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PROBABILISTIC SEISMIC RISK MAPPING FOR THAILAND

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ABSTRACT

In this paper, a probabilistic analysis of seismic hazard in Thailand is presented. The analysis begins with the formulation of average seismicity models for 11 regional seismic source zones based on 80-year instrumental earthquake records. All the records are corrected for completeness by a statistical technique, and the upper bound of earthquake magnitude for each of the source zones is determined and incorporated in each model. An appropriate attenuation model is then chosen and combined with the seismicity models in the modified Cornell's probabilistic analysis. The obtained results are presented by a map showing contours of the expected peak ground acceleration with a 10% chance of being exceeded in a 50-yr period. Based on the map, the country is then divided into various seismic zones according to the zoning criterion used in the current U.S. Uniform Building Code (UBC). The seismic zoning map clearly shows that the northern and western Thailand can be classified as moderate risk and moderately high risk zones that are equivalent to the UBC zone 2B and 3, respectively.

KEYWORDS

Seismic hazard analysis, Thailand, Uniform Building Code, seismic zoning map, probabilistic ground acceleration, magnitude-recurrence relationship, attenuation model, Cornell's method, seismic source zone.

INTRODUCTION

Thailand has long been thought of as a low seismic risk country. During the past two decades, however, seven shallow earthquakes of moderate magnitude (5 < magnitude(local) < 6) have occurred in the northern and western regions of the country. Fortunately, the strong ground shaking in the vicinity of these earthquake epicenters have never coincided with any town or city, hence neither buildings have been destroyed nor people have been killed so far. The occurrence of these moderate earthquakes, nevertheless, generated enormous interest in seismic risk to Thai public, engineering communities, and several government departments that are responsible for public safety. Various efforts have been carried out to gain more understanding in the phenomena and their potential adverse effects. These efforts include the establishment of a national network of seismograph stations, the installation of strong-motion accelerographs, the collection of historical earthquake records and instrumental earthquake data from several worldwide seismological data sources, and the identification of seismic source zones and major faults.

It was then recognized that one of the most effective ways to mitigate the destructive effects of earthquakes was to have seismic design requirements together with a national seismic hazard map in the Thai Building Code. For this reason, Chandrangsu (1986) developed a seismic hazard map showing the largest historical intensity in Modified Mercalli scale; the map is comparable to the seismic zoning map in the 1982 U.S. Uniform Building Code (UBC). Based on the map, some parts of the northern and western Thailand can be classified as a moderate risk zone equivalent to the UBC zone 2. Then, seismic design requirements were drafted by using the 1982 UBC as a model code (Chandrangsu, 1986). The drafted requirements were made in the form of mandatory ministerial regulations under the national building control act of legislation, so the requirements have attracted considerable attention from many practicing engineers, academics, and concerned policy decision makers. However, due to (1) the wide-spread perception of general public (as well as engineers) that earthquakes are not a serious problem, (2) the doubt about the credibility and reasonableness of the seismic hazard map that was developed from the scant data, and (3) the fear that seismic design requirements will significantly increase the cost of buildings and thus jeopardize the economic development of the country, these drafted seismic regulations, up to now, have not yet been implemented.

During the last decade, while the move to adopt seismic regulations in Thailand has made no progress, the concept of seismic zonation in the UBC has undergone a significant change. In the 1988 UBC, the deterministic intensity-based zoning map was replaced by a new probabilistic acceleration-based zoning map. The new map was developed based on the 1978 ATC seismic hazard maps which were prepared by Algermissen and his co-workers (Algermissen *et al.*, 1982). In the meantime, in Thailand, a rather complete seismological data base for making preliminary probabilistic seismic hazard map has become available. Consequently, attempts have been made both by Nuttalaya and Shrestha (1990) and by Lukkunaprasit and Kuhatasanadeekul (1993) to develop probabilistic acceleration-based zoning maps of Thailand. However, in the development of these maps, some critical steps recommended by Algermissen and his co-workers have not been followed by these investigators. For example, completeness of instrumental data has not been checked and bounded magnitude-recurrence relationships have not been employed. Hence, the reliability of these maps was in question.

Since the credibility of a seismic zoning map is essential to promoting widespread acceptance of seismic regulations in Thailand, the authors then decided to develop a probabilistic acceleration-based zoning map based upon the concepts, analysis procedure, and criteria used in the development of the UBC zoning map as much as the available information permitted. The detailed procedure is described in the subsequent sections in this paper. The final results are presented by a map showing contours of expected peak ground acceleration with a 10% chance of being exceeded in a 50-yr period. Based on the map, some parts of the northern and western Thailand can be considered as moderate risk and moderately high risk zones that are equivalent to the UBC zone 2B and 3, respectively.

SEISMOLOGICAL DATA BASE

The principal part of seismological data base for the subsequent seismic hazard analysis is the results of a 4-year research, data compilation, and interpretation effort by the Southeast Asia Association of Seismology and Earthquake Engineering (Nuttalaya *et al.*, 1985). This data base contains instrumental data of earthquakes from 1910 to 1983 within the region bounded by latitudes 5°N to 25°N and longitudes 90°E to 110°E, which includes Thailand, Indochina, and parts of Burma and China. These data were collected from several agencies which include the U.S. Geological Survey (USGS), the International Seismological Centre (ISC) in U.K., and the Thai Meteorological Department (TMD). In addition, 12 seismic source zones within the region (zones A to L in Fig. 1) have been identified on the basis of the spatial distribution of seismicity and regional seismotectonic structure (Nuttalaya *et al.*, 1985).

Note that the first seismograph station of TMD was established in 1963. Therefore, all instrumental earthquake data during 1910-1963 were obtained from the worldwide network of seismograph stations outside Thailand, and due to the sparsity of the stations, a considerable number of small and moderate earthquakes that occurred in this region were not detected or recorded, i.e. data incompleteness. After 1963, as TMD kept on installing new seismograph stations at various parts of the country, the earthquake detection capability was rapidly inproved. In 1982, the number of TMD stations reached seven, and the TMD data were appeared to be more complete than those from any other data sources. Hence, the TMD instrumental earthquake data from 1984 to 1989 (Prachuab and Weckbunthung, 1992) were added to the 1910-1983 data to form an 80-year instrumental data base.

Certain adjustment, selection, and categorization of these data were made in order to make them suitable for subsequent analyses. First, as the instrumental data have been collected from several sources, various types of magnitude scales were used, with the two most common types being Richter (or local, m) and P body wave (m_b). So, all the magnitude data were adjusted to the local magnitude scale by using the relation suggested by Gutenberg and Richter (1956) : $m = m_b + 0.4 (m_b - 6)$. Second, as earthquakes are normally not independent events, but tend to cluster in space and time in the form of foreshocks, main shock, and aftershocks, care had been taken to select only the main shock from each earthquake series. Then, earthquake data, which had been adjusted and selected, were categorized according to their corresponding source zone, magnitude, and occurring in 10-year periods of time as shown in Table 1. The spatial distribution of epicenters of these

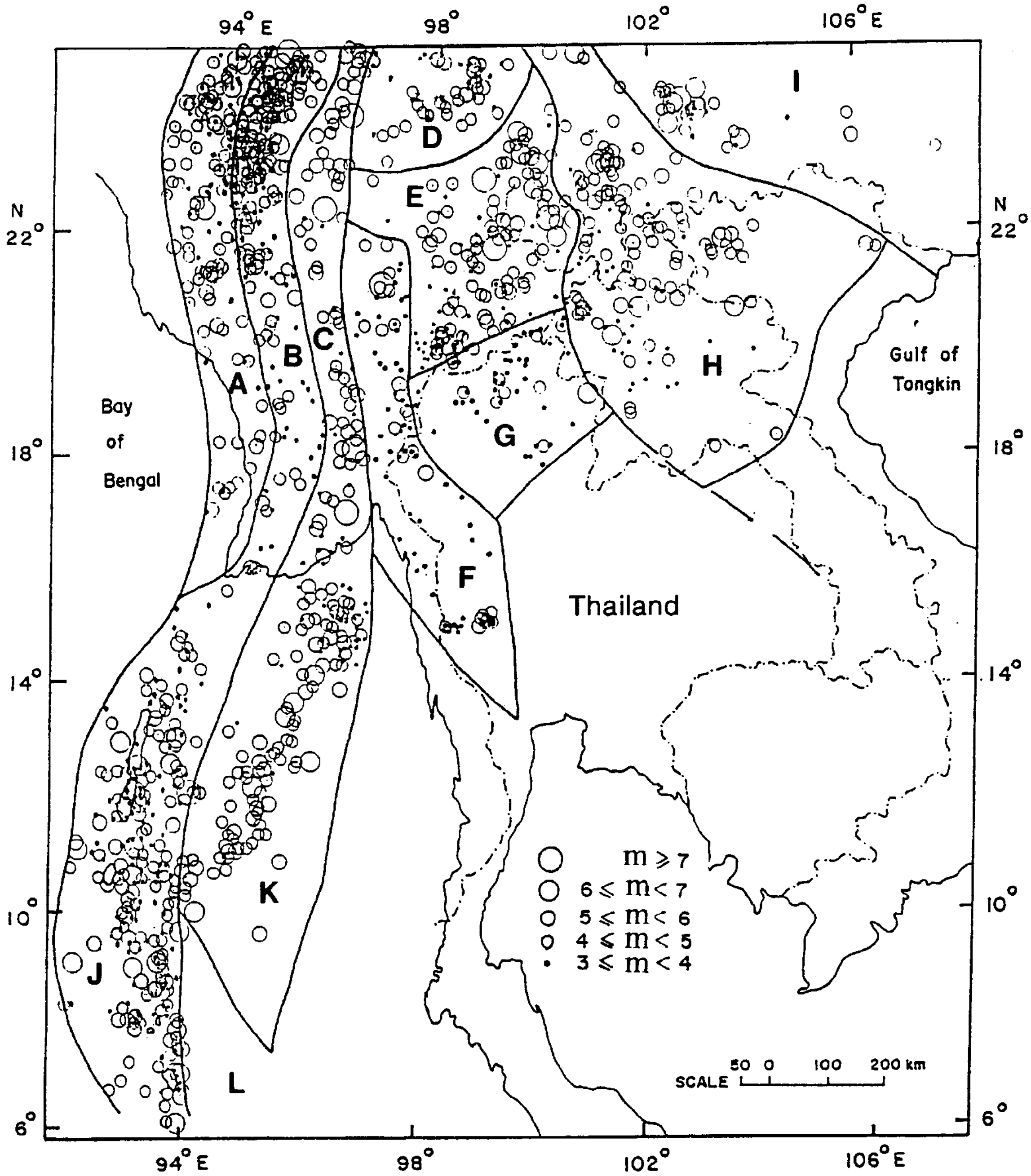

Fig. 1. Twelve seismic source zones (A – L) of Burma-Thailand-Indochina region and epicenters of earthquakes during 1910 to 1989.

earthquakes are presented in Fig. 1. The data of the source zone L were not considered in the seismic hazard analysis because of their incompleteness and insignificance.

MODELLING OF EARTHQUAKE SOURCES

With the earthquake data shown in Table 1, the relation between the average rate of earthquake occurrence and earthquake magnitude, i.e. magnitude-recurrence relationship, for each seismic source zone can be determined. The relation is described by the well-known Gutenberg-Richter exponential model :

$$\log N(m) = a - b\,m \tag{1}$$

where N(m) is the average number per year of earthquakes having magnitude greater than m, and a and b are positive constants which describe the seismicity of the source zone.

Table 2. Parameters and properties of 11 seismic source zones of the region

Zone	a	b	h_{av} (km)	m_{obx}	Area (km^2)
A	3.71	0.79	60	6.75	131,270
B	3.32	0.68	80	7.40	116,355
C	2.42	0.53	30	7.75	98,963
D	2.62	0.66	30	5.86	73,159
E	3.35	0.64	20	7.30	144,921
F	2.97	0.64	20	7.90	144,920
G	2.78	0.68	20	6.50	96,563
H	2.95	0.65	20	6.75	323,057
I	1.97	0.46	25	8.38	225,907
J	3.42	0.69	60	7.20	235,642
K	3.88	0.80	30	6.50	222,089

point where m is equal to the expected largest possible magnitude (Algermissen *et al.*, 1982). In this work, instead of the sharp cut off, a soft truncation is applied by letting

$$\overline{N}(m) = N(m)\cdot W(m) \qquad (2)$$

where $\overline{N}(m)$ is a softly bounded magnitude-recurrence relationship, and

$$W(m) = 1 / \{1 + (0.9\ m/m_{obx})^{50}\} \qquad (3)$$

where m_{obx} is the largest earthquake that had occurred in the source zone (see Table 2). The comparison of $\overline{N}(m)$ and N(m) for the seismic source zone A is shown in Fig. 2.

ATTENUATION RELATIONSHIPS

The next critical step in the seismic hazard analysis is to determine an appropriate acceleration attenuation relationship. The relationship is essential for estimating the peak ground acceleration (PGA) at a specific site from an earthquake occurring in this region. Numerous attenuation relationships for many earthquake-prone regions such as the western U.S., Mexico, Japan have been developed in the past, and they were typically developed from the analyses of a large number of ground acceleration records and proper studies on tectonic environment. For this region, however, only a few tectonic studies are available, and it appears that none of them can be used as a basis to determine an appropriate attenuation relationship for this region. Moreover, only 7 sets of acceleration records have been obtained so far.

Out of these available acceleration records, 6 sets were recorded by the network of 3 SMA-1 strong-motion accelerographs installed on Srinagarind dam in Kanchanaburi province when 6 earthquake events of m between 3.6 and 5.5 occurred during April 15 to August 29, 1983 in the reservoir, approximately 55 km from the dam; another set was recorded by the network of 4 SMA-1 accelerographs installed on Khao Laem dam in the same province when an earthquake with m = 3.9 occurred at 6-8 km northwest of the dam site on July 10, 1985 (Sittipod *et al.*, 1986). By comparing the recorded PGA with those predicted by several existing attenuation relationships, Nuttalaya and Shrestha (1987) found that the Esteva's attenuation relationship gives the best fit, so they suggested that the relationship could be used for this region. The relationship is given as

$$\text{PGA}\ (cm/sec^2) = \{5600.\ \exp(0.8\ m)\} / (R+40)^2 \qquad (4)$$

where R is the focal distance (km); $R = \sqrt{d^2 + h^2}$, d is the distance from the earthquake epicenter to the site, and h is the depth of the earthquake. Note that Eq.(5) is inappropriate for d less than 15 km.

Although it is clear that more studies are required before the appropriate attenuation relationship for this region can be determined with confidence, the Esteva's relationship is chosen here in this study.

Table 1. Number of earthquakes categorized by occurring time and magnitude for 11 regional seismic source zones. (Data which are completely recorded are enclosed by thick solid lines.)

Zone	Time Interval	Magnitude Range										Zone	Time Interval	Magnitude Range									
		2.95-3.45	3.45-3.95	3.95-4.45	4.45-4.95	4.95-5.45	5.45-5.95	5.95-6.45	6.45-6.95	6.95-7.45	7.45-7.95			2.95-3.45	3.45-3.95	3.95-4.45	4.45-4.95	4.95-5.45	5.45-5.95	5.95-6.45	6.45-6.95	6.95-7.45	7.45-7.95
A	1980-89	4	18	24	12	4	3	-	-	-	-	B	1980-89	4	44	42	27	5	1	-	-	1	-
	1970-79	4	11	16	10	4	1	-	-	-	-		1970-79	3	29	31	16	3	1	-	-	-	-
	1960-69	1	2	4	5	3	1	1	-	-	-		1960-69	-	3	12	12	8	1	1	-	-	-
	1950-59	-	-	-	-	1	-	1	-	-	-		1950-59	-	-	-	-	2	1	2	-	1	-
	1940-49	-	-	-	-	-	-	-	1	-	-		1940-49	-	-	-	-	-	-	-	-	-	-
	1930-39	-	-	-	-	-	2	1	1	-	-		1930-39	-	-	-	-	-	-	1	2	1	-
	1920-29	-	-	-	-	-	-	-	-	-	-		1920-29	-	-	-	-	-	-	-	1	-	-
	1910-19	-	-	-	-	-	-	-	-	-	-		1910-19	-	-	-	-	-	-	-	1	-	-
C	1980-89	12	19	19	12	1	1	-	-	-	-	D	1980-89	2	6	2	4	1	-	-	-	-	-
	1970-79	5	8	11	7	1	-	-	-	-	-		1970-79	1	11	10	5	2	2	-	-	-	-
	1960-69	-	1	2	1	-	1	-	-	-	-		1960-69	-	-	1	2	-	-	-	-	-	-
	1950-59	-	-	-	-	1	1	-	-	1	-		1950-59	-	-	-	-	-	-	-	-	-	-
	1940-49	-	-	-	-	-	-	-	-	-	1		1940-49	-	-	-	-	-	-	-	-	-	-
	1930-39	-	-	-	-	-	3	-	-	2	-		1930-39	-	-	-	-	-	1	-	-	-	-
	1920-29	-	-	-	-	-	-	-	-	-	-		1920-29	-	-	-	-	-	-	-	-	-	-
	1910-19	-	-	-	-	-	-	-	-	-	-		1910-19	-	-	-	-	-	-	-	-	-	-
E	1980-89	15	46	36	28	7	1	-	1	-	-	F	1980-89	70	39	18	9	1	1	-	-	-	-
	1970-79	6	14	13	1	-	-	-	-	-	-		1970-79	4	3	2	-	1	-	-	-	-	-
	1960-69	-	-	-	1	1	-	-	-	-	-		1960-69	-	-	-	-	-	-	-	-	-	-
	1950-59	-	-	-	-	-	-	-	2	1	-		1950-59	-	-	-	-	-	-	-	-	-	-
	1940-49	-	-	-	-	-	-	-	2	1	-		1940-49	-	-	-	-	-	-	-	-	-	-
	1930-39	-	-	-	-	-	-	1	-	-	-		1930-39	-	-	-	-	-	-	-	-	-	-
	1920-29	-	-	-	-	-	-	-	1	1	-		1920-29	-	-	-	-	-	-	-	-	-	-
	1910-19	-	-	-	-	-	-	-	-	-	-		1910-19	-	-	-	-	-	-	-	-	-	1
G	1980-89	22	20	8	1	-	-	-	-	-	-	H	1980-89	8	28	26	23	2	1	1	-	-	-
	1970-79	2	6	1	-	-	-	-	-	-	-		1970-79	4	16	11	6	1	-	3	-	-	-
	1960-69	-	-	-	-	-	-	-	-	-	-		1960-69	-	-	1	2	2	-	-	-	-	-
	1950-59	-	-	-	-	-	-	-	-	-	-		1950-59	-	-	-	-	-	-	-	-	-	-
	1940-49	-	-	-	-	-	-	-	-	-	-		1940-49	-	-	-	-	-	-	-	-	-	-
	1930-39	-	-	-	-	-	-	-	1	-	-		1930-39	-	-	-	-	-	-	2	1	-	-
	1920-29	-	-	-	-	-	-	-	-	-	-		1920-29	-	-	-	-	-	-	1	1	-	-
	1910-19	-	-	-	-	-	-	-	-	-	-		1910-19	-	-	-	-	-	-	-	-	-	-
I	1980-89	1	3	-	3	2	-	-	-	-	-	J	1980-89	18	46	39	27	6	3	2	-	-	-
	1970-79	-	1	9	7	-	-	-	-	-	1		1970-79	4	23	17	19	8	1	1	-	-	-
	1960-69	-	-	-	1	-	-	-	-	-	-		1960-69	-	11	5	16	8	5	2	-	-	-
	1950-59	-	-	-	-	-	-	-	-	-	-		1950-59	-	-	-	-	1	-	3	-	1	-
	1940-49	-	-	-	-	-	-	1	-	-	-		1940-49	-	-	-	-	-	2	3	-	-	-
	1930-39	-	-	-	-	-	-	2	1	-	-		1930-39	-	-	-	-	-	4	2	1	-	-
	1920-29	-	-	-	-	-	-	-	-	-	-		1920-29	-	-	-	-	-	-	1	1	-	-
	1910-19	-	-	-	-	-	-	-	1	-	-		1910-19	-	-	-	-	-	-	1	-	1	-
K	1980-89	9	38	35	31	6	-	-	-	-	-												
	1970-79	1	10	7	11	4	-	-	-	-	-												
	1960-69	-	-	7	3	2	2	1	-	-	-												
	1950-59	-	-	-	-	-	-	1	1	-	-												
	1940-49	-	-	-	-	-	-	-	-	-	-												
	1930-39	-	-	-	-	-	-	2	-	-	-												
	1920-29	-	-	-	-	-	-	1	1	-	-												
	1910-19	-	-	-	-	-	-	-	-	-	-												

As it was recognized that some parts of earthquake data are incomplete, and that failure to correct the data incompleteness may lead to the underestimate of the average rates of earthquake occurrence, the statistical technique suggested by Stepp (1972) to determine the time period over which earthquakes of a given magnitude interval are completely recorded was applied. The time periods of complete data, identified by this technique, are presented in Table 1. The reliable average rate of earthquake occurrence for each magnitude range was then estimated from the complete data, and for each source zone the log N(m) = a - b m relationship was fitted to the estimated rates using the least-square technique. The results in terms of a and b for each source zone are presented in Table 2.

Note, however, that the exponential magnitude-recurrence relationship, as shown in Eq. (1), will not hold for earthquakes of sufficiently large magnitude because for each source zone there is a physical limiting value of the largest possible earthquakes. By this reason, Algermissen suggested that N(m) should be truncated at the

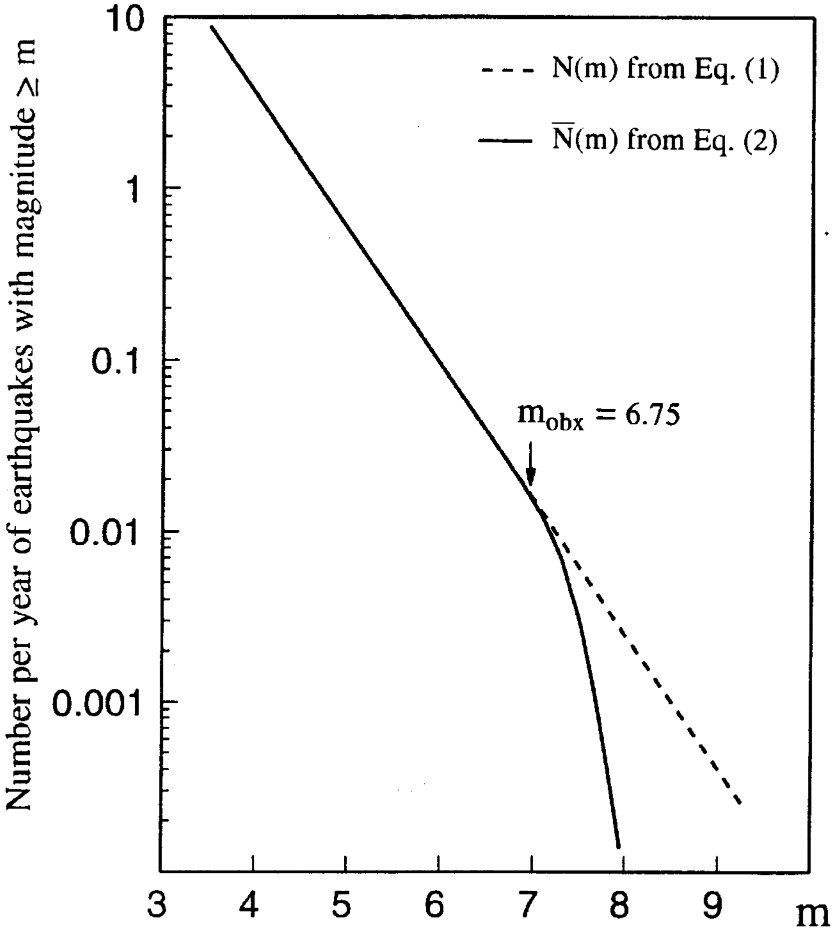

Fig. 2. Comparison of unlimited and bounded magnitude-recurrence relationships of seismic source zone A.

PROBABILISTIC SEISMIC HAZARD MAPPING

The analysis method which Algermissen and his colleagues employed for the probabilistic estimation of PGA at sites in the U.S. is essentially the method developed by Cornell (1968). This method can integrate the individual influences of all potential earthquake sources and takes into account of their average activity rates and their source-to-site distances. Cornell's method is therefore employed in this seismic hazard analysis.

The analysis is based upon the following assumptions: (1) earthquake epicenters are located within seismic source zones; (2) within a source zone, the spatial probability distribution of epicenters is uniform and the earthquake focal depths are equal to h_{av}, where h_{av} is the average focal depth of past earthquakes in the source zone as shown in Table 2; (3) earthquake occurrences in different seismic source zones are statistically independent; (4) within a source zone, earthquakes randomly occur in time according to a Poisson distribution in which the average rate of occurrence of earthquakes is constant in time and is derived from the bounded magnitude-recurrence relationship $\bar{N}(m)$ as shown in Eq.(2); (5) the effects of earthquake with $m < 4$ can be neglected; and (6) PGA at any given site with epicentral distance $d > 15$ km can be computed by the Esteva's attenuation relationship as shown by Eq. (4). Moreover, in the probabilistic computations, the 11 regional seismic source zones are divided into 149 area segments. The size of these area segments are so small that the center of a segment can be reasonably treated as the approximate location of earthquake epicenters in the segment. This segmentation transforms certain probabilistic integrations over irregular-shape source zones into simple discrete summations; this technique was also employed by Algermissen (Algermissen *et al.*, 1982).

By using the Cornell's method with some minor modifications to incorporate all of the above assumptions and approximation, the PGA having a 10% probability of being exceeded in a 50-year period at any given site, denoted by PGA_o, can be computed. This PGA_o has been widely used as a rational basis for characterizing probabilistic seismic hazard and for seismic-resistant design in the current UBC. The computation of PGA_o was carried out for 320 closely spaced sites in the region bounded by latitudes 6°N to 25°N and longitudes

92°E to 107°E; the spacing between sites in either latitude or longitude was set to 1°. Based upon this computed results, a seismic hazard map showing contours of PGA_o was constructed as shown in Fig. 3.

For the purpose of earthquake-resistant design, Thailand is then divided into various seismic zones, as shown in Fig. 3, according to the following criteria : zone 0 for $PGA_o < 0.025g$, where g is the acceleration of gravity; zone 1 for $0.025g < PGA_o < 0.075g$; zone 2A for $0.075g < PGA_o < 0.15g$; zone 2B for $0.15g < PGA_o < 0.20g$; zone 3 for $0.20g < PGA_o < 0.30g$; and zone 4 for $PGA_o > 0.30g$. These criteria are similar to those used in the 1988, 1991, and 1994 UBC zoning maps except that in the UBC, effective peak acceleration (EPA) is used instead of PGA. By its definition, EPA is the peak ground acceleration after the ground-motion record has been filtered to remove the very high frequencies that have little influence upon structural response. However, it appeared that for PGA < 0.3g there is no significant different between PGA and EPA. Therefore, it is reasonable to state that the newly developed seismic zoning map of Thailand is compatible with the current U.S. zoning maps in the UBC. The zoning map of Thailand shows that some parts of the northern and western Thailand can be considered as moderate risk and moderately high risk zones equivalent to the UBC zone 2B and 3, respectively. Thus, the necessity of the seismic regulations for Thailand is confirmed.

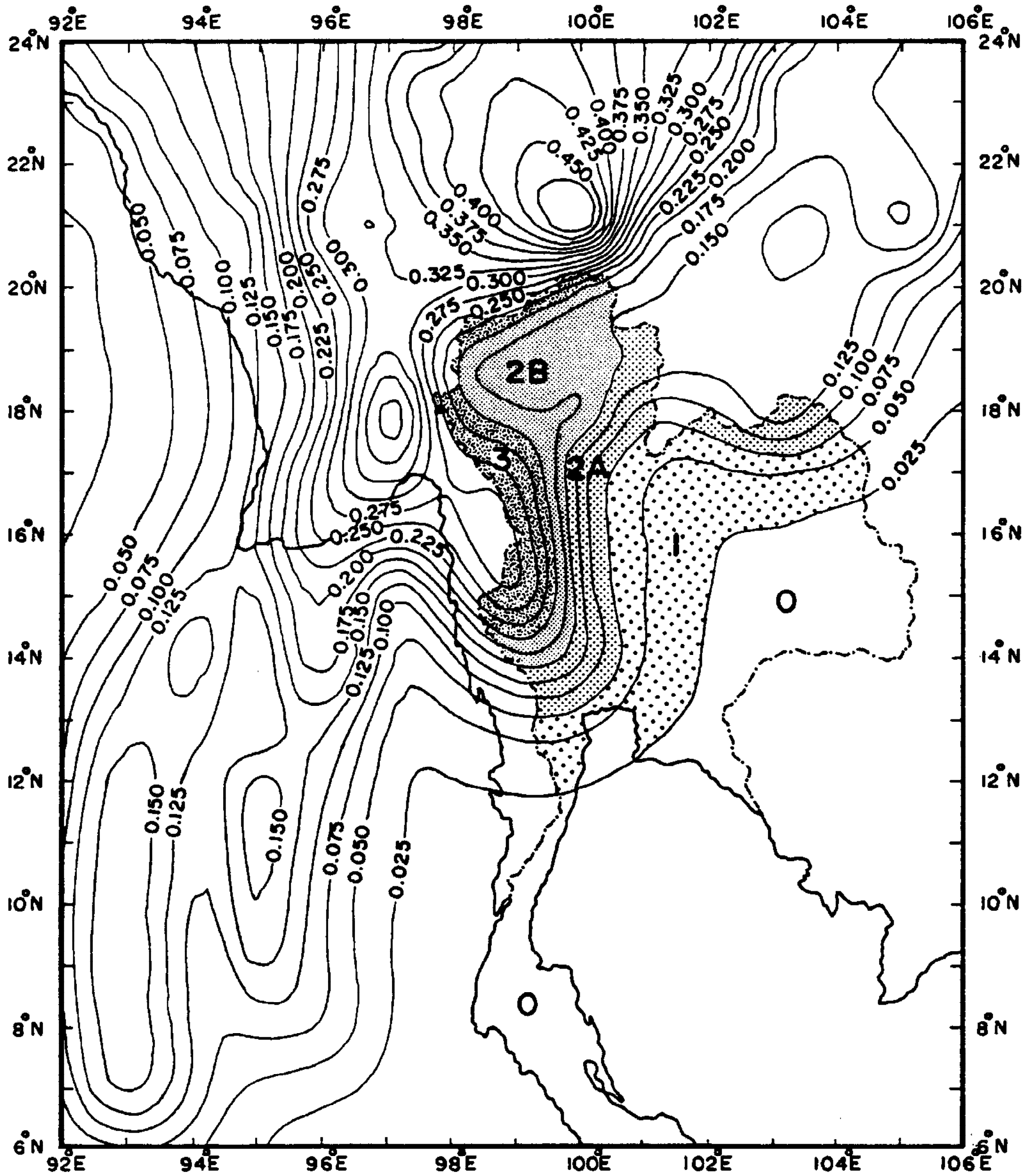

Fig. 3. Map showing contours of peak ground acceleration (in units of acceleration of gravity) with 10 % chance of being exceeded in a 50-year exposure time, and seismic zones for earthquake-resistant design.

CONCLUDING REMARKS

The probabilistic acceleration-based zoning map presented in this paper has been carefully developed based on the concepts, analysis procedure, and criteria used in the development of the UBC zoning map. Therefore, it can be used as a key element in the seismic design code of Thailand which has been drafted based on the UBC. Moreover, as the map presents the levels of seismic hazard of Thailand in the form that can be compared with those in the U.S. and several other countries, the concerned policy decision makers and Thai public can directly see the need of the seismic design regulations, and hence promoting wider acceptance of the regulations. It is further recommended that more detailed studies on seismic sources, by trenching and dating prehistoric movements of several active faults in the western and northern Thailand, and more extensive studies on the attenuation relationship for this region should be conducted. With these studies, more accurate and reliable estimates of probabilistic hazard can be obtained in the future.

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