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SEISMIC HAZARD IN BANGKOK DUE TO LONG-DISTANCE EARTHQUAKES

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SUMMARY

A seismic hazard assessment of Bangkok is conducted. The results are presented in the form of predicted peak ground accelerations for various levels of probability of exceedance in a 50-year period and the corresponding elastic response spectra. The results indicate that Bangkok, though located at a remote distance from seismic sources, is still at risk of damaging earthquake ground motions similar to those found in Mexico City during the 1985 Michoacan earthquake. The risk is essentially caused by three factors. First, several regional seismic sources that may contribute significantly to the seismic hazard of Bangkok are capable of generating large earthquakes. Second, the attenuation rate of ground motions in this region appears to be rather low and well represented by attenuation models of Central and Eastern North America. Third, the surficial deposits in Bangkok have the ability to amplify earthquake ground motions about 3 to 4 times.

INTRODUCTION

It has been recently recognized that urban areas located at rather remote distances from earthquake sources may, under some special conditions, possess a danger of earthquake disaster. A well-known example is the 1985 Michoacan earthquake, in which a large earthquake (M_s = 8.1) on the coastal Mexico caused considerable destruction and loss of life in Mexico City, 350 km from the epicentral location. Much of the destruction was due to significant amplification of earthquake ground motions by thick surficial deposits in the downtown area of Mexico City [Seed et al., 1987]. Despite our improved understanding of seismic hazard potential from distant earthquakes, several cities around the world that possess such potential are still being considered by most people as being free from seismic risk. Bangkok, the capital city of Thailand, with a population of over eight million, seems to be one of these cities. The nearest zone of active faults is located only about 120 to 300 km from the city, but their rate of seismic activity is rather low. More active seismic sources are between 400 km and 1000 km from Bangkok. The surficial geologic setting at Bangkok also appears qualitatively similar to the setting of Mexico City, and hence Bangkok, by analogy, appears to be susceptible to the same type of soil amplification of ground motions.

Throughout the two-century history of Bangkok, more than 20 earthquake ground shaking events have been felt and recorded [Nutalaya et al., 1985]. Although some were strong enough to cause general panic among the people, there has never been a destructive earthquake so far. As a result, most buildings and structures in Bangkok have been designed and constructed without any consideration on seismic loading. A closer examination of historical records and instrumental data, however, reveals that most ‘strongly felt’ events during the past 90 years were caused by either a large earthquake at an extremely long epicentral distance of 600 to 900 km or a moderate earthquake at a distance of 200 to 400 km. Hence, it is reasonable to anticipate a much stronger ground shaking from a large earthquake at a relatively closer distance of about 120 to 300 km. Such severe ground shaking has probably never happened in the short history of Bangkok but may occur sometime in the future.

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In this paper, a seismic hazard assessment of Bangkok is presented. It is intended to provide the ‘best estimate’ of Bangkok’s earthquake ground motion parameters based on currently available information, so that engineers can use them for improved building design and construction. The scope of work first consists of formulating models that describe the location, shape, and activity of seismic sources in the region. Second, identifying models that can reasonably represent the regional attenuation characteristics of earthquake ground motions. Third, performing probabilistic integration of the individual influences of seismic sources into the probabilistic distribution of peak rock outcrop acceleration in the Bangkok area by using the Cornell method. Finally, conducting one-dimensional seismic site response analyses for a generalized soil profile of Bangkok to quantify the potential amplification of earthquake ground motions and to predict motions at the ground surface in the Bangkok area. The results are presented in the form of predicted peak ground accelerations for various levels of probability of exceedance in a 50-year exposure period and the corresponding elastic response spectra. The results indicate clearly that there is a possibility of an earthquake disaster in Bangkok similar to the Mexico City event, and that there is an urgent need to upgrade the existing building design code by incorporating some necessary seismic design requirements.

MODELLING OF REGIONAL SEISMIC SOURCES

Based on seismotectonic features of the Burma-Thailand-Indochina region and the spatial distribution of earthquake epicenters, twelve seismic source zones in this region were identified by Nutalaya et al. (1985). They are named zones A to L as shown in Fig. 1. An earthquake catalogue containing instrumental data of earthquakes occurring in this region from 1910 to 1983 was also compiled by Nutalaya et al. (1985) using data collected from USGS, ISC (U.K.), the Thai Meteorological Department (TMD), and several other agencies. Note that most of the data before 1970s were recorded by global networks of seismograph stations outside Thailand. Due to the sparsity of the stations a large number of small and moderate earthquakes in this region were neither detected nor recorded, i.e. data incompleteness. After a TMD network of seismograph stations inside Thailand was established and began to operate in the late 1970s, the capability to detect small regional earthquakes has been significantly improved. As TMD has continued to improve its network by installing new stations, Warnitchai and Lisantono (1996) found that the TMD’s instrumental data of regional earthquakes after 1982 were more complete than the data from the global networks. Therefore, they combined the Nutalaya’s data (1910-1983) with the TMD’s data from 1984 to 1989 to form an 80-year instrumental database for their probabilistic seismic hazard assessment of Thailand.

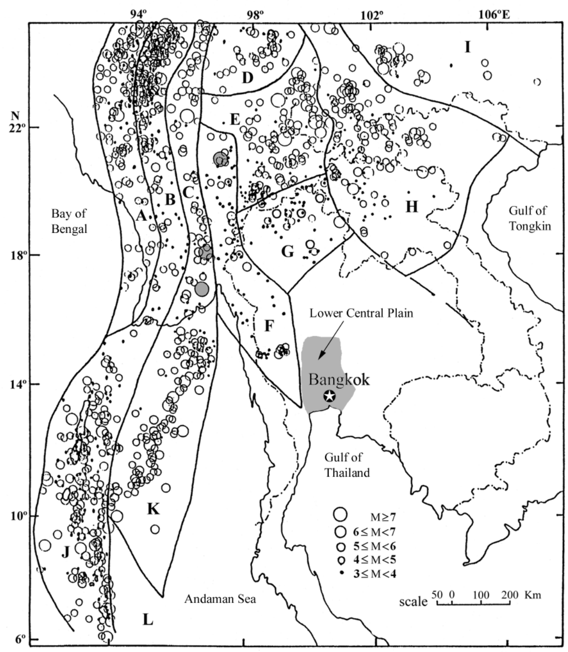

Figure 1: Twelve regional seismic source zones (A-L) and epicenters of earthquakes during 1910 - present

In order to make the database suitable for an unbiased estimate of earthquake recurrence, Warnitchai and Lisantono (1996) made some corrections of the database. First, all dependent events, either foreshocks, aftershocks or smaller events within an earthquake swarm were identified and deleted from the database, so the remaining data show only independent events (mainshocks). The spatial distribution of epicenters of these independent earthquake events are presented in Fig. 1. Second, a statistical analysis of data was conducted in order to identify the time periods of complete data. The time periods represent the time span over which earthquakes of a given magnitude range are completely recorded. The reliable average rate of earthquake occurrence for each magnitude range for each source zone was then estimated from the corresponding complete data.

Warnitchai and Lisantono (1996) assumed that the magnitude-recurrence relationship for each seismic source zone is in the form of the Gutenberg-Richter exponential relationship with a soft truncation:

$$\text{Log } N(\text{M}) = (a - b\,M) - \text{Log } W(\text{M}) \qquad (1) \text{where} \qquad W(\text{M}) = 1 + (\alpha M/ M_o)^{\beta} \qquad (2)$$

in which N(M) is the average number per year of earthquakes having (moment) magnitude greater than M; a and b are positive constants which describe the seismicity of the source zone; W(M) is the truncation function; α and β are positive constants which are used for the adjustment of the truncated shape of the function; and M_o is the largest recorded earthquake magnitude in the source zone.

Table 1: Key parameters of regional seismic source zones

Zone	a	b	h_a (km)	M_o	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	2.95	0.72	20	6.50	96,563
H	2.96	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	3.89	0.80	30	6.50	222,089

Warnitchai and Lisantono (1996) identified the parameters a and b of each seismic source zone by fitting the Log N(M) = a – b M relationship to the estimated occurrence rate (from the complete instrumental data) using the least-square technique. The results for zones A to K are presented in Table 1. Zone L was disregarded in their seismic hazard assessment because its data are incomplete and its influences are negligible. In this assessment, we adopted the above magnitude-recurrence relationship with the parameters a and b identified by Warnitchai and Lisantono (1996). We set the parameters α and β for every source zone to 0.95 and 100, respectively, so that the magnitude-recurrence relationship of Eq. (1) will start to deviate from the Log N(M) = a – bM relationship at $M = M_o$ and will be bounded at approximately $M_o + 0.5$.

In addition, there is new information regarding the expected maximum earthquake magnitude for zones F and G from two site-specific seismic hazard assessments conducted recently by Woodward-Clyde Federal Services (WWC)—one for a large irrigation dam to be constructed in northern Thailand [DMR, 1996] and another one for two existing large dams in western Thailand [EGAT, 1998]. As a principal part of each assessment, WWC conducted a preliminary paleoseismic investigation over a region within approximately a 200-km radius from the site. The paleoseismic investigation used an appropriate mix of remote sensing imagery, aerial photographic interpretation, and field investigation. The investigation concentrated on the geomorphic expression of faulting, and the comparison of these features with the features observed along other active faults around the world. The investigation results indicated that there are at least seven active faults in northern Thailand (zone G) and five active faults in western Thailand (the lower portion of zone F). Although these active faults exhibited low levels of seismicity, it was estimated from their expected rupture dimensions that a maximum earthquake of magnitude (M_w) 6.8 to 7.2 ± 0.3 and 7.3 to 7.5 ± 0.3 could be generated in northern and western Thailand, respectively, by these active faults. Based on these paleoseismic investigation results, we decided to replace M_o in Eq. (2) for zones G and F by 7.0 and 7.4, respectively, in order to make the truncation more reasonable.

ATTENUATION MODELS FOR DISTANT LARGE EARTHQUAKES

Traditionally an attenuation model for a specific region is empirically developed from statistical regression analyses of hundreds of earthquake ground motion records. For this region, however, a very limited number of strong motion records are available, and most of them were recorded during small to moderate earthquake events in 1983-85 in western Thailand with source-to-station distances of less than 60 km. One solution to this data limitation is to assume that some existing attenuation models developed for other regions with similar seismotectonic characteristics can adequately represent ground motion attenuation in this region. With this in mind, Nutalaya and Shrestha (1990) compared the recorded peak ground acceleration (PGA) values in western Thailand with those predicted by several existing attenuation models, and they found that the Esteva model [Esteva and Villaverde, 1973] gives the best fit. So they suggested that the model could be used for seismic hazard assessments in this region.

In this assessment, in addition to the Esteva model, many new attenuation models for shallow crustal earthquakes are considered in order to improve assessment reliability. Attenuation models for subduction zone earthquakes are not included because our instrumental and seismotectonic data indicate that most earthquakes within approximately a 600-km radius from Bangkok belong to the shallow crustal type. The first group of new models to be considered are four empirical models developed for Western North America (WNA) by Boore et al.

(1997), Abrahamson and Silva (1997), Campbell and Bozorgnia (1994), Sadigh et al. (1993). The second group are two new empirical models for Europe (EU) developed from regression analyses of European and Italy strong-motion data by Ambraseys and Bommer (1992) and Sabetta and Pugliese (1987), respectively. These two groups represent the attenuation characteristics of shallow crustal earthquakes in active tectonic regions. The third group are three new models for Central and Eastern North America (CENA) developed by Toro and McGuire (1987), Atkinson and Boore (1995), and Hwang and Huo (1997). These models are for shallow crustal earthquakes in a stable continental region. Note that, due to the low seismicity rate of the region, there are very few strong motion data available, so these three models were formulated on the basis of numerically simulated motions instead of recorded motions. The motions were simulated by using seismological models that account for source, path, and site effects, and hundreds of weak-motion seismograms were employed to constrain some of the parameters in the seismological models.

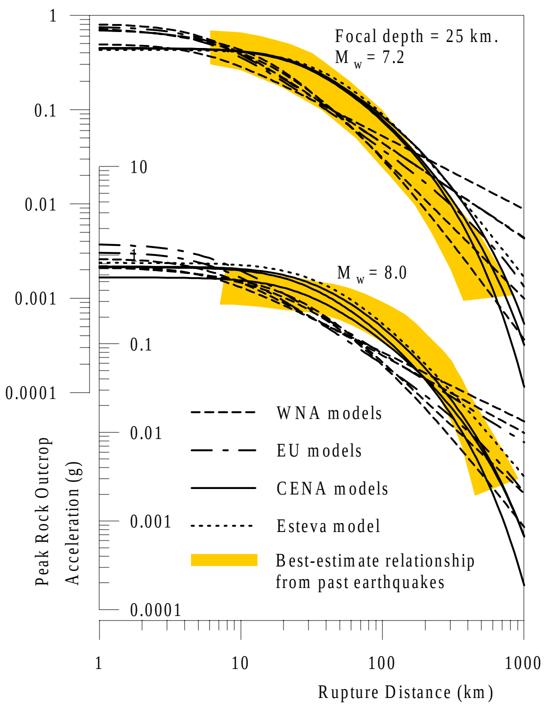

Figure 2: Comparison of attenuation relationships

A rough estimate using these attenuation models indicates that a destructive ground motion in Bangkok can only be induced by a large earthquake of magnitude (M_w) 6.5 to 8 at a source-to-site distance of 120 to 300 km. Therefore, the peak rock outcrop acceleration (PRA) attenuation curves computed from these models for earthquakes of magnitude (M_w) 7.2 and 8 are compared in Fig. 2. It can be observed that all WNA and EU models, which are developed for active tectonic regions, yield very similar PRA curves for rupture distances less than about 100 km. Beyond this distance range, the PRA curves diverge from each other. This is also beyond the prediction limits of these models; they are not intended to be used for such long rupture distances. CENA models, on the other hand, have much higher distance limits—up to 200 to 300 km or more. Their PRA curves lie very close to each other over a wide rupture distance range, up to several hundreds kilometers. Compared with WNA and EU models, CENA models predict higher PRA values for rupture distances between 10 and 200 km due to the lower attenuation rate in stable continental region. Another point worth noting is that the PRA curves of the Esteva model match surprisingly well with those of CENA models. The question then arises: "Between WNA/EU models and CENA/Esteva models, which group is a better representation of the attenuation characteristics of this region?".

To answer this question, we searched through past earthquake records and reports for more information on the ground motion attenuation of large earthquakes in this region. The best available information is from isoseismal maps of the Mandalay earthquake (M_s =8) of 23 May 1912; the Pegu earthquake (M_s =7.2) of 5 May 1930; and the Pyu earthquake (M_s = 7.2) of 3 December 1930 [Nutalaya, 1985]. The epicenters of these Burmese earthquakes are shown by shaded circles in Fig. 1. The isoseismal maps show contour lines of ground shaking intensity in the Rossi-Forel scale over the whole country of Burma and some portion of Thailand. We first converted the intensities into those in the Modified Mercalli (MM) scale, and then computed equivalent PGA values by using an empirical relationship proposed by Trifunac and Brady (1975). We assumed that each MM intensity value contains an error of ± 0.3 scale; this is to account for possible errors in the transformation process. The PGA values were further scaled into the corresponding PRA values by assuming that typical surficial deposits are stiff soils. For this scaling, the ratio of PGA at a stiff soil site to PRA was assumed to be 1.0, 1.3, 1.5, 1.8, and 2.0 for PRA values of 600, 250, 130, 30, and 5 cm/sec^2, respectively. From the results obtained, two bands of best-estimate regional PRA attenuation relationship were constructed as shown in Fig. 2. The attenuation characteristic of these bands looks more like those of CENA and Esteva models than WNA and EU models. Although a definite conclusion can not be drawn from these limited results, we tend to believe that the group of CENA and Esteva models is a better representation of the regional attenuation characteristics.

PROBABILISTIC SEISMIC HAZARD ANALYSIS

Using the well-known Cornell method, a probabilistic prediction of PRA in the Bangkok area was conducted under the following assumptions: (1) earthquakes are uniformly distributed within each defined seismic source zone and their focal depths are equal to h_a, where h_a is the average focal depth of past earthquakes in the source zone as shown in Table 1; (2) within each source zone, earthquakes randomly occur in time according to a Possion distribution, in which the average rate of occurrence is derived from the magnitude-recurrence relation as described earlier; (3) in any earthquake event, PRA at Bangkok can be computed from the earthquake magnitude and source-to-site distance by the median attenuation relationship for rock sites; and (4) the probability that any one event will result in PRA at Bangkok in excess of a specified level is independent of the occurrence of other events. For the probabilistic integration, the eleven regional source zones were divided into as many as 9860 segments in order to achieve a reasonable accuracy. The results are presented in Table 2. They are PRA values having 70%, 50%, 10%, 5%, 2%, 1%, and 0.5% probabilities of exceedance in a 50-year exposure period computed for ten different attenuation models. Note that some of these probabilities of exceedance are often used to define the maximum probable earthquake (50%), the design-basis earthquake (10%), and the maximum capable earthquake (2%). It can be clearly observed from Table 2 that the PRA values computed by CENA and Esteva models are significantly higher than those by WNA and EU models. This is mainly due to the relatively lower attenuation rate of CENA and Esteva models as explained earlier. Since these models were considered to be good representations of the regional attenuation characteristics, their predicted PRA values were then averaged to make the best-estimate PRA values as shown in the bottom row of Table 2.

Table 2: Predicted peak rock outcrop acceleration in Bangkok (in the unit of milli-g)

Attenuation model		Prob. of exceedance in a 50-yr period						
		70%	50%	10%	5%	2%	1%	0.5%
WNA	Boore (97)	20	23	38	44	53	59	64
WNA	Abrahamson (97)	16	19	30	37	45	51	56
WNA	Campbell (94)	5	7	16	22	30	36	42
WNA	Sadigh (93)	4	5	14	19	27	33	39
EU	Ambraseys (92)	10	13	23	28	35	40	44
EU	Sabetta (87)	13	15	29	36	45	52	57
CENA	Toro (87)	13	17	38	50	66	78	89
CENA	Hwang (97)	11	15	40	55	76	92	106
CENA	Atkinson (95)	19	24	48	59	72	81	88
	Esteva (73)	15	20	46	62	85	102	117
CENA & Esteva (avg)		15	19	43	56	75	88	100

AMPLIFICATION OF GROUND MOTIONS IN BANGKOK

The city of Bangkok is situated on a large and extremely flat plain, commonly known as the “lower Central plain” of Thailand. The length from north to south of the plain is about 250 km and the average width is approximately 200 km (see Fig. 1). The natural ground elevations vary from 1 to 2 m above MSL at Bangkok to only 5 m above MSL at Ayutthaya, 100 km further inland. The lower Central plain consists of a broad deep basin filled with alluvial and deltaic sediments with occasional shallow sea sedimentation, forming alternate layers of sand, gravel and clay. The depth of bedrock surface is estimated to be between 550 and 2000 m. The uppermost soil layer is a “soft” silty marine clay, usually referred to as “soft Bangkok clay”. Throughout this large area of the lower Central plain, the composition and thickness of the clay are remarkably consistent with gradual coarsening and thinning towards the margin of the plain. The clay is about 10 to 18 m thick in the Bangkok metropolitan area. The soft Bangkok clay was deposited during the latest transgression of the sea over the plain, which began about 10,000 years ago [AIT, 1980]. After the sea withdrew at about 2,700 years ago, the soft clay was exposed and the uppermost 1 to 2 m has been weathered. Since its sedimentation, the clay has never been subjected to mechanical over-consolidation due to over-stressing. Hence, it is highly compressible and its shear strength is extremely low. The soft clay is underlain by a layer of “stiff” silty clay known as the first stiff clay layer. Similar to the soft clay layer, the thickness of the stiff clay is rather uniform, varying between 5 to 10 m in the Bangkok area. The stiff clay, however, is significantly older than the soft clay and is clearly separated from it by a pronounced disconformity. The shear strength of the stiff clay is much greater than that of the soft clay, and the compressibility is much less. The deeper strata consist of alternate layers of sand deposits and stiff clay with high strength and low compressibility extending horizontally over a large area.

Since the soil deposits underlying the whole Bangkok and its surrounding areas consist of nearly uniform and horizontal layers of clay and sand, the response of these deposits to bedrock motions can be reasonably evaluated by a one-dimensional wave propagation analysis. Thus, the method of one-dimensional site response analysis using the computer program SHAKE91 [Idriss and Sun, 1992] is adopted in this study. The method assumes that the main responses in a soil deposit are caused by the upward propagation of shear waves from the underlying rock formation, and the method is capable of incorporating nonlinear soil behavior by using an iterative equivalent linear analysis procedure. The method has been shown to give results in good agreement with field observations in many cases and has been used routinely in engineering practice in the US. To conduct site response analyses for the Bangkok area using this method, a generalized soil profile must be developed with corresponding dynamic soil properties necessary for the analyses. These properties are: shear wave velocity (or low-strain dynamic shear modulus), mass density, and relationships for variation of dynamic shear modulus and damping ratio as a function of strain.

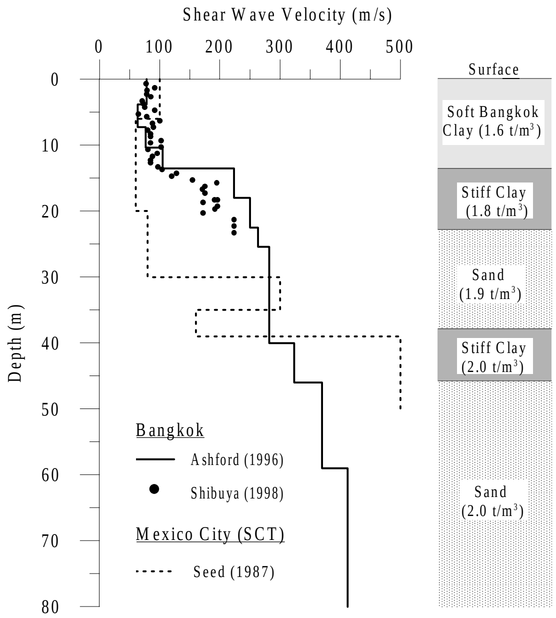

Figure 3: Generalized Bangkok soil and shear wave velocity profiles

From a comprehensive investigation of soil characteristics at 9 different sites around the Bangkok metropolitan area, Ashford et al. (1996) developed a generalized soil profile and a corresponding generalized shear wave velocity profile of Bangkok as shown in Fig. 3. They first estimated shear wave velocity (denoted by V_s) from specific field and laboratory soil data of the 9 sites using several published empirical correlations, and then confirmed such estimates with actual insitu V_s measurements at another 4 sites around Bangkok using a downhole method. Excellent agreement was found between the estimated and measured V_s profiles. Note that in this downhole method, the travel time of the shear wave between the source at the ground surface and a receiver in the borehole is first measured, and the V_s profile is then computed from the measured travel times for various depths of the receiver. The obtained generalized V_s profile shows extremely low V_s in soft Bangkok clay (about 60 to 100 m/s). This is comparable to Mexico City clay. The velocity increases sharply and considerably to about 200 to 250 m/s in the first stiff clay, and it continues to increase at a slower rate in the deeper stratra.

The high contrast in V_s between the uppermost soft clay layer and the underlying layer in the Bangkok area is similar to that in Mexico City as shown in Fig. 3. In Mexico City, the V_s discontinuity interface allows the upward propagating shear waves to easily propagate through, but it acts more like a reflector to the downward propagating shear waves coming from the reflection at the ground surface. Hence, a major portion of shear waves is trapped within the soft clay layer. During the 1985 earthquake, this created a wave resonance when the trapped waves interacted constructively with the continual upward propagating waves from the bedrock, and resulted in a significant amplification of motions in the soft clay layer. Therefore, the discontinuity of the V_s profile in Bangkok, though not as sharp as in Mexico City, suggests that a similar amplification mechanism may occur in this area.

When the generalized soil profile for Bangkok was developed by Ashford and his coworkers, there was no laboratory test data on the variation of dynamic shear modulus and damping ratio with shear strain available. So, they suggested that the empirical relationships developed by Vucetic and Dobry (1991) for clay and Seed et al. (1984) for sand could be used for the case of Bangkok; these relationships are widely used for purposes of site response analysis. A few years later, a series of comprehensive insitu and laboratory tests of soils at a site in central Bangkok area were conducted by Shibuya and Tamrakar (1999). These tests include an insitu seismic cone (SC) test at the site and a laboratory undrained cyclic torsional shear (CTS) test of several hollow cylindrical clay specimens taken from the site at depths of 4, 8, and 12 meters. In the CTS test, each specimen was isotropically consolidated to its insitu effective overburden pressure, and then subjected to a multi-stage undrained cyclic shear at the frequency of 0.1 Hz. The test results are presented by plotting the ratio of G/G_{max} (i.e. the ratio of shear modulus at a given strain, G, over the low-strain shear modulus, G_{max}) and the damping ratio versus shear strain. The results are found to be in excellent agreement with the Vucetic-Dobry relation for clay with plasticity index (PI) of 50. Note that PI of soft Bangkok clay varies between 30 to 70 with an average value of about 50. This excellent agreement indicates that the Vucetic-Dobry empirical relationships can be reasonably used for Bangkok clays. In the SC test, the shear wave was generated on the ground surface by plank hammering, and a cone with two receivers at 1 m apart was used for the insitu V_s measurement. The measured results are also in good agreement with the generalized V_s profile as shown in Fig. 3.

In this study, the generalized soil and V_s profiles of Bangkok proposed by Ashford et al. (1996) and the relationships for strain-dependent modulus and damping of clay by Vucetic and Dobry (1991) and sand by Seed et al. (1984) were employed for Bangkok's site response analyses. Below the depth of 80 m, no data was available to make a reasonable estimate of the V_s profile, so it was assumed that rock-like material exists below this depth with a V_s of 900 m/s. Note that a series of site response analyses were also made for assumed rock-like depths of 160 and 300 m in order to examine the sensitiveness of this assumption. The results show that the assumed depth to a rock-like layer has essentially little effect on the amplified motions at the ground surface. This is probably due to the fact that the soil amplification effect is mainly caused by the 'wave-trap mechanism' in the uppermost soft clay layer as explained earlier.

Seven different accelerograms were employed to represent rock outcrop motions in the Bangkok area. These accelerograms were selected from actual acceleration records at rock sites generated by magnitude 7 to 8 earthquakes at source-to-site distances from 80 to 350 km. The peak acceleration values of these selected records vary from 0.005 g to 0.09 g, and the predominant periods from 0.5 sec to 2 sec. These records were scaled to various peak acceleration values between 0.002 g and 0.075 g and used as input rock outcrop motions. All together, about 90 individual site response analyses were conducted using these input motions. In each analysis, the amplification factor (i.e. the ratio of PGA to input PRA) was computed, and in some selected cases the elastic response spectrum of the computed ground motion was also evaluated in order to examine its frequency content and damage potential on buildings and structures.

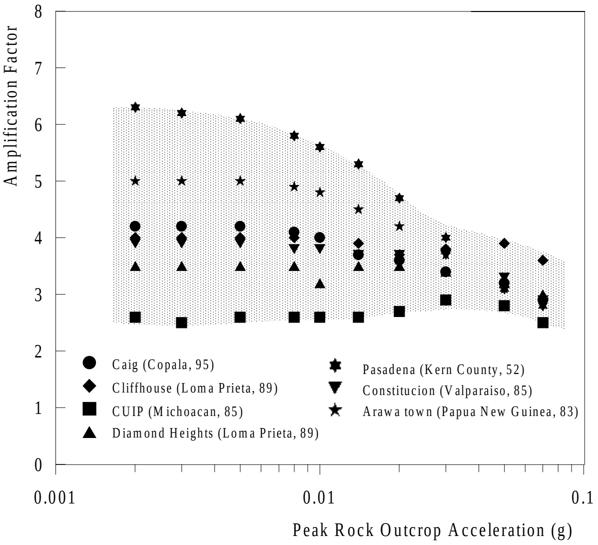

Figure 4: Relationship between computed amplification factor and peak rock outcrop acceleration

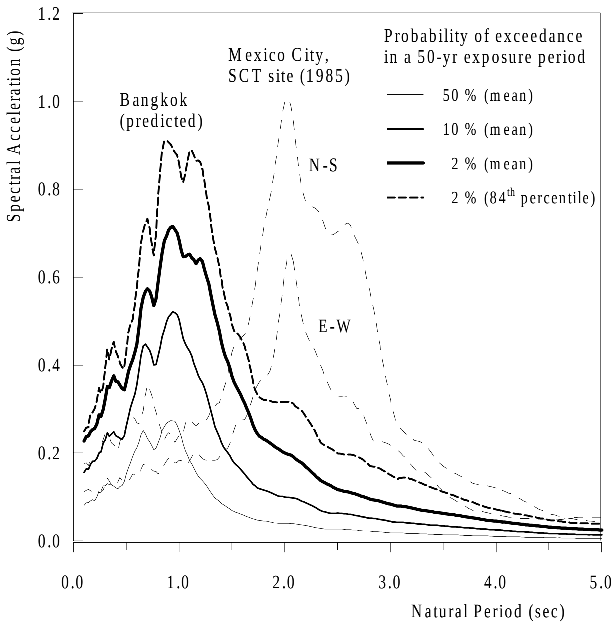

Figure 5: Comparison between the elastic response spectra of predicted ground motions and the spectra of the damaging ground motions in Mexico City

The relationship between amplification factor and PRA, shown in Fig. 4, clearly indicates that the soil profile underlying Bangkok has the ability to amplify earthquake ground motions about 3 to 6 times for extremely low intensity input motions and about 3 to 4 times for relatively stronger input motions. This range of amplification factors is comparable to those found in Mexico City. The mean PGA values for input PRA values of 0.015, 0.019, 0.043, 0.056, 0.075, 0.088, and 0.10 g are 0.056, 0.072, 0.14, 0.18, 0.22, 0.24, and 0.26 g, respectively. These are the best-estimate PGA values for Bangkok that have, respectively, 70%, 50%, 10%, 5%, 2%, 1%, and 0.5% probabilities of exceedance (P_e) in a 50-year exposure period. The amplified ground motions can be described as narrowband random motions with a relatively long predominant period of about 1 second. This is clearly illustrated by the mean elastic response spectra (5% damping) for computed ground motions of 50%, 10%, and 2% P_e as shown in Fig. 5. Each spectrum shows a high spectral amplification in a narrow range of periods centered at about 1 second. The mean and 84th percentile spectra for ground motions of 2% P_e, which characterize the maximum capable earthquake ground motion in the Bangkok area, are comparable in peak spectral acceleration to those of the damaging ground motions in Mexico City during the 1985 earthquake event. Based on these results, it is reasonable to infer that the maximum capable ground motion, if it occurred, would most likely cause severe damage or even complete collapse to structures with fundamental periods ranging from about 0.5 sec to 1.5 seconds as well as to short-period structures that do not have sufficient lateral strength.

CONCLUDING REMARKS

The seismic hazard assessment presented in this paper indicates that Bangkok, though located at a remote distance from seismic sources, is still at risk of strong earthquake ground motions. The risk is essentially caused by three major factors: the ability of regional seismic sources to generate large earthquakes, the low attenuation rate of ground motions in this region, and the ability of thick unconsolidated surficial deposits in Bangkok to considerably amplify earthquake ground motions. The predicted strong earthquake ground motions could cause extensive building destruction and considerable loss of life in Bangkok. To avoid such unacceptable economic and social consequences, the existing building design code must be improved by incorporating necessary seismic design requirements, and the safety of existing important buildings and hazardous facilities must be critically reviewed. The predicted earthquake ground motion parameters from this assessment can be directly used for these purposes.

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