SEISMIC HAZARD ANALYSIS FOR MYANMAR

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In this study, the seismic hazards of Myanmar are analyzed based on both deterministic and probabilistic scenarios. The area of the Sumatra–Andaman Subduction Zone is newly defined and the lines of faults proposed previously are grouped into nine earthquake sources that might affect the Myanmar region. The earthquake parameters required for the seismic hazard analysis (SHA) were determined from seismicity data including paleoseismological information. Using previously determined suitable attenuation models, SHA maps were developed. For the deterministic SHA, the earthquake hazard in Myanmar varies between 0.1 g in the Eastern part up to 0.45 g along the Western part (Arakan Yoma Thrust Range). Moreover, probabilistic SHA revealed that for a 2% probability of exceedance in 50 and 100 years, the levels of ground shaking along the remote area of the Arakan Yoma Thrust Range are 0.35 and 0.45 g, respectively. Meanwhile, the main cities of Myanmar located nearby the Sagaing Fault Zone, such as Mandalay, Yangon, and Naypyidaw, may be subjected to peak horizontal ground acceleration levels of around 0.25 g.

Keywords: Earthquake; seismic hazard analysis; deterministic; probabilistic; Myanmar.

1. Introduction

Tectonically, Myanmar is situated within one of the seismically active zones in Mainland Southeast Asia. The recent to present-day activity of the Indian–Eurasian Plate Collision has left clear tectonic evidence and seismic activities are still prominent [Kundu and Gahalaut, 2012]. For the last 100 years (1912-present), at least 20 major earthquakes in Myanmar or nearby have been reported (Fig. 1(a)), with the highest magnitude (Mw 8.6) recorded at the Indian–Myanmar border in 1950, and then at Mw 8.0 (1912) at Mandalay and at Mw 7.6 (1931) close to Myitkyina [Brown, 1914; Brown and Leicester, 1933]. Thus, quantitative seismic hazard analysis (SHA) is really needed for Myanmar in order to provide an effective mitigation plan for upcoming earthquakes.

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Fig. 1. (Color online) (a) Map of Myanmar and the neighboring area showing the earthquake fault lines [Bender, 1983; Pailoplee et al., 2009] in gray and the epicenters of major earthquakes (red dots) reported during the last 100 years (1912-present). (b) Seismic source zones in Myanmar and the nearby area showing the distribution of main shock earthquakes (blue dots) with a $M_w > 4$ after the earthquake de-clustering process [Gardner and Knopoff, 1974]. The numbers in this figure are equivalent to the numbers in the column “zone” in Table 1.
Based on literature reviews, some researchers have attempted to examine the seismic hazard situation in the Myanmar region. Zhang et al. [1999], in the Global Seismic Hazard Assessment Program (GSHAP) in Continental Asia, proposed a SHA map for Asia including the high hazard region of Myanmar. However, this approximate investigation was mainly based on the assumptions, models and SHA’s resolution from a global scale. After the Sumatra–Andaman earthquake (Mw-9.0) in 2004, Martin [2005] and Petersen et al. [2007] modified the SHA maps for Mainland Southeast Asia. Although the Myanmar area is excluded in this SHA, the maps of Thailand showed SHA results in some parts of Myanmar. The most up-to-date SHA established specifically for Myanmar is that of Htwe and Wenbin [2010]. However, they proposed the SHA maps only for Yangon, and not for the country as a whole.

This study, therefore, aims to contribute directly the SHA maps for the whole country of Myanmar based on the most up-to-date data and suitable models with the world-wide accepted SHA methodology [Kramer, 1996].

2. Seismotectonic

Due to the continued Northward subduction of the Indian Plate underneath the Burma Platelet (which is the Western part of the Eurasian Plate) and the Northward movement of the Burma Platelet from a spreading center in the Andaman sea [Bertrand and Rangin, 2003; Curray, 2005], earthquakes in Myanmar have resulted from three major seismotectonic regimes as follows;

(i) **Sumatra–Andaman Subduction Zone to the West of the Myanmar coast.** In detailed classification, three separate portions of seismotectonic setting can be distinguished (see also Fig. 1(b) and Table 1), as follows. (a) The Sumatra–Andaman Inter Plate where shallow-focus earthquakes are normally generated along the trench, (b) the Sumatra–Andaman Intra Slab that is bounded by the occurrence of intermediate to deep-focus earthquakes underneath the Western fold belt of Myanmar [Paul et al., 2001], and (c) the portion of the Western fold belt that we call the “Arakan Yoma Thrust Range” [Curray, 2005] where compressive tectonic activity, that is, reverse faulting, usually causes shallow-focus earthquakes.

(ii) **Major active strike-slip fault along the Central lowlands of Myanmar.** Beside the Sumatra–Andaman Subduction Zone, Myanmar has a great strike-slip active fault zone called the “Sagaing Fault Zone” [Bertrand and Rangin, 2003; Htwe and Wenbin, 2009]. This 1,200km-long fault trends roughly North–South and moves right-laterally with a velocity of 23mm/yr [Bertrand and Rangin, 2003]. As a result, Myanmar is subjected to major earthquakes from this fault (Fig. 1(a)).

(iii) **Regional shear zone in the highlands of Eastern Myanmar.** This seismotectonic regime is continuous with the earthquake zones in Southern China, North–Western Laos and the Northern and Western part of Thailand (Fig. 1(b)).
Table 1. Summary of the earthquake potential parameters of the nine earthquake sources for the country of Myanmar.

<table>
<thead>
<tr>
<th>Zone</th>
<th>Earthquake source</th>
<th>Paleoseismological data</th>
<th>Seismicity data</th>
<th>Reference for S</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Zone</td>
<td>SRL</td>
<td>$M_{\text{max}}$</td>
<td>$A_f$</td>
</tr>
<tr>
<td>1</td>
<td>Sumatra–Andaman Inter Plate</td>
<td>—</td>
<td>9.0</td>
<td>93972</td>
</tr>
<tr>
<td>2</td>
<td>Sumatra–Andaman Intra Slab</td>
<td>—</td>
<td>9.0</td>
<td>93972</td>
</tr>
<tr>
<td>3</td>
<td>Arakan Yoma Thrust Range</td>
<td>340</td>
<td>8.0</td>
<td>6391</td>
</tr>
<tr>
<td>4</td>
<td>Sagaing Fault Zone</td>
<td>944</td>
<td>8.5</td>
<td>18754</td>
</tr>
<tr>
<td>5</td>
<td>Hsenwi–Nanting Fault Zone</td>
<td>359</td>
<td>8.0</td>
<td>6760</td>
</tr>
<tr>
<td>6</td>
<td>Western Thailand</td>
<td>259</td>
<td>7.9</td>
<td>4781</td>
</tr>
<tr>
<td>7</td>
<td>Jinghong–Mengxing Fault Zone</td>
<td>174</td>
<td>7.7</td>
<td>3151</td>
</tr>
<tr>
<td>8</td>
<td>Northern Thailand–Dein Bein Fhu</td>
<td>177</td>
<td>7.7</td>
<td>3208</td>
</tr>
<tr>
<td>9</td>
<td>Red River Fault Zone</td>
<td>407</td>
<td>8.1</td>
<td>7715</td>
</tr>
</tbody>
</table>

Note: $SRL$ is the surface rupture length (km), $M_{\text{max}}$ is maximum earthquake magnitude, $A_f$ is rupture area (km$^2$), $S$ is slip rate (mm/yr). The values $a$ and $b$ are constants representing entire seismicity rate and seismicity potential, respectively, in the Gutenberg–Richter relationship. $M_{\text{min}}$ is the considered minimum magnitude.
Pailoplee et al. [2009] proposed a large number of possible active fault zones in this area. For instance, the Hsenwi–Nanting Fault Zone in the Eastern Myanmar–Southern China border area [Lacassin et al., 1998], the zone of right-lateral strike-slip faults in Western Thailand which spread out from the Sagaing Fault System [Fenton et al., 2003], and the Dein Bein Fhu Fault Zone [Zuchiewicz et al., 2004] that includes the Red River Fault Zone [Duong and Feigl, 1999] in Vietnam.

Based on tectonic environments, regional geomorphology, and the orientation of earthquake fault lines, including the epicentral distribution of earthquakes, Pailoplee and Choowong [2012] demarcated 13 seismic source zones for investigating the characteristics of earthquake occurrences in Mainland Southeast Asia. Nine of these 13 zones were defined as being earthquake sources that might affect the Myanmar region. These selected sources are centered inside and around Myanmar with a radius of about 300 km, in accord with that suggested by Gupta [2002] for an effective SHA study. The boundary of each individual zone is illustrated in Fig. 1(b) and described in detail in Table 1.

3. Seismicity

Based on the survey data, the international catalogues that have captured earthquake events in and around Myanmar during 1967–2012 are the Incorporated Research Institutions for Seismology (IRIS), the U.S. Geological survey (USGS), and the global Centroid-Moment-Tensor catalogue (CMT). These various catalogues have both advantages and disadvantages in terms of the continuity and time span of their records. Hence, we prepared a new composite earthquake catalogue for this SHA according to the procedure suggested by Caceres and Kulhanek [2000]. All obtained earthquake catalogues (i.e. IRIS, USGS, and CMT), including the reported major earthquakes mentioned in Fig. 1(a) were merged. The merged catalogue was then checked for duplicate entries and, where they existed, one representative earthquake event was retained.

3.1. Earthquake magnitude conversion

The new merged catalogue contained a variety of earthquake magnitude scales: body wave magnitude ($M_b$), surface wave magnitude ($M_s$) and moment magnitude ($M_w$), which were derived by a specific analytical method. For the SHA performed here, the $M_w$ value was used because it directly represents the physical properties of an earthquake source [Ottemoller and Havskov, 2003]. Since the CMT catalogue provides $M_b$, $M_s$, and $M_w$ magnitudes for individual earthquake events, we, therefore, contribute the relationship of $M_s$ to $M_w$ and $M_b$ to $M_w$ (Fig. 2) which formulated in Eqs. (1) and (2). Thereafter, all earthquakes reported in $M_b$ or $M_s$
Fig. 2. Empirical relationships between (a) $M_s - M_w$, and (b) $M_b - M_w$.

are converted to $M_w$ according to these proposed equations.

\begin{align*}
M_w &= 0.1749M_s^2 - 1.3396M_s + 7.6876, \\
M_w &= 0.2674M_b^2 - 1.8983M_b + 7.9123.
\end{align*}

3.2. Earthquake de-clustering

For the SHA, earthquake records require de-clustering by filtering the main shocks from the foreshocks and aftershocks [Kramer, 1996]. We applied the model of Gardner and Knopoff [1974] to de-cluster the earthquake events. By using the ZMAP software package [Wiemer, 2001], we distinguished 1463 clusters from 27,355 earthquake events. Of these events, a total of 24,386 events (89%) are classified as foreshocks or aftershocks and were, therefore, eliminated. This derived main-shock catalogue (Fig. 1(b)) was then used to evaluate the earthquake parameters needed for the SHA as described in Sec. 3.3.

3.3. Earthquake parameters

The earthquake parameters considered for each seismic source zone are the expected maximum earthquake magnitude ($M_{\text{max}}$), considered minimum earthquake magnitude ($M_{\text{min}}$), rupture area ($A_f$) and the slip rate ($S$), including the earthquake activity which are represented by values $a$ and $b$ of the Gutenberg–Richter (G–R) relationship [Gutenberg and Richter, 1944].

$M_{\text{max}}$ is the most important parameter because the highest magnitude contributes the most to the analysis. To determine $M_{\text{max}}$, the relationship between $M_w$ and the surface rupture length of the fault ($SRL$) proposed by Wells and
Coppersmith [1994] was demonstrated. The SRL used for the $M_{\text{max}}$ calculation was taken from the length of the longest fault segment in each fault zone (Table 1). Moreover, the $A_f$ value was also determined using the relationship of the obtained $M_w$ and $A_f$ [Wells and Coppersmith, 1994]. For $M_{\text{min}}$, it was taken as 4.0 for all earthquake source zones. Below this lower threshold magnitude it is assumed that there is no significant earthquake hazard on engineering structures [Kramer, 1996].

1. Sumatra–Andaman Inter Plate
2. Sumatra–Andaman Intra Slab
3. Arakan Yoma Thrust Range
4. Sagaing Fault Zone
5. Hsenwi–Nanting Fault Zone
6. Western Thailand
7. Jinghong–Mengxing Fault Zone
8. Northern Thailand–Dein Bein Fhu
9. Red River Fault Zone

Fig. 3. G–R relationships of the nine seismic source zones recognized in this SHA. Triangles indicate the number of earthquakes of each magnitude; squares represent the cumulative number of earthquakes equal to or larger than each magnitude. Solid lines are the lines of best fit according to Woessner and Wiemer [2005]. $M_c$ is defined as the magnitude above which all earthquakes are considered to be fully reported.
In addition, the S value of individual fault zones were cited in previous publications mentioned in Table 1. The earthquake activities are quantified using the G–R relationship, shown in Eq. (3).

$$\log(n(M)) = a - bM,$$

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

This relationship is a key element in estimating the probability that an earthquake with magnitude $M$ or larger will occur within a specific time interval. Thus, the obtained main-shock events were captured by the boundary of individual earthquake source. The number of earthquake events from each source were shown in Table 1. Thereafter, the number of events with a magnitude equal to or larger than $M$, denoted by $n(M)$, is plotted (Fig. 3). The optimal values of $a$ and $b$ to yield the G–R relationship are evaluated according to Woessner and Wiemer [2005]. All earthquake parameters representing the earthquake potential of each earthquake source, finally, are summarized in Table 1.

4. Attenuation Models

As well as clarification of the earthquake source, strong ground-motion attenuation models are also essential for SHA. In this study, we classified the nine earthquake sources into two categories on the basis of seismotectonic setting; the subduction-related earthquake zones for the Sumatra–Andaman region (zones 1 and 2 in Table 1), and the shallow crustal earthquake zones (inland active fault zone) (zones 3–9 in Table 1).

For the subduction-related earthquakes, Chintanapakdee et al. [2008] compared 55 strong ground-motion data with some candidate attenuation models and concluded that the model of Crouse [1991], shown in Eq. (4), was the most suitable relationship for the Sumatra–Andaman Subduction Zone.

$$\ln y_{\text{Crouse}}(M, R) = p_1 + p_2 M + p_4 \ln(R + p_5 e^{(p_6 M)}) + p_7 h,$$

where $y$ is the peak horizontal ground acceleration or PGA (cm/s$^2$), $M$ is the moment magnitude ($M_w$), $R$ is the source-to-site distance (km), $p_1 = 6.36$, $p_2 = 1.76$, $p_4 = -2.73$, $p_5 = 1.58$, $p_6 = 0.608$, $p_7 = 0.00916$, the focal depth, $h$, varies between 0 and 238 km, and the standard deviation ($\sigma$) = 0.773.

For the earthquakes generated by inland active faults, Htwe and Wenbin [2010] analyzed the SHA for Yangon (Central Myanmar) according to the attenuation relationship of Boore et al. [1997], which is represented by

$$\ln y_{\text{Boore}}(M, R) = b_1 + b_2 (M - 6) + b_3 (M - 6)^2 + b_4 R + b_5 \log(R) + b_6 G_h + b_7 G_c,$$
where \( y, M, \) and \( R \) are as defined in Eq. (4), for a randomly-oriented horizontal component (or geometrical mean) \( b_1 = 0.105, \ b_2 = 0.229, \ b_3 = 0, \ b_4 = 0, \ b_5 = -0.778, \ b_6 = 0.162, \ b_7 = 0.251, \ G_B = 1, \ G_C = 0, \) and \( \sigma = 0.23. \)

Consequently for this SHA, we selected the strong ground-motion attenuation model of Boore et al. [1997] for shallow crustal earthquakes and the model of Crouse [1991] for the Sumatra–Andaman Subduction Zone.

5. Seismic Hazard Analysis

For the SHA, the MATLAB-based software that employs an algorithm to calculate the PGA (in g unit) was used assuming the rock site condition. A real sources of subduction zones 1 and 2 and earthquake fault lines delineated in zones 3–9 (Fig. 1) were converted systematically to 0.05° × 0.05° points. All parameters needed to define the potential of each earthquake source were added in, including the suitable attenuation models. The SHA was calculated for 0.2° × 0.2° grid cells covering the whole country of Myanmar. Both deterministic SHA (DSHA) and probabilistic SHA (PSHA) were employed.

For the DSHA [Krinitzsky, 2003], the \( M_{\text{max}} \) determined for each earthquake source was assumed to be generated within the source at the shortest distance from source to site. Using this worst-case scenario, the attenuation relationships of ground shaking were applied to estimate the PGA, and the obtained PGA values were then contoured to construct the DSHA map, as shown in Fig. 4.

This DSHA map illustrates that Myanmar has a chance of ground shaking up to the 0.45g level, particularly for the Western part along the Arakan Yoma Thrust Range. Meanwhile, in Central and Eastern Myanmar, DSHA indicates a possible ground shaking between 0.25–0.35g at the area nearby the faults and 0.1–0.2g for the other regions.

In contrast to the DSHA, the PSHA [Cornell, 1968] considers the likelihood of an earthquake (i.e. both magnitudes and locations) and the uncertainty of ground shaking attenuation. The probability density functions of magnitudes are demonstrated according to the characteristic earthquake model [Youngs and Coppersmith, 1985] recognizing the paleoseismological data (i.e. \( M_{\text{max}}, A_f \) and \( S \)). The magnitudes of interest were subdivided equally into 10 case studies between \( M_{\text{max}} \) and \( M_{\text{min}} \) (Fig. 5(a)). Meanwhile, the source-to-site distances were subdivided equally into 50 portions ranging from the shortest to the longest possible distances (Fig. 5(b)). In addition, using the selected attenuation models, the hazard curves, plotted as the PGA (X-axis) against the probability of exceedance (POE) (Y-axis) were evaluated for each SHA grid cell (Fig. 5(c)).

For instance from Fig. 5(c), the hazard curves indicate that Hakha city, situated near the West coast of Myanmar, is located in the most earthquake-prone area. Ground shaking equal to or larger than 0.16g occurs around 0.001 times per year (once every 1000 years). The hazard level decreases for the cities of Myitkyina, Naypyidaw, Sittwe, Mandalay, Bago, Yangon, Taunggyi, and Dawei.
PSHA can be presented in maps that depict the PGA with a fixed POE (%) in a finite-time period of interest [Kramer, 1996]. In the PSHA of this study for Myanmar, four maps with different POEs (2 and 10%) and time periods (50 and 100 years) were created (Fig. 6). The highest hazard levels were observed in the Western part of Myanmar, the same as that predicted by the DSHA. In this area, the maximum PGA values for a 2% POE are between 0.35 and 0.45 g for time periods of 50 and 100 years, respectively, whereas in Central and Eastern Myanmar, the SHA levels ranged from 0.05 to 0.25 g.

With respect to a 10% POE, the relative distribution of hazard levels are similar to those at a 2% POE, but the PGA values for the 10% POE are approximately 0.5 times larger than that for the 2% POE. The highest ground motion, at around 0.1–0.2 g, was found in the Western part of Myanmar, whereas in some regions in the Central and Eastern part of Myanmar it drops down to 0–0.05 g (Fig. 6).

6. Conclusions and Recommendations

In this study, both DSHA and PSHA maps were formed for the whole country of Myanmar. DSHA is strongly recommended for a critical project in a specific area.
where the protection is needed against this worst-case situation. We also expect that these PSHA maps will help Myanmar to provide a basis for long-term preparedness for earthquake hazards and to create an International Building Code for improved building design and construction.

Based on the obtained SHA results, the most destructive area is the Western side of Myanmar due to the high earthquake activities of the Sumatra–Andaman Subduction Zone. However, it may be less vulnerable than the remote area of Arakan Yoma Thrust Range which is currently sparsely populated.

Although the earthquake hazard in Central and Eastern Myanmar is lower than the Western part, the PGA of 0.35 g analyzed from the DSHA, or even the PGA value of 0.25 g derived from the PSHA are enough to impact the important urban areas of Myanmar, and in particular for the cities that are located close to the Sagaing Fault Zone such as Mandalay, Bago, Yangon, and Naypyidaw (the capital city of Myanmar).

Although we believe that the SHA presented here can provide more detailed and up-to-date results than that previously available, more work is still needed to refine this analysis. For example, it is important to note that the strong ground-motion attenuation models considered in this study derive the PGA for the rock
site condition. In areas covered by thick, soft soils the ground shaking will be much more severe than that indicated by our maps. Consequently, more observations of the strong ground-motion in the region are needed and further paleoseismological research should be encouraged.
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