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Original Article

Seismic activities in Kanchanaburi: Past and present

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Abstract

Seismic activities in Kanchanaburi Province of the western Thailand have been a major concern among the Thai public due to the fear that a big earthquake caused by the Three Pagodas Fault Zones (TPFZ) and the Sri Sawat Fault Zone (SSFZ), one of the largest active fault zones in Thailand, could damage the large dams and generate a great disaster to the communities. Four hundred and thirty seven earthquakes that occurred in Kanchanaburi since 1983 have been analyzed for the time and location distributions along with the frequency magnitude relationship. There are no clear correlations between the epicenters of these earthquakes and the known locations of the active faults in the region. The seismic catalog used in this study is complete for M_w=3.0 for Kanchanaburi region. The analysis of G-R relationship yields a-value of 5.15 and b-value of 0.86. A deterministic seismic hazard analysis of the TPFZ and SSFZ suggests that the characteristic earthquakes magnitudes of the TPFZ and the SSFZ are 7.3 and 7.0, respectively, with a maximum PGA of 0.31 and 0.28 g at the faults lines for the earthquake occurring at 15 km depth.

Keywords: earthquake, G-R relationship, Three Pagodas Fault Zone, Sri Sawat Fault Zone, Kanchanaburi, seismic hazard

1. Introduction

Systematic studies of the seismic hazard in Thailand have started a few decades ago (Nutalaya *et al.*, 1985; Hinthong, 1995; Warnitchai and Lisantono, 1996; Charusiri *et al.*, 1999; Palasri, 2006; Petersen *et al.*, 2007; Pailoplee *et al.*, 2009, 2010; Ornthammarath *et al.*, 2010). Seismicity records (Figure 1a) have shown a large number of earthquakes occurring in the northern and western Thailand (Nutalaya *et al.*, 1985; Kosuwan *et al.*, 1998). In addition, seismotectonically, the northern and western Thailand are also active regions where several active faults have been detected (Charusiri *et al.*, 1999, 2002; Fenton *et al.*, 2003; Figure 1b). Although magnitudes of most earthquakes occurring in these regions are generally less than 5, recent studies on active faults in western Thailand indicate that the occurrences of earthquakes with magnitudes greater than 6 in the region are possible (Charusiri *et al.*, 1999; Fenton *et al.*, 2003). Therefore, the western Thailand has recently gained major attention for seismic hazard studies (Nutalaya *et al.*, 1985; Kosuwan *et al.*, 1998; Charusiri *et al.*, 1999; Fenton *et al.*, 2003; Rhodes *et al.*, 2005). In this study, seismicities (as a whole) in the western Thailand, especially in Kanchanaburi Province, are analyzed in order identify the frequency-magnitude relationship, the distribution of the magnitude, the frequency and the time that the earthquakes occurred, including the correla-

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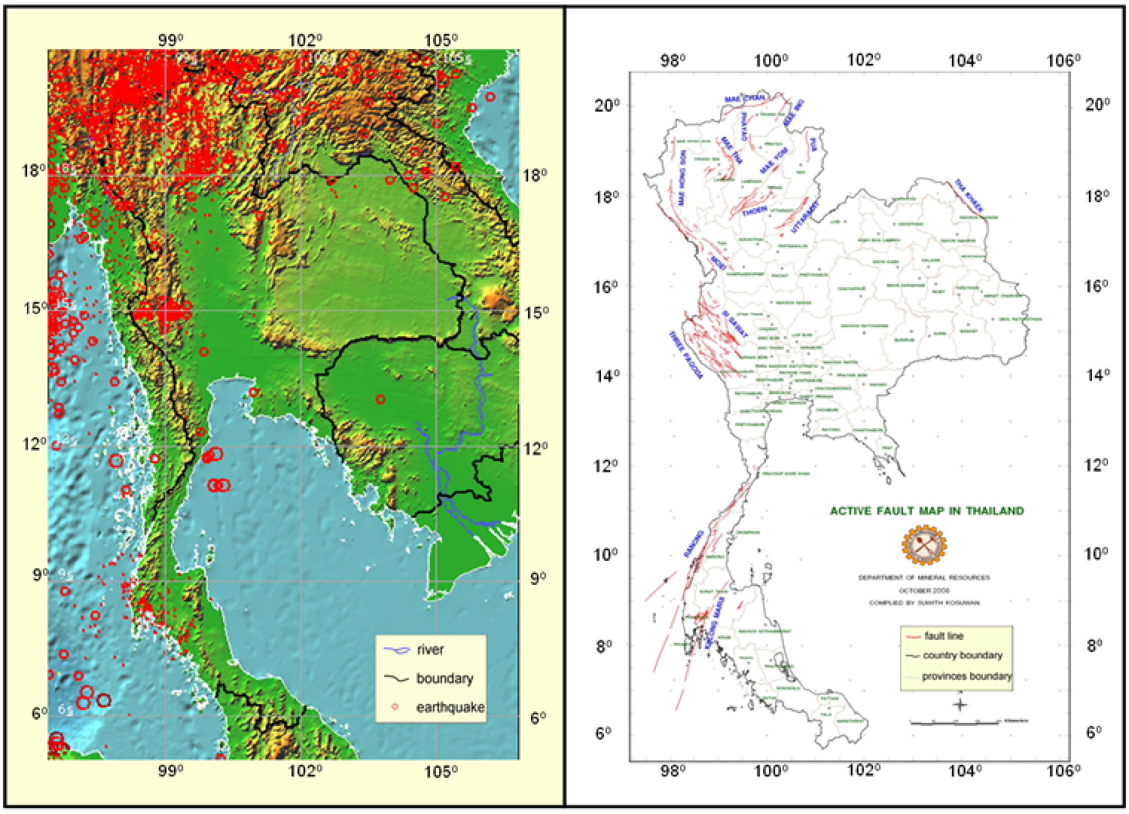


(a) (b)

Figure 1. (a) Seismicities of Thailand (data from NEIC, TMD, and IRIS). (b) Active fault map of Thailand (after DMR, 2006).

tion of the hypocenters of the earthquakes with the locations of the active faults in the region for the earthquakes occurring along the Three Pagodas Fault Zone and the Sri Sawat Fault Zone.

The Three Pagodas Fault Zone (TPFZ) and the Sri Sawat Fault Zone (SSFZ) were originally thought to be inactive faults and western Thailand was considered an aseismic region before the construction of large dams (Klaipongpan *et al.*, 1991). There were no reports of the seismicities in the area before this period, possibly due to the lack of the seismic monitoring networks. However, the importance of these fault zones has been recognized since the construction of the two large dams; the Srinagarind Dam (capacity of 17,750 million cubic meters) and the Vachiralongkorn Dam (aka. Khao Laem Dam, capacity of 8,860 million cubic meters). The seismicities in the region have been reported after the construction of the dams. The largest earthquake occurred on April 22nd, 1983 in the northern part of the Srinagarind reservoir, six years after the dams' impoundments. This earthquake registered a magnitude of m_b 5.9 (Gupta *et al.*, 2002). The largest earthquake, registered M_L 4.5, was reported on January 23rd, 1985 (Hetrakul et al., 1991) in the Vachiralongkorn reservoir area. The seismicity occurrence after the dam impoundment was interpreted as reservoir triggered earthquakes (Hetrakul *et al.*, 1991; Klaipongpan *et al.*, 1991 and Gupta *et al.*, 2002). The local communities were and still are concerned that potential earthquakes generated by these faults could cause a major damage to the dams due to the proximity of the dam sites to these faults and that any dam failure could initiate a severe inundation hazard to the community.

2. Tectonic Setting and Faults' Structures

The majority of Thailand's neotectonics is associated with the collision of the India and Eurasia plates since over 50 Ma (Tapponnier and Molnar, 1976; Tapponnier *et al.*, 1982, 1986; Morley *et al.*, 2000; Morley, 2001, 2004, 2009; Tingay *et al.*, 2010b). Most fault systems that have surface expressions in Thailand have strike-slip components with either northeast-southwest orientations with current sinistral movement or northwest-southeast orientations with current dextral movement (Figure 1b).

Western Thailand, especially Kanchanaburi Province, is an area where two major fault systems are situated; the Three Pagodas Fault Zone and the Sri Sawat Fault Zone (Figures 1b and 2). These faults show a more or less northwest-southeast orientation and continuing from eastern Myanmar to western Thailand in Kanchanaburi Province. At present, both faults have dextral movements (Charusiri *et al.*, 2010).

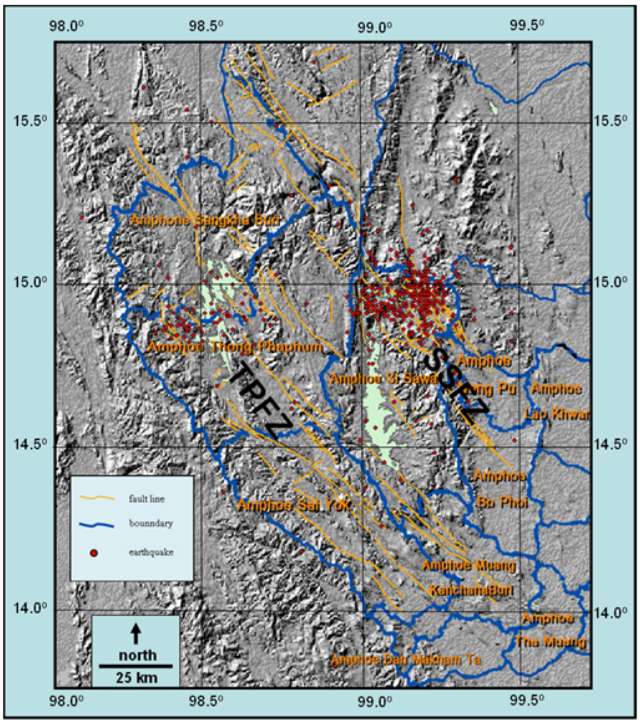


Figure 2. Seismicities in Kanchanaburi, western Thailand (red dots) overlain on the DEM. Yellow lines are the probable locations of the active faults. Blue lines are political boundaries.

From the interpretation of the remote sensing data, the TPFZ appears to be 215 km long and about 30 km wide and the SSFZ, located to the northeast of the TPFZ, appear to be 220 km long and about 25 km wide. Charusiri et al. (2010) proposed that the TPFZ can be subdivided into 60 smaller segments and the SSFZ can be subdivided into 52 smaller segments. The lengths of the longest segment are 78 km for the TPFZ and 48 km for the SSFZ.

The TPFZ developed as a result of the Indian-Asian collision during the Eocene (Fenton *et al.*, 2003, Rhodes *et al.*, 2005). It was initially developed as left-lateral shear zone in a transpression environment with over 300 km in total offset (Peltzer and Tapponnier, 1988) and then reactivated with right-lateral slip when the stresses rotated clockwise in mid-Tertiary (Lacassin *et al.*, 1997; Rhodes *et al.*, 2005). Tingay *et al.* (2010a, 2010b) analyzed the present-day stress orientations in Thailand's basins from caliper and image logs of petroleum wells using borehole breakouts and drilling-induced fractures and concluded that the majority of the present-day stress in Thailand's basins orientates in north-south direction, which has been controlled by the forces generated at the eastern Himalayan syntaxis.

3. Seismicity of Kanchanaburi

Seismicities in western Thailand, especially in Kanchanaburi region near the Srinagarind and Vachiralongkorn Dams, were primarily reported in early 1983. The biggest earthquake was the m_b 5.9 occurred on Aril 22nd, 1983, about six years after the impoundment of the Srinagarind Dam (Klaipongpan *et al.*, 1991). This earthquake was later classified as a reservoir triggered earthquake (Gupta, 2002).

In this work, the epicenters of 437 earthquakes occurring since 1983 have been complied from the Thai Meteorological Department (TMD), NEIC, and IRIS database. The epicenters of these earthquakes cover latitude between 13.7-15.7 °N and longitude 98.0-100.0 °E. The magnitude types from these datasets consist of m_b, M_L, M_S and M_w. The minimum magnitude is m_b 1.0 and the maximum magnitude is m_b 5.9.

As the data came from different agencies that use different magnitude units, these different earthquakes' magnitudes need to be converted to a unified magnitude in order to do a frequency-magnitude relationship analysis. In this work, we use the M_w because it is widely accepted as the most accurate magnitude type that reflects the real geometry of the fault slip during the earthquake (USGS, 2011).

The magnitude conversion relationships for various magnitude types to M_w used here were following Mueller *et al.* (1997) and Palasri (2006) as shown below:

$$M_w = 0.67 \times (m_b + 1.5) \quad \text{for } m_b < 3.0 \quad (1)$$
$$M_w = m_b \quad \text{for } 3.0 \leq m_b < 6.8 \quad (2)$$
$$M_w = 0.67 \times (M_L + 1.5) \quad \text{for } M_L < 3.0 \quad (3)$$
$$M_w = M_L \quad \text{for } 3.0 \leq M_L < 6.8 \quad (4)$$
$$M_w = 0.67 \times (M_S + 2.7) \quad \text{for } M_S < 5.5 \quad (5)$$
$$M_w = M_S \quad \text{for } 5.5 \leq M_S < 8.3 \quad (6)$$

After the conversion, the minimum and maximum magnitudes of the reported earthquakes are between M_w 1.7 and M_w 5.9. The distribution of the magnitudes after the magnitude conversion from the earthquakes in the study is shown in Table 1. The epicentral distribution of these earthquakes is shown in Figure 2. Three major earthquakes reported by the NEIC catalog are shown in Table 2.

Table 1. Distribution of the magnitude ranged (after magnitude conversion) of the earthquakes used in this study.

Magnitude Range (M_w)	Number of Earthquakes
1.3-1.7	1
1.8-2.2	7
2.3-2.7	91
2.8-3.2	185
3.3-3.7	66
3.8-4.2	49
4.3-4.7	25
4.8-5.2	7
5.3-5.7	5
5.8-6.2	1

Table 2. Hypocenter locations of the main seismic events in the vicinity of the Srinakarind Dam (data from NEIC catalog).

Event No.	Date	Origin Time (UTC)	Latitude (°N)	Latitude (°E)	Depth	m_b
1	4/15/1983	9:23:59	14.91	99.09	10	5.3
2	4/22/1983	0:37:37	14.93	99.02	10	5.9
3	4/22/1983	3:21:41	14.93	99.08	33	5.2

Several hundreds aftershocks followed the main shock on April 22nd, 1983. Chung and Lui (1992) analyzed the focal mechanisms of these earthquakes and suggested a strike-slip motion for the m_b 5.3 earthquake occurring on April 15th, 1983 and thrust movement for the m_b 5.9 and m_b 5.2 earthquakes occurring on April 22nd, 1983, respectively (Figure 3).

The earthquakes in the vicinity of the Vachiralongkorn reservoir are located in the west side of the reservoir. The biggest earthquakes in this area reported by TMD had a magnitude of m_b 4.5 occurring on January 23rd, 1985.

When plotting the epicenters of these earthquakes with the possible active faults, the TPFZ and the SSFZ (Figure 2), it is clearly seen that the main clusters are located along the SSFZ to the north-northeast of the Srinagarind reservoir. There is no clear correlation between the locations of the epicenters and the surface expressions of these faults, which could be due to the quality of the epicenter locations, possibly caused by the lack of the correct crustal velocity model during the time the earthquake data were analyzed for the hypocenter locations. The depths of these earthquakes vary between 0.7 and 68 km with the majority at 10 and 33 km, representing depths values that could be set by the earthquake location program (Figures 4a, 4b). The locations of the hypocenters of these earthquakes also do not show a clear image of the faults' planes.

4. Frequency-magnitude Relationship of the Earthquakes in Kanchanaburi

The Gutenberg–Richter frequency-magnitude (G–R) relationship (Gutenberg and Richter, 1956) can portray the correlation between the frequency of earthquake occurrence and the magnitude which is given by:

$$\text{Log}_{10}(N) = a - bM \quad (7)$$

where N is the cumulative number of the events having magnitude larger than or equal to M. a and b are constants.

The constant b value (or b-value) is one of the most important parameters in the frequency-magnitude relationship as it can affect the number of big earthquake occurrence in seismic hazard analysis. For example, a b-value equals to one means that for any one earthquake with magnitude 4, there will be 10 earthquakes of magnitude 3 and 100 earthquakes of magnitude 2. An increase or decrease of the b-value will decrease or increase the number of possible large earthquakes that could happen and will decrease or increase the seismic hazard level in a given region accordingly. The spatial variation of the b-value can also been related to the increase of the stress accumulation that could precede the relative large earthquake in the region (Kebede and Kulhanek, 1994; Nuannin *et al.*, 2005).

Four hundred and thirty-seven earthquakes that occurred since 1983 are used in the G-R relationship analysis. There are some seismicity gaps between 2003-2006 and 2008-2009 (Figures 5 and 6).

The frequency-magnitude relationships of these earthquakes are plotted with minimum magnitude of M_w 1.7 and maximum magnitude of M_w 5.9 (Figure 7a). The magnitude completeness (M_c) of these dataset is about M_w 3.0. The logarithm scale of the cumulative number of earthquakes is plotted in Figure 7b. The best fit of the curve in Figure 7a yields an a-value of 5.15 and a b-value of 0.86 (R^2=0.96).

The number of seismicities reported since 1983 decreased rapidly from 258 events in the first year to less than 60 events in the second years (Figure 5). The numbers of earthquakes per year have been less than 10 since 1990. Klaipongpan *et al.* (1991) reported b-vales of the foreshocks and the aftershocks to be 0.93 and 0.76, respectively, in the Srinagarind reservoir area. They then concluded that most of the earthquakes occurring in this region area are reservoir

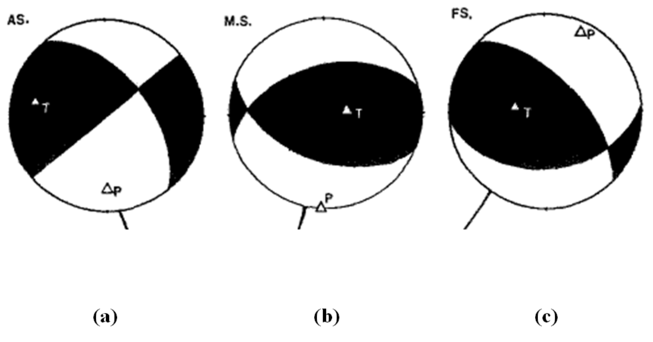
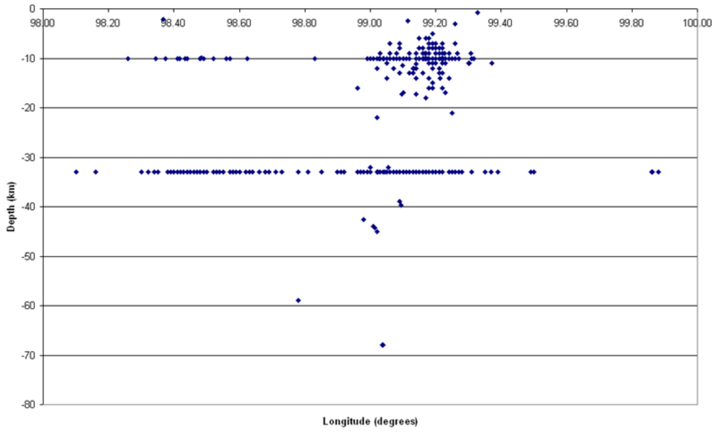
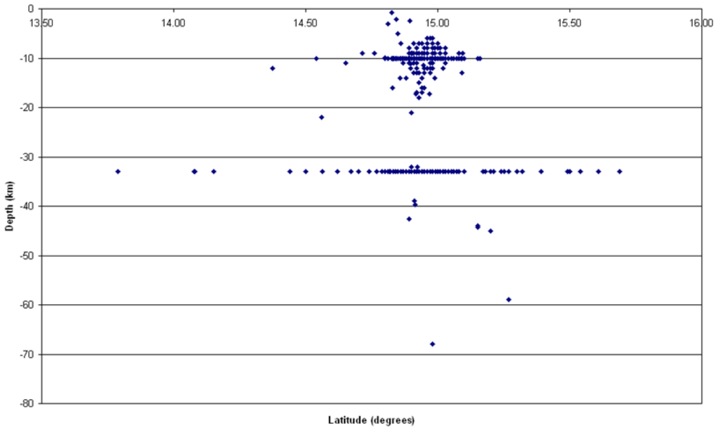


Figure 3. Focal mechanisms of the important earthquakes originated in the study area (after Chung and Liu, 1992). (a) m_b 5.3 earthquake on April 15th, 1983, (b) m_b 5.9 earthquake on April 22nd, 1983, (c) m_b 5.2 earthquake on April 22nd, 1983.



(a)



(b)

Figure 4. Locations of earthquake hypocenters used in this study: (a) Longitude versus depth, (b) Latitude versus depth.

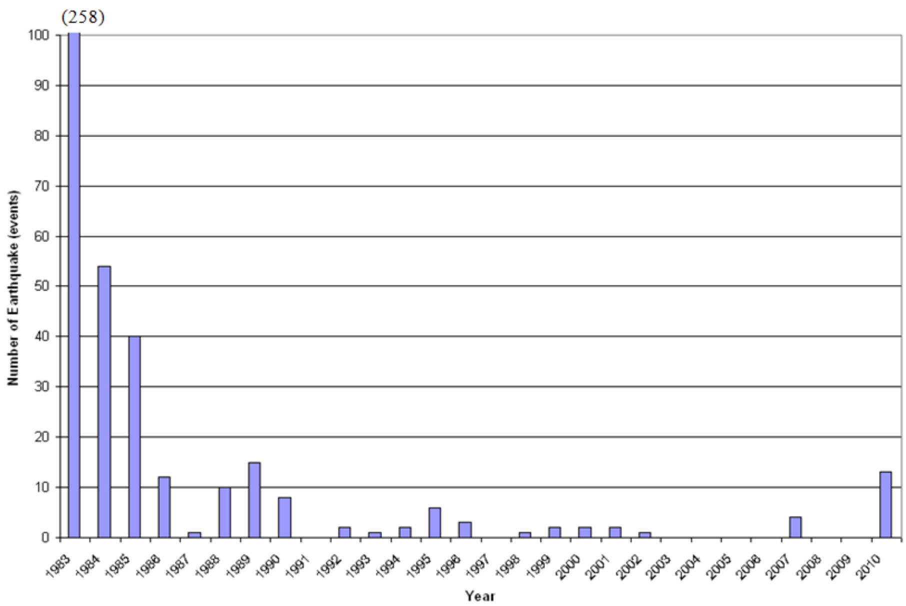


Figure 5. Earthquake distributions versus time in the Kanchanaburi region. Significant decrease in number of seismicities after year 1983 is notable.

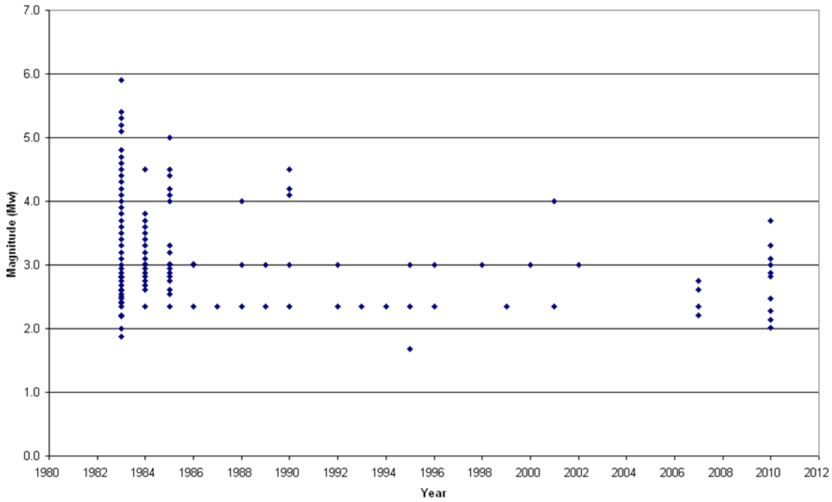
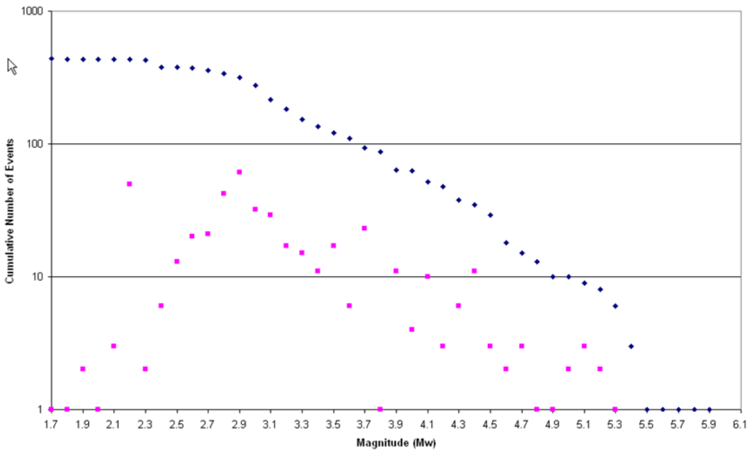
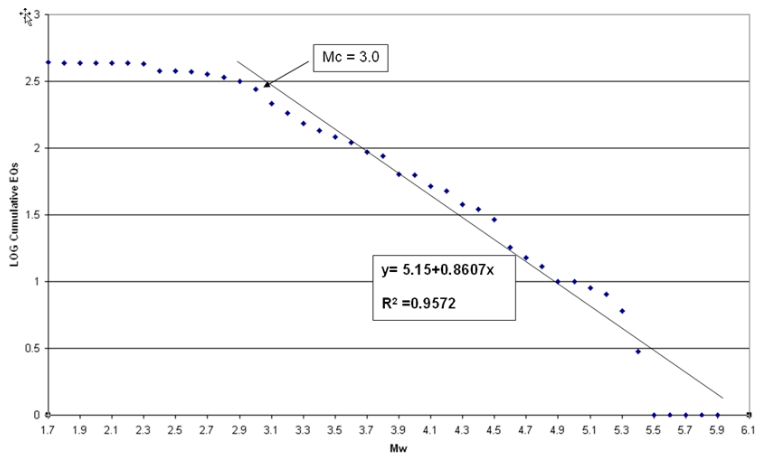


Figure 6. Earthquake magnitude distributions versus time in the Kanchanaburi area. Significant decrease in magnitude after the main shock on April 22nd, 1983 is notable.



(a)



(b)

Figure 7. Magnitude-frequency relationship for the earthquakes in this study.(a) Earthquake magnitudes versus cumulative number of earthquakes (blue diamonds). The total number of earthquakes for each magnitude is shown with pink rectangles. (b) Earthquake magnitudes and the logarithm of the cumulative number of the earthquakes. Best fit line suggest a-value = 5.15 and b-value = 0.86.

triggered seismicities, which corresponds to the study by Gupta *et al.* (2002). The reduction in earthquake occurrences may suggest that the crust in the vicinity of these reservoirs has been gradually stabilized after the dams' impoundments. Soralump and Chaisrakaew (2009) observed that there were no obvious relationships between the reservoirs' water level and the frequency, magnitude, and timing of the earthquakes occurring in the region. However, there are at least 13 reported seismic events with a magnitude range from M_w 2.1 to M_w 3.7 in the year 2010. The causes and relationships between the earthquakes and the reservoirs water level are still unclear.

5. Seismic Hazard of Kanchanaburi

The seismic hazard in Kanchanaburi has created a scare in the community that a large earthquake may damage either of the two big dams of the region. These fears have deteriorated the spirits along the communities. It has also generated a negative impact to the tourism industry as more than five million tourists visit Kanchanaburi annually. Through the history, since the construction of the dams, the local community has been frightened several times by small to moderate earthquakes in the area. Unfortunately, most of the panics were caused by rumors and false information regarding the seismic hazard in Kanchanaburi. Various groups have studied the seismic hazard in the Kanchanaburi area (Charusiri *et al.*, 1999, 2002, 2010; Fenton *et al.*, 2003) using active fault investigations and seismicities. Naksawee *et al.* (2010) calculated the peak ground acceleration (PGA) using the deterministic seismic hazard approach from the fault traces appearing from the remote sensing data and proposed that the possible PGA from an earthquake in Kanchanaburi varied between 0.039-0.319 g.

In order to calculate the PGA of the affected area in Kanchanaburi, we calculate the maximum credible earthquake magnitude (MCE) using the relationship between a surface rupture length and the magnitude proposed by Wells and Coppersmith (1994) as following:

$$M_w = 5.08 + 1.16\,(\mathrm{Log}_{10}\,(\mathrm{SRL})) \qquad (8)$$

where SRL is a surface rupture length of an interested fault in kilometers.

Charusiri *et al.* (2010) proposed that the longest segment of TPFZ is 78 km and the longest segment of the SSFZ is 48 km. This yields the maximum credible earthquake magnitudes of 7.3 for the TPFZ and 7.0 for the SSFZ.

The peak ground acceleration is calculated from the attenuation model using the MCEs of each fault. Most of the attenuation models used in seismic hazard analysis were aimed for applications in the western U.S.A. due to abundant seismic stations and several occurrences of the moderate to large earthquakes (Abrahamson and Silva, 1997; Boore *et al.*, 1997; Campbell, 1997; Sadigh *et al.*, 1997).

Ruangrassamee and Palasri (2011) measured the ground motions at several places in Thailand that are affected by the M_w 6.8 earthquake in Myanmar, occurring on March 24th, 2011, at latitude 20.71 °N and longitude 99.95 °E, about 30 km to the north of Mae Sai District in Chiang Rai Province, northern Thailand. They found that the ground motion at the Mae Sai station, located about 30 km from the earthquake epicenter, showed a PGA value of 0.2 g. They also compared the measured ground motion data with the various attenuation relationships and found that the values of ground accelerations from this earthquake were close the attenuation model from the study by Sadigh *et al.* (1997). Therefore, this work will use their attenuation models to calculate the ground motions from the potential faults for a seismic hazard analysis.

The results from the ground motion calculation using the attenuation model of Sadigh *et al.* (1997) for the assumed shallow crustal earthquake occurring at 15 km depth from the calculated MCEs yield a predicted maximum PGA at the fault line of 0.31 g for the TPFZ and 0.28 g for the SSFZ respectively (Figure 8). The PGA values calculated in this work are very different than those of Pailoplee *et al.* (2009) who reported the PGA at both faults over 2-3 g using a deterministic method. The discrepancy between these works is a result of the different attenuation models used in the PGA calculation. Pailoplee *et al.* (2009) use the attenuation model proposed by Kobayashi *et al.* (2000) while this work uses the attenuation model proposed by Sadigh *et al.* (1997). It is interesting to note that these authors even suggested that their PGA calculations are for the worst case scenario and might be overestimated (Pailoplee *et al.*, 2009).

6. Conclusions

Four hundred and thirty seven earthquakes occurring since 1983 have been reported in Kanchanaburi. The seismicity data were analyzed for time and location distributions along with the frequency-magnitude relationships. There are no clear correlations between the epicenters of these earthquakes and the known locations of the active faults in Kanchanaburi, which could be due to the uncertainty of the reported location of the earthquakes. The seismic catalog used in this study is essentially complete for M_w=3.0 for Kanchanaburi region. The analysis of G-R relationship yields a-value equals to 5.15 and b-value equals to 0.86 for the earthquakes occurring in this region. It is important to note that the frequency-magnitude relationships were analyzed as a whole (all earthquakes). In the future, the detailed work is needed to analyze these earthquakes separately as an individual effect from each reservoir. One difficulty is that these two reservoirs are so close to each other (only 50 km apart) that it will be difficult to separate the main shocks and the aftershocks occurring along these two adjacent reservoirs using a method suggested by Gardner and Knopoff (1974). A deterministic seismic hazard analysis of the TPFZ and SSFZ suggest that characteristic earthquakes magnitude of the TPFZ and the SSFZ are 7.3 and 7.0, respectively, with a maximum PGA of 0.31 and 0.28 g at the faults lines.

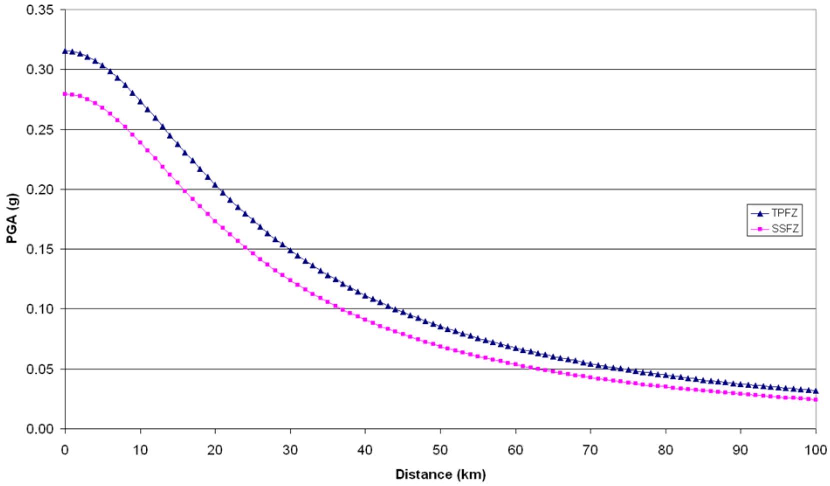


Figure 8. PGA versus epicentral distance of the TPFZ and the SSFZ calculated from their surface rupture lengths using the Sadigh *et al.* (1997) relationship. See text for detailed explanation.

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