PROBABILISTIC AND DETERMINISTIC SEISMIC HAZARD ANALYSES OF THAILAND AND LAO PDR: A NEW SCENARIO

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Abstract

In both Thailand and Laos seismic hazards have been classified as the low-lying region of mainland Southeast Asia. Nevertheless in recent times few intermediate and large earthquakes have taken place until recently. Therefore our prime objective is to characterize seismic hazards in Thailand and Lao PDR (or Laos) by utilizing geologic fault and most update seismic data.

We identified more than 60 active faults using remote sensing, morpho-tectonic, paleoseismic trenching, and quaternary dating information from the current and previous studies. At least six seismic source zones have been utilized based upon the most recent geologic, tectonic, and seismicity data. Earthquake catalogues from various sources have been determined, registered, and filtered. Strong ground motion attenuation model have been selected by comparing several well-accepted published models with strong ground motion recorded in both Thailand and Laos. Seismic hazard analysis (SHA) can be performeded by using 2 methods: deterministic seismic hazard analysis (DSHA) and probabilistic seismic hazard analysis (PSHA). DHSA has been adopted for the designs of critical construction and PSHA has been acquired for the noncritical construction. The established SHA maps by this two methods can be carried out by applying past earthquake events and new active fault data.. The DSHA map displays possible ground shaking up to 0.35 g in northern and western Thailand and up to 0.4 g in northwestern Laos, whereas the ground shaking computed from the PSHA approach is <0.3 g in northern Thailand and <0.32 g in Laos for 2 % probability of exceedance in the next 50 yrs and roughly become higher in the northern part of both countries. The DSHA map reveals relatively high hazard level in areas of central and northwestern Laos as well as northern and western Thailand, medium hazard level in northeastern Laos and southern Thailand, and low hazard level in southern Laos as well as central and eastern Thailand. The PSHA map generally displays seismic hazard distribution almost similar to that of the DSHA map but with comparatively lower hazard levels.

Paleoseismic investigations are quite essential for defining seismotectonic faults, new seismic source zones, and hazard level. It is also believed that several fault lines may have occurred within the weak and major crustal structures. Effective mitigation plan to reduce impact of seismic hazard is, therefore, formulated urgently and in many major cities located in northern and western Thailand as well as in northwestern and central Laos.

Keywords: DSHA, PSHA, Thailand, Laos, seismic hazard analysis, active fault, seismic source zones

1. Introduction

Basically, the hazard associated with earthquake is referred to as the seismic hazard which is one of the most devastating of all natural hazards. At present there is no method to reliably predict when an earthquake will happen, its strength or length. Thailand and Lao PDR (hereafter called Laos) are located far away from the present -day plate boundaries of Southeast Asia (i.e., Andaman Sumatra subduction zone) to the west. However, in recent years, several lines of evidence support the concept that both Thai and Laos are also earthquake –prone areas. Tectonically, previous and recent paleoseismological investigations show that the two countries are, to some extent, controlled by inland active faults [1, 2, 3, 4, 5, 6, 7, 8] as shown in Fig. 1. Pailoplee and Choowong [9] reported that several seismic source zones in mainland Southeast Asia are tectonically and seismically active. Additionally, by using the region – time – length algorithm [10], four active seismic regions along the Andaman – Sumatra subduction zone proposed by Sukrungsri and Pailoplee [11] might experience major earthquakes in the future. Moreover, several earthquakes with magnitudes larger than 6 have been reported to occur near borders of Thailand, Laos, and Myanmar (e.g., 2007 Mw 6.3 Bokeo earthquake in northern Laos, 2011 Mw 6.8 Tarlay earthquake in eastern Shan State of Myanmar, 2014 Mw 6.1 Mae Lao earthquake in Chiang Rai area of northern Thailand, and 2019 Mw 6.1 Xayaburi earthquake in northwest Laos). As a result of these and past earthquakes, several ancient remains and historical monuments within these regions were damaged or broken [8].

It is therefore tentatively believed that there must be strong temporal and spatial relationships between active faults and earthquakes. The aim of this research work is to utilize the newly discovered active faults and most updated seismic data to determine seismic hazard analysis (SHA) of Thailand and Laos.

In general seismic hazard can be investigated by using two approaches, i.e., deterministic seismic hazard analysis (DSHA) and probabilistic hazard analysis (PSHA). In these two methods, the seismic hazard can be evaluated from past earthquake/tectonic activities as well as active fault data. Therefore, to mitigate earthquake damages, seismic hazard analysis is required in order to quantitatively estimate ground shaking hazards at a particular site. DSHA can be analyzed when a specific earthquake scenario or hazard from the most severe earthquake event is assumed [12], and PSHA can be evaluated from the past earthquake event database concerning uncertainties in earthquake sizes, locations, and times of occurrences are mutually considered [13, 14]. A critical part of SHA is the determination of peak ground acceleration (or PGA) and response acceleration (spectral acceleration) for an area/site. Spectral acceleration (SA) is used particularly for the design of engineering structures [15]. It is a widely accepted trend in engineering practice to develop design response spectrum for different types of foundation materials such as rock, hard soil and weak soils. However, analyses of lineaments and faults can help to understand the regional seismotectonic activity of the specific site or area. Lineaments, or linear features observed on the earth surface, represent faults, shear zones, joints, lithological contacts, dykes, etc; and are of great relevance to geoscientists [14].

2. Seiesmic Source Zones (SSZs) and Activities

As a result of the neotectonic activities of Indian – Eurosian plate collision, several active faults have been generated within the Southeast Asian region [1, 16, 17, 18]. Nonetheless, owning to the scarcity of the seismotectonic or active fault information, previous PSHA have used the SSZs as the earthquake sources [7, 19; 20, 21]. The first seismic map of Thailand was proposed by Hatori [22] who analyzed the seismicity data reported by the National Oceanic and Atmospheric Administration (NOAA) and the strong ground-motion attenuation model of McGuire [23]. Subsequently, this map was modified by Santoso [24] based upon the seismicity data from both the NOAA and the Thai Meteorological Department (TMD) to form two maps with the PGA for 36-y and 74-y return periods, respectively. Nutalaya et al. [25] proposed 12 seismic source zones (SSZs) for Thailand and mainland Southeast Asia. Shrestha [19] used their seismic source zones to determine their PSHA for Thailand using the attenuation model of Esteva and Villaverde [26], which was slightly different from previous work, and determined the PGA for a return period of 13 and 90 years. Warnitchai and Lisantono [20] later applied the data proposed by Shrestha [16] for a PSHA to contribute a map with the PGA of a 10% probability of exceedance (POE) in the next 50 years.

The active fault data in many PSHA maps reported previously by Kobayashi et al. [27], Petersen *et al.* [28], and Ornthammarath *et al.* [29] were constrained only to Thailand. In fact, the configuration of individual faults does not conform well to the details compared with the morphotectonic evidence, such as, offset strams, shutter ridges, sag ponds, fault scarps, and triangular facets. Moreover, some seismogenic faults are ambiguously applied, e.g., in the Chao Phaya Basin [25] and the Chumphon basin faults [28]. Therefore in this study we display the active fault/lineament map (Fig. 1a) which has been modified after Pailoplee et al. [3]. The utilized map which includes the study countries (Thailand and Laos) comprise 60 active fault zones in mainland Southeast Asia (Fig. 1a). These fault lines/lineaments have been compiled using the geomorphological evidence based on satellite image interpretation together with field and ground - truth survey. Hypothetically, the paleoseismological parameters, including the maximum credible earthquake (MCE), the rupture area, and the fault slip rate, should be determined in individual segments. In the map, we add 3 new fault zones, including (1) the fault zone in Nan (northern Thailand) and Sayaburi (western Laos), (2) Phetchabun fault zone in central Thailand recently added in the map by Department of Mineral Resources [30], and (3) Thakhek fault zone in central Laos which consists of quite long lineaments/faut line and shows prominent morphotectonic evidence.

At least 60 sites of paleoseismological investigations in Thailand and Laos have been documented up to the present (Fig. 1a). About 31 locations in northern Thailand have been reported for paleoseismological results based largely on the works of [31, 32, 33], the Royal Irrigation Department (RID) [34], and Charusiri *et al.* (2). The fault slip rates vary considerably from 0.03 mm/yr in the Phrae Fault Zone to 1 mm/y in the Lampang-Thoen Fault Zone. However, more than one site for each active fault has been investigated in some fault segments. For example, there are seven paleoseismological trenches were investigated in the Mae Chan Fault, and the slip rates have been reported from 0.29 to 0.16 mm/yr by DMR [32] and about 1.4 mm/yr by Wiwegwin et al. [35]. In western Thailand (Fig. 1a), 13 trench sites have been examined and have shown the slip rates of the southern SriSawat Fault varying from the highest rate of 2.87 mm/yr to the lowest rate of 0.22 mm/yr [36, 37]. Additionally, there are 11 paleoseismological sites in southern Thailand (Fig. 2a) have been reported by the RID [38]. Three out of these 11 sites entirely concentrate on the Ranong Fault Zone and yield a fault slip rate of 0.18 mm/y at Ban Bangborn Nai and 0.7 mm/y at Ban Phracha Seri. The other eight sites, which are located along the Klong Marui Fault to the north of Phuket Island, gave the slip rate between 0.01 mm/yr and 0.5 mm/yr as reported by RID [38] and Kaewmuangmoon et al. [39]. However, based on the report of Suthiwanich et al. [40], these two faults yield the slip rates between 0.3 and 0.4 mm/yr.

Similarly, the seismic activities in Laos and adjacent areas are largely influenced by several active faults, such as Red River (or Song Hong) Fault [41], Mae Ing Fault [1], and Nam Ma Fault [42]. Based solely upon instrumental earthquakes data, several shallow earthquakes have been recorded in the vicinities of Laos during the last three decades (Fig. 1). At least 17 earthquake records with magnitude (M_w) ≥ 6 and 3 large earthquakes including M_w 7.0 and 7.7 in 1988 and the latest M 7.1 earthquake in 2011 have been reported. Therefore, Laos has also experienced hazardous ground shaking. Up to now, only two seismic hazard maps have been documented: one is the map developed by the United Nation Office for Human Affairs [43], and the other by Pailoplee and Charusiri [6]. The former is a preliminary map which illustrates the earthquake severity with modified Mercalli Intensity (MMI) scale for 50-yr return period, and the latter is much more sophisticated, however both do not contain the new data on recent earthquake activities. Up to now, two paleoseismic trenches have been performed for the Luang Prabang Fault and the slip rates have been calculated to range from 0.19 to 0.21 mm/yr [35].

Seismic activity is herein defined as the types, frequency and size of earthquakes that happen over a period of time in a certain area [44]. So its characterization in the specific region is usually expressed in 3 seismic hazard parameters [14] including the maximum credible earthquake (MCE) [45] and the frequency magnitude distribution model (FMD) a- and b- coefficient values [46] as displayed in Eq. (1);

$$\text{Log (N)} = \text{a-b (M)} \quad (1)$$

where N is the number of earthquake events with magnitude M ≥ 6. The values of a and b are positive constants that can vary in both space and time aspects and are the same for all values of *N* and *M*.

It is widely accepted that paleoseismological data are important characteristics in determining a reliable PSHA [47, 48]. Therefore in the current investigation, locations, geometry, and orientations of individual faults were determined. In addition, the fault parameters (such as fault length) for the PSHA were changed to the MCE and the rupture area using the Wells and Coppersmith [45] relationship. Based on these 60 paleoseismological investigations, i.e., slip rate, all fault segments that provided new paleoseismological evidence were identified as new earthquake sources. As earlier mentioned, 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 (and also Laos) required for the PSHA were obtained from publications and technical reports [3]. The MCE, the rupture areas, and the fault slip rates were obtained from the investigation of the active faults at the specific individual site.

According to Pailoplee et al. [3] several 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 same SSZs were also applied in this study as the background seismicity. Based on the available literatures, there are at least three models of SSZs for mainland Southeast Asia [9, 7, 25]. According to the updated data and reasonable assumptions, the 13 SSZs of zones A–M proposed by Pailoplee and Choowong [9] were used in this study (Fig.1b). The *a* and *b* values of the SSZs H and K are not available, so both values proposed by Pailoplee and Choowong [9] are employed for the SSZs H and K.

3. Deterministic Seismic Hazard Analysis (DSHA)

Generally, DSHA aims at finding the most probable ground shaking at a given site. This hypothesis is based on the concept that the engineering structures can withstand the computed MCE. Based on the work by Krinitzsky [48], each MCE has been assumed to take place within the seimic source zone at the shortest distance from the source to the site. In the SHA calculation, six seismic source zones (Fig. 1b) have been converted equally to 0.25° x 0.25°. The three seismic parameters have been subsequently applied to evaluate earthquake potentials for individual seismic zones. In this study the strong ground motion attenuation model of Sadigh et al. [49] have been used as suggested by Chintanapakdee et al. [50]. Using this attenuation model, the seismic hazards were evaluated with regard to peak ground acceleration (PGA) without the possibility of earthquake occurrence.

The current DSHA map of both Thailand and Laos (Fig. 2) displays the distribution of PGA varying from 0 to 0.5 g. In Thailand the peak ground acceleration (PGA) determined by DSHA for the maximum credible earthquake varies from 0 g in areas far away from the active fault zones to 0.5 at or alongside the active faults. The high hazard levels (0.4 to 0.5 g) have been observed in northern and western Thailand, and the relatively much lower levels (0 to 0.05g) have been found in several parts of northeastern, eastern, and southern Thailand. Three zones of high levels appear in northern Thailand, which are mostly related spatially to major active fault zones, i.e., Mae Chan Fault, Mae Lao Fault, Thoen Fault, and Uttaradit Fault. In the south, earthquake – prone areas are limited to two areas with PGA ranging mainly from 0.2 to 0.35.

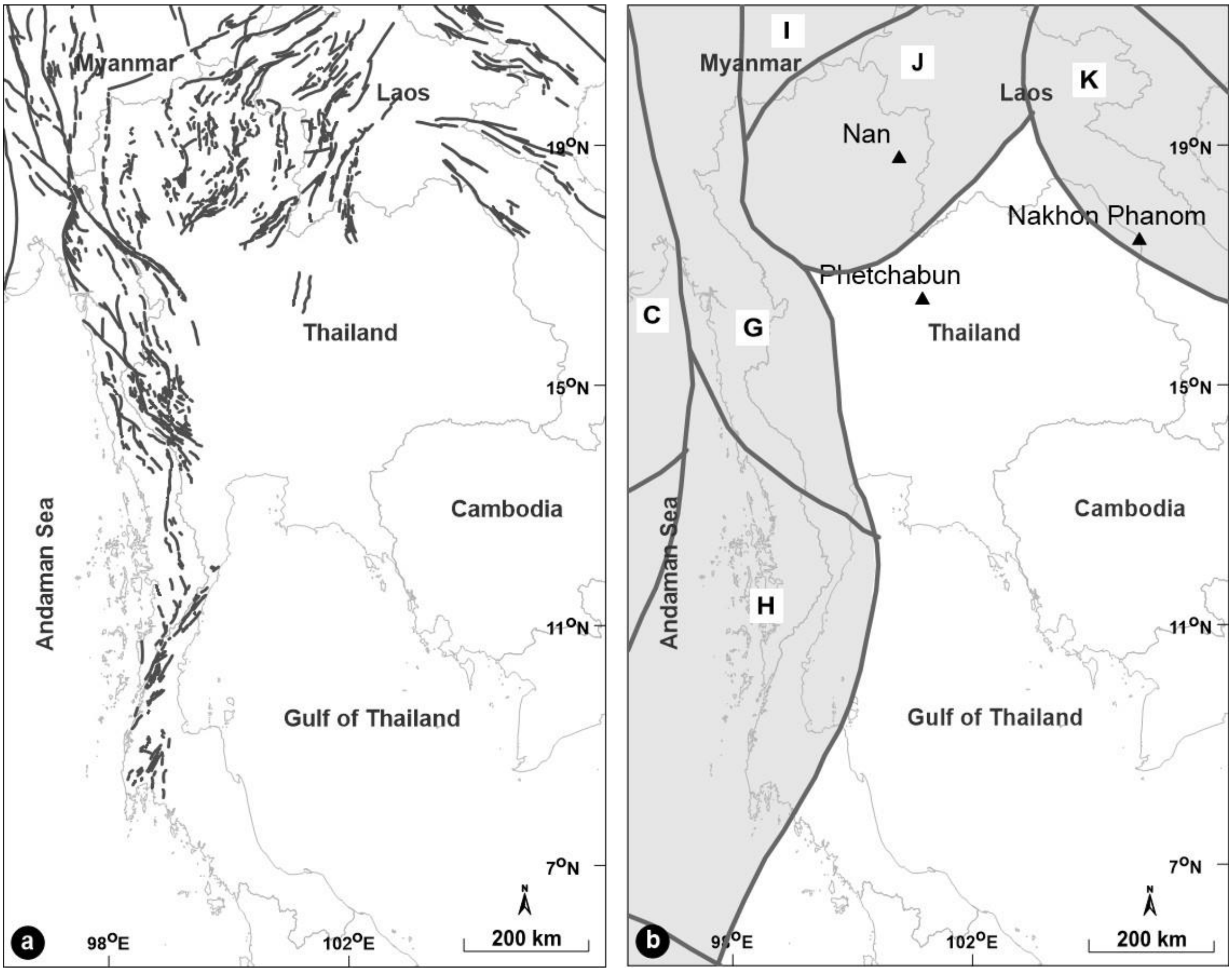

Fig. 1 -Map of Thailand and the neighboring areas illustrating (a) the possible active fault lines or lineaments and (b) seismic source zones covering Thailand and Laos, as proposed by Pailoplee and Choowong [9]. The black triangles are the new sites of paleoseismological investigations used in this study.

Similar situation has been found in Laos, our DSHA map (Fig. 2) also displays the PGA ranging from 0 to 0.5 g. It is clear that the strong earthquake prone areas are located mainly in northern and central Laos. There are 3 areas in northern Laos, which are of interest and are roughly located to the east of Nan area in Thailand side (Fig. 1b), including the northwesternmost (or Luang Namtha area), the western (or Luang Prabang – Xaibouli area), and the northeastern (or Sam Nuea area) areas. However, based on our current DSHA, field and paleoseismic investigation, the central Laos (or Thakhek area) opposite to Nakhon Phanom of Thailand side (see Fig. 1a) seems to be the most dangerous earthquake prone area with the length of about 300 km. The calculated PGA values in the the northwesternmost area vary from 0.4 to 0.5g, in the western area from 0.4 to 0.5g, and in the northeast area from 0.4 to 0.45g.

It is also quite clear for both countries that the PGA at or near these active faults becomes higher (up to 0.5 g) and outward to both sides of the fault lines the PGA decrease continuously (down to 0.25 g). In southern Laos to Cambodia border, the PGA is 0 g which is ascribed to neither earthquake activity nor active faults being discovered.

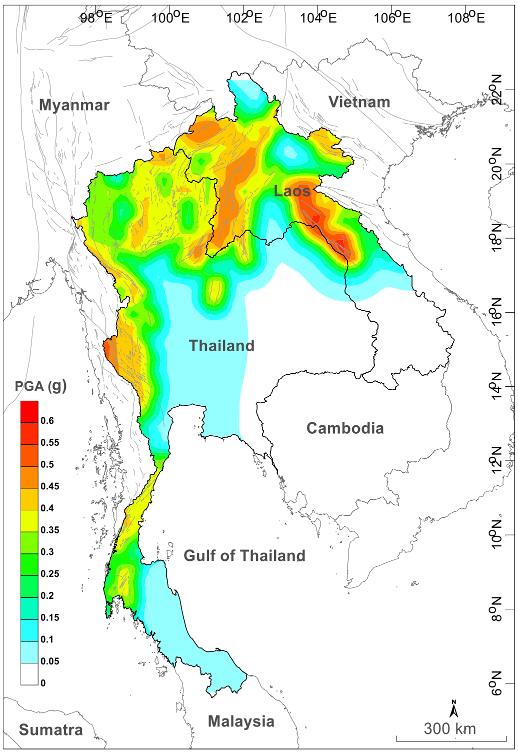

Fig. 2 -Deterministic seismic hazard analysis (DSHA) map of Thailand and Laos showing distribution of peak ground acceleration (PGA) in g.

4. Probabilistic Seismic Hazard Analysis (PSHA)

Unlike DSHA, the probabilistic seismic hazard analysis (PSHA) is to quantify the rate (or probability) of exceeding various ground-motion levels at a site (or a map of sites) given all possible earthquakes. The numerical/analytical approach to PSHA was first formalized by Cornell [13].

With PSHA, the worst-case scenario of ground motion intensity is not considered. Conceptually, all possible earthquake events and resulting ground motions are concerned along with their associated probabilities of occurrence, in order to find the level of ground motion intensity exceeded with some tolerably low rate. At its most basic level, PSHA comprises five steps including (1) identify all seismic sources capable of producing damaging ground motions, (2) characterize the distribution of earthquake magnitudes (the rates at which earthquakes of various magnitudes are expected to occur), (3) characterize the distribution of source-to-site distances associated with potential earthquakes, (4) Predict the resulting distribution of ground motion intensity as a function of earthquake magnitude, distance, etc., and (5) combine uncertainties in earthquake size, location and ground motion intensity, using a calculation known as the total probability theorem. In order to obtain PGA in this study, CU PSHA software [51] was utilized to establish the probability density function of magnitude [52] and for source – to – site distance [53]. Based on the evaluated probability density functions supplemented by attennuation model at each investigated site, the seismic hazard curve (Fig. 3) showing the relationship between POE and PGA in the Y – and X- axis, respectively can be generated. In this study, only three sites, where the nearby active faults have been newly discovered, are reported, viz. Nakhon Panom (or Thakhek), Phetchabun, and Nan. It is clearly seen that the Nakhon Panom site shows the higher hazard curve than those of the other two sites.

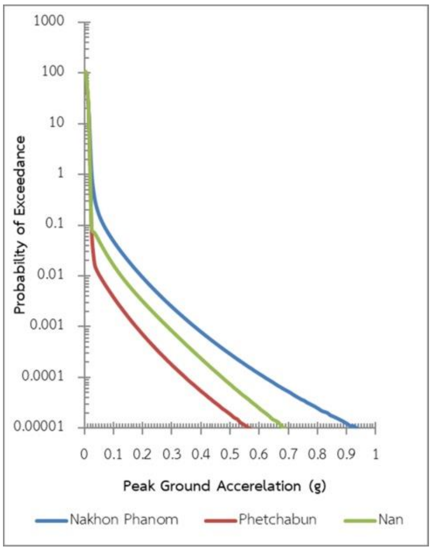

Fig. 3-Hazard curves showing relationship of peak ground acceleration (PGA) and probability of exceedance (POE) for 3 new locations where active faults have been recently recognized. Their geographical locations are shown in Fig. 1b.

The current PSHA maps as shown in Fig. 4 in general were produced for bedrock conditions for 2 % and 10 % probability of exceedance in 50 years and 100 years – time period. With regards to the PSHA map with 10 % POE in the next 50 yr (Fig. 4b), two zones of the seismic hazard in Laos can be clearly classified. The high hazard of PGA (≥ 0.12 – 0.3g) dominates in the northern and central parts of Lapos whereas the southern part is almost zero (~ 0.05g). In Thailand the high hazard of PGA (0.2 – 0.4g) dominates in the northern and western parts, the intermédiate hazard of PGA (0.1 – 0.2 g) is seen in the southern part, and the low hazard of PGA (< 0.05g) appears in the central, eastern, and northeastern parts. As obsderved in Fig. 4b, the northernmost part of Thailand near Myanmar –Thailand – Lao border show the highest PGA (up to 0.4g).

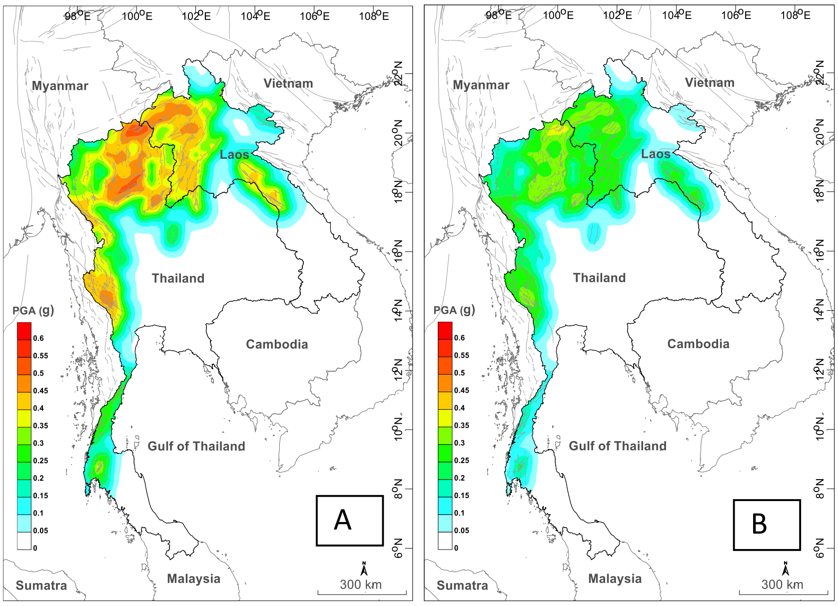

Fig. 4. Probabilistic seismic hazard analysis (PSHA) maps of Thailand and Laos illustrating the PGA distribution with (a) 2% POE within the next 50 yr and (b) 10% POE within the next 50 yr

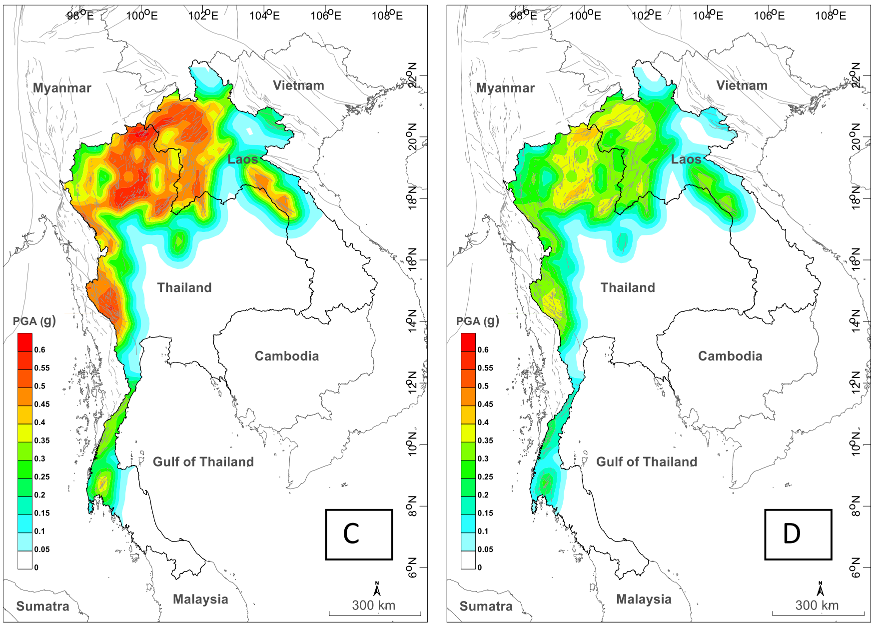

Fig. 4. (cont.) (c) 2 % POE within the next 100 yr and (d) 10% POE within the next 100 yr.

5. Discussion

Due to the appearance of 3 new active faults reported in this study area, both DHSA and PSHA maps are different from the previous maps reported by Pailoplee and Charusiri [6] for Thailand and these two kinds of SHA maps are almost similar to those of Pailoplee and Charusiri [6] for Laos. For instance, the high PGA from the DSHA map in western and northwestern Laos varies from 0.32 to 0.4g [6]. In northeastern Laos, the DSHA yields lower PGA varying from 0.24 to 0.32g and in southern Laos the PGA is usually much lower than 0.12g [6]. In comparison with our current result shown in Fig. 2, it is likely that with the exception of southern Laos the PGA values from our study are slightly higher than those of Pailoplee and Charusiri [6]. The quite obvious area is located in the central part of Laos where PGA values are unusually high. We therefore interpret that the appearance of new active faults in Thakhek area of southern Laos may have been responsible for the PGA values. Paleoseismic investigations are urgently needed. Additionally, as shown in Fig. 3, the hazard curves for the new sites where three active faults have been recently recognized indicate that Nakhon Phanom site, where the long, NW-SE trending Thakhek active fault is situated, displays the highest curve and the other two sites at Phetchabun and Nan areas show obviously lower hazard curves.

One of the outstanding and interesting aspects is the presence of the Phetchabun active fault zone in north-central Thailand near Phetchabun city (see Fig. 1b). Its preliminary slip rate reported very recently by DMR [54] varies from 0.07 mm/yr up to 1.5 mm/yr. This result together with the nearby epicentral locations southeastward leads to suspect that the new seismic source zone in the Phetchabun area and its vicinities to the north and the south. However, paleoseismic investigations are required in order to draw a seismic zone in the concerned area. It is not impossible to mention, however, that the northeastern part of Thailand and also central Laos may not be as low sismic zone as previously thought.

Table 1 displays the DSHA and PSHA data for areas where 3 new fault zones are recognized in this study. The DSHA PGA for NanThe other significant aspect needs to address is that some of the high seismic zones may follow the so – called suture zones which we consider as the weak and major structures. For examples, the zone following the Mae Chan Fault corresponds to the so-called Chieng Mai- Chiang Rai Suture [55], the Nan fault zone conforms well to the so – called Nan suture [56], and the Phetchabun Fault follows the so called – Loei suture zone [16].

Table 1. Summarized SHA in some provinces discussed in this study based on various conditions of interest.

Parameter	Nan	Phetchabun	Nakhon Panom
DSHA	0.39g	0.35g	0.49g
PSHA			
- PGA of 2% POE in 50 y	0.45g	0.22g	0.34g
- PGA of 10% POE in 50 y	0.29g	0.11g	0.21g

6. Conclusion

Several approaches have been performed so far to evaluate the PSHA and DSHA for Thailand and Laos. Due to the fact that paleoseismological data (e. g., slip rates) have become applicable for many active fault segments, PSHA can therefore be reevaluated in the current study. The advantage of this PHSA is that it has been derived from the most up – to – date data and can be constrained for paleoseismological data that are significant factors in reliably estimating long-term and large earthquakes. The values of a and b of the Gutenberg-Ritcher relationhips were also applied according to the most reliable investigations. By adopting the strong ground motion attenuation relationship, both probability and ground shaking maps were developed. Therefore earthquake mitigation plan is required to reduce losses and environmental impact.

Our new results also reveal that northern Thailand contains the most earthquake-prone areas with 2 % and 10 % POE in the next 50 years of 0.1 to 0.55g and 0.1 to 0.35g PGA, respectively. In western and southern Thailand the ground shaking levels within 50 years become lower, being in the range of 0.1 to 0.35g and 0.1 to 0.25g PGA, respectively. In northern Laos the most earthquake – prone area with 2% and 10 % POE in the next 50 years varies from 0.1 to 0.45 g and from 0.1 to 0.27g PGA, respectively. In central Lao the ground shaking levels become smaller and lower, ranging from 0.1 to 0.45g in the next 50 years.

The DSHA map exhibits high hazard level in areas of northwestern and central Laos as well as northern and western Thailand, medium hazard level in northeastern Laos and southern Thailand, and low hazard level in southern Laos and central Thailand. The PSHA map generally displays seismic hazard distribution almost similar to that of the DSHA map but with comparatively lower hazard levels. Therefore, effective mitigation plan to reduce impact of seismic hazards should be generated promptly and in several major cities/towns located in northern Thailand as well as northern and central Laos.

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