NEW USGS SOUTHEAST ASIA SEISMIC HAZARD MAPS

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ABSTRACT :

The U.S. Geological Survey (USGS) Southeast Asia Seismic Hazard Project originated in response to the 26 December 2004 Sumatra earthquake (M9.2) and the resulting tsunami that caused significant casualties and economic losses in Indonesia, Thailand, Malaysia, India, Sri Lanka, and the Maldives. Hazard models and maps were produced, with input from several international science organizations, by the USGS in Golden, Colo., for the region encompassing Thailand, Malaysia, Singapore and eastern Indonesia using the methodologies established for producing the United States national seismic hazard maps. A new subduction zone model was developed that considers historic seismicity, paleoseismic investigations, geodetic data, and ground motion studies. Seismicity catalogs and hazard models were updated to 2007. Fault maps were compiled and fault parameters were discussed at workshops held in Thailand, Malaysia, and Indonesia. In addition, geology and shear-wave velocity maps and a seismic risk analysis were produced for a region surrounding Padang, Indonesia.

KEYWORDS: Seismic hazard, earthquake risk, ground shaking, fault model, Southeast Asia

1. INTRODUCTION

The U.S. Geological Survey (USGS) Southeast Asia Seismic Hazard Project originated in response to the 26 December 2004 Sumatra earthquake (M 9.2) and the resulting tsunami that caused significant casualties and economic losses in Indonesia, Thailand, Malaysia, India, Sri Lanka, and the Maldives. During the course of this project, several additional large earthquakes ruptured subduction zones along the southern coast of Indonesia causing further losses. Future structural damage and societal losses from large earthquakes can be mitigated by providing advance warning of tsunamis and by introducing seismic hazard provisions in building codes that allow buildings and structures to withstand strong ground shaking. This project was funded through a USAID—Indian Ocean Tsunami Warning System to develop seismic hazard maps that would assist engineers in designing buildings that will resist earthquake strong ground shaking. An additional objective of the project was to openly discuss regional hazard issues with local building code officials, scientists, and engineers.

This paper describes the USGS hazard assessment for south-east Asia and applies the best available science information and methodologies employed by the USGS in developing the U. S. National Seismic Hazard Maps. Many previous models and assessments have been used in building codes and risk assessments and are too numerous to present in this short paper. However, the information used here is dependent on the data gathered by many international universities, industries, and government agencies. This information has been critical to the building of this model and more information more complete source models, descriptions of the analysis, references, and hazard maps can be found in a paper (Petersen et al., 2004) and an administrative report to USAID by Petersen et al. (2007). Hazard assessments require development of (1) earthquake source models that indicate potential sources that can affect a site and (2) ground motion prediction equations that provide the range of ground motions from each modeled earthquake. Source models consider historical earthquake information, geological studies of fault ruptures (paleoseismology), and geodetic data. Ground motion models consider global strong motion accelerograms recorded from earthquakes M>5. Hazard models and maps were produced at the USGS in Golden, Colo., using the methodologies established for producing the United States national seismic hazard maps (Frankel and others, 2002; Petersen and others, 2008). Fault, seismicity, and ground shaking parameters were discussed at workshops held in Thailand, Malaysia, and Indonesia.

2. EARTHQUAKE SOURCE MODELS

Southeast Asia is a region of variable seismic hazard, ranging from high seismic hazard associated with the subduction process beneath the Indonesian and Philippine archipelagos to moderately low seismic hazard across a large stable region that contains the Malaysian peninsula. The Indonesian island chain is characterized by widespread volcanic activity and earthquake activity resulting from the sliding of the India and Australia tectonic plates beneath the Sunda and Burma tectonic plates. Reverse, thrust-, strike-slip, and normal-focal mechanisms are reported within the region. The Sunda subduction zone produces thrust-fault earthquakes within the subducted India and Australia plates that extend down to depths of hundreds of kilometers, intraplate normal-fault and reverse-fault earthquakes within the India and Australia plates, and shallow seismicity within the upper 30 km of the overriding Sunda and Burma plates.

2.1 Earthquake Catalog and Background Seismicity Model

Earthquake catalogs are used to estimate future seismic activity from the locations and rates of past earthquakes. From the locations and frequency-magnitude distributions of past earthquakes we can estimate the locations and rates of future larger shocks that dominate the hazard. In most parts of the world the seismic record is too short to include a complete sample of these larger, rarer shocks. For this study we compiled a new catalog of instrumentally recorded earthquakes by combining four pre-existing global catalogs: (1) the IASPEI Centennial catalog compiled by Engdahl and Villaseñor (2002); (2) the catalog originally compiled by Engdahl and others (1998), and updated by Engdahl; (3) the USGS/NEIC Preliminary Determination of Epicenters on-line catalog (http://neic.usgs.gov); and (4) the International Seismological Centre on-line catalog (http://www.isc.ac.uk). In the following we refer to these source catalogs as EVC, EHB, PDE, and ISC, respectively. The combined catalog covers an area from long. 88° E. to long. 122° E. and lat. 17° S. to lat. 26° N.

Background seismicity in the model accounts for random earthquakes on unmapped faults and smaller earthquakes on mapped faults. These models are based on the earthquake catalog described above. We include two types of background seismicity: (1) gridded models that are based on spatially smoothed earthquake rates and (2) a background zone that accounts for a constant low rate of earthquakes across a broad Sunda plate. Background sources are based on the declustered (dependent events removed) earthquake catalog that begins in 1964. This model accounts for the observation that larger earthquakes (M≥5) occur near smaller (M≥ 4 or 5) earthquakes. Gridded seismicity included in the model is based on earthquakes at five depth intervals (shallow 0-50 km, intermediate depth 50–100 km and 100–150 km, and deep 150–200 km and 200–250 km). A truncated-exponential or Gutenberg-Richter magnitude-frequency distribution between M5.0 and M7.0 is used to model rates for different sizes of earthquakes in each grid cell or zone. Parameters of the magnitude-rate distribution (regional b-values and a-values in cells or zones) are computed using a maximum-likelihood method. For the smoothed seismicity models the earthquake rates in cells are spatially smoothed using a two-dimensional Gaussian smoothing operator with 50 km correlation distance. This procedure yields a magnitude-frequency distribution for each grid point separated by 0.1 degrees in longitude and latitude.

2.2 Sunda Plate

Earthquakes beneath the Sunda Plate are too sparse to define any linear pattern to suggest the presence of a tectonically active structure dividing the Sunda plate into smaller units, and GPS data have not been able to detect significant deformation within the region (Rangin and others, 1999). The largest historical earthquake observed within the Stable Sunda zone was a M5.8 event. Consistent with USGS treatment of tectonically stable regions in the most recent United States National Seismic Hazard Maps, we take M7.0 as the size of the maximum plausible earthquake in this zone. This value corresponds to the median magnitude of the largest earthquakes that have occurred in previously quiescent, generally tectonically stable, regions of plate interiors in other parts of the world. The calculated b-value is 1.08, but this value has very high uncertainty because of the low rate seismicity. We have applied a b- value of 1.0 for this zone based on the regional constraints. A major limitation of the smoothed seismicity model is that we only have a 36-yr catalog, which is very short with respect to earthquake recurrence rates on faults. The short record probably does not represent all possible future earthquakes in these regions. In order to compensate for the short historical record, we developed a second model, the background zone model, which assumes that the entire zone can have a random earthquake with a constant rate determined from the historical seismicity distributed over the broad zone. These two models were weighted 50-50 in the hazard analysis.

The regions of the Sunda plate adjacent to the Sunda subduction zone have a moderate to high rate of earthquake activity. The largest instrumentally recorded earthquake in this zone had M_w7.7. Non Sumatran fault earthquakes within the 'Sumatra back-arc' zone and earthquakes in the 'Java back-arc' zone reflect strains that are generated at the plate boundary but that are not accommodated by thrust-faulting at the plate interface or (in Sumatra) by slip on the Sumatran fault. This earthquake activity occurs on faults that have either not been geologically mapped or that have not been studied to the extent that their current rates of activity can be estimated from geologic evidence. The importance of understanding these faults was emphasized by the Mw 6.3 Yogyakarta earthquake of May 26, 2006, which occurred on such a fault. These earthquakes are modeled as gridded-smoothed seismicity models as described above.

2.3 Sunda Subduction Zone

For purposes of seismic hazard mapping, we divide the Sunda subduction zone into four major sections: the Burma, Northern Sumatra-Andaman, Southern Sumatra, and Java zones. The Burma zone corresponds to the subduction of the India plate beneath the Burma plate and the Burma orogen in western Burma. Le Dain and others (1984) and Guzman-Speziale and Ni (1996) note the absence of instrumentally recorded earthquakes with locations and focal-mechanisms corresponding to slip on the interface between the India plate and the northern Burma plate. The lack of recent seismicity may be due to the zone being permanently incapable of producing great earthquakes or it may be due to the plate having been locked during the relatively short record of instrumental seismicity, but still accumulating elastic strain that might be released in a future great earthquake. Socquet and others (2006) present Global Positioning Systems (GPS) observations that may suggest the plate are locked and accumulating strain due to oblique northeastward convergence of about 20 mm/yr along the Arakan Trench on the west coast of Burma. This model is not a unique interpretation of the GPS data, but it is favored by Socquet and others (2006) and would imply that this region has a high long-term potential for the occurrence of great underthrust earthquakes.

The Northern Sumatra-Andaman zone encompasses offshore northern Sumatra, the Nicobar Island chain, and the Andaman Island chain. In this area, the Indian plate is subducting obliquely beneath the Burma plate. This zone strikes nearly north-south as opposed to the nearly east-west trending section of the Sunda subduction zone near the island of Java, which we are calling the Java zone where the estimated rate of subduction is 20 mm/yr to 40 mm/yr, with the higher rates to the south (Rajendran and others, 2007; Socquet and others (2006); and Chlieh and others, 2006). The Northern Sumatra-Andaman zone last ruptured in the 26 December 2004 Sumatra earthquake (M9.2). The seismic/geodetic model of Chlieh and others (2006), however, shows that some patches of the subduction zone interface between lat. 2° N. and 14° N. apparently did not rupture during the course of the December 2004 mainshock or during the month following the mainshock. Some of these patches are large enough to produce sizeable earthquakes, if they are capable of accumulating and releasing elastic strain.

The Southern Sumatra zone encompasses one of the most seismically active plate tectonic margins in the world, and accommodates oblique north-eastward convergence of about 50 mm/yr between the Australia plate and the Sunda plate. Large subduction zone (plate-interface) earthquakes occurred in 1833 (~M9.0±0.2), 1861 (M8.5), 2000 (M_w7.9), and 2005 (M_w8.6) (Newcomb and McCann, 1987).

Within the Java zone, earthquakes produced damage from shaking or tsunamis as the result of thrust-faulting on the plate interface and faulting within the Australia or Sunda plates. The largest interface thrust earthquakes in the Java-Timor zone since 1900 were the 1994 June 2 (M_w7.8) and 2006 July 17 (M_w7.7) earthquakes, both of which produced destructive tsunamis but neither of which caused recognized damage from shaking. These earthquakes were an uncommon type of earthquake, commonly called “tsunami earthquake” (*e.g.*, Ammon and others, 2006). “Tsunami earthquakes” produce relatively low-levels of the high-frequency energy that cause shaking damage to buildings but are unusually efficient at generating tsunami waves. Although the seismological evidence is clear that the Java zone can produce interplate thrust-fault earthquakes with magnitudes approaching M_w8.0. Since the mid-nineteenth century, there have been no cataloged earthquakes of M_w8.0 or larger in the Java zone that appear likely to have been due to thrust-faulting on the interface (Newcomb and McCann, 1987). Newcomb and McCann (1987) suggest that this region of the eastern Sunda arc is much less likely to experience great underthrust earthquakes than the western Sunda arc. Smaller earthquakes are suspected because of weak coupling at the plate interface that may be due to the nature of the high density, old, subducting lithosphere beneath the Java zone. Geodetic observations (Simons and others, 2007) are consistent with weak coupling on the subduction interface. The largest earthquake in the Java zone since 1900 was the 19 August 1977 (M_w8.3) earthquake, which was an intraplate earthquake occurring within the subducting Australia plate rather than an interplate earthquake occurring on the thrust interface between the Australia plate and the overriding Sunda plate. The 1977 earthquake produced a destructive tsunami; little or no damage resulted from shaking due to its distance offshore.

2.4 Crustal Fault Sources

Long-term slip rates and estimates of earthquake size define the rate of large-magnitude earthquakes on crustal faults in hazard analysis. The length of the mapped fault and down-dip width estimates from seismicity may be used to calculate maximum magnitudes of earthquakes expected to occur on these faults (*e.g.*, Wells and Coppersmith, 1994). For determining magnitude from fault area or surface length on different segments or multi-segment ruptures surface length relations of Wells and Coppersmith (1994). For making the hazard calculations from fault sources, an uncertainty (±M0.2) was applied for the characteristic earthquake magnitude and the maximum magnitude of the Gutenberg-Richter distribution. In addition, we apply a combination of 50-percent characteristic and 50-percent Gutenberg-Richter magnitude frequency distributions and account for uncertainties in the characteristic or maximum magnitudes in the northern south-east Asia faults. We also include an aleatory uncertainty in the magnitude using a normal distribution, with sigma of ±0.12, which was applied in the United States National Seismic Hazard Maps (Frankel and others, 2002). For the Sumatran fault we use a equally weighted combination of two different characteristic models, a Gutenberg and Richter model, and a floating M7.9 rupture model.

As part of this project we required an inventory of Quaternary faults on the islands of Sumatra and Java and portions of Bali and Kalimantan (west of long. 115° E.). We solicited the support of Dr. Kerry Sieh of the California Institute of Technology and his colleagues at the Indonesian Institute of Sciences, all of whom have been involved in geological studies of Indonesian faults, deformation, and tectonics for many years. Within the scope of this work, Dr. Sieh and Dr. Danny Hilman Natawidjaja compiled and a geographic information system (GIS) database of active faults and folds in the study area. The compilation relies on publicly released and published information, but in areas where there are obvious, active structures but no published data, they conducted preliminary reconnaissance mapping of landforms that indicate active faulting and tectonics using shaded-relief Shuttle Radar Topography Mission (SRTM) maps and digital topography. In addition, they assembled information on the region's contemporary deformation and a catalog of instrumental and preinstrumental earthquakes from a variety of sources along with topography, published maps, geological features, cultural features, and GPS slip vectors. The major crustal fault is the Sumatran fault that is discussed in more detail in Petersen et al., 2004.

Even though no surface-faulting earthquakes have been documented in Thailand in the past 700 yr wide spread evidence of Holocene surface deformation has been recognized for nearly two decades. These inter- and intra-plate faults have tectonic histories that are complex; their origin, distribution, and tectonic history are driven by distant convergent-plate motions. In northern Southeast Asia, a broad zone of generally east-west, sub-parallel, well-defined sinistral faults extend from the Burma coast eastward into Vietnam and China. These faults, join with the Himalayan deformation zone, and define an arc of the India-Asia collision belt. The strike-slip faults of northern and western Thailand give way to transtensional, normal faults in the northeastern corner of the country. They bound Tertiary basins that reflect similar origin, style of faulting, spatial distribution, and rates of activity as faults the Basin and Range Province; similarly, northern Thailand is undergoing east-west to northwest-southeast extension (Fenton and others, 1999, 2003). There has been an extensive effort in Thailand to document and characterize potentially active faults (Kosuwan and others, 1999, 2000) by the Department of Mineral Resources with cooperative research studies by Chulalongkorn University, Thailand, and Akita University, Japan. In the decade since the earliest of these compilations, many trenching investigations have been completed that identify where large-magnitude Holocene (and earlier) earthquakes have occurred. We rely on published data to assign slip rates, and our discussions of fault parameters in the Thailand workshops.

3. GROUND MOTION MODELS

The ground motion models are referred to as attenuation relations or ground motion prediction equations. These models predict the ground motion for a particular fault source, fault type, magnitude, distance, stress drop, Q attenuation properties of the crust, and local soil condition. We apply attenuation relations for intraplate earthquakes within stable continental regions, interplate crustal earthquakes near plate boundaries, subduction zone earthquakes on the plate interface, as well as intermediate and deep earthquakes within the subducting slab. We apply separate attenuation relations for the interplate crustal, intraplate crustal, deep, and subduction earthquakes. The Southeast Asia seismic hazard maps are made using a reference site condition that is specified to be the boundary between NEHRP classes B and C, with an average shear-wave velocity in the upper 30 m of the crust of 760 m/s (Building Seismic Safety Council).

Once the earthquake sources are defined, attenuation relations relate the source characteristics of the earthquake and propagation path of the seismic waves to the ground motion at a site. Predicted ground motions are typically quantified in terms of a median value (a function of magnitude, distance, site condition, and other factors) and a probability density function of peak horizontal ground acceleration or spectral accelerations for different periods (McGuire, 2004). Seismic hazard is calculated using ground motion prediction equations (empirical attenuation relations) that relate the peak ground acceleration or spectral acceleration to the distance between the source and site, characteristics of the earthquake rupture, and soil conditions at the site.

For the stable Sunda plate we use crustal intraplate attenuation relations to characterize ground motions (see attenuation relations applied to the central and eastern U.S. in Petersen et al., 2008). Most of the intraplate relations account for higher stress drop events that generate ground motions that do not attenuate as fast as ground motions in interplate regions. For shallow earthquakes not associated with earthquakes on the interface subduction events or the intraplate regions, we apply crustal interplate attenuation relations (see attenuation relations applied to the western U.S. in Petersen et al., 2008). Research sponsored by the Pacific Earthquake Engineering Research Center (PEER) and involved in the Next Generation Attenuation Relation project (NGA) developed a global strong motion database containing strong motion records from 173 earthquakes. These data were used to revise crustal interplate ground motion prediction equations.

For this hazard analysis, we apply the crustal interplate attenuation relations to all crustal faults in Thailand and Indonesia. There was some discussion about whether the faults in Thailand should be treated as intraplate events since the ground motions may persist to longer distances as they propagate into a region of lower attenuation. This issue was unresolved at our workshops and should be a topic of future studies to improve the maps.

Ground motions for great subduction zone earthquakes were determined from several subduction zone interface equations (see Cascadia subduction zone model in Petersen et al., 2008). In addition, we applied separate ground motions for earthquakes deeper than 40 km.

4. RESULTS

Ground motion maps are produced by considering the ground motion distributions from each of the potential earthquakes that will affect the site and by calculating the ground motion with an annual rate of 1/475 or 1/2475 (10% and 2% probability of exceedance in 50 yr) for building code applications. Figure 1 shows a PGA map of the hazard in southeast Asia for a 10% probability of exceedance in 50 years. The highest hazard is associated with the Sunda subduction zone and crustal faults (e.g., Sumatran Fault). Additional work is needed to define earthquake sources and recurrence, refine attenuation relations for different tectonic areas, and develop maps that consider site effects.

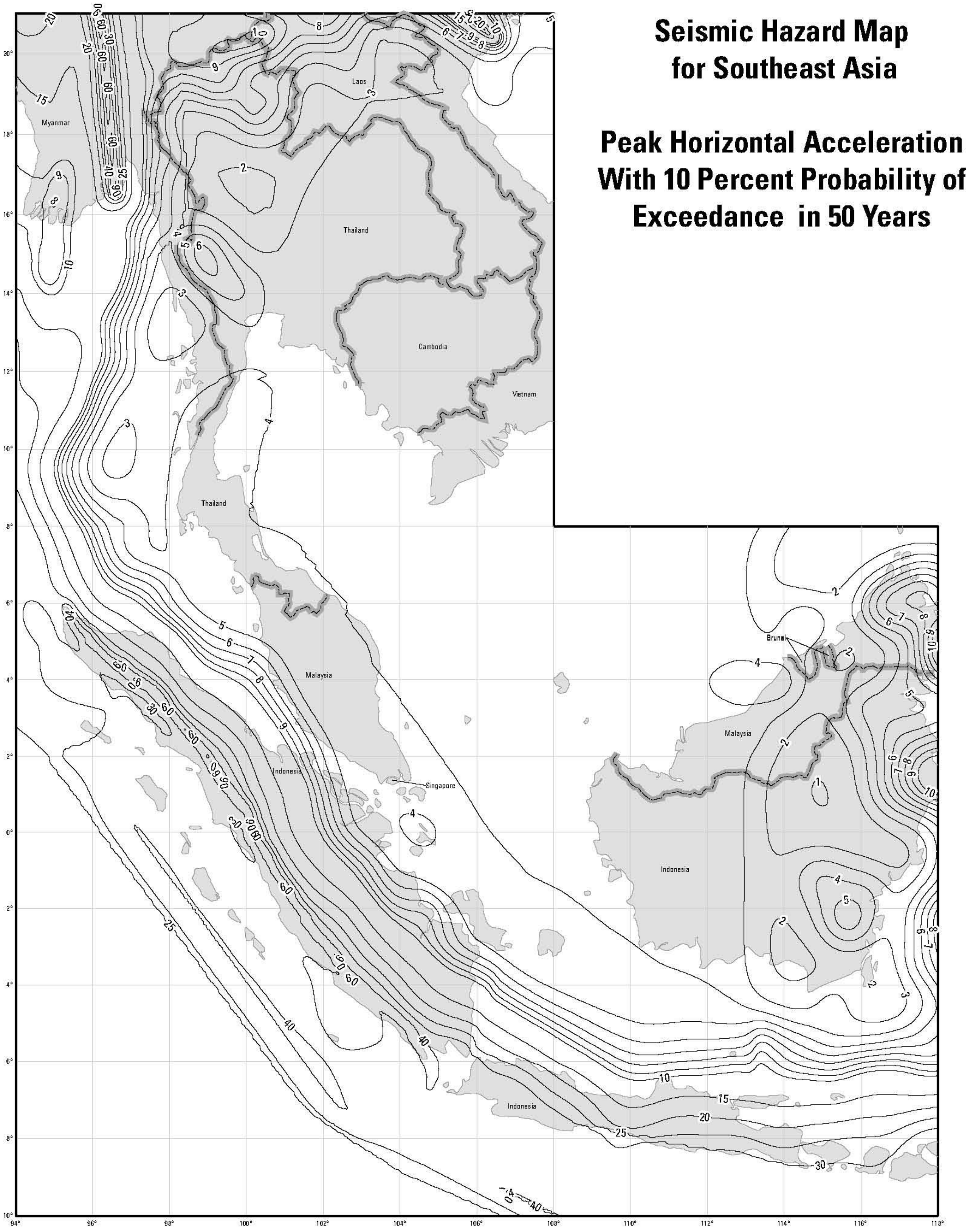

Figure 1. Seismic hazard map of southeast Asia for 10% probability of exceedance in 50 years (firm rock).

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6. REFERENCES

Ammon, C.J., Kanamori, H., Lay, T., and Velasco, A.A. (2006). "The 17 July 2006 Java tsunami earthquake", Geophysical Research Letters, v. 33, L24308, doi:10.1029/2006GL028005, 5 p.

Chlieh, M., Avouac, J.-P., Hjorleifsdottir, V., Song, T.-R. A., Ji, C., Sieh, K., Sladen, A., Hebert, H., Prawirodirdjo, L., Bock, Y., and Galetzka, J. (2006). "Coseismic slip and afterslip of the great (M_w9.15) Sumatra-Andaman earthquake of 2004", Bulletin of the Seismological Society of America, v. 97, no. 1A, p. S152–S173.

Engdahl, E.R., van der Hilst, R., and Buland, R. (1998). "Global teleseismic earthquake location with improved travel-times and procedures for depth determination", Bulletin of the Seismological Society of America, v. 88, p. 722–743.

Engdahl, E. R., and Villaseñor, A. (2002). "Global seismicity— 1900-1999", *in* Lee, W.H.K., Kanamori, H., Jennings, P.C., and Kisslinger, C., eds., International handbook of earthquake and engineering seismology, pt. A: Amsterdam, Academic Press, p. 665–690.

Fenton, C.H., Charusiri, P., Hinthong, C., Lumjuan, A., and Mangkonkarn, B. (1999). "Late Quaternary faulting in northern Thailand", in Dheeradilok, P., Hinthong, C., Chaodumrong, P., Putthapiban, P., Tansathien, W., Utha-aroon, C., Sattyarak, N., Nuchanong, T., and Techawan, S., eds., Proceedings of the International Conference on Stratigraphy and Tectonic Evolution of Southeast Asia and the South Pacific: Bangkok, Thailand, August 19–24, 1997, p 436-452.

Fenton, C.H., Charusiri, P., and Wood, S.H. (2003). "Recent paleoseismic investigations in northern and western Thailand", Annals of Geophysics, v. 46, p. 957–981.

Frankel, A.D., Petersen, M.D., Mueller, C.S., Haller, K.M., Wheeler, R.L., Leyendecker, E.V., Wesson, R.L., Harmsen, S.C., Cramer, C.H., Perkins, D.M., Rukstales, K.S. (2002). "Documentation for the 2002 Update of the National Seismic Hazard Maps", U.S. Geological Survey Open-File Report 02-420.

Guzman-Speziale, M., and Ni, J.F. (1996). "Seismicity and active tectonics of the western Sunda arc", *in* Yin, A., and Harrison, T.M., eds., The tectonic evolution of Asia, Cambridge University Press, New York, p. 63–84.

Kosuwan, S., Hinthong, C., Charusiri, P. (1999). "The preliminary use of MapInfo programme to earthquake hazard assessment in Thailand and mainland SE Asia", Journal of Geology, Series B, no. 13–14, p. 174–178.

Le Dain, A.Y., Tapponnier, P., and Molnar, P. (1984). "Active faulting and tectonics of Burma and surrounding regions", Journal of Geophysical Research, v. 89, p. 453–472.

Newcomb, K.R., and McCann, W.R. (1987). "Seismic history and seismotectonics of the Sunda arc", Journal of Geophysical Research, v. 92, p. 421–439.

Petersen, M.D., Dewey, J., Hartzell, S., Mueller, C., Harmsen, S., Frankel, A.D., and Rukstales, K. (2004). "Probabilistic seismic hazard analysis for Sumatra, Indonesia and across the southern Malaysian Peninsula", Tectonophysics, v. 390, p. 141–158.

Petersen, M.D., Frankel, A.D., Harmsen, S.C., Mueller, C.S., Haller, K.M., Wheeler, R.L., Wesson, R.L., Zeng, Y., Boyd, O.L., Perkins, D.M., Luco, N., Field, E.H., Wills, C.J., and Rukstales, K.S. (2008). "Documentation for the 2008 update of the United States National Seismic Hazard Maps", USGS Open-file report 1128, http://earthquake.usgs.gov/research/hazmaps/.

Petersen, Mark, Stephen Harmsen, Charles Mueller, Kathleen Haller, James Dewey, Nicolas Luco, Anthony Crone, and David Lidke (2007). "Probabilistic seismic hazard for southeast Asia", USGS Administrative report submitted to USAID http://apps.develebridge.net/usiotws/4/USGS_SEASIA-SeismicHazards_Sep07.pdf .

Rajendran, C.P., Rajendran, K., Anu, R., Earnest, A., Machado, T., Mohan, P.M., and Freymueller, J. (2007). "Crustal deformation and seismic history associated with the 2004 Indian Ocean earthquake—A perspective from the Andaman-Nicobar Islands", Bulletin of the Seismological Society of America, v. 97, p. S174–S191.

Rangin, C., Le Pichon, X., Mazzotti, S., Pubellier, M., Chamot-Rooke, N., Aurelio, M., Walpersdorf, A., and Quebral, R. (1999). "Plate convergence measured by GPS across the Sundaland/Philippine Sea Plate deformed boundary—The Philippines and eastern Indonesia", Geophysical Journal International, v. 139, p. 296–316.

Simons, W.J.F., Socquet, A., Vigny, C., Ambrosius, B.A.C., Abu, S. H., Promthong, Chaiwat, Subarya, C., Sarsito, D.A., Matheussen, S., Morgan, P., and Spakman, W. (2007). "A decade of GPS in Southeast Asia—Resolving Sundaland motion and boundaries", Journal of Geophysical Research, v. 112, B06420, doi:10.1029/2005JB003868, 20 p.

Socquet, A., Vigny, C., Chamot-Rooke, N., Simons, W., Rangin, C., and Ambrosius, B. (2006). "India and Sunda plates motion and deformation along their boundary in Myanmar determined by GPS", Journal of Geophysical Research, v. 111, B05406, doi: 10.1029/2005JB003877, 11 p.

Wells, D.L., and Coppersmith, K.J. (1994). "New empirical relationships among magnitude, rupture length, rupture width, and surface displacements", Bulletin of the Seismological Society of America, v. 84, p. 974–1002.