

Original Article

Probability seismic hazard maps of Southern Thailand

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Abstract

Seismic hazard maps of southern Thailand were obtained from the integration of crustal fault, areal and subduction source models using probability seismic hazard analysis and the application of a logic tree approach. The hazard maps show the mean peak ground and spectral accelerations at 0.2, 0.3 and 1.0 second periods with a 10%, 5%, 2% and 0.5% probability of exceedance in 50-year hazard levels. The highest hazard areas were revealed to be in the Muang, Phanom, and Viphavadi districts of Surat Thani province, the Thap Put district of Phang Nga province, and the Plai Phraya district of Krabi province. The lowest hazard areas are in the southernmost part of Thailand e.g. Yala, Pattani and Narathiwat provinces. The maximum values of the mean peak ground acceleration for the 475–9,975 yr return period are 0.28-0.52 g and the maximum spectral accelerations at 0.2 seconds for the same return period are 0.52-0.80 g. Similar hazard is also obtained for different return periods. Presented seismic hazard maps are useful as a guideline for the future design of buildings, bridges or dams, for rock sites to resist earthquake forces.

Keywords: probability seismic hazard map, Southern Thailand, logic tree, earthquake recurrence, CRISIS 2007

1. Introduction

The neotectonics of Thailand appear to be related to the interactions among the Indo-Australian, Eurasian, Philippine and Pacific plates combining with the opening of the Andaman Sea (Suensilpong; 1981, Polachan; 1988; Metcalfe, 2009) as shown in Figure 1. Thailand is situated within the Eurasian plate that is surrounded by the convergent margins of the Andaman subduction zone in the west, the Sunda and Java trenches in the south and the Philippine trench in the east.

The present tectonic regime in Thailand is transtension with extension along the north-south faults, right-lateral slip on the northwest-striking faults and left-lateral slip on

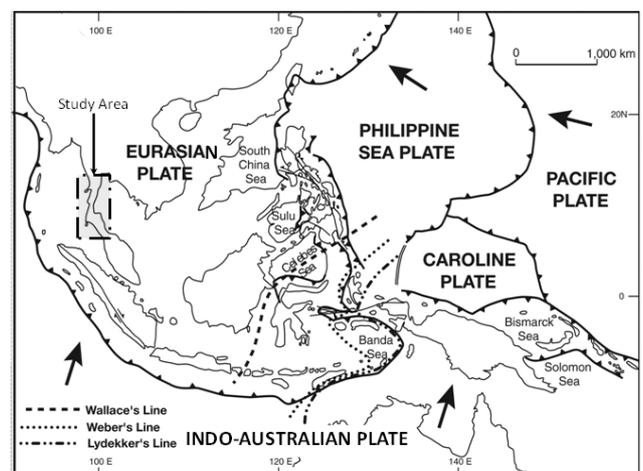


Figure 1. Plate tectonic map of Southeast Asia consisting of Eurasia, India-Australia, Philippine Sea, and Pacific plates and major plate boundaries (Metcalfe, 2009).

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the northeast-striking faults. The southern part of Thailand extends southward from the Three Pagodas fault (TPF) zone in Kanchanaburi province to the Malaysian border. It consists mainly of Carboniferous to Jurassic meta-sedimentary bedrocks intruded by Late Paleozoic to Mesozoic igneous rocks. The basement has been extensively faulted and folded with the orientation of predominant geologic structures being in the northeast-southwest direction. The inferred strike-slip faults in southern Thailand, the Ranong (RNF) and Khlong Marui (KMF) faults, do not suggest the presence of any large movement in the last 30 Ma (Morely, 2001). Based on the GPS data, there appears to be no motion of southern Thailand relative to the remainder of the country (Iwakuni *et al.*, 2004), and the whole of Thailand moves to the east at an equal rate of 3-4 cm per year (Phromthong *et al.*, 2005; 2006). Before 2004, it was believed that southern Thailand was a tectonically stable region (Warnitchai and Lisantoso, 1997). This is partly because there was no morphotectonic investigation of the surface faults associated with natural earthquakes in southern Thailand. However, many researchers have reported that the RNF and KMF in the Thai Peninsula are potentially active (Nutalaya *et al.*, 1985; Chuavirot, 1991; Hinthong, 1995; DMR, 2002). After the occurrence of two large earthquakes with a magnitude of M_w 9.0 to 9.3 (USGS, 2005a; Park *et al.*, 2005; Stein and Okal, 2005; Bilham, 2005; Ishii *et al.*, 2005) on the 26th December 2004 and one of M_w 8.6 (USGS, 2005b) on the 28th March 2005 that were located northwest of Sumatra Island, a number of small earthquakes have been recorded in Thai Peninsula (Duerrast *et al.*, 2007) and differential movement of Thai territory has been observed from the GPS (Simons *et al.*, 2005; Vigny *et al.*, 2005; Phromthong *et al.*, 2005; 2006). As a result, it can be inferred that the Thai Peninsula is not tectonically stable as had previously been thought.

Based on the earthquake data prior to the occurrence of the 2004 great Sumatra-Andaman earthquake and the lack of detailed information of potential active faults, most of Thailand's seismicity hazard maps show no seismic hazard in southern Thailand (Shrestha, 1986; Lukkunaprasit and Kuhatasanadeekul, 1993; Lisantono, 1994; Warnitchai and Lisantono, 1997; Charusiri *et al.*, 1997; Warnitchai, 1998). However, after 2004 there are at least three published papers presenting the seismic hazard of Thailand and nearby regions (Petersen *et al.*, 2007; Pailoplee, 2009; Palasri and Ruangrassamee, 2010) that reveal that southern Thailand will encounter earthquakes with either a low (Palasri and Ruangrassamee, 2010) or a very high (Pailoplee, 2009) seismic hazard. These different levels of ground shaking result from the use of different attenuation models and characteristics of the seismic sources are to be studied for a realistic hazard map. Therefore, the objective of this research work was to construct new probabilistic seismic hazard maps of southern Thailand with crustal fault sources derived from the paleoseismic investigations of the Department of Mineral Resources (DMR, 2007) and Sutiwanich (2010). A logic tree approach to reduce uncertainties of attenuation relationships,

recurrence models, and the parameters of seismic sources was adopted. A workflow of the research is presented schematically as shown in Figure 2.

The study area of this report is limited within the region bound by latitude 5.58°N to 13.5°N and longitude 97.5°E to 102.12°E.

2. Material and Methods

2.1 Seismic sources

All earthquake sources with demonstrated and trusted Holocene movement that could produce the ground motion hazard in southern Thailand due to their activities, duration, or distance to southern Thailand are included in this analysis. Source classifications are explained below and the locations are shown in Figure 3.

2.1.1 Crustal fault sources

The crustal fault sources that contribute significantly to the ground shaking of southern Thailand consist of the two major northeast-southwest trending faults (RNF and KMF) in southern Thailand (DMR, 2007; Sutiwanich, 2010), the TPF in western Thailand, the Kungyuangale (KYF), Tenessarim (TNF) and Tavoy (TVF) faults in southeastern Myanmar, and the Sumatra-Andaman subduction zone in the Andaman Sea.

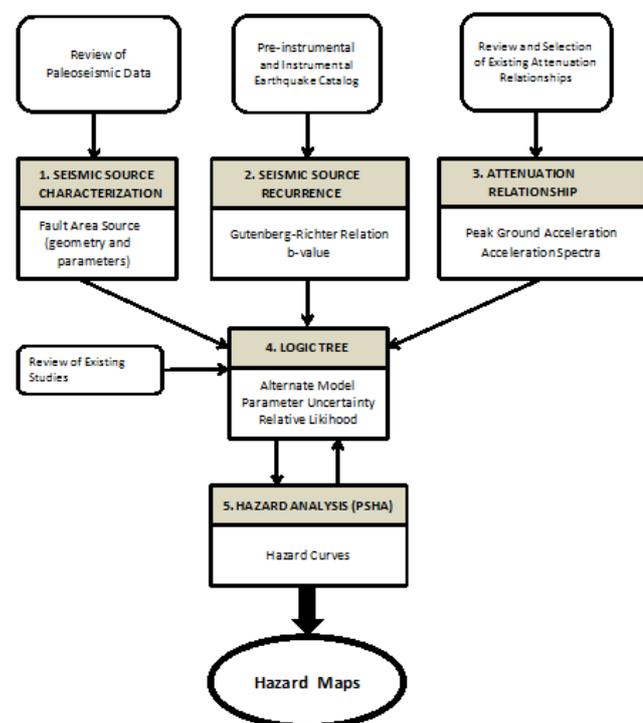


Figure 2. Flow chart showing steps of work in this study.

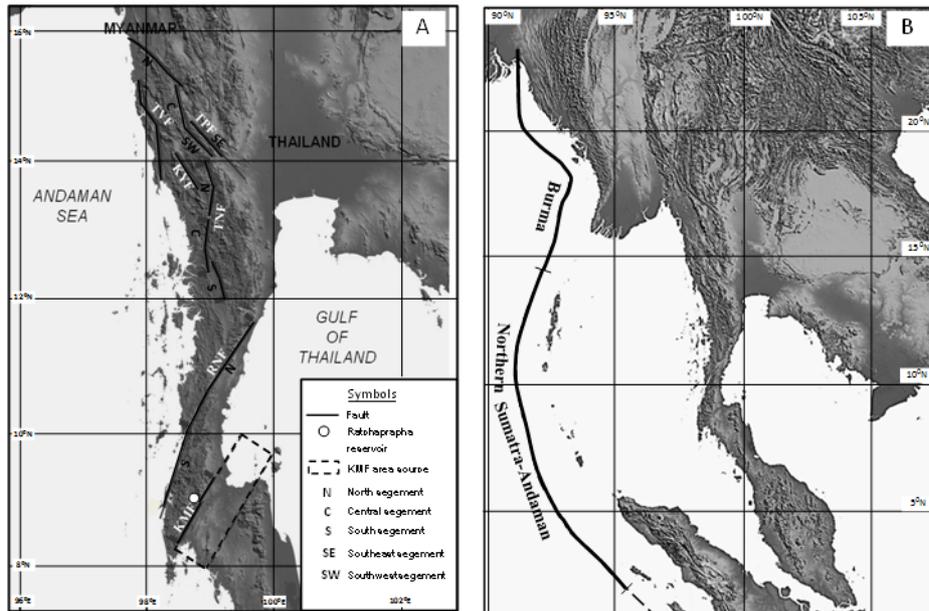


Figure 3. Seismicity sources in southern Thailand and adjacent areas, A = crustal source and B = subduction zone source, KMF = Khlung Marui fault, RNF = Ranong fault, TNF = Tenasserim fault, KYF = Kungyauangale fault, TVF = Tavoy fault, TPF = Three Pagoda fault, and Northern Sumatra-Andaman subduction zone

Based on the interpretation of the shuttle radar topographic mission (SRTM) images (NASA, 2006), field checking and re-evaluation of previous paleoseismic investigations (RID, 2006, 2008; DMR, 2007; Sutiwanich, 2010), the characteristics of the KMF and RNF can be concluded as follows.

The longest segment of the KMF extends from southwestern Thap Put district, Phang Nga province northeastwards passing through Phanom district, Surat Thani province to Viphavadi district, Surat Thani province, with a total length about 115 km. The KMF is an active fault with a potential maximum earthquake magnitude of M_w 7.5, and with the latest movement occurring about 1,700-2400 years ago and with a slip rate of 0.08-0.5 mm/yr. The RNF is located from the Thap Sakae district, Prachuab Khirikun, at the Gulf of Thailand and passes Chumporn province and to end at Takua Pa district, Phang Nga province, and Ban Ta Khun district, Surat Thani province. The RNF can be divided into two distinct segments. The first segment, from Thap Sakae district at the coast of the Gulf of Thailand proceeds to Kra Buri district, Ranong province, with a length of 180 km. The second segment extends from the first segment at Kra Buri district, and goes along the Andaman coast, to terminate at Takua Pa district of Phang Nga province with a length of 160 km. The maximum paleo-earthquake magnitude generated by the RNF is estimated to be equivalent to M_w 7.9. In accordance with the re-evaluated RNF activity, it is inferred that the RNF is active with the latest movement occurring about 8,300 years ago, has a mean recurrence interval of approximately $8,300 \pm 6,400$ years, and a slip rate of 0.04-0.17 mm/yr.

According to Wong *et al.* (2005) and the Royal Irrigation Department (RID (2006, 2008, 2009), the results of

satellite image show that the TNF is located in Myanmar, just west of Prachuab Khirikun province. It is a 200-km long northwest- to north-northwest-striking, right-lateral strike-slip fault. Based on geomorphic expression, the fault can be classified into three sections. The first (north) section has a length of 80 km and transverses an upland area to the north of the Tenasserim river valley. The second (central) section is about 100 km long and is the upper reach of the Tenasserim river valley. The third (south) section has a length of 55 km and is situated along the Tenasserim river valley. Based on the surface rupture length equation proposed by Well and Coppersmith (1994), if the TNF ruptures entirely, it would potentially produce an earthquake of M_w 7.6 maximum magnitude. The estimated slip rate falls within the range of 0.1-4 mm/yr (Wong *et al.*, 2005; RID, 2006, 2008, 2009; Pailoplee, 2009).

The orientation, characteristic and other parameters of the KYF for the hazard analysis are derived from the reports of Wong *et al.* (2005) and RID (2006, 2008, 2009). In summary, the KYF is a 235-km long, northwest striking fault that is located in the Tenasserim province of Myanmar. On the satellite images, the geomorphic features of the fault indicate that it is an active right lateral strike-slip fault with a slip rate of 0.1-4.0 mm/yr, and could generate an earthquake of a maximum magnitude of M_w 7.0.

The characteristics of the TVF are derived from the report on the seismic hazard evaluation of Khao Laem and Srinagarind dams by WCFS (1998). The TVF is a north-northwest-striking right-lateral strike-slip fault. Remote sensing analysis demonstrates that the TVF is about 300 km in length without any segmentation. So, based on the likely

rupture behavior, it is assumed to generate an earthquake with a maximum magnitude of M_w 7.5, which could be triggered anywhere along the whole length of the fault. The slip rates of the fault are estimated to be within the range of 1-10 mm/yr.

The TPF extends from Myanmar southeastward to the northwest of Kanchanaburi province, passing through the Khao Laem and Srinagarin dams. The fault orientates in the northwest-southeast direction and has a right-lateral movement. In terms of geomorphology, the fault is an active structure and can be divided into the following four segments: (i) a 165-km-long north segment (in Myanmar), (ii) a 95-km-long central segment, (iii) a 70-km-long southwest segment, and (iv) an 80-km-long southeast segment (WCFS, 1998). The north, central, southwest and southeast segments can generate earthquakes with potential maximum magnitudes of M_w 7.5, 6.5, 6.8 and 6.8, respectively, whilst the slip rate of the entire TPF is estimated to range from 0.1 to 4 mm/yr (WCFS, 1998).

2.1.2 Areal sources

Based on the occurrence of earthquakes, there are two types of areal sources identified in this study, i.e. (1) Ratchaphra reservoir-triggered seismicity (RTS) and (2) background earthquakes of which the epicenters are distributed in the KMF zone (KMFZ), as illustrated in Figure 4.

The construction of the Ratchaphra dam in Surat Thani province was completed on June 1988. Twenty four RTSs with magnitudes of M_L 0.4-3.4 occurred from June 1988 to December 1993 due to impoundment of the Ratchaphra reservoir (TEAM, 1995). The latest RTS event of M_L 1.4 was recorded by the Electricity Generating Authority of Thailand (EGAT) on the 27th October 2006. In the hazard analysis, the preferred seismogenic depth of the RTS is 10 km, based on the RTS recorded at the reservoirs of Srinagarind and Wachiralongkorn dams (Wong *et al.*, 2005), and the maximum magnitude is that of M_w 5.5 (WCFS, 1998). The Ratchaphra dam's reservoir area is, therefore, defined as the areal earthquake source in this study.

Besides the small aftershock earthquakes recorded by the mobile recorders between 14th January 2005 and 30th June 2005 (Duerrast *et al.*, 2007), four earthquake events were also recorded by the Thai Meteorological Department (TMD) in the KMFZ during the years 2006-2008 (Figure 4). The area covering these earthquakes is specified as the areal earthquake source in this study as well.

2.1.3 Sumatra-Andaman subduction zone

The Sumatra-Andaman subduction zone or Sunda subduction zone can be divided into four major sections: the Burma, Northern Sumatra-Andaman, Southern Sumatra, and Java zones (Petersen *et al.*, 2007). The Northern Sumatra-Andaman section appears to be the most significant zone affecting the ground shaking in southern Thailand (Figure 3)

and is included in the hazard analysis. In addition, the earthquake produced from the megathrust with a magnitude of M_w 9.1 in 2004 is included in the hazard analysis.

2.2 Earthquake recurrence

Seismicity data from 1962 to 2008 were compiled for the study area and nearby regions. They were mainly derived from that reported by Nutalaya *et al.* (1985), the TMD seismicity catalogue, the U.S. Geological Survey (USGS), the International Seismological Center (ISC) catalogue, the International Seismological Summaries (ISS), the National Earthquake Information Service (NEIC) Preliminary Determination of Epicenter (PDE), EGAT's earthquake data and the Department of Geophysics, at the Prince of Songkhla University.

In this study, all magnitudes shown in these catalogues, which were recorded in various terms of the body wave magnitude (m_b), the surface wave magnitude (M_s) or the local magnitude (M_L), were first converted to M_w . The local relationship developed from earthquake data in Thailand and adjacent areas by Palasri (2010) was adopted to convert M_L to m_b and then the global relationship established by Idriss (1985) was used to convert m_b and M_s to M_w . The dependent events, i.e. induced seismicity, foreshocks, aftershocks and

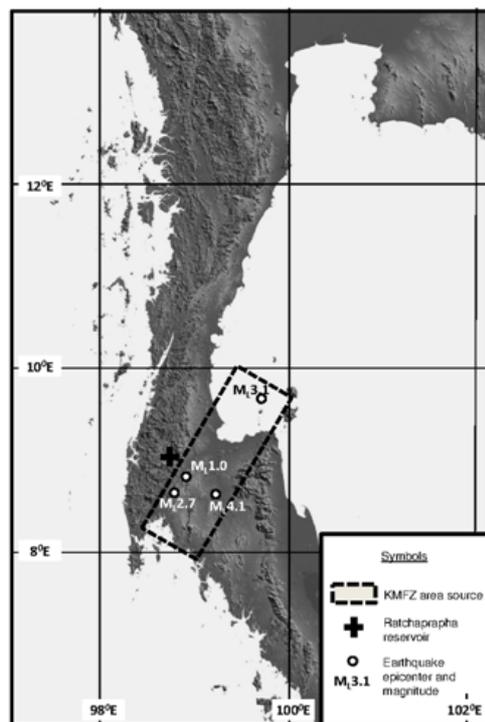


Figure 4. Four earthquakes were detected by TMD in the KMFZ during the years 2006-2008, namely M_L 1.0 = epicenter at Phanom district, Surat Thani province, M_L 3.1 = epicenter Ang Thong Island belt, Surat Thani province, M_L 2.7 = epicenter at Pli Phraya district, Krabi province, and M_L 4.1 = epicenter at Phra Saeng district, Surat Thani province.

smaller earthquakes within an earthquake swarm, were identified and cleaned out from the catalogues using the technique developed by Gardner and Knopoff (1974).

From the completely filtered catalogues, the set of earthquakes for which the magnitude was more than the chosen threshold magnitude, the so-called lower bound magnitude (equal or more than M_w 4 or M_w 4.5) were selected for the establishment of magnitude-recurrence relationships according to the Gutenberg-Richter recurrence law (Kramer, 1996). This relationship specifies the average rate at which an earthquake of a given magnitudes will be exceeded. There are a few earthquakes that were associated with all the fault sources in southern Thailand and southeastern Myanmar, except for the Sumatra-Andaman subduction zone (Figure 5). Since it is not possible to develop the recurrence relationships of individual fault sources, the application of all available background (floating or random) earthquakes was performed to estimate the earthquake recurrence in the region. Estimation of the historical recurrence rate (b-value) was carried out based on the maximum likelihood procedure developed by Weichert (1980). We assume that the background recurrence rate corresponds to the fault recurrence.

2.2.1 Southern Thailand and adjacent areas

The recurrence relationships of the background earthquakes in southern Thailand and the adjacent areas covering the southern, eastern, western and central Thailand, and the Andaman Sea (approximately 800,000 km²) were developed. Using the earthquake events collected from 1962 to 2008, a total of 47 earthquake events were obtained for hazard evaluation. These events were classified as the quantity of earthquakes in 0.5 M_w magnitude intervals, and the recurrence curve is plotted (Figure 6). The computed recurrence curve fits the data quite well and the estimated b-value is 1.03 ± 0.04 (σ), which is almost equal to the global average of 1.00.

2.2.2 Sumatra-Andaman subduction zone

The recurrence for the intraslab zone of the Sumatra-Andaman subduction zone was analyzed in a similar manner to the recurrence calculation of the southern Thailand and adjacent areas (section 2.2.1). The earthquake data with magnitudes of M_w 4.5-7.5 were compiled from 1962 to 2008. The total of 498 such defined independent events were then classified as the number of earthquakes in each 0.5 M_w magnitude interval and the recurrence curves were plotted (Figure 7). The b-value was calculated to be 0.97 ± 0.03 (σ), which again is almost equal to the global average of 1.00.

The recurrence relationships for the fault sources used in this study are derived using the exponentially truncated Gutenberg-Richter model (Cornell and Van Marcke, 1969) and the characteristic model (Schwartz and Coppersmith, 1984; Youngs and Coppersmith, 1985). However, only the truncated exponential recurrence model is assumed to be suitable for

the areal sources.

2.3 Attenuation relationships

The most important factor concerning the calculation of the ground motion at the site is how the seismic wave attenuates with distance from the source. This decrease in the ground motion with increasing distance from the earthquake source is dependent upon many factors, including geometrical spreading, damping or absorption by the earth, scattering, reflection, refraction, diffraction and wave convection.

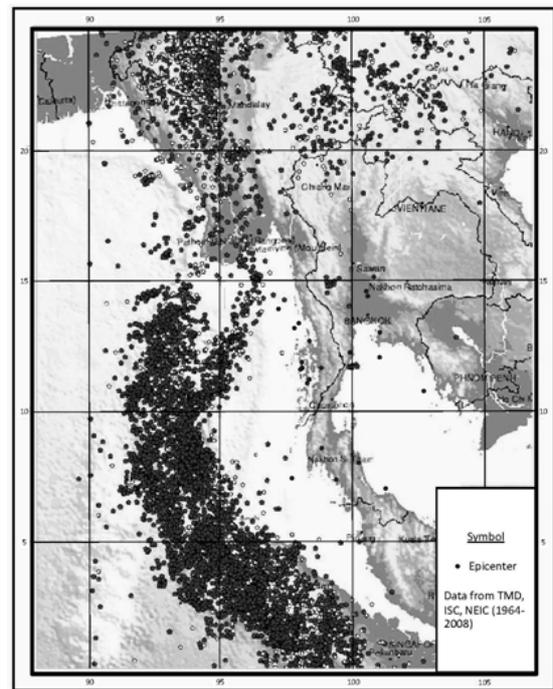


Figure 5. Map of epicenters for the period of 1964-2008, data obtained from the TMD, ISC and NEIC.

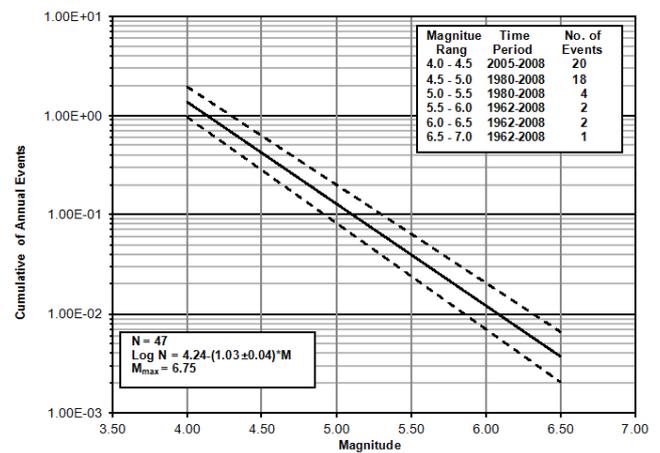


Figure 6. Earthquake recurrence for southern Thailand and adjacent areas.

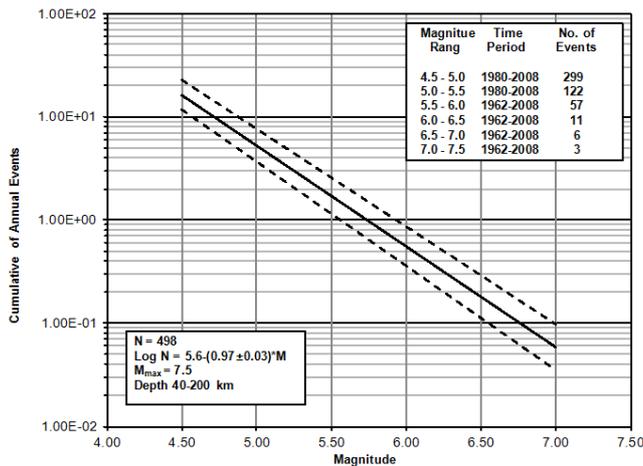


Figure 7. Earthquake recurrence for the intrslab zone of Sumatra-Andaman subduction zone.

Regardless, this phenomenon can be predicted using empirical attenuation models that have been developed from numerous strong ground motion records by applying the statistical regression method. Usually, the attenuation relationships can only be used in the region where they were developed. However, they may be adopted in other regions of similar seismotectonic settings. In Thailand, there are insufficient strong ground motion records for developing the attenuation models correctly and so the applied attenuation models have to be selected from other places. However, at present there are many different attenuation models that have been developed empirically from the strong ground motion triggered by several crustal faults and subduction zones, as summarized by Douglas (2001). In this study, both crustal earthquake and subduction zone sources are included. Therefore, the most suitable attenuation models developed from the crustal earthquake and subduction zone were chosen for the hazard analysis.

In southern Thailand, the RID (2006, 2008, 2009) reported that only four strong ground motion models developed in western North America for crustal earthquakes, namely those of Boore *et al.* (1997), Abrahamson and Silva (1997), Campbell and Bozorgnia (2003) and Sadigh *et al.* (1997) are suitable for seismic hazard application in the southern part of Thailand. Moreover, Pailoplee (2009) concluded that the model of Sadigh *et al.* (1997) was suitable for application in PSHA in Thailand. In addition, Harnpattapanich (2010) emphasized that the geology of central and eastern Thailand is broadly similar to that of the western USA. Therefore, four attenuation relationships were selected for the PSHA in this study.

The calculation of the ground motion in southern Thailand generated by the Sumatra-Andaman subduction zone is applied by using the attenuation relationships developed by Youngs *et al.* (1997) and Atkinson and Boore (2003). These two relationships were established from the strong motion data from Japan, Mexico, Chile, and the 2001

Nisqually earthquake in the Puget Sound of Washington (U.S.).

2.4 Logic tree approach

The logic tree approach was first introduced into PSHA by Power *et al.* (1981) and then became a well-defined standard method used in the analysis (Coppersmith and Youngs, 1986; Reiter, 1990). However, this PSHA has various inherent uncertainties associated with it due to the incomplete understanding of earthquake phenomena. Assumptions on the constrained parameters for the PSHA are composed of earthquake locations and sizes, potential occurrence of future earthquakes, and what earthquake affects. The best approach to deal with these uncertainties in the PSHA is to utilize a logic tree concept. Logic trees can be applied and implemented easily with a common form and are comprised of two steps: (1) to specify the sequence of the hazard analyses, and (2) to define the uncertainties in each of these analyses in a sequential manner.

The logic tree is a decision flow path consisting of nodes and branches. Each branch represents a discrete choice of a parameter and is assigned a likelihood of being correct. The nodes are connecting points between input elements. Practically, various branches are specified in a given node to sufficiently represent the uncertainties in the estimated parameters. Probabilities or weights are assigned in each parameter that are usually based on the subjective judgments. The summation of the probability at each node is unity.

In this study, discrete values representing the likelihood of an actual earthquake as derived from the source parameters were included in the logic tree approach. These input parameters consisted of the seismogenic crustal thickness, fault segmentation, maximum magnitude, probability of activity and the slip rate. Other than the source characteristics, the attenuation relationships and recurrence model are also considered in the logic tree approach. The input parameters, such as the seismogenic crustal earthquake, maximum magnitude and slip rate are normally defined by three values, consisting of a preferred value and a range of higher and lower values that are similar to the normal or lognormal statistical distribution (US Army Corp of Engineer, 1999). Weights were assigned to each parameter in order to specify their distribution, and these were based on the results of the statistical analyses of Keefer and Bodily (1983) and subjective judgments. Keefer and Bodily (1983) reported that the best discrete approximation of the continuous distribution is the three point distribution with 5th, 50th and 95th percentiles weighted at about 0.2, 0.6 and 0.2, respectively. These weighted values were applied to the weight of the seismogenic depth and magnitude in this study. Furthermore, Keefer and Bodily (1983) found that if the data are limited to determine the 5th and 95th percentiles of the distribution, the 10th, 50th and 90th percentiles are optimally weighted at about 0.3, 0.4 and 0.3, respectively. So, these values were also adopted

to weight the slip rates in this study. In case of two branches, the strongly preferred branch was weighted as 0.9 and the remaining branch as 0.1 (US Army Corp of Engineer, 1999). These weights were then applied to the earthquake source types of the KMF with the weights of the KMF's line and areal sources being 0.1 and 0.9, respectively.

In case of the earthquake source activity, the probability of the source activity and slip rates were characterized. The weights assigned to the activity of the sources were derived from the ability of the sources to independently produce the earthquake and the possibility that it is still active within the present stress field. Any fault that has evidence of active faults, based on USGS's definition, means the fault has moved one or more times in the last 10,000 years and are ascribed as a weight for activity of 1.0.

The attenuation models used for the crustal seismic sources and the Sumatra-Andaman subduction zone are not well developed in Thailand. Furthermore, strong ground motion data in Thailand is insufficient to prove which model is the most suitable for application. So, the four attenuation relationships for the crustal earthquakes were equally weighted as were the two attenuation relationships for the Sumatra-Andaman subduction zone earthquakes.

An example of the logic tree approach, showing that used for the KMF, is illustrated in Figure 8. The parameters

and their weights applied in the logic tree for each earthquake source are given in Table 1.

2.5 Probabilistic seismic hazard analysis (PSHA)

The PSHA approach applied in this study is based on the methodology initially developed by Cornell (1968). The analysis was performed using the CRISIS 2007 software program (Ordaz, Aquila and Arboleda, 2007) for 224 sites in southern Thailand that cover the southernmost Yala province northwards to Phetchaburi province. The sites are determined by a grid system basis of 5.58°N to 13.5°N latitude, and 97.5°E to 102.12°E longitude. Each point of the grid crossing has a spacing of about 0.33° or approximately 36 km. The hazard maps of southern Thailand, shown as contour maps for the mean PGA and the spectral acceleration at 0.2, 0.3, and 1.0 second natural periods at a 5% damping ratio with a 10%, 5%, 2% and 0.5% probability of exceedance in 50-year hazard levels, which correspond to a return period of 475-, 975-, 2,475- and 9,975-years, respectively, are depicted in Figures 9 to 12. These hazard maps are based on the rock site condition with a shear wave velocity ranging from 360 to >1,500 m/s for the upper 30 m of the crust (Building Seismic Safety Council, 2003 and 2010).

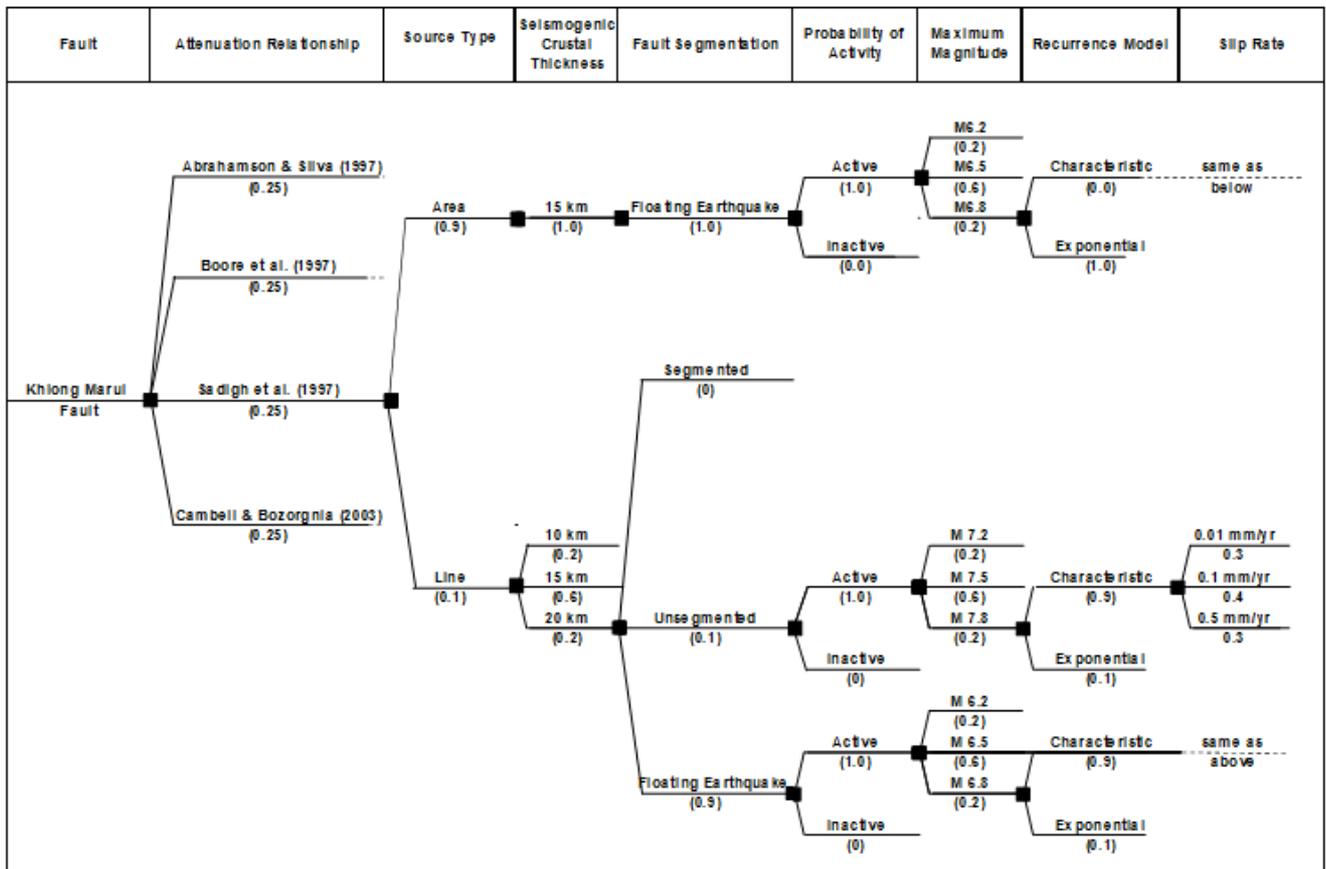


Figure 8. An example of the logic tree applied for the Khlong Marui fault in this study.

Table 1. Parameters and their weights adopted in the logic tree approach for each earthquake source.

Source	Fault Width		Earthquake Source			Rupture Scenario			Magnitude		Recurrence Models		Slip Rate						
	(km)	Weight	Type	Weight	Type	Weight	Length (km)	Weight of Activity	(M)	Weight	Models	Weight	(mm/yr)	Weight					
KMF	15	1.0	Area	0.9	Floating	1.0	1.0	6.2	0.2	C	0.9	0.01 ^{1,2}	0.3						
									0.6	E		0.1			0.1 ^{1,3}				
									0.2						0.5 ¹				
	10	0.2	Line	0.1	Unsegmented	0.1	115	1.0	7.2	0.2									
									7.2	0.6									
									7.8	0.2									
									Floating	0.9						1.0	6.2	0.2	
																	6.5	0.6	
																	6.8	0.2	
									RNF	10						0.2	Line	1.0	Unsegmented
7.9	0.6	E	0.5	0.05 ¹															
8.2	0.2			0.1 ^{1,2}	0.3														
15	0.6									7.4	0.2								
										7.7	0.6								
										8.0	0.2								
										South						160	1.0	7.2	0.2
																		7.5	0.6
																		7.8	0.2
										Floating	0.9					1.0	6.5	0.2	
6.75	0.6																		
7.0	0.2																		
TNF	10	0.2	Line	1.0	Unsegmented	0.1	235	1.0	7.3	0.2	C	0.7	0.1 ⁴	0.3					
									7.6	0.6			E		0.3	2 ⁴			
									7.9	0.2						4 ^{3,4}	0.3		
	15	0.6								6.9	0.2								
										7.2	0.6								
										7.5	0.2								
										Central	0.9					100	1.0	7.0	0.2
																		7.3	0.6
																		7.6	0.2
										South						55	1.0	6.7	0.2
KYF ^{4,5}	10	0.2	Line	1.0	Unsegmented	0.9	55	1.0	6.7	0.2	C	0.5	0.1	0.3					
									7.0	0.6			E		0.5	2			
									7.3	0.2						4	0.3		
	15	0.6								6.2	0.2								
										6.5	0.6								
										6.8	0.2								
										Floating	0.1					1.0	6.2	0.2	
																	6.5	0.6	
																	6.8	0.2	
										TVF ⁶	10					0.2	Line	1.0	Unsegmented
7.5	0.6	E	0.5	4															
7.8	0.2			10	0.1														
TPF ⁶	10	0.2	Line	1.0	North		165	0.9	7.2		0.2	C	0.7	0.1	0.2				
									7.5		0.6			E		0.3	2		
									7.8		0.2						4	0.1	
	15	0.6									6.5	0.2							
											6.8	0.6							
											7.1	0.2							
											Central	1.0					100	0.4	6.2
										6.5									0.4
										6.8									0.3
										Southwest		70					0.5	6.2	0.3
6.5	0.4																		
6.8	0.3																		
Southeast		80	0.5	6.5	0.3														
				6.8	0.4														
				7.1	0.3														
SASZ	40	1.0	Line	1.0	Unsegmented	1.0	1.0		8.9	0.2	C	1.0	20	0.5					
									9.1	0.6			40						
									9.3	0.2			0.5						
RPP RTS	8	0.2	ARE	1.0	Floating	1.0			5	0.2	E	1.0							
									5.5	0.6									
									15	0.2									

Note: KMF = Khlong Marui fault, RNF = Ranong fault, TNF = Tenessarim fault, KYF = Kungyuangale fault, TVF = Tavoy fault, TPF = Three Pagoda fault, SASZ = Sumatra-Andaman subduction zone, RPP RTS = Ratchaprapha reservoir triggered seismicity
¹this study, ²Petersen *et al.* (2007), ³Pailoplee (2009), ⁴Wong *et al.* (2005), ⁵RID (2006, 2008, 2009), ⁶WCFS (1998)

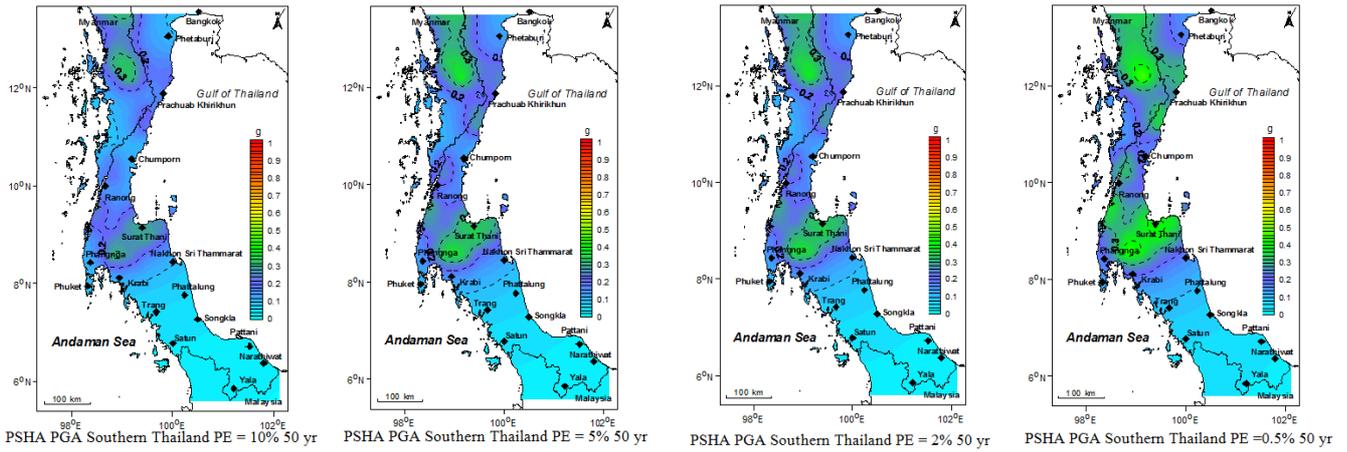


Figure 9. Hazard maps of southern Thailand showing the PGA with 10%, 5%, 2% and 0.5% probability exceedance in 50-yr hazard level for firm rock site condition.

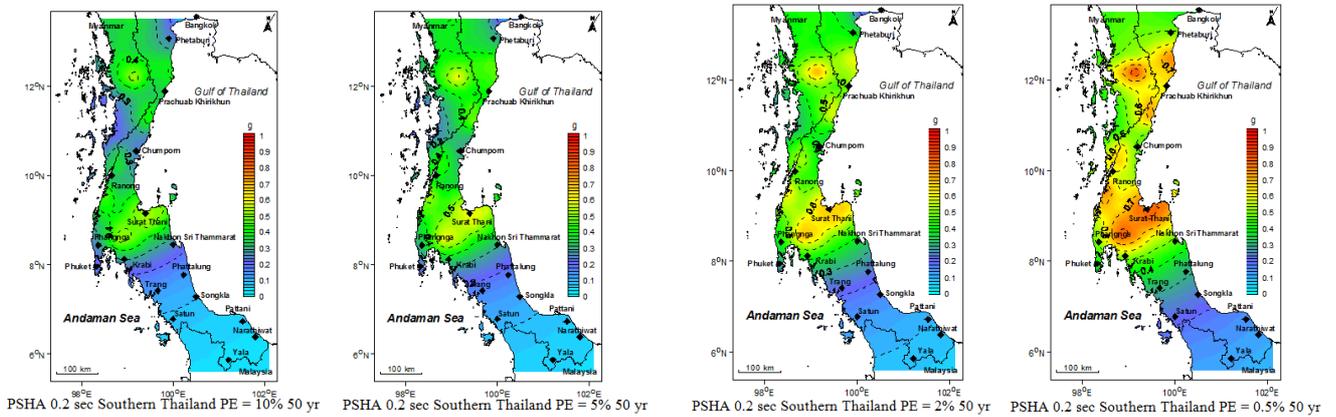


Figure 10. Hazard maps of southern Thailand showing 0.2 sec spectral acceleration with 10%, 5%, 2% and 0.5% probability exceedances in 50-yr hazard level for firm rock site condition.

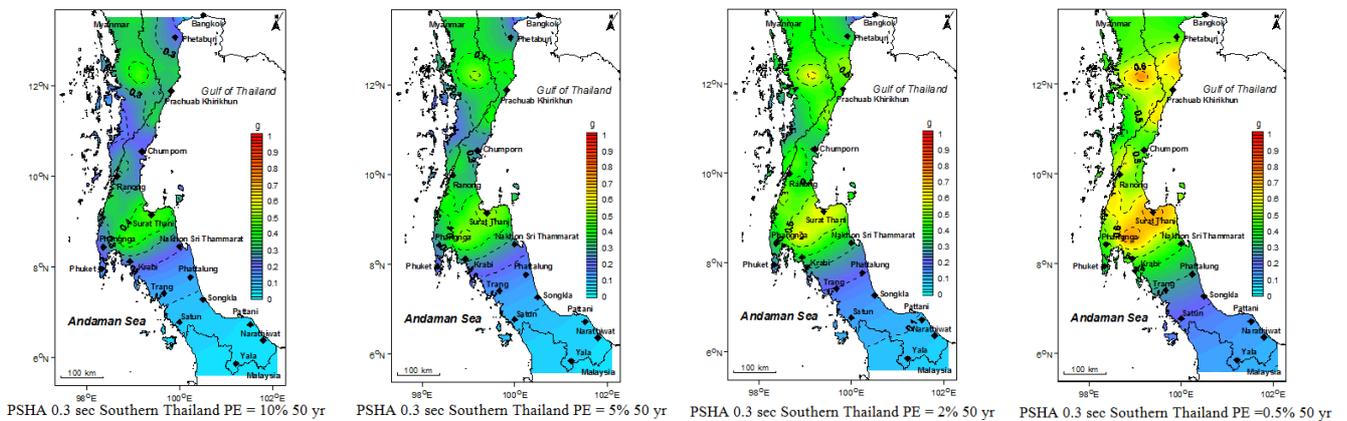


Figure 11. Hazard maps of southern Thailand showing 0.3 sec spectral acceleration with 10%, 5%, 2% and 0.5% probability exceedances in 50-yr hazard level for firm rock site condition.

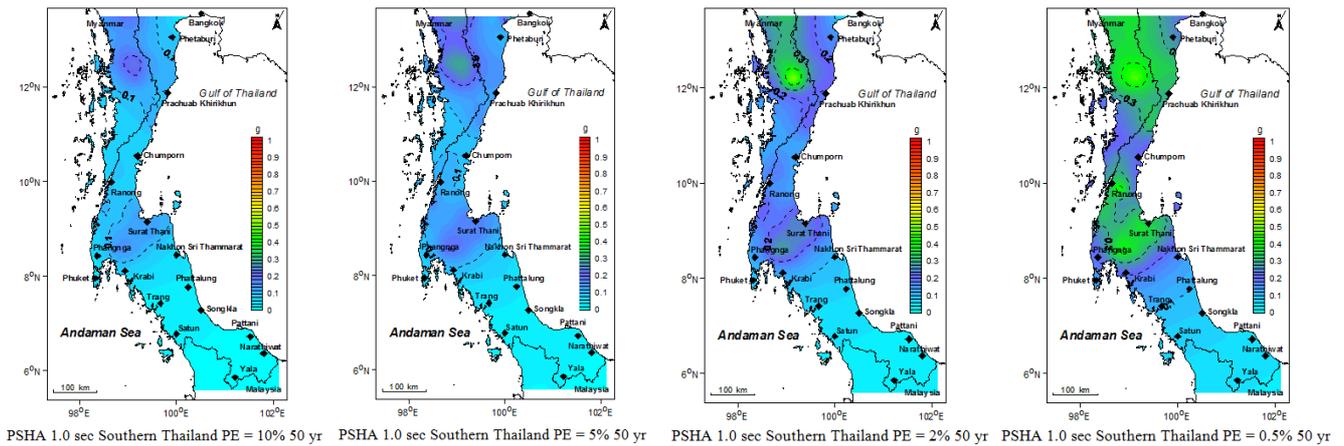


Figure 12. Hazard maps of southern Thailand showing 1.0 sec spectral acceleration with 10%, 5%, 2% and 0.5% probability exceedances in 50-yr hazard level for firm rock site condition.

3. Results

The horizontal PGA in southern Thailand is in the range of 0.02-0.30 g, 0.02-0.34 g, 0.03-0.42 g and 0.05-0.54 g, corresponding to a return period of 475, 975, 2,475 and 9,975 years, respectively. In case of the long structural period of 1.0 second, the spectral acceleration is <0.02-0.16 g, 0.02-0.22 g, 0.02-0.30 g and 0.04-0.40 g for 475-, 975-, 2,475- and 9,975-year return periods, respectively. The highest ground motion derived from the moderate period for stiff structures (0.2 second) is in the spectral acceleration range of 0.05-0.52 g, 0.06-0.58 g, 0.08-0.68 g and 0.11-0.80 g for the return periods of 475, 975, 2,475 and 9,975 years, respectively. The spectral acceleration of the ground motion for the period of 0.3 second is 0.04-0.44 g, 0.05-0.52 g, 0.07-0.60 g and 0.11-0.73 g for the return period of 475, 975, 2,475 and 9,975 years, respectively. It can be seen that the calculated ground motion for the PGA and long period of 1.0 second at the return period of 9,975 years is about two times higher than that at the return period of 475 years whereas for the moderate period of 0.2 second the spectral acceleration at the 9,975-year return period is approximately 1.5 times higher than that at the 475-year return period. The ranges of accelerations for the same time period with different return periods for each province in southern Thailand are also summarized in Table 2. In general, it can be concluded that the highest hazard areas are in Surat Thani province and some parts of northern Krabi, eastern Phang Nga and northern Nakhon Sri Thammarat provinces, whilst the lowest hazard areas are in the deepest southern part of Thailand, consisting of Yala, Pattani and Narathiwat provinces.

4. Conclusions

The seismic hazards of southern Thailand have previously been analyzed as a part of seismic hazard analysis of

the whole of Thailand and the adjacent areas using regional seismic source zones under the implicit assumption of no significant regional variance. A PSHA in this study was carried out using the most recent data on seismic source characteristics. Three seismic source models, namely the background, crustal faults, and subduction zone, were included in the analysis. The earthquake generated from the intraslab is excluded in the analysis because the intensity of earthquakes originating from the intraslab rapidly decreases with the distance away from the origin (Atkinson & Boore, 2003). In order to consider epistemic uncertainties of seismogenic depths, fault ruptures, magnitudes, slip rates, recurrence models and attenuation models, a logic tree approach was applied. The contribution of the ground motion at southern Thailand from the crustal faults was found to be more important than that of the Sumatra-Andaman subduction zone. The PSHA derived maps show the high ground shaking along the KMF and RNF. The maximum ground motion is located along the KMFZ at Thap Put district of Phang Nga province, Muang, Phanom and Viphavadi districts of Surat Thani province, and Plai Phraya district of Krabi province. The highest mean PGAs in southern Thailand were 0.28 g, 0.34 g, 0.42 g and 0.54 g at the 10%, 5%, 2% and 0.5% probability of exceedance, respectively, in 50 years for a rock site condition. The seismic hazard maps derived from this research are useful as a guideline for the preliminary design of buildings and high hazard structures located on the rock stratum to resist the earthquake force. If any high hazard structures, such as high dams, are to be designed, then the suitable PGA at specified return periods should be studied and evaluated repeatedly. For structures to be founded on soil, as opposed to on rock, it was found that the PGA or spectral accelerations from the seismic hazard maps could not be adapted directly to the design, as the earthquake amplification and liquefaction phenomena need to be considered as well. Based on the integration of up-to-date earthquake activity and

Table 2. Mean peak ground accelerations and the spectral acceleration at 0.2, 0.3, and 1.0 seconds with a 10%, 5%, 2% and 0.5% probability of exceedance in 50-year hazard levels (475, 975, 2,475, and 9,975 years) for rock site condition at each province in southern Thailand.

Province	Minimum-Maximum Acceleration (g)															
	475-return year			975-return year			2,475-return year			9,975-return year						
	PGA	Spectral Acceleration		PGA	Spectral Acceleration		PGA	Spectral Acceleration		PGA	Spectral Acceleration					
		0.2 sec	0.3 sec		1.0 sec	0.2 sec		0.3 sec	1.0 sec		0.2 sec	0.3 sec	1.0 sec	0.2 sec	0.3 sec	1.0 sec
Phetchaburi	0.1-0.22	0.24-0.38	0.20-0.35	0.07-0.16	0.13-0.28	0.30-0.42	0.26-.39	0.1-0.22	0.16-.32	0.34-0.52	0.32-0.48	0.14-0.30	0.24-0.38	0.44-0.70	0.44-0.64	0.25-0.37
Prachuab																
Khirkhun	0.14-0.22	0.22-0.40	0.18-0.35	0.06-0.15	0.18-0.28	0.28-0.48	0.22-0.42	0.08-0.20	0.26-0.34	0.32-0.58	0.26-0.52	0.13-0.30	0.34-0.46	0.56-0.76	0.55-0.68	0.2-0.32
Chumporn	0.12-0.16	0.28-0.38	0.20-0.30	0.08-0.09	0.16-0.22	0.30-0.42	0.26-0.38	0.09-0.12	0.18-0.30	0.36-0.48	0.33-0.45	0.12-0.18	0.26-0.40	0.48-0.64	0.47-0.58	0.20-0.39
Ranong	0.12-0.24	0.26-0.44	0.22-0.34	0.07-0.10	0.16-0.30	0.32-0.52	0.28-0.42	0.1-0.14	0.20-0.38	0.40-0.60	0.34-0.50	0.14-0.20	0.30-0.50	0.52-0.74	0.44-0.64	0.23-0.38
Surat Thani	0.16-0.30	0.34-0.52	0.30-0.44	0.08-0.14	0.20-0.34	0.40-0.58	0.34-0.52	0.15-0.18	0.26-0.42	0.48-0.66	0.42-0.59	0.16-0.26	0.34-0.52	0.58-0.80	0.52-0.72	0.26-0.39
Phangnga	0.10-0.26	0.24-0.46	0.19-0.42	0.05-0.09	0.12-0.30	0.28-0.52	0.24-0.48	0.07-0.18	0.16-0.38	0.34-0.62	0.30-0.56	0.10-0.24	0.22-0.48	0.44-0.68	0.40-0.68	0.16-0.36
Krabi	0.08-0.30	0.18-0.52	0.14-0.44	0.04-0.14	0.10-0.34	0.22-0.58	0.18-0.52	0.05-0.18	0.12-0.42	0.28-0.68	0.24-0.60	0.08-0.26	0.16-0.54	0.38-0.80	0.34-0.73	0.13-0.40
Phuket	0.07-0.09	0.14-0.20	0.14-0.19	0.04-0.05	0.08-.10	0.20-0.28	0.18-0.24	0.05-.07	0.11-0.15	0.24-0.32	0.23-0.31	0.07-0.10	0.16-0.22	0.36-0.46	0.32-0.40	0.12-0.16
Nakhon Sri																
Thamarat	0.07-0.26	0.14-0.48	0.13-0.42	0.03-0.12	0.08-0.30	0.20-0.56	0.16-0.47	0.05-0.16	0.10-0.36	0.26-0.65	0.22-0.55	0.07-0.22	0.14-0.46	0.32-0.78	0.30-0.67	0.11-0.32
Trang	0.05-0.09	0.11-0.22	0.10-0.19	0.03-0.07	0.06-0.12	0.14-0.26	0.12-0.24	0.04-0.06	0.08-0.14	0.18-0.34	0.16-0.30	0.05-0.09	0.11-0.18	0.27-0.44	0.24-0.40	0.06-0.18
Phatallung	0.05-0.07	0.11-0.18	0.09-0.15	0.03-0.04	0.06-0.10	0.13-0.22	0.11-0.19	0.03-0.06	0.07-0.12	0.17-0.29	0.15-0.26	0.05-0.08	0.10-0.17	0.24-0.38	0.23-0.33	0.08-0.13
Songkhla	0.02-0.06	0.07-0.16	0.06-0.13	0.01-0.05	0.04-0.06	0.08-0.21	0.07-0.16	0.02-0.05	0.05-0.07	0.11-0.26	0.10-0.22	0.04-0.09	0.07-0.14	0.16-0.32	0.14-0.31	0.05-0.11
Satun	0.03-0.05	0.08-0.11	0.07-1.00	0.02-0.03	0.04-0.06	0.10-0.14	0.09-0.12	0.03-0.04	0.06-0.08	0.13-0.18	0.11-0.16	0.04-0.05	0.08-0.11	0.18-0.27	0.17-0.24	0.06-0.09
Yala	0.02	0.05-0.07	0.05-0.06	<0.02	0.02	0.07-0.09	0.06-0.08	0.02-0.03	0.04-0.05	0.09-0.11	0.08-0.11	0.02-0.04	0.05-0.07	0.12-0.16	0.11-0.15	0.04-0.06
Narathiwat	0.02	0.05-0.06	0.04-0.05	<0.02	0.02	0.06-0.07	0.05-0.07	0.02-0.03	0.04-0.05	0.08-0.10	0.07-0.09	0.02-0.04	0.05-0.06	0.11-0.14	0.11-0.16	0.04-0.05
Pattani	0.02	0.06-0.07	0.05-0.07	<0.02	0.02	0.07-0.09	0.07-0.08	0.02-0.03	0.03-0.04	0.10-0.12	0.09-0.11	0.02-0.04	0.06-0.07	0.14-0.18	0.14-0.16	0.05-0.06

paleoseismic investigation data, the application of all existing earthquake source models and a logic tree approach to overcome the epistemic uncertainties, the seismic hazard maps of southern Thailand presented here are believed to be more accurate and explainable than previous maps. In the future, if suitable attenuation models are developed in Thailand or new data on types and characteristics of seismic sources that affect the ground shaking in southern Thailand are obtained, the seismic hazard maps of southern Thailand can be revised.

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