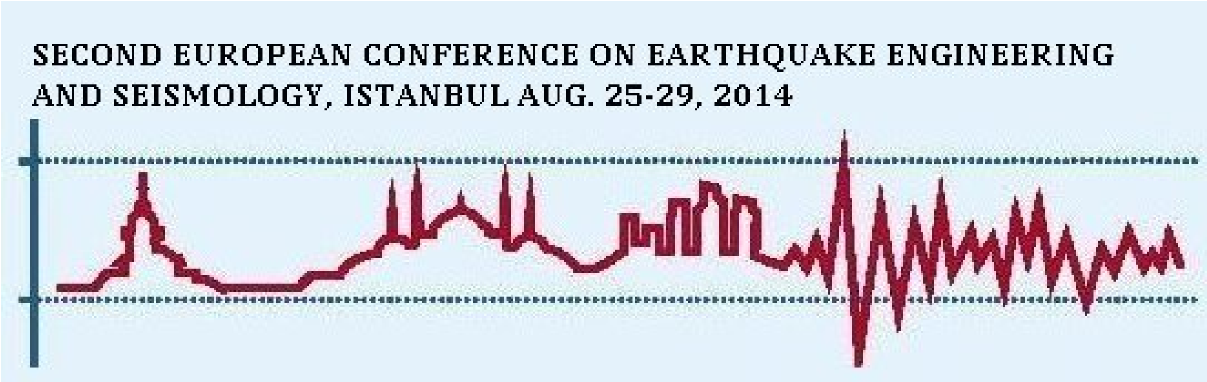

A NOTE ON GROUND MOTION RECORDED DURING THE MW 9.2 GREAT SUMATRA-ANDAMAN EARTHQUAKE IN MYANMAR, MALAYSIA, AND THAILAND ON 26 DECEMBER 2004

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ABSTRACT

This study aims to investigate previously unpublished ground motion records produced by Mw 9.2 Northern Sumatra earthquake on 26 December 2004 in Malaysia, Thailand, and Myanmar. The epicentre of this event initiated off the northwest coast of Sumatra, and it ruptured northward between the Indo-Australian plate and the Eurasian plate boundary along north-western Sumatra, the Nicobar Islands, and the Andaman Islands. Twelve digital broad-band seismometers and accelerometers are located over a rupture distance range from 600 to 1600 km. The preliminary results show large spatial variation in the ground shaking, with the strongest ground motions observed along stations located within fault rupture direction. Several different ground motion prediction equations (GMPEs) for interface subduction earthquakes captures well the distance scaling and dispersion of the data, but some of them under-predicts the overall ground motion level for stations located in ruptured direction. The 2004 Great Sumatra earthquake generated unusual long period response spectra for station located in Pyay, Myanmar. The ground motion recorded from long distance and large earthquake demonstrated the substantial spatial variation of the long-period shaking observed within this region and its implication toward site-specific prediction of long period structures. Some unique features of observed ground motion include very long duration, long-period spectral content, and effects due to spatial variability as well as direction of rupture/wave propagation have been presented and summarized.

INTRODUCTION

Shortly before 8.00 am (local time) in Indonesia on 26 December 2004, an earthquake with magnitude greater than 9 ruptured the Northern Sumatra Trench. The location of epicenter is about 90 km off Northern Sumatra Island with shallow focal depth of 30 km. Called the Great Sumatra earthquake, this shock was the strongest ever record event in South East Asia region. Although comparable in size and type to the quake that devastated Chile in 1960 (Mw 9.5), Alaska earthquake in 1964 (Mw 9.2), and Tohoku earthquake in 2011 (Mw 9.0), the Great Sumatra earthquake caused the longest rupture length (approximately 1,200 - 1,300 km). Though extensive damage and casualties had been widely acknowledged and studied due to tsunami wave generated from this event. Only few

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ground motion records from this event has been reported and analyzed because of few seismic instruments in the region at that time.

Fortunately, 12 digital broad-band seismometers and accelerometers had been able to operate and to record this event. These stations are located at regional distance over a rupture distance range from 600 to 1600 km in Myanmar, Malaysia, and Thailand. Several different ground motion prediction equations (GMPEs) for interface subduction earthquakes have been used to compare with observed motion. The preliminary results show large spatial variation in the recorded ground shaking. The selected GMPEs captures well the distance scaling and dispersion of the data, but some of them under-predicts the overall ground motion level for stations located in India and Myanmar. This article provides an overview of the local seismotectonic settings relating to 26 December 2004 event, characteristic of observed strong motion with available ground motion prediction equations (GMPEs), and some interesting results observed from strong ground motion recorded at Pyay station. In addition, with increasing large-scale structures has greatly changed the situation of urban areas, consideration of displacement controlled long period structure become important, comparison of observed displacement spectra at Pyay station have also been provided.

REGIONAL TECTONIC SETTINGS AND 26 DECEMBER 2004 EARTHQUAKE

Prior to 2004 Great Sumatra earthquake, the northern Sumatra-Andaman subduction region had not been considered to be able to generate M ~ 9 earthquake. It was believed that subduction zones capable of producing great earthquakes are those with young subducting plates and fast subduction rates (Ruff & Kanomari, 1980). Convergence at the trench off Sumatra is likely 40 to 50 mm yr^{-1}.To the north, because the orientation of the Andaman-Nicobar section of the trench (Curray 2005) is nearly parallel to the direction of relative motion, convergence is thought to be much slower, <20 mm yr^{-1}. In comparison to other subduction zones where great earthquakes have occurred in recorded history, the trench-normal convergence rate is large,11 cm/yr for Chile and 6cm/yr for Alaska. The slow convergence was among the reasons that, prior to 2004, a great earthquake was not contemplated in the Andaman section of the subduction zone. In addition, no event comparable to the 2004 tsunami is recorded in known historical sources from the Indian Ocean region (Dominey-Howes et al., 2007). Only the 1907 Sumatra earthquake with 7.8 magnitude located at 250 km southwest from 2004 event epicenter is the largest event prior 2004, (Kanamori, et al., 2010). This lack of fully understanding Sumatra-Andaman subduction zone leads to no instruments near 2004 Sumatra and 2005 Nias earthquakes. But after the 2004 Sumatra-Andaman earthquake, which occurred where old plates have modest subduction rates, Stein & Okal (2007) have shown that plate ages and subduction rate do not fully predict earthquake magnitudes on subduction zones.

Different analysis methods helped to confirm the total rupture length of 1,200 - 1,300 km, which is approximately the same as observed aftershock distribution within few days after earthquake, Ni et al. (2005); Ishii et al. (2005); and Tsai et al. (2005). Based on broadband seismograms (20 to 2,000 s), the slip distribution of finite fault model have been able to construct, Ammon et al. (2007). The 26 December 2004 Sumatra-Andaman earthquake ruptured largely unilaterally, and initiated slowly, with small slip and a slow rupture speed for the first 40 to 60 seconds. Then the rupture expanded at a speed of about 2.5 kilometers per second toward the north northwest. The large amounts of slip occurred off the west coast of Sumatra between 4ºN and 5ºN with peak displacement reached ~ 15 meters. However, slip was less in the northern 400 to 500 kilometers of the aftershock zone, and at least some slip in that region may have occurred on a time scale beyond the seismic band. Analysis of teleseismic short period body waves of the December event by Ammon et al. (2005) showed that the source duration of the event was about 500 seconds, consistent with rupture propagation at 2.5 km/sec over a 1,200 km rupture length. Figure 1 shows rupture area of 2004 earthquake with the main shock epicenter. Most of the aftershocks occur in a region approximately 1200 - 1300 km long (along strike) by 200 km wide.

RECORDED REGIONAL GROUND MOTION

The ground motion of the Great Sumatra earthquake were recorded by 12 seismic stations at regional distance by different national metrological networks in South East Asia (nine Malaysian, two Thai, and one Myanmar); however, only four Malaysian seismic stations are located at distance less than 1,000 km from originated fault, Table 1. The closest distances from the instruments to the surface projection of the fault are taken from the approximated large energy rupture zone located at 4.2ºN and 94.5ºE as indicated in previous section. Various instruments have been used to record 2004 event. Most of these instruments are triaxial digital accelerometers, but only CHTO station that data recorded by broadband seismometer, and it have been acquired for current analysis. Based on available geotechnical soil profiles of these seismic stations, of those 12 stations, 11 sites can be classified as soil type B, and only station in Myanmar (PYAY) that there is no available soil profile description. However, station is located near the river, the soil profile of PYAY station could be on top of soil deposit.

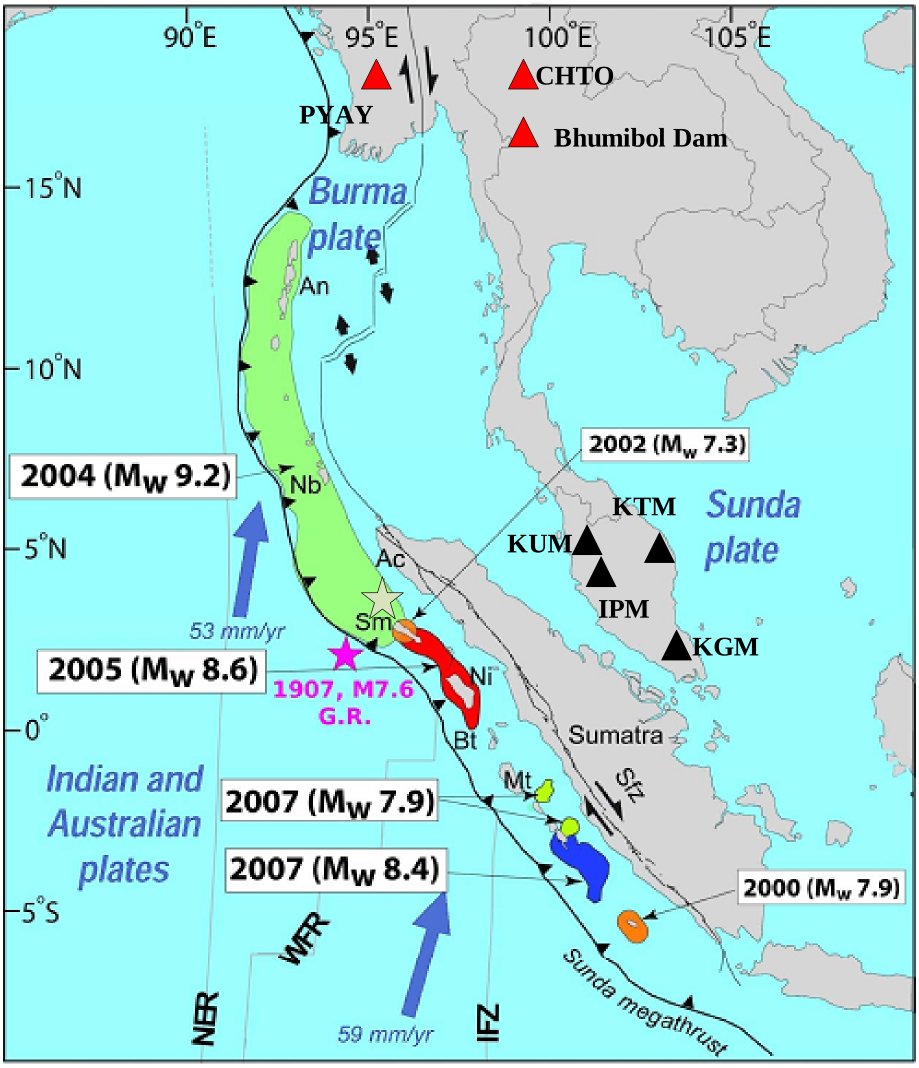

Figure 1. Rupture zone of 2004 Great Sumatra earthquake and other large events along Andaman-Sumatra Trench. Red triangles represent seismic stations located in forward directivity, and Black triangles represent Malaysian seismic stations located in backward directivity, Modified from Kanamori et al. (2010).

All records have been obtained and visually inspected to remove any obvious errors. Subsequently, digitized data is scaled according to sensor gain to convert to acceleration units. To remove non-zero means, records are performed the standard zero-order correction. No digital filtering is performed on this acceleration time series. This is because high-pass filtering may remove low-frequency components of the signal carrying information pertaining to gigantic earthquake. All reported ground motions are a direction-independent average horizontal ground motion. Those recordings as shown in Table 1, located less than or within about rupture area of the 2004 earthquake, which by some definitions would make them "near source," but that source dimension is very large, about 1,200 - 1,300 km. The recordings, shown in Figure 2, have strong spatial variations in amplitude particularly at PYAY station comparing to other stations. Unfortunately, only part of ground motion records at PYAY could be able to obtain since the accelerograph station had poor maintenance. However, this data reviewed that PYAY and CHTO, in the forward rupture directivity direction to the north in Myanamr and Thailand, respectively, has large and similar ground motion amplitudes compared to those stations recorded in Malaysia, which are located at much closer distance (less than 1,000 km). Backward rupture directivity at these Malaysian stations caused the ground motion durations to be much longer, on the order of 1,000 seconds.

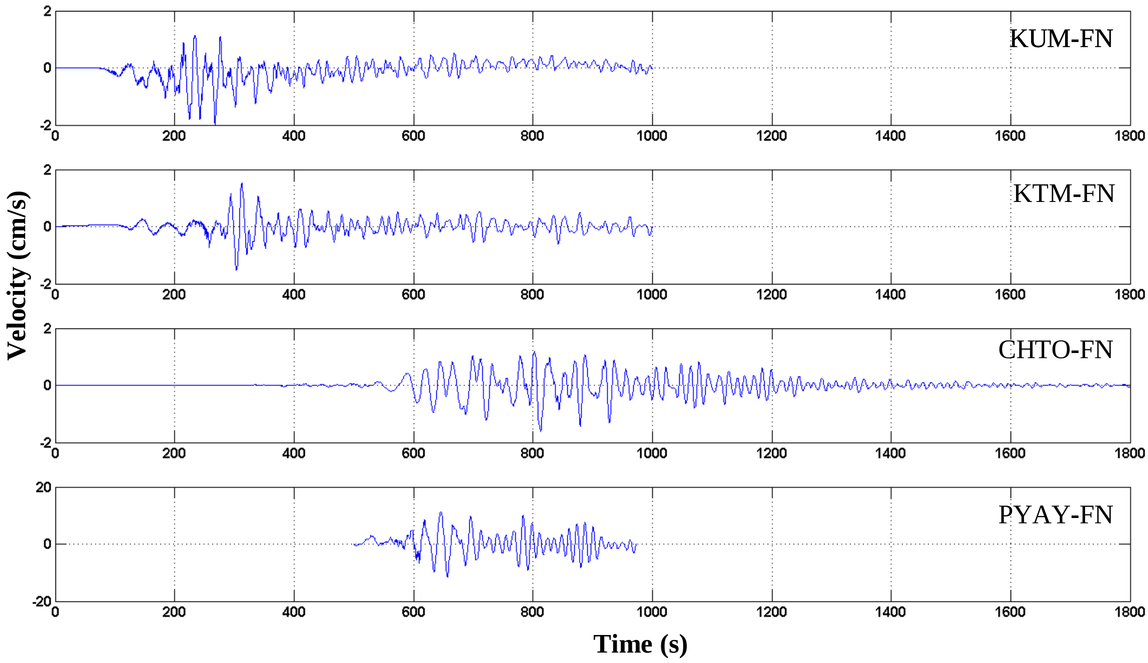

Figure 2. Broadband velocity seismograms of the 26 December 2004 Great Sumatra-Andaman event recorded by seismic station in Malaysia, Thailand, and Myanmar at regional distance. Notice that the scale of PYAY station is not the same compared to other stations.

Comparison of observed ground motion from Mw 9.2 Great Sumatra earthquake to Youngs et al. (1997); Zhao et al. (2006); and Atkinson and Boore (2003; 2008), versus distance are shown in Figure 3 for PGA and Spectral acceleration (SA) at 1.0 and 2.0 s, Figure 4 and 5. Since, in this region, there is a very limited number of available ground motion records, some existing GMPEs developed for other similar seismotectonic setting is assumed to be adequately represent ground motion scaling in this region. In addition, these three relations have been adopted in recent probabilistic seismic hazard analysis for Thailand (Ornthammarath et al. 2011). The selected VS_{30} for rock condition between B/C NEHRP site class is 760 m/x. For Youngs et al.(1997) relation, the rock site condition has been chosen to compare with observed strong motion data. Median (μ) and ± one standard deviation (σ) are shown for three equations. It could be quickly noticed that the observed ground motion in India, Thailand, and Myanamr (red circles) is consistently larger than that of similar distance recorded in Malaysia (black circles) for about 2 to 3 times for all considered structural periods. In addition, observed PGA and PGV in Myanmar and Thailand are well consistent to what have been reported in India, (Singh et al., 2005; Nath et al., 2005). The difference of long-period motions at widely separated stations with different azimuths and site conditions, Figure 5, suggests that they are a source, rather than a path or site, effect.

Table 1. Regional ground motion that recorded the mainshock with their parameters

Station	Location		Rjb (km)	Source-to-site azimuth (Degree)	PGA (g)	PGV (cm/s)
	Lat (N)	Long (E)				
KUM	5.29	100.65	680	79	1.2×10^{-3}	2.5
IPM	4.58	101.03	712	86	1.3×10^{-3}	2.0
KTM	5.33	103.14	948	82	1.0×10^{-3}	1.0
KGM	2.01	103.32	994	104	5.0×10^{-4}	0.8
Bhumibol Dam	17.245	99.024	1,500	18	9.0×10^{-4}	1.8
CHTO	18.814	98.944	1,677	16	7.0×10^{-4}	1.7
PYAY	18.825	95.220	1,616	2	0.0046	9.2

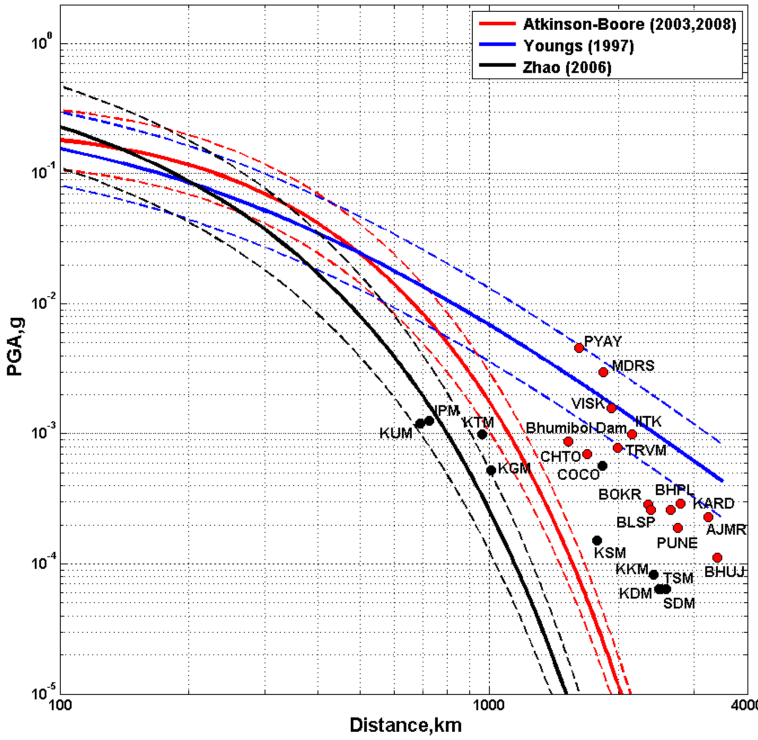

Figure 3. Comparison of observed PGA from Great Sumatra-Andaman earthquake ground motion and median ± one standard deviation of Atkison and Boore (2003; 2008); Youngs et al. (1997); and Zhao et al. (2006), Observed ground motion is in black circle for stations located in back azimuth (e.g. Malaysia) while red circles represent stations located in northern azimuth (e.g. Myanmar, India, and Thailand) . Recorded India ground motion parameters are from Singh et al. 2005; and Nath et al. 2005).

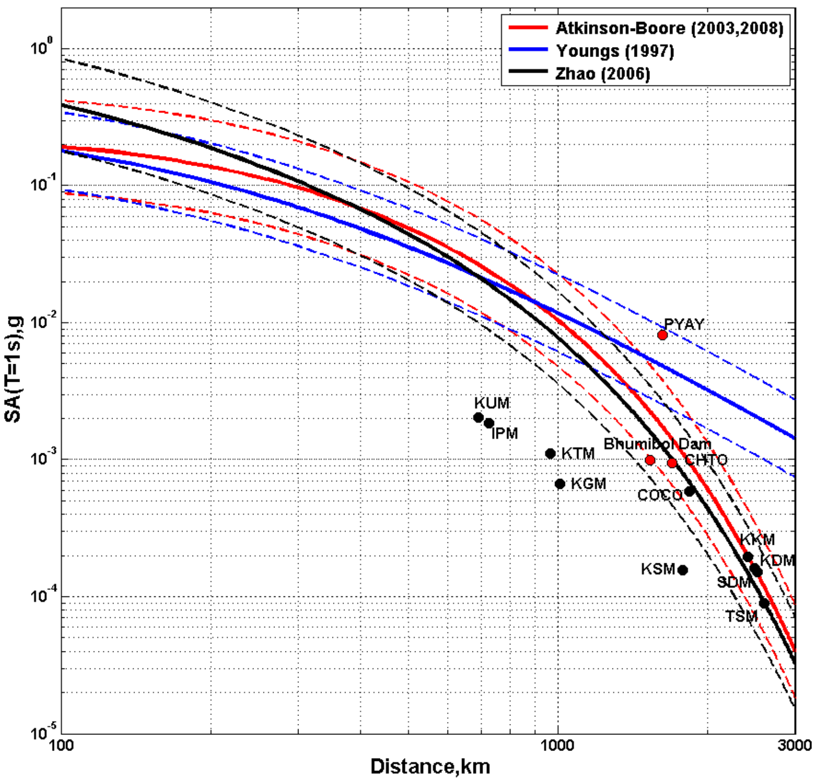

Figure 4. Comparison of observed SA at 1 second from Great Sumatra-Andaman earthquake ground motion and median ± one standard deviation of Atkison and Boore (2003; 2008); Youngs et al. (1997); and Zhao et al. (2006), Observed ground motion is in black circle for stations located in back azimuth (e.g. Malaysia) while red circles represent stations located in northern azimuth (e.g. Myanmar, India, and Thailand).

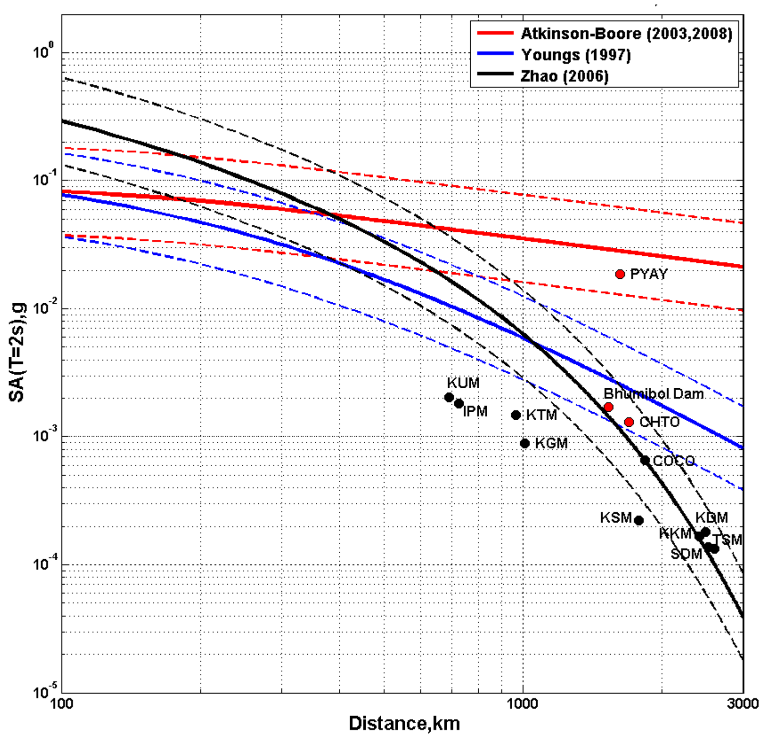

Figure 5. Comparison of observed SA at 2 second from Great Sumatra-Andaman earthquake ground motion and median ± one standard deviation of Atkison and Boore (2003; 2008); Youngs et al. (1997); and Zhao et al. (2006), Observed ground motion is in black circle for stations located in back azimuth (e.g. Malaysia) while red circles represent stations located in northern azimuth (e.g. Myanmar, India, and Thailand).

REGIONAL GROUND MOTION AT PYAY STATION

Figure 6 presents the acceleration time histories for recorded ground motion at PYAY station. This record is of special interested due to its location along the 2004 event rupture process. As indicated in Table 1, this is the closest instrument to record the fault directivity process, with rupture distances of 1,616 km. The acceleration time histories contain very long period motion which could be clearly identified. The initial part of the trace corresponds to high-frequency body-wave phases, and the long-period surface waves begin to arrive well before the end of the body-wave phases. From approximately 100 to 150 second, relatively low frequency and large amplitude waves arrived. This phasing of the ground motions, likely originating from the largest slip zone, imposes potentially important seismic demands on long period structures. In Figure 7, the horizontal response spectra of this record after rotating the horizontal ground motions into the fault parallel and fault normal directions are shown. The predicted geometric mean spectra from the Atkinson and Boore (2003; 2008) GMPE for rock ground condition (Site Class B), is the only attenuation equation to be able to predict the PYAY spectra, while Youngs et al. (1997) and Zhao et al. (2006) largely under-predicts the PYAY spectra. Both fault-normal and fault parallel components are comparable with amplification at long period. The PYAY records demonstrate distinct spectral shapes, with relatively large spectral peaks around 0.02 g at long period (~2.0 s).

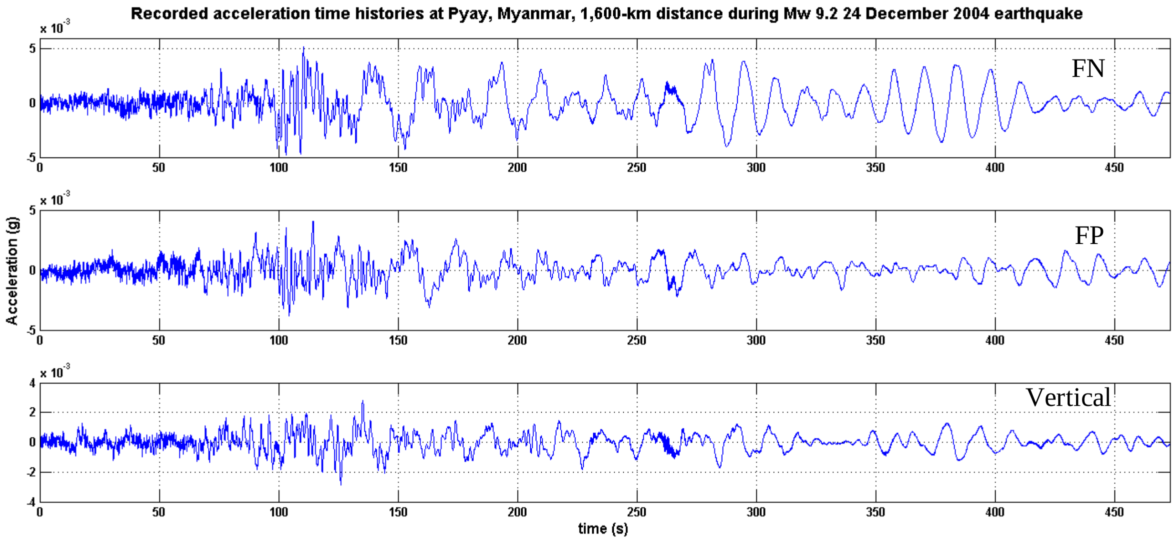

Figure 6. Acceleration time history of Pyay station, Myanmar, recorded during 2004 great Sumatra earthquake.

In addition, following the development of performance-based seismic design, strong emphasis on displacement consideration and capacity design concepts (Park and Paulay, 1976), the primary descriptor of the seismic demand becomes the relative displacement of the structure caused by the imposed ground motion, quantified through the displacement response spectra. The displacement spectra used within HAZUS (FEMA, 2003) and the ASCE 7-10 standard (ASCE7-10) feature an increase in SDs until a magnitude-dependent period at which a SD plateau begins. However, the period at which this constant SD plateau ends is not given. The calculated elastic displacement spectra for 5 % damping at PYAY station are displayed in Figure 8. The spectral displacement at PYAP station showed energy content of 2004 Great Sumatra event from 20 to 35 second. This is coincidence to what has been observed from ground motion recorded in Singapore, Pan et al. (2006). The beginning of the maximum spectral displacement plateau, the corner period, are around 12 and 20 seconds for fault normal and fault parallel, respectively.

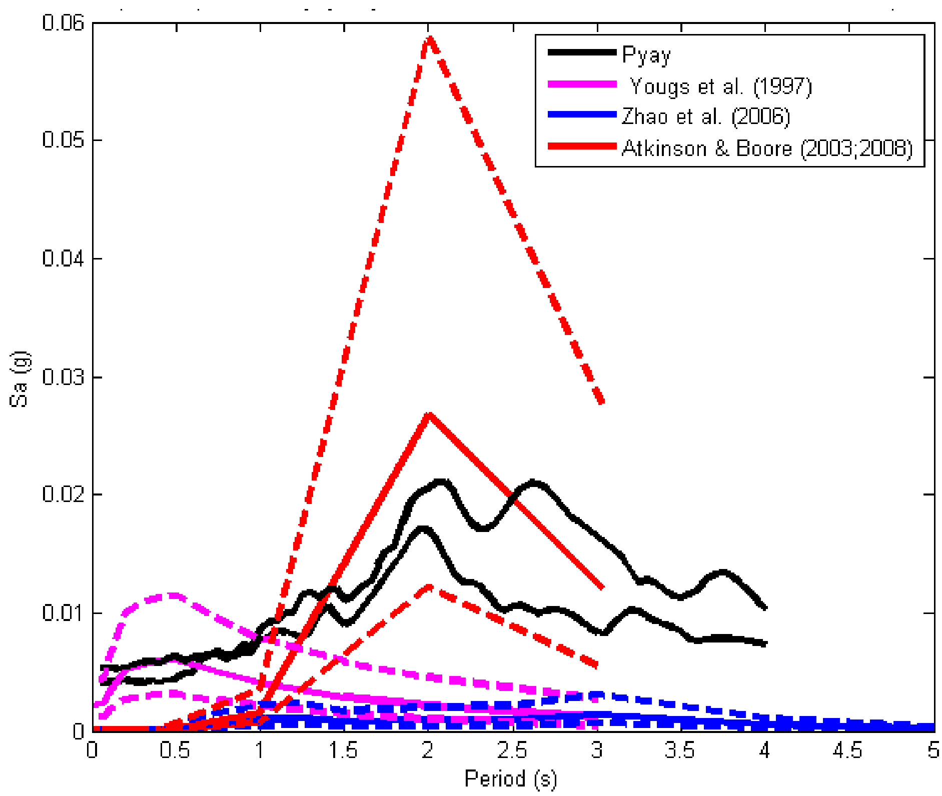

Figure 7. Comparison of recorded spectral acceleration spectra at PYAY station (at 5% damping) with selected GMPEs.

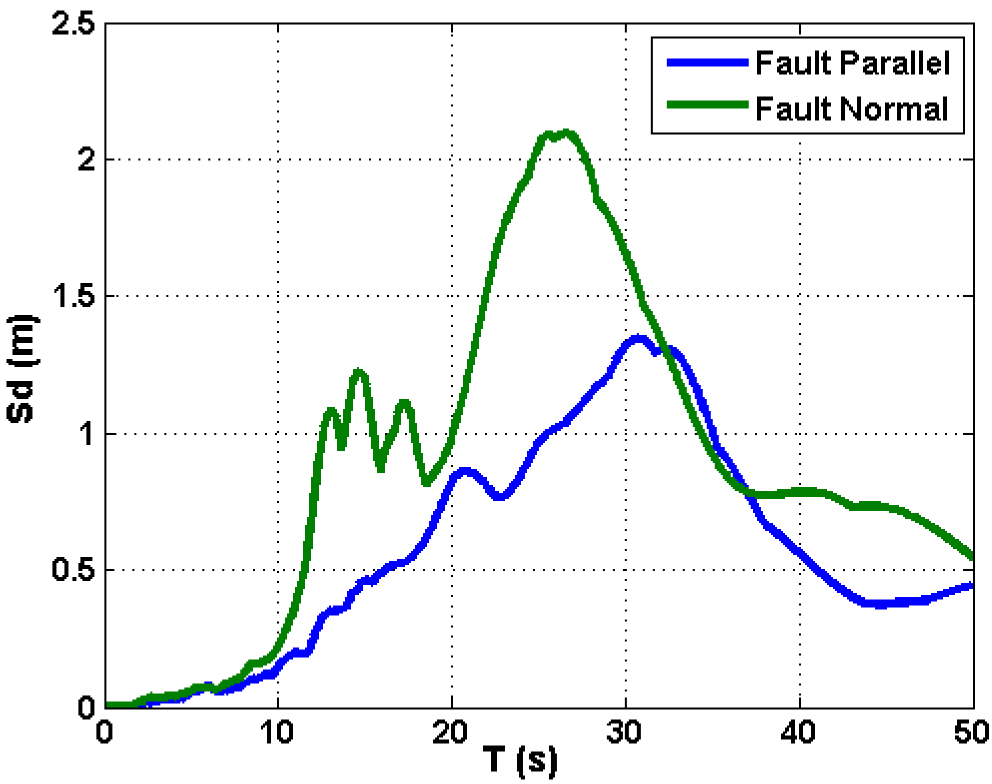

Figure 8. Observed elastic displacement response spectra at PYAY station from 26 December 2004.

CONCLUSIONS

Based on available seismotectonic information and instrumental data, a brief summary of the 26 December 2004 Mw 9.2 Great Sumatra-Andaman earthquake has been presented. The earthquake occurred along Andaman Trench, which has been previously identified as an active subduction zone; however, the capability of subduction zone that capable to produce M ~ 9 had not been perceived. Observed ground motion has been compared with that of global empirical equations, and they are in fair agreement over the distance range; however, some of them under-predicts the overall ground motion level for stations located in ruptured direction. The recorded ground motion at PYAY station shows large amplification at long period. The observations of large magnitude and long distance ground motions that could produce long period seismic demand has a major threat toward distant urban area in South East Asia with relatively low seismic activity with deep soil deposit basin (i.e. Bangkok). This supports the continued monitoring and research in developing engineering design parameters for earthquake-resistant design in these developing urban cities, which become the focus of high-rise buildings and long-period structures.

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REFERENCES

Ammon, C. J., Ji, C., Thio, H.-K., Robinson, D., Ni, S., Hjorleifsdottir, V., Kanamori, H., Lay, T., Das, S., Helmberger, D., Ichinose, G., Polet, J., and Wald, D., 2005. Rupture process of the 2004 Sumatra-Andaman earthquake, Science308□5725□, 1133-1139.

ASCE (American Society of Civil Engineers) (2010). ASCE 7-10, Minimum Design Loads for Buildings and Other Structures, pp. 658

Atkinson GM, Boore DM (2003) Empirical ground-motion relations for Subduction-zone earthquakes and their application to Cascadia and other regions. Bull Seism Soc Am 93(4):1703–1729

Atkinson GM, Boore DM (2008) Erratum to empirical ground-motion relations for subduction zone earthquakes and their application to Cascadia and other regions. Bull Seism Soc Am 98(5):2567–2569

Dominey-Howes, D.; Cummins, P. & Burbidge, B.(2007). Historic records of teletsunami in the Indian Ocean and insights from numerical modeling. Natural Hazards, Vol. 42, 1-17

FEMA.HAZUS-MH (2003). Technical Manual, Federal Emergency Management Agency, Washington, DC.

Kanamori, Hiroo and Rivera, Luis and Lee, William H. K. (2010) Historical seismograms for unravelling a mysterious earthquake: The 1907 Sumatra Earthquake. Geophysical Journal International, 183 (1). pp. 358-374. ISSN 0956-540X.

Ishii, M., Shearer, P. M., Houston, H., and Vidale, J. E., 2005. Extent, duration and speed of the 2004 Sumatra-Andaman earthquake imaged by the Hi-Net array, Nature 435(7044), 933–936.

Nath, S. K., Bhattacharya, S. N., Vyas, M., Pal, I., Sengupta, P., Mitra, S., Mohanty, W. K. and Ganguli, S. S. (2005) The Great Sumatra-Andaman Earthquake of 26 December 2004 as perceived from the broadband seismograms of IIT, Kharagpur Seismological Observatory Current Science 88(9) 1381-1383

Ni, S., Kanamori, H., and Helmberger, D., 2005. Seismology—Energy radiation from the Sumatra earthquake, Nature 434(7033), 582–582.

Ornthammarath T, Warnitchai P, Worakanchana K, Zaman S, Sigbjörnsson R, Lai CG (2011) Probabilistic seismic hazard assessment for Thailand. Bull Earthquake Eng 9(2):367–394

Ruff, L. & Kanamori, H. (1980). Seismicity and the subduction process. Physics of the Earth and Planetary Interiors , Vol. 23, 240-252

Singh, S. K., Dattatrayam, R. S., Suresh, G., Iglesias, A., Bansal, B. K., Xyoli Pérez, Ordaz, M., Gupta, H. K., Baidya, P. R., Gautam, J. L., Kumar, G., and Singh, R. K. (2005) The Great Sumatra-Andaman Earthquake of 2004: Regional Broadband Seismograms from India Seismological Research Letters, November/December, v. 76, p. 684-692,

Stein, S. & Okal, E. A. (2007). Ultra-long period seismic study of the December 2004 Indian Ocean earthquake and implications for regional tectonics and the subduction process. Bulletin of the Seismological Society of America , Vol. 97, S279-S295

Tsai, V. C., Nettles, M., Ekstrom, G., and Dziewonski, A. M., 2005. Multiple CMT source analysis of the 2004 Sumatra earthquake,Geophys. Res. Lett.32□17□L17304, doi:10.1029/2005GL023813.

Youngs RR, Chiou SJ, Silva WJ, Humphrey JR (1997) Strong ground motion attenuation relationships for subduction zone earthquakes. Seismol Res Lett 68(1):58–73

Zhao JX, Zhang J, Asano A, Ohno Y, Oouchi T, Takahashi T, Ogawa H, Irikura K, Thio H, Somerville P, Fukushima Y, Fukushima Y (2006) Attenuation relations of strong ground motion in Japan using site classification based on predominant period. Bull Seism Soc Am 96(3):898–913