazard was calculated for 0.25° × 0.25° grid cells located between longitudes 92 - 106°E and latitudes 0 - 21°N. MATLAB-based software employing an algorithm modified from Palasri (2006) was used to calculate the PGA while assuming the rock site condition. The PGA values were then contoured to construct seismic hazard maps of the study area (Fig. 6).

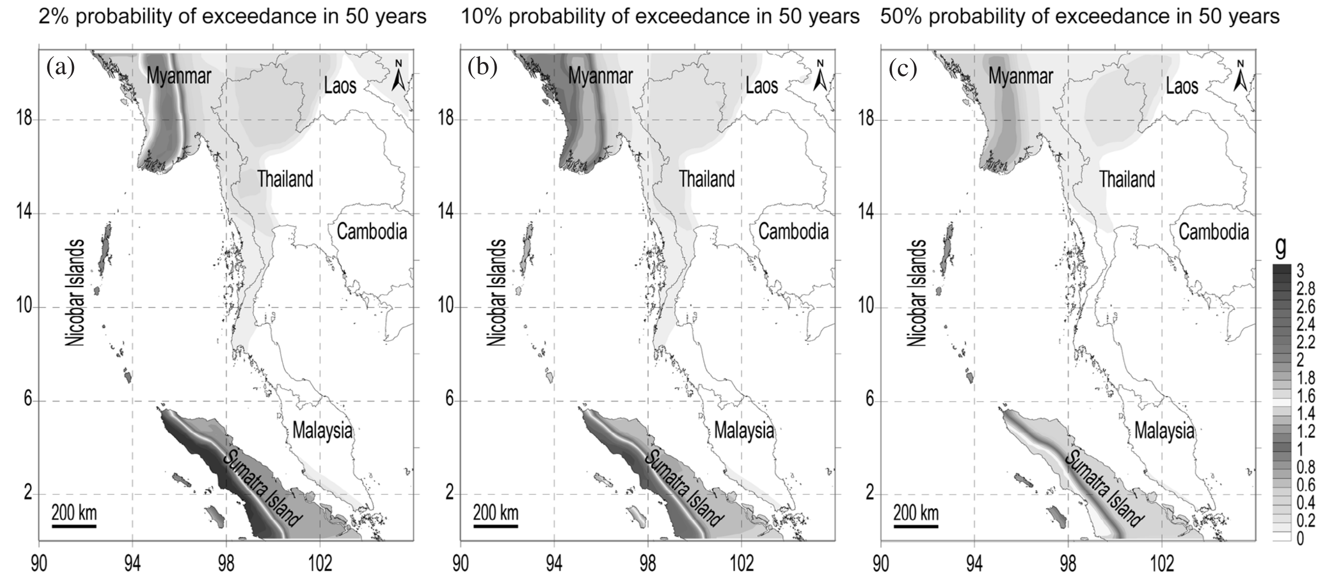
The seismic hazard levels shown by the PGA maps (Fig. 6) vary from 0 g in eastern and central Thailand to 3 g in western Sumatra. The highest level of seismic hazard in Thailand is in northern and western regions. The PGA values for 2% probability of exceedance in these areas are around 0.3 - 0.4 g for a 50-year time period. In southern Thailand, the 2% probability PGA ranges from 0 to 0.2 g, whereas in central, eastern, and northeastern Thailand the seismic hazard level is zero.

It is important to note that the strong ground-motion attenuation models considered in this study derive PGA for the rock site condition. In areas covered by thick, soft soils, ground shaking will be much more severe than that indicated by our seismic hazard maps.

7. CONCLUSIONS

We developed probabilistic seismic hazard maps for Thailand and adjacent areas. These maps show seismic hazard potential and provide a basis for long-term preparedness for earthquake hazards. They also provide useful information for other purposes, such as estimation of earthquake insurance premiums and site-specific evaluation of seismic hazards.

The spatial distributions of the seismic hazard levels we have estimated are directly dependent on both the shape of individual seismic source zones and the seismic source potential. We used the most up-to-date model for seismic source zones, one that covers Thailand in its entirety as well as some adjacent regions. However, some seismic source zones are truncated by the boundaries of the study area such that their full spatial extents are not represented in our calculations (Fig. 1). In addition, the reliability of earthquake source parameters (i.e., M_{max}, M_{min}, a, and b) for some seismic source zones is limited by the number of earthquake


2% probability of exceedance in 50 years

10% probability of exceedance in 50 years

50% probability of exceedance in 50 years

Fig. 6. Probabilistic seismic hazard maps of Thailand and adjacent areas showing the distribution of Peak Ground Acceleration (PGA) that exceeds 2%, 10%, and 50% probabilities for a 50-year time period.

events recorded within them, particularly those zones that are truncated. To achieve a more accurate seismic hazard evaluation for this region, further studies are needed that use seismic source zones that extend beyond the current study area.

Because of the limited amount of strong ground-motion data in the study area, we could not develop a strong ground-motion attenuation model specific to the study area and therefore selected the attenuation model (Kobayashi et al. 2000) that best explained the data reported by Palasri (2006). These data, however, lack strong ground-motion records at short distances (< 140 km) from the source (Fig. 5). The appropriateness of the attenuation model of Kobayashi et al. (2000) for the study area should be re-examined by including strong ground-motion data at short distances from the source. Remarkably high PGA modeled in western Myanmar and western Sumatra (up to 3 g for a 2% probability of exceedance in a 50-year time period) may be overestimated by the Kobayashi et al. (2000) model because of the lack of ground-motion attenuation data at short distances from the seismic source.

Although we believe that the seismic hazard analysis presented here is an important step toward an accurate evaluation of seismic hazard potential in Thailand and adjacent areas, more work is needed to refine our analysis. More observations of strong ground-motion in the region are needed and further seismo-tectonic research should be encouraged.

Finally, we emphasize that the extent to which geological information contributes to seismic hazard assessment in Thailand and adjacent areas depends on the quantity and quality of the data collected. To further refine seismic hazard analysis in this region, more detailed active fault data is indispensable.

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