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Seismic hazards in Thailand: a compilation and updated probabilistic analysis

Santi Pailoplee* and Punya Charusiri

Abstract

A probabilistic seismic hazard analysis (PSHA) for Thailand was performed and compared to those of previous works. This PSHA was based upon (1) the most up-to-date paleoseismological data (slip rates), (2) the seismic source zones, (3) the seismicity parameters (*a* and *b* values), and (4) the strong ground-motion attenuation models suggested as being suitable models for Thailand. For the PSHA mapping, both the ground shaking and probability of exceedance (POE) were analyzed and mapped using various methods of presentation. In addition, site-specific PSHAs were demonstrated for ten major provinces within Thailand. For instance, a 2 and 10 % POE in the next 50 years of a 0.1–0.4 g and 0.1–0.2 g ground shaking, respectively, was found for western Thailand, defining this area as the most earthquake-prone region evaluated in Thailand. In a comparison between the ten selected specific provinces within Thailand, the Kanchanaburi and Tak provinces had comparatively high seismic hazards, and therefore, effective mitigation plans for these areas should be made. Although Bangkok was defined as being within a low seismic hazard in this PSHA, a further study of seismic wave amplification due to the soft soil beneath Bangkok is required.

Keywords: Seismic hazard analysis, Probabilistic method, Active fault, Seismic source zone, Thailand

Introduction

At present, much evidence supports the idea that Thailand is an earthquake-prone area. Paleoseismological investigations have indicated that Thailand is dominated by active fault zones (Charusiri et al. 2004a; Pailoplee et al. 2009a; Wiwegwin et al. 2012, 2014), which are shown in Fig. 1a. The broken ancient remains of Wat Chedi Luang, in the Chiang Mai province (P3 in Fig. 1a) (Kázmér et al. 2011), and the existing historical earthquake records (Charusiri et al. 2005) imply that Thailand has experienced hazardous earthquake ground shaking. During the past century (1912–2012), seven published isoseismal maps (Pailoplee 2012) have depicted that Thailand and, in particular, the northern and western parts have been subjected to earthquakes of an intensity range of II–VII on the modified Mercalli intensity (MMI) scale according to both local-moderate (M_w of 5.0–5.9) and distant-major (M_w of 7.0–7.9) earthquakes. Based mainly on the present-day instrumental seismicity data, Pailoplee and Choowong (2014) investigated and revealed that most of the seismic source zones in mainland Southeast Asia area are seismically active. In addition, according to the region–time–length algorithm (Huang et al. 2002), Sukrungsri and Pailoplee (2015) proposed four prospective areas along the Sumatra–Andaman subduction zone that might experience a major earthquake in the future, namely (1) Sittwe city in western Myanmar; (2) the area offshore of the northern Nicobar Islands; (3) Aceh city in the northernmost area of Sumatra Island; and (4) the area offshore of western Sumatra Island. This evidence indicates that Thailand is not shielded from earthquake hazards. As a result, the probabilistic seismic hazard analysis (PSHA) (Cornell 1968; Kramer 1996) in Thailand has been progressively modified over the last three decades (Table 1).

Hattori (1980) proposed the first PSHA map of Thailand as the peak ground acceleration (PGA) for a 100-year return period, based mainly on the seismicity data reported by the National Oceanic and Atmospheric Administration (NOAA) and the strong ground-motion

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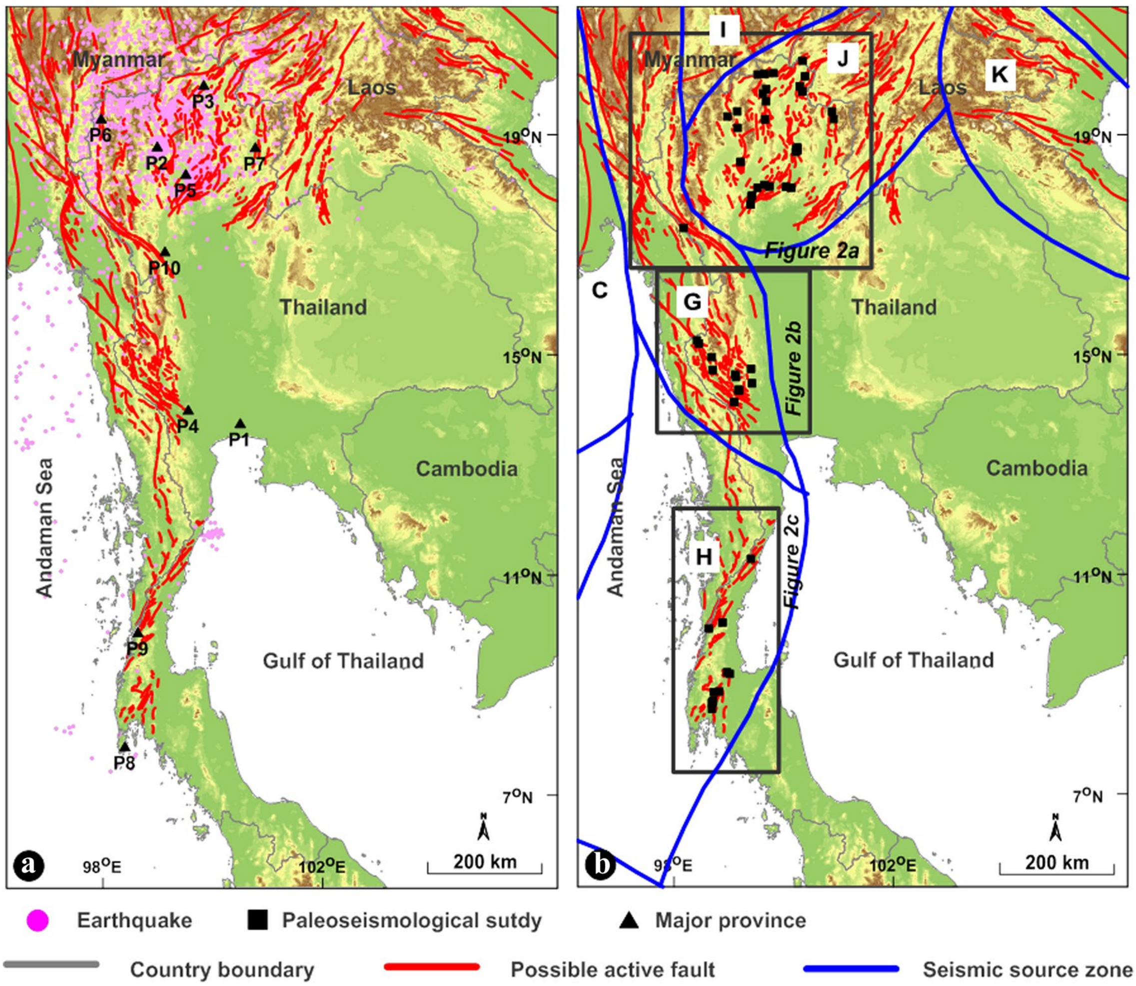

Fig. 1 **a** Map of Thailand and the neighboring area illustrating the possible active faults (*red lines*). The detailed location and earthquake source parameters of each fault are expressed in Additional file 1. The *pink dots* are the earthquake data recorded from 1912 to present. *Triangles* denote the locations of the ten significant provinces recognized in this PSHA. **b** Seismic source zones (*blue polygon*) recognized in this PSHA (Pailoplee and Choowong 2013). The *black squares* are the new sites of paleoseismological investigations used in this study with more details shown in Fig. 2

attenuation model of McGuire (1974). Thereafter, Santoso (1982) modified this map utilizing the seismicity data from both the NOAA and the Thai Meteorological Department (TMD) to form two maps showing the PGA for 36- and 74-year return periods, respectively.

Five years later, Shrestha (1987) applied the 12 seismic source zones (SSZs) defined by Nutalaya et al. (1985) to establish their PSHA for Thailand using the attenuation model of Esteva and Villaverde (1973), which was different from previous work, and determined the PGA for a return period of 13 and 90 years. Warnitchai and Lisantono (1996) then used the conditions proposed by Shrestha (1987) for a PSHA to contribute a map showing the PGA of a 10 % probability of exceedance (POE) in the next 50 year.

After the devastation following the M_w 9.0 earthquake on December 26, 2004, Petersen et al. (2007) analyzed the PSHA of Southeast Asia, including Thailand. Based on 10 seismic source zones (SSZs), 18 active faults in Thailand, and various weighting schemes in attenuation models (Youngs et al. 1997; Atkinson and Boore 2006), they developed the maps of Thailand showing the 2 and 10 % POE of PGA values in the next 50 years.

In addition, Pailoplee et al. (2009b, 2010) evaluated the PSHA based upon 55 possible active fault zones (Pailoplee et al. 2009b) and 21 SSZs (Charusiri et al. 2005) and used the seismicity data of the National Earthquake Information Center (NEIC), the International Seismological Centre (ISC), and TMD to evaluate the earthquake potential. Compared with the nine existing strong ground

Table 1 Summary of the derived PSHA for Thailand since 1980

Reference	Earthquake sources	Earthquake activities	Attenuation models	Map types
Hattori (1980)	–	Seismicity (NOAA)	McGuire (1974)	RI 100 years
Santoso (1982)	–	Seismicity (NOAA, TMD)	McGuire (1974)	RI 36 years RI 74 years
Shrestha (1987)	12 SSZs (Nutalaya et al. 1985)	Seismicity (Nutalaya et al. 1985)	Esteva and Villaverde (1973)	RI 13 years RI 90 years
Warnitchai and Lisantono (1996)	12 SSZs (Nutalaya et al. 1985)	Seismicity (Nutalaya et al. 1985)	Esteva and Villaverde (1973)	10 % POE in 50 years
Petersen et al. (2007)	10 SSZs (Petersen et al. 2007) 18 FZs (Compiled)	Seismicity (NEIC, ISC) Paleoseismological data	Youngs et al. (1997) Atkinson and Boore (2006)	2 % POE in 50 years 10 % POE in 50 years
Pailoplee et al. (2009b)	55 FZs (Pailoplee et al. 2009b)	Seismicity (NEIC, ISC, TMD) Paleoseismological data	Kobayashi et al. (2000) Petersen et al. (2004)	2 % POE in 50 years 10 % POE in 50 years
Pailoplee et al. (2010)	21 SSZs (Charusiri et al. 2005)	Seismicity (NEIC, ISC, TMD)	Kobayashi et al. (2000) Petersen et al. (2004)	2 % POE in 50 years 10 % POE in 50 years
Palasri and Ruangrassamee (2010)	21 SSZs (Charusiri et al. 2005)	Seismicity (NEIC, ISC, TMD)	Idriss (1993) Sadigh et al. (1997) Petersen et al. (2004)	2 % POE in 50 years 10 % POE in 50 years
Ornthammarath et al. (2010)	5 SSZs (Ornthammarath et al. 2010) 21 FZs (Compiled)	Seismicity (NEIC, ISC, TMD) Paleoseismological data	Zhao et al. (2006) Chiou and Youngs (2008)	2 % POE in 50 years 10 % POE in 50 years

Remarks: *SSZ* seismic source zone, *FZ* fault zone, *RI* recurrence interval, *POE* probability of exceedance

motions that had been recorded in northern Thailand, the attenuation models of Kobayashi et al. (2000) and Petersen et al. (2004) were applied for shallow crustal and subduction zone earthquakes, respectively, to derive the maps for a 2 and 10 % POE in the next 50 years. Although Palasri and Ruangrassamee (2010) also performed a PSHA using the SSZs of Charusiri et al. (2005), they applied the attenuation models of Idriss (1993) and Sadigh et al. (1997) for the shallow crustal earthquakes, which resulted in different maps for the 2 and 10 % POE in the next 50 years compared with those of Pailoplee et al. (2009b, 2010).

Finally, Ornthammarath et al. (2010) defined five SSZs and compiled 21 fault zones as the earthquake sources affecting Thailand. The earthquake potential was determined from the seismicity data from the NEIC, ISC, and TMD, as used by Pailoplee et al. (2009b, 2010). After weighting some attenuation models (Zhao et al. 2006; Chiou and Youngs 2008), the maps of a 2 and 10 % POE in the next 50 years were published.

From the original work of Hattori (1980) to the latest PSHA maps by Ornthammarath et al. (2010), it is found that the assumptions of earthquake sources and activities, including the attenuation models used, are different between each study and are related to the data used in each PSHA. During the last 5 years, some data, assumptions, and models have been improved and altered significantly. The SSZs of mainland Southeast Asia have been modified (Fig. 1b) (Pailoplee and Choowong 2013), the seismicity data have been updated to the present (Pailoplee and Choowong 2014), new paleoseismological data have become available (Figs. 1b, 2), and suitable attenuation models for Thailand have been constrained differently (Chintanapakdee et al. 2008). In addition, based on the latest hazardous earthquakes of 6.8 M_w (Wang et al. 2014) and 6.3 M_L (Soralump et al. 2014) that occurred on March 24, 2011, and May 5, 2014, respectively, in the vicinity of Thailand, Myanmar, and Laos, the PSHA in Thailand can be more accurately assessed using the up-to-date data and constrained models now available. The results obtained should help in the understanding of the severity of earthquake hazards and allow the necessary action to be taken to sustain the development of new, as well as the ongoing, engineering works, including serving as a resource for the further development of effective earthquake mitigation plans for Thailand.

Earthquake sources and activities

With the present-day tectonic activities of the Indian-Eurasian plate collision, a number of seismogenic faults have originated within and nearby Thailand. However, due to the limitations of the investigated fault data, most previous PSHA has roughly applied the SSZs as the earthquake sources (Shrestha 1987; Warnitchai and Lisantono 1996; Pailoplee et al. 2010; Palasri and Ruangrassamee 2010). Although Petersen et al. (2007) and Ornthammarath et al. (2010) recognized the fault data in their PSHA, the most investigated faults were limited to only those within Thailand. The geometry and strike of each fault do not exactly conform to the details compared with the geomorphological evidence, e.g., fault scarp, shutter

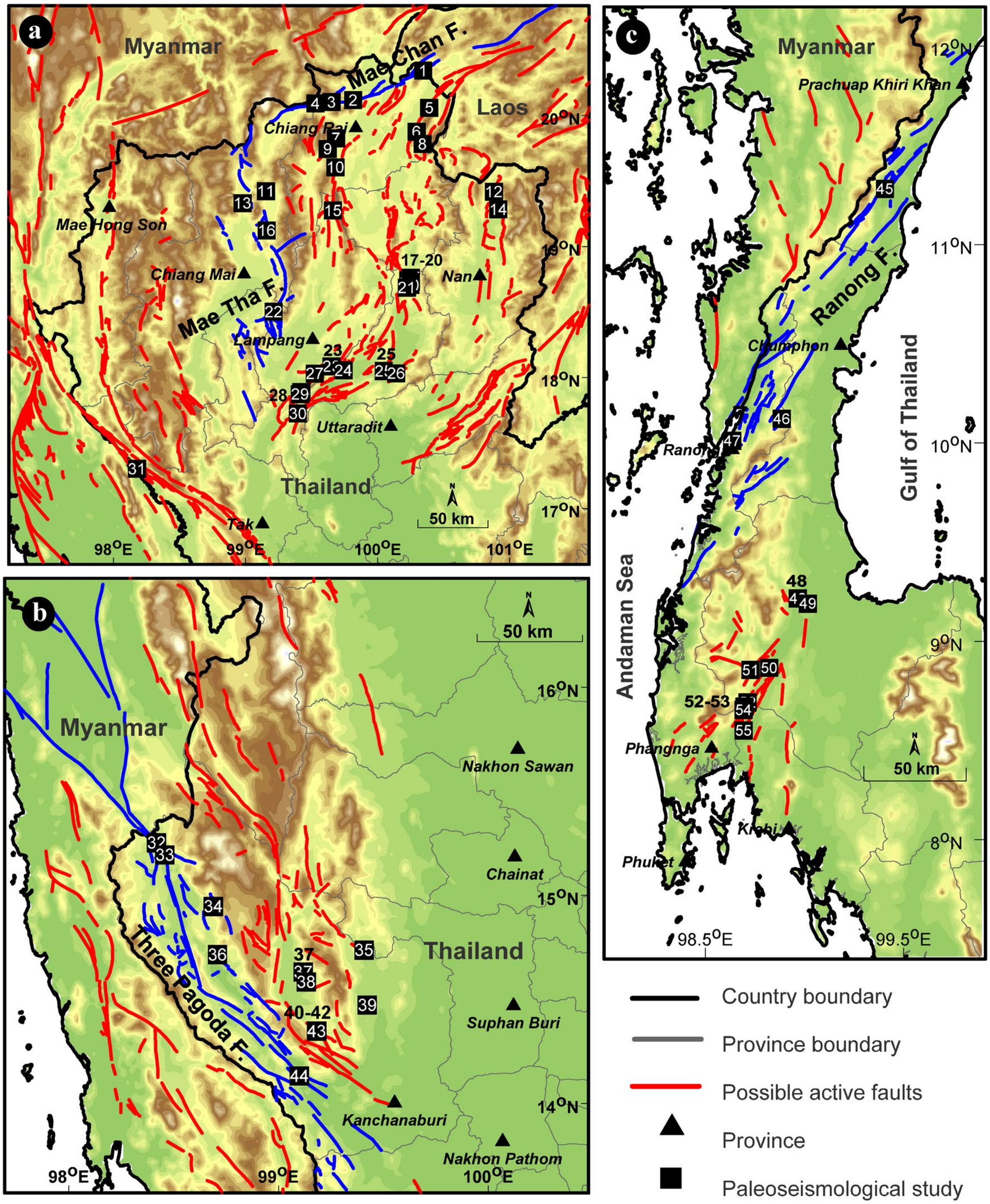

Fig. 2 Maps of different provinces in Thailand showing the locations of the new paleoseismological investigations used in this study. The index of these maps is illustrated in Fig. 1b. The number of each site is equivalent to the column no. in Table 2. **a** Northern, **b** western and **c** southern Thailand

ridge, and triangular facet (e.g., Petersen et al. (2007) and Ornthammarath et al. (2010)). In addition, some utilized seismogenic faults are ambiguous, e.g., in the Chao Phaya Basin and the Chumphon basin faults (Ornthammarath et al. 2010). Quantitatively, Pailoplee et al. (2009b) compiled 55 seismogenic fault zones in mainland Southeast Asia constrained by the geomorphological evidence illustrated in the satellite images. Theoretically, the paleoseismological parameters of (1) the maximum credible earthquake (MCE), (2) the rupture area, and (3) the rate of fault slip should be defined in each fault segment. Nevertheless, according to the limitation of paleoseismological data, Pailoplee et al. (2009b) determined equally the paleoseismological data in each fault zone, which are composed of a number of fault segments. For example, Pailoplee et al. (2009b) assumed the rate of fault slip at 0.1 and 1 mm/year for all the fault segments in the Ranong and Klong Marui Fault Zones, respectively. In addition, according to the strong ground-motion attenuation model of Kobayashi et al. (2000) applied in Pailoplee et al. (2009b), the hazard levels are dramatically high comparing to the other PSHA mentioned above.

Up to the present, at least 55 sites of paleoseismological investigations in Thailand have been reported in addition to 13 technical reports of paleoseismological investigations (Table 2). For example, there are 31 locations (no. 1–31) for paleoseismological results in the northern part of Thailand (Fig. 2a) based on the investigations of the Department of Mineral Resources (DMR 2009a, b, 2011), the Royal Irrigation Department (RID 2006), and Charusiri et al. (2004a). The fault slip rates cover a range of 0.03 mm/year in the Phrae Fault Zone (no. 26) to 1 mm/year in the southern segment of the Lampang-Thoen Fault Zone (no. 29). In some fault segments, more than one site for each active fault has been investigated. For instance, in the Mae Chan Fault, four paleoseismological trenches were investigated, one each at Ban Huai Yen, Pong Namron, Pong Phakheam, and Seuk Reuthai (no. 1–4 in Table 2). This gave fault slip rates from 0.29 to 0.16 mm/year (DMR, 2009b). In western Thailand (Fig. 2b), 13 trench sites (no. 32–44) have been examined and have revealed a fault slip rate range from a maximum rate of 2.87 mm/year at Ban Khaeng Kabe (no. 43) to a minimum of 0.22 mm/year at Ban Song Karia (no. 32) (Nuttee et al. 2001; Charusiri et al. 2004b). In addition, according to the projects by the RID (2009), 11 sites (no. 45–55) of paleoseismological investigation in the southern part of Thailand (Fig. 2c) have been reported. Among these, three sites (no. 45–47) focus on the Ranong Fault Zone and yield a fault slip rate of 0.18 mm/year at Ban Bangborn Nai and 0.7 mm/year at Ban Phracha Seri (DMR 2007b). For the other eight sites, all in the Klong Marui fault (no. 48–55), the DMR (2007b) and RID (2009) reported the fault slip rate to vary between 0.01 mm/year (Ban Pho Pana, no. 49) and 0.5 mm/year (Ban Kuan Sabai, no. 55) (Fig. 2c).

It is widely recognized that paleoseismological data are significant characteristics in deriving a reliable PSHA (Andreou et al. 2001). When more paleoseismological evidence is used, the PSHA is likely to be more accurate. In this study, the location, the geometry, and the strike of each fault were, therefore, recognized according to Pailoplee et al. (2009b). In addition, the fault parameters necessary for the PSHA (fault length) were converted to the MCE and the rupture area using the Wells and Coppersmith (1994) relationship. According to the 55 additional paleoseismological investigations, i.e., slip rate (Fig. 2; Table 2), all the fault segments that provided new paleoseismological evidence were identified as new earthquake sources. As mentioned above, where fault segments had active fault data at more than one site, the highest fault slip rate was utilized. The other paleoseismological data from outside Thailand also required for the PSHA were obtained from publications and technical reports (Pailoplee et al. 2009b). The MCE, the rupture areas, and the fault slip rates were obtained from the investigation of the active faults at each specific individual site.

In Fig. 1a, most earthquake epicenters generated inland were not related to the traced fault, supporting that the SSZs were also needed for the earthquake source evaluation. Therefore, in addition to the active faults recognized in this PSHA, the SSZs were also applied in this study as the background seismicity. Based on the available literature, there are at least three models of SSZs for mainland Southeast Asia (Nutalaya et al. 1985; Charusiri et al. 2005; Pailoplee and Choowong 2013). According to the updated data and reasonable assumptions, the 13 SSZs of zones A–M proposed by Pailoplee and Choowong (2013) were used in this study (Fig. 1b). The *a* and *b* values of the Gutenberg–Richter relationships of each SSZ, including the fault data within each SSZ, were provided by the most up-to-date data provided by Pailoplee and Choowong (2014), as given in Table 3. However, the *a* and *b* values of the SSZs H and K are not available, and both values proposed by Pailoplee and Choowong (2013) are employed for the SSZs H and K. In final, 75 earthquake sources of the seismogenic faults and SSZs were recognized in this PSHA. The detailed location and earthquake source parameters of each earthquake sources are expressed in Additional file 1.

Probabilistic seismic hazard analysis (PSHA)

Conceptually, the PSHA evaluated numerically the probability that a particular ground shaking level of interest A was equal to or exceeded the ground shaking level A_0, as expressed in Eq. (1) (Cornell 1968):

$$\lambda(A \geq A_0) = \sum_{i=1}^{Ns} v_i \iint P[A(m,r) \geq A_0|m,r] f_{Mi}(m) f_{Ri}(r) \mathrm{d}m\mathrm{d}r, \quad (1)$$

where $\lambda(A \geq A_0)$ represents the frequency of the exceedance of a given threshold value A_0; $f_{Mi}(m)$ denotes the probability density function (PDF) of earthquake occurrence of each magnitude range; $f_{Ri}(r)$

Table 2 New earthquake source parameters (paleoseismological data) complied in this study

No.	Longitude	Latitude	Site	Slip rate (mm/y)	References
1	100.35	20.34	Huai Yen	0.29	DMR (2009b)
2	99.81	20.12	Pong Namron	0.29	DMR (2009b)
3	99.65	20.11	Pong Phakheam	0.29	DMR (2009b)
4	99.53	20.09	Seuk Reuthai	0.16	DMR (2009b)
5	100.39	20.06	Sri Lanna	0.29	DMR (2009b)
6	100.30	19.88	Tao	0.07	DMR (2009b)
7	99.68	19.83	Phang Moung	0.16	DMR (2009b)
8	100.34	19.78	Phang Kam	0.09	DMR (2009b)
9	99.62	19.75	Tai Sarn Yao	0.11	DMR (2009b)
10	99.68	19.61	Pha Jor	0.18	DMR (2009b)
11	99.15	19.42	Nong Krok	0.50	DMR (2009a)
12	100.88	19.42	Thung Ang	0.60	DMR (2011)
13	98.98	19.33	Chom Khiri	0.10	DMR (2009a)
14	100.91	19.29	Doo	0.60	DMR (2011)
15	99.66	19.28	Pha Neng	0.34	DMR (2009b)
16	99.16	19.12	Long Khod	0.10	DMR (2009a)
17	100.25	18.76	Huai Pae	0.8	RID (2006)
18	100.23	18.74	Huai Pae	0.33	RID (2006)
19	100.25	18.73	Huai Pu	0.14	RID (2006)
20	100.25	18.71	Mae Yom	0.37	RID (2006)
21	100.22	18.69	Mae Yom	0.33	RID (2006)
22	99.21	18.50	Tha Pladeuk	1.00	DMR (2009a)
23	99.65	18.09	Mai	0.15	Charusiri et al. (2004a)
24	99.74	18.05	Mae Long	0.40	DMR (2009a)
25	100.05	18.05	Huai Nong Bor	0.60	DMR (2009a)
26	100.14	18.03	Man	0.03	Charusiri et al. (2004a)
27	99.52	18.03	Bom Luang	0.60	Charusiri et al. (2004a)
28	99.42	17.89	Samai	0.83	Charusiri et al. (2004a)
29	99.41	17.87	Umlong	1.00	DMR (2009a)
30	99.40	17.73	Pang Ngoon	0.40	DMR (2009a)
31	98.18	17.30	Mae Usu	0.55	Saithong (2006)
32	98.42	15.25	Song Karia	0.22	Charusiri et al. (2004b)
33	98.46	15.20	Rong Wai	0.54	Charusiri et al. (2011)
34	98.69	14.95	Thi Puye	1.94	DMR (2007a)
35	99.41	14.74	Khao Son	0.25	Charusiri et al. (2011)
36	98.71	14.72	Ong Thi	1.58	DMR (2007a)
37	99.12	14.63	Dong Salao	1.30	DMR (2007a)
38	99.13	14.58	Pong Wai	1.33	DMR (2007a)
39	99.42	14.47	Pong Ree	0.56	Charusiri et al. (2011)
40	99.18	14.35	Khaeng Kabe	0.67	Charusiri et al. (2004b)
41	99.18	14.35	Khaeng Kabe	1.42	DMR (2007a)
42	99.18	14.35	Khaeng Kabe	0.67	Charusiri et al. (2004b)
43	99.18	14.35	Khaeng Kabe	2.87	Nuttee et al. (2001)
44	99.10	14.13	Pu Khlon	0.33	Charusiri et al. (2011)
45	99.41	11.28	Neun Kruad	0.27	DMR (2007b)
46	98.89	10.12	Phracha Seri	0.7	DMR (2007b)
47	98.64	10.01	Bangborn Nai	0.18	DMR (2007b)
48	98.97	9.22	Vipawadi	0.17	DMR (2007b)
49	99.02	9.19	Pho Pana	0.01	RID (2009)

Table 2 continued

No.	Longitude	Latitude	Site	Slip rate (mm/y)	References
50	98.82	8.87	Ma Leaw	0.01	RID (2009)
51	98.73	8.86	Song Peenong	0.01	RID (2009)
52	98.71	8.69	Bang Wo	0.11	DMR (2007b)
53	98.70	8.67	Bang Leuk	0.50	DMR (2007b)
54	98.69	8.65	Bang Leuk	0.43	DMR (2007b)
55	98.69	8.55	Kuan Sabai	0.50	DMR (2007b)

Table 3 Earthquake source parameters (seismicity data) of the 13 SSZs (zones A–M) defined by Pailoplee and Choowong (2014) and used in this study

Zone	Name	*a*	*b*
A	Sumatra–Andaman Interplate	5.98	0.77
B	Sumatra–Andaman Intraslab	6.58	0.88
C	Sagaing Fault Zone	5.8	0.86
D	Andaman Basin	4.51	0.61
E	Sumatra Fault Zone	4.75	0.61
F	Hsenwi-Nanting Fault Zone	6.02	1.01
G	Western Thailand	3.98	0.67
H	Southern Thailand	3.10	0.66
I	Jinghong-Mengxing Fault Zones	4.87	0.71
J	Northern Thailand-Dein Bein Fhu	4.72	0.73
K	Song Da-Song Ma Fault Zones	3.48	0.74
L	Xianshuihe Fault Zone	6.14	0.92
M	Red River Fault Zone	5.99	1.03

is the PDF for the possible distance from the recognized earthquake source and the site of interest; $P[A(m,r) \geq A_0|m,r]$ represents the POE of a threshold value A_0, under the condition that the earthquake with magnitude m was located at the source-to-site distance r. The term $P[A(m,r) \geq A_0|m,r]$ depends directly on the utilized model of ground-motion attenuation. The coefficient v_i denotes the average rate of earthquake occurrence for each fault i from all recognized faults (Ns). When a single fault i is considered to be a threat for the areas of interest, it is critical to select the appropriate frequency–magnitude model (i.e., probability density function) and activity rate.

In this PSHA, both fault lines and areal SSZs, including the study areas of Thailand, were gridded equally as 0.25° × 0.25° grid cells. Conceptually, every point within each earthquake source was assumed to have the same probability of being the epicenter of a future earthquake (Erdik et al. 1982). Using the CU-PSHA software (Pailoplee and Palasri 2014), each grid cell was then evaluated in the PSHA according to Eq. (1).

The PDF of magnitude ($f_{Mi}(m)$)

With respect to the earthquake sources, 75 fault segments and SSZs were evaluated to derive the PDF of the earthquakes. Where there was sufficient paleoseismological data, the fault slip rate was converted to the seismic activity, particularly for the long recurrence interval of large earthquakes (Todorovska and Jordanovski 1994). Therefore, based on the earthquake model proposed by Youngs and Coppersmith (1985), not only the *a* and *b* coefficient values available in Table 3, but also the rupture areas, the MCE, and the slip rates values (Table 2), including those reported by Pailoplee et al. (2009b), were considered simultaneously to evaluate the PDF of magnitude for each earthquake source.

Based on the input parameters and the characteristic earthquake model, the PDF of the magnitude of the four earthquake sources (Mae Chan, Mae Tha, Three Pagoda, and Ranong Fault Zones) was demonstrated. For example, at the Mae Tha Fault Zone in northern Thailand (yellow line in Fig. 3a), the probability was about 0.001 at M_w 4.0 and decreased exponentially to 0.00007 at M_w 6.0. Thereafter, the PDF of the magnitude showed a constant characteristic earthquake at 0.0001 from a M_w 6.5–7.0, which is the MCE defined in this study for the Mae Tha Fault Zone.

The PDF of source-to-site distance ($f_{Ri}(r)$)

In each grid cell, the distance between the grid of interest and the recognized earthquake source was calculated. The minimum and maximum values of the calculated distances were considered to be the lower and the upper bound of the PSHA considered distances. Thereafter, for each distance determined above, $f_R(r)$ was estimated over 50 equal intervals between the minimum and maximum possible distance, as expressed in Fig. 3b.

In Fig. 3b, most $f_R(r)$ had probabilities between 0.0005 and 0.00001. For example, the PDF distribution of the source-to-site distance measured from Chiang Mai province to the Ma Tha Fault Zone had the shortest possible distance of around 26.3 km and a probability of 0.99, whereas the longest possible distance was 113.8 km with a probability of <0.0003.

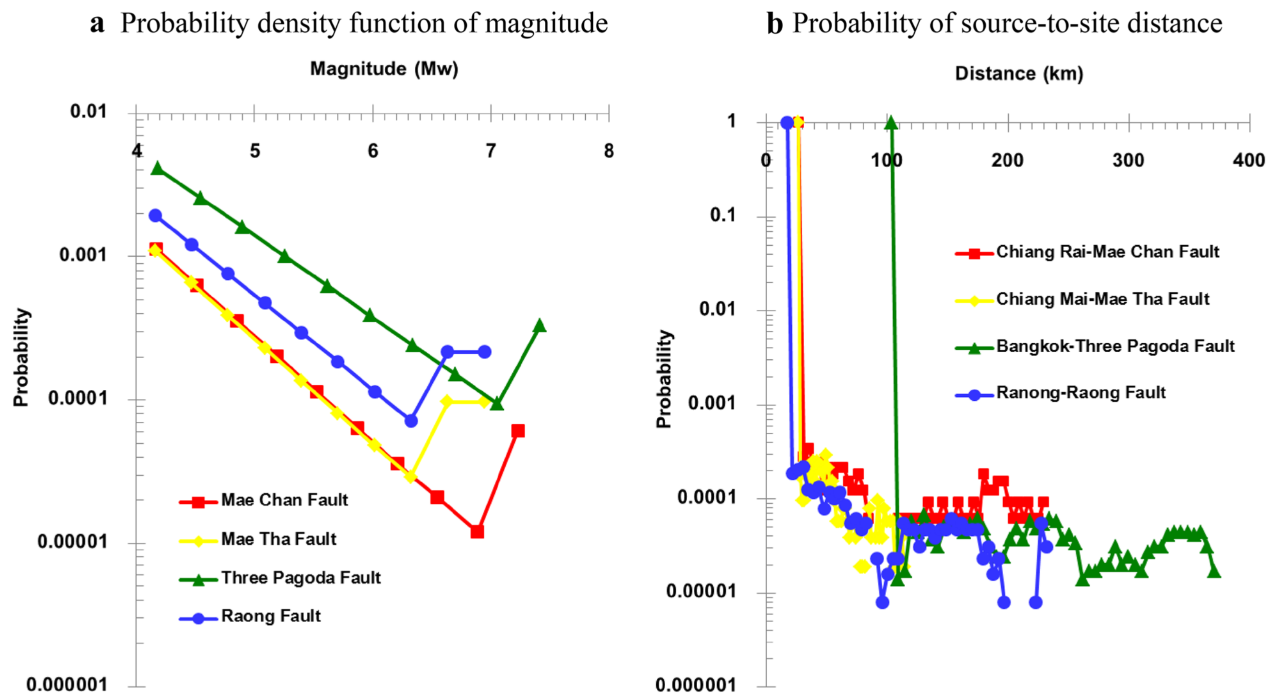

Fig. 3 **a** Probability density function estimated from the characteristic earthquake model of the four fault zones demonstrated in the northern, western, and southern part of Thailand. **b** The probability distribution of distances measured from the individual major provinces to the indicated fault zones

Evaluation of the POE of a threshold value A_0 ($P[A(m,r) \geq A_0|m,r]$)

The threshold value A_0 is the projected value of the ground shaking (PGA or MMI) of interest in the PSHA. Using the CU-PSHA software and implementing 10 cases of $f_{Mi}(m)$ and 50 cases of $f_R(r)$, 300 cases of A_0 that varied between 0.005 and 2.995 g with increments of 0.01 g were considered. The main aim of this section was to determine the POE of an individual A_0 ($P[A(m,r) \geq A_0|m,r]$).

Regarding the strong ground-motion attenuation models, Chintanapakdee et al. (2008) calibrated 163 ground motions of 45 earthquake events recorded by the TMD with some attenuation equations proposed previously for the other regions. The results indicate that the attenuation models developed by Idriss (1993) and Crouse (1991) are the most suitable models for shallow crustal and subduction zone earthquakes, respectively, generated in mainland Southeast Asia. Utilizing the selected attenuation models of Idriss (1993) and Crouse (1991) as suggested for Thailand by Chintanapakdee et al. (2008), the obtained PGA was identified to be the mean PGA ($\overline{PHA}$), which may vary according to the ground shaking. Thereafter, from the evaluated $\overline{PHA}$ and standard deviation (σ), the probability that a target PGA (A_0) will be exceeded in a given magnitude and distance, ($P[A(m,r) \geq A_0|m,r]$), can be computed from Eq. 2;

$$P[A(m,r) \geq A_0|m,r] = 1 - \Phi\left(\frac{\log(A_0) - \log \overline{PHA}}{\sigma}\right), \quad (2)$$

where Φ is the probability based on a normal distribution.

For the given $f_M(m), f_R(r)$, and $P[A(m,r) \geq A_0|m,r]$ including ν, the value of $\lambda(A \geq A_0)$ at different A_0 values (0.005–2.995 g) was evaluated from Eq. (1) in each grid, providing the PSHA.

Site-specific PSHA

After each PSHA was calculated according to Eq. (1), the hazard curves, plotted as $\lambda(A \geq A_0)$ in the X-axis and the POE in the Y-axis, were derived for each specific site or grid. In a seismological context, this curve clarifies simultaneously both the (1) POE of an individual ground shaking of interest and (2) the ground shaking level in any POE of interest. In order to demonstrate the PSHA at a specific site, the hazard curves of ten major provinces within Thailand were evaluated and are presented in Fig. 4.

According to the hazard curve shown in Fig. 4, among the 10 analyzed provinces, Kanchanaburi province (P4) had a high seismic risk, which reflects its close proximity to the Three Pagoda Fault Zone that is recognized in this study. For Bangkok (P1), the capital city of Thailand, this PSHA illustrated it as being a seismic safe area compared

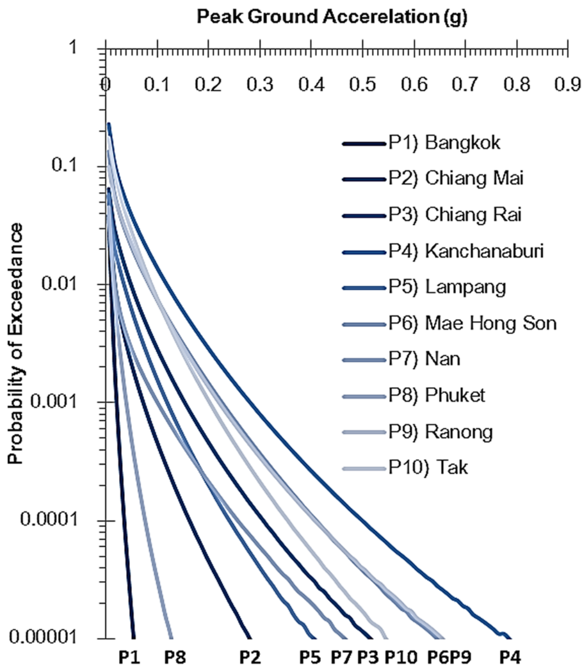

Fig. 4 Hazard curves of the ten major provinces recognized in this study. Locations are shown in Figs. 1a, 5

with the other provinces examined. Therefore, a ground shaking in Bangkok of <0.1 g occurs around 0.01 time/year (once every 100-year return period), whereas for Kanchanaburi province a PGA of around 0.14 g might occur in the next 100 years (Fig. 4).

PSHA maps

In PSHA mapping, the results are presented empirically in terms of a specific time span depending on the recognized lifetime of the infrastructure of interest. To satisfy this, Kramer (1996) demonstrated two types of PSHA maps: (1) the ground shaking map, which expresses the shaking level (PGA) that might be exceeded in any specific % POE of interest, and (2) the probability map, which illustrates the % probability that the shaking level may exceed the ground shaking level of interest. However, in any individual grid, both kinds of PSHA maps are evaluated from the same hazard curve. The details of the individual types of PSHA maps are described in "Ground shaking maps" and "Probability maps" sections.

Ground shaking maps

From the obtained hazard curve, the ground shaking level (in units of g) at each grid can be evaluated from a fixed POE (Prob) in the specific time span (T), as shown in Eq. (3) (Kramer 1996).

$$\text{Prob\_hazard} = -\frac{\ln(1 - \text{Prob})}{T} \tag{3}$$

The calculated Prob_hazard is equivalent to the POE (Y-axis) of the ground shaking level (X-axis) of the recognized hazard curve. In this study, the ground shaking maps were produced for a 2 and 10 % POE in the next 50 years (Fig. 5). The Prob_hazard in the ten major provinces mentioned previously ("Site-specific PSHA" section) were also estimated according to Eq. (3), and the results are given in Table 4. For instance, taking a 2 % POE of a given PGA value (Fig. 5a), a comparatively high seismic hazard (PGA = 0.1–0.4 g) in the vicinity of western Thailand was found, where the Kanchanaburi province (P4) is located (Table 4). In southern Thailand, there are two major fault zones, the Ranong and Klong Marui Fault Zones. Based on the PSHA calculated in this study, the area in the vicinity of the Klong Marui Fault Zone, with a maximum PGA of around 0.35 g, has a greater seismic hazard level than the Ranong Fault Zone at a PGA of 0.3 g (Fig. 4a). For the northern part of Thailand, where a number of major provinces are located, the PGA values for a 2 % POE were between 0.1 and 0.2 g for the next 50 years (Fig. 5a). The 10 % POE maps (Fig. 5b) reveal that the PGA levels are around 0.5 times that of the 2 % POE maps.

Compared with previous studies, the distribution of the PGA is similar, but not the same. Most PSHA illustrate that the high seismic hazards in Thailand were found in the western, northern, and southern regions, whereas in the central, eastern, and northeastern Thailand, the ground shaking is quiescent. However, the hazard level of each region is different. The PSHA analyzed from Pailoplee et al. (2009b) is much higher than the PSHA obtained in this study in the whole of Thailand. This is according to the attenuation model of Kobayashi et al. (2000) applied in Pailoplee et al. (2009b) as mentioned above. The PGA level estimated in this study is higher than the PSHA of Ornthammarath et al. (2010), in particular in the western and southern parts of Thailand. This may be related to the number of paleoseismological data added in this study.

Probability maps

In addition to the ground shaking maps, the probability map showing the probability that the ground shaking (Prob) will exceed the ground shaking level of interest (Prob_hazard) in the return period (T) may be written as shown in Eq. (4),

$$\text{Prob} = 1 - e^{(-(\text{Prob\_hazard})(T))} \tag{4}$$

Although the ground shaking maps reported in "Ground shaking maps" section (Figs. 4, 5) are more precise, which is useful for any field of engineering design and construction, this type of PGA map is potentially difficult for the untrained person to understand, in

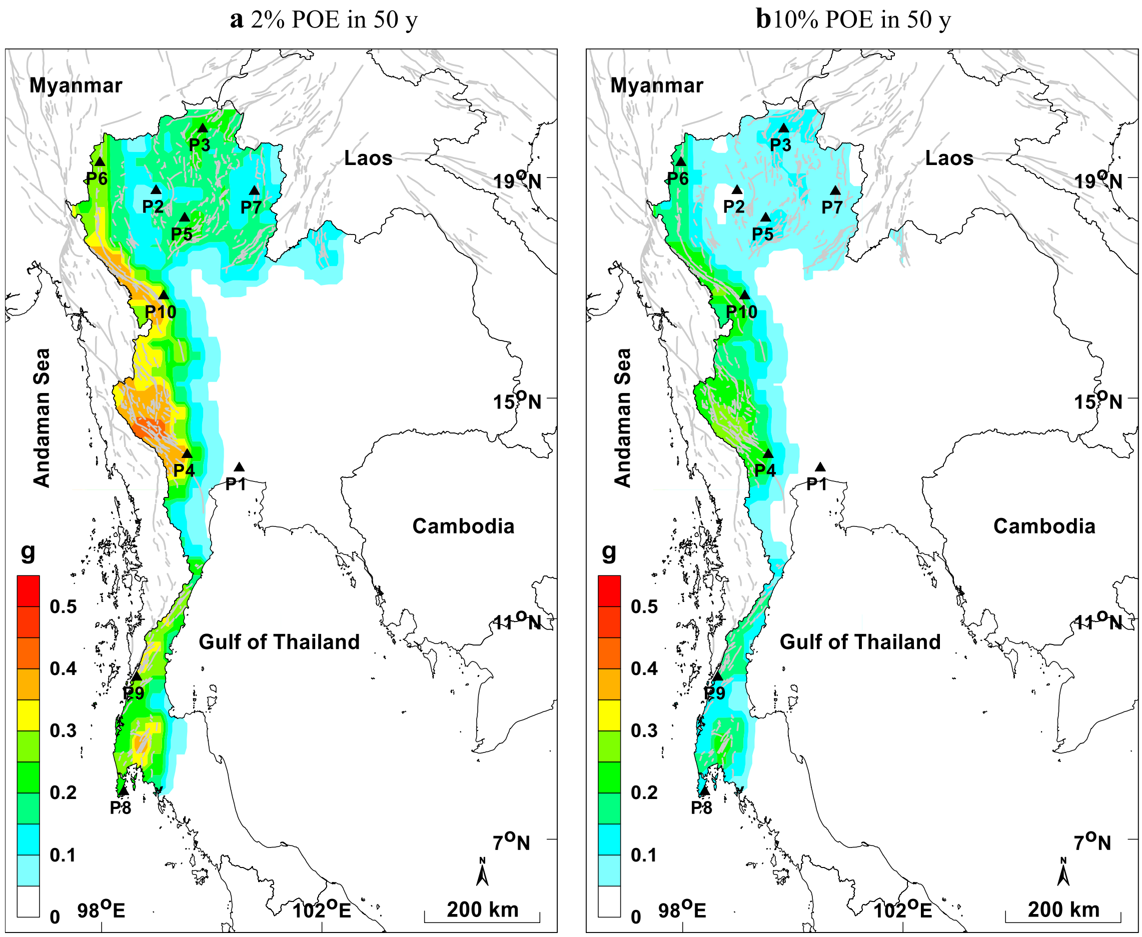

Fig. 5 PSHA maps of Thailand illustrating the PGA distribution with a **a** 2 % and **b** 10 % POE within the next 50 years

Table 4 PSHA for ten major provinces in Thailand showing different POE intensity levels in the next 50 years

	Bangkok (P1)	Chiang Mai (P2)	Chiang Rai (P3)	Kanchanaburi (P4)	Lampang (P5)	Mae Hong Son (P6)	Nan (P7)	Phuket (P8)	Ranong (P9)	Tak (P10)
2 % POE	0.03 g	0.10 g	0.21 g	0.36 g	0.16 g	0.29 g	0.16 g	0.05 g	0.29 g	0.26 g
10 % POE	0.02 g	0.05 g	0.11 g	0.22 g	0.09 g	0.18 g	0.06 g	0.03 g	0.17 g	0.16 g
MMI IV POE	7 %	35 %	72 %	99 %	59 %	92 %	35 %	25 %	91 %	98 %
MMI V POE	0	16 %	50 %	93 %	37 %	76 %	18 %	6 %	77 %	87 %
MMI VI POE	0	6 %	26 %	72 %	16 %	50 %	9 %	1 %	51 %	57 %
MMI VII POE	0	1 %	9 %	37 %	5 %	22 %	3 %	0	22 %	21 %

Locations of P1–10 are shown in Figs. 1a, 5

particular for informing the general public. Therefore, the POE maps (in unit of %) of each severity of earthquake hazard were prepared according to Eq. (4). In order to convert the PGA to any level of MMI of interest, the empirical relationships between the MMI and PGA contributed by Pailoplee (2012) were employed. From the hazard curve of each grid point, the POE of MMI levels IV–VII in the next 50 years was then evaluated and mapped (Fig. 6). As before, the PHSA of the ten major provinces ("Site-specific PSHA" section) was also estimated according to Eq. (4), and the results are summarized in Table 4.

For the probability maps (Fig. 6), the western, northwestern, and southern parts of Thailand had a 60–80 %

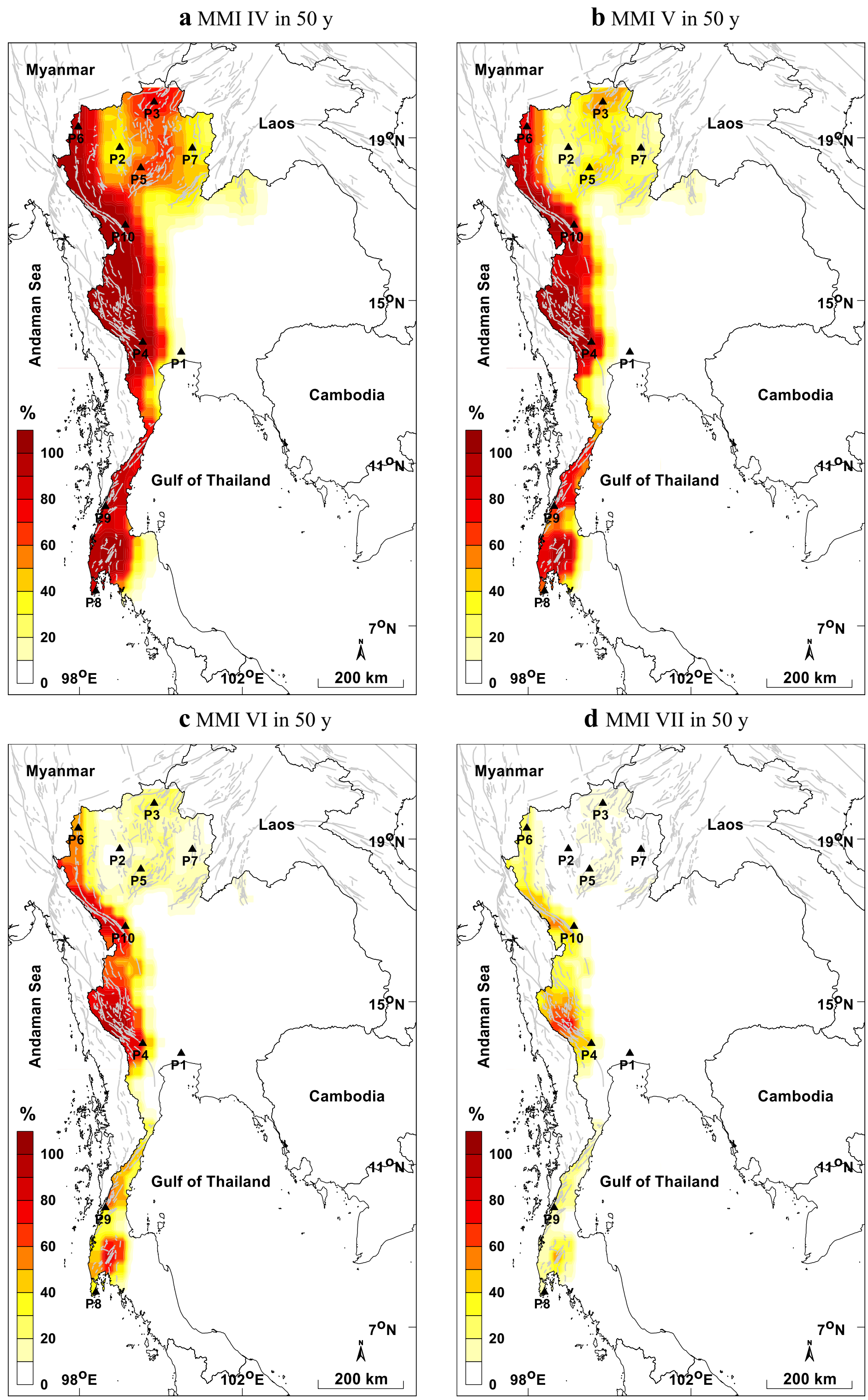

Fig. 6 PSHA maps of Thailand showing the probabilities (%) that earthquake intensity will be equal to or greater than each MMI level in the next 50 years. **a** IV: Felt indoors by many, outdoors by a few during the day. At night, some awakened. Dishes, windows, doors disturbed; walls make cracking sound. **b** V: Felt by nearly everyone; many awakened. Some dishes, windows broken. Unstable objects overturned. Pendulum clocks may stop. **c** VI: Felt by all, many frightened. Some heavy furniture moved; a few instances of fallen plaster. Damage slight. **d** VII: Damage slight to moderate in well-built ordinary structures; considerable damage in poorly built or badly designed structures; some chimneys broken

POE of earthquake intensity up to MMI level VI [level VI description: Felt by all, many frightened. Some heavy furniture moved; a few instances of fallen plaster. Damage slight.] for the next 50 years, highlighting the severe seismic hazard in this region. However, there was a <30 % POE of a MMI level VI earthquake in northern Thailand in the next 50 years. For the rest of the study area, the possible earthquake intensity was less than an MMI level IV [level IV description: Felt indoors by many, outdoors by few during the day. At night, some awakened. Dishes, windows, doors disturbed; walls make cracking sound.] and is zero in some places, such as in eastern, central, and northeastern Thailand (Fig. 6).

With respect to the ten major provinces evaluated, Kanchanaburi and Tak (P4 and P10 in Table 4) were defined as being comparatively high hazard areas, where the POE of a MMI level IV–VII earthquake was 99–37 %. The second highest hazard levels were located at Mae Hong Son (P6) and Ranong (P9) at around a 22 % POE of an intensity level VII earthquake in the next 50 years [level VII description: Damage slight to moderate in well-built ordinary structures; considerable damage in poorly built or badly designed structures; some chimneys broken.}. Surprisingly, Bangkok, the capital city of Thailand, which is located quite close to a number of earthquake sources in western Thailand, had only a 7 % POE of intensity level IV earthquake in the next 50 years (Table 4).

Conclusion

For Thailand, various approaches to evaluating the PSHA have been performed. However, since new paleoseismological data (fault slip rates) have become available for different fault segments, the PSHA was re-evaluated in this study. The advantage of this PSHA is that it was compiled from the most up-to-date data and was constrained theoretically, in particular for the paleoseismological data that are a significant factor in reliably estimating the characteristic long period and large earthquake effect to improve the accuracy of the PSHA. The a and b values of the Gutenberg–Richter relationships (seismicity parameters) were also used according to the most reliable statistical investigation (Pailoplee and Choowong 2014). By using the suitable strong ground-motion attenuation relationship, both ground shaking and probability maps were developed. In addition, the PSHA of specific sites was also estimated for ten major provinces in Thailand.

The results reveal that western Thailand contains the most earthquake-prone areas with a 2 and 10 % POE in the next 50 years of a 0.1–0.4 g and 0.1–0.2 g PGA, respectively. In northern Thailand, the ground shaking levels are lower, being in the range of 0.1–0.2 g. Among the ten major provinces in Thailand evaluated, Kanchanaburi and Tak were comparatively high hazard zones, with a 99–37 % POE of an MMI level IV–VII event. Therefore, effective mitigation plans for the provinces mentioned here should be developed.

However, according to the severity of the two last hazardous earthquakes during 2011–2014, i.e., the M_w 6.8 Tarlay (Wang et al. 2014) and M_L 6.3 Mae Lao (Soralump et al. 2014) earthquakes, the estimated ground shaking (PGA) or earthquake intensity (MMI) is still underestimated, even though the PSHA presented here used the most up-to-date maps of Thailand. For the M_L 6.3 Mae Lao earthquakes located at the Chiang Rai province, northern Thailand (latitude 19.66°N, longitude 99.67°E), the PGA measured at 20 and 1500 km distance from the epicenter is 0.3 and 0.00004 g, respectively (Soralump et al. 2014). Meanwhile in this PSHA, the PGA estimated in the northern part of Thailand is around 0.25 and 0.1 g for 2 and 10 % POE in the next 50 years.

In addition, according to the macroseismic survey after the M_L 6.3 Mae Lao earthquakes (Naksawee and Laddakul 2014), the levels of earthquake intensities are estimated up to IX and VIII covering an estimated 160 and 1600 km^2 in some parts of the Chiang Rai and Phayao provinces. Meanwhile, it is indicated in this study that there is only a 0–10 % that an earthquake of intensity level VII might be experienced in northern Thailand in the next 50 years. This underestimated PSHA may be caused by the inexact geometry of the seismogenic faults. With the limitation of the subsurface data, the existence of subsurface blind faults, including the exact fault segmentation, cannot be estimated accurately. Therefore, as the earthquake geology is estimated in greater detail, the PSHA accuracy will increase.

In addition, it is important to note that the PGA presented here was derived mainly for the rock site condition. In areas covered by thick, soft soils, the PGA will be much more severe than that indicated by this study. As a result, although Bangkok, the capital city of Thailand, was defined as being in a low seismic hazard area, further detailed investigation of the seismic wave amplification, due to the soft soil that dominates underneath Bangkok, is still needed.

Additional file

Additional file1: 1.txt-75.txt. Earthquake source files containing longitude (degree), latitude (degree), and depth (km), respectively. EQ-parameters.txt. 6 columns of earthquake source parameters used for this PSHA.

Authors' contributions

SP performed the seismic hazard analysis, designed the study and the sequence alignment, and drafted the manuscript. PC carried out the geological and paleoseismological data preparation. Both authors read and approved the final manuscript.

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Competing interests
The authors declare that they have no competing interests.

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