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AN INVESTIGATION ON THE ATTENUATION CHARACTERISTICS OF DISTANT GROUND MOTIONS IN PENINSULAR MALAYSIA BY COMPARING VALUES OF RECORDED WITH ESTIMATED PGA AND PGV

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Abstract : The development of a design motion requires some input on ground motion characteristics. For a country such as Malaysia, where historical data is lacking and seismic activities are low, the information on characteristics of ground motion may be obtained by utilizing established attenuation relationships. This study aims to investigate the characteristics of distant ground motions in Peninsular Malaysia, which originated from the active tectonic plate of Sumatra, by comparing recorded peak ground acceleration (PGA) and peak ground velocity (PGV) values with those estimated using four attenuation models. Selected attenuation models are the Atkinson and Boore (1995), the Toro *et al*. (1997), the Dahle *et al*. (1990), and the Si and Midorikawa (1999) models. The analysis for comparison was made by employing a maximum of 46 horizontal component accelerograms, recorded at 14 seismic stations. These are data derived from 15 interplate earthquakes between May 2004 and July 2007. Recorded PGA and PGV values were plotted on respective attenuation curves to examine ground motion attenuation characteristics. Results indicated that attenuation models, established for stable tectonic regions, provide good estimation of PGA and PGV for Sumatran earthquakes for magnitude range of 5.9 to 9.0. The study shows that the Dahle *et al*. (1990) model best represents the characteristics of ground motions in terms of PGA, while the Atkinson and Boore (1995) model gives appropriately estimate ground motions in terms of PGV.

Key words: *Distant ground motion, Peninsular Malaysia, peak ground acceleration, peak ground velocity, attenuation relationship*

1.0 Introduction

Peninsular Malaysia is located within the low seismicity region of the stable Sunda tectonic plate; however, for the past 25 years it has been affected by strong ground motions several times. Sources of these strong ground motions include the Sumatran subduction zone, the most active plate tectonic margins in the world (Petersen *et al.*, 2004), and the 1650 km long Sumatran fault. While no real structural damage has been reported following these earthquake tremors, there have been reports of swaying motion and panicked attack suffered by occupants of tall buildings in densely populated cities such as Kuala Lumpur, Putrajaya, Penang, and Johor Bharu. Such reports have motivated a good number of researches on seismic hazard assessment and reflected the importance of deriving a seismic design motion for engineering evaluation and design in Malaysia.

Development of a design motion requires ample information on the characteristics of ground motions, which may affect a structure. This information may be found by analyzing important time-domain parameters, such as peak ground acceleration (PGA) and, or peak ground velocity (PGV). However, for a country such as Malaysia where historical data is scarce and seismic activities are low, established attenuation models may be utilized to examine the characteristics of ground motions at site. This entails the selection of appropriate attenuation models which best represent Malaysia and in doing so, comparison between recorded and estimated PGA and PGV is likely inevitable.

In determining characteristics of ground motions, PGA has become the most widely used parameter simply because strong motion seismometers record time history accelerations, hence PGA values can be instantly read off the accelerograms. In addition to using PGA, Chandler and Lam (2004) suggested that the characteristics of low frequency, long period seismic waves, resulting from large and distant earthquakes, as are typically recorded across Malaysia, may be better described by using PGV.

Therefore, in this study, the characteristics of distant ground motions in Peninsular Malaysia shall be investigated by making and observing comparisons of recorded and estimated PGA and PGV values. Based on the results, recommendation on distant ground motion attenuation characteristics shall be made by way of selecting appropriate attenuation models, which in turn may be used in determining a design motion for Peninsular Malaysia.

2.0 Strong Motion Dataset

Malaysia has a national network of seismic stations to gather information on seismic activities in the country and from around the region. The network comprises of fourteen three-component and real time stations with eight stations being installed with broadband sensors while the remaining six stations are equipped with short-period field seismometers. Figure 1 depicts the locations of strong motion stations across Malaysia. The Malaysian Meteorological Department (MMD) monitors and gathers information on seismic activities; and keeps records of strong motion data, in the form of accelerograms, beginning the year 2004. For this reason, earthquake accelerograms recorded beginning in the year 2004 shall be considered in the study.

The ground motion records used herein come from earthquake events, which occurred between May 2004 and July 2007, giving us access to about 150 ground motion records for analysis. However, usable records for analysis were further reduced to a maximum of 46 accelerograms due to constraints on source-to-site distance and earthquake magnitude posed by selected attenuation relationships. These are visible records with background noises removed during analysis. As a result, although ground motions recorded at stations , as far out as 2400 km away from the earthquake sources were initially included in the analysis, they were ultimately excluded from the study. In this study, only horizontal component accelerograms were considered for analysis, whereby recorded PGA and PGV values have been derived by taking the larger of the North-South (N-S) and East-West (E-W) components.

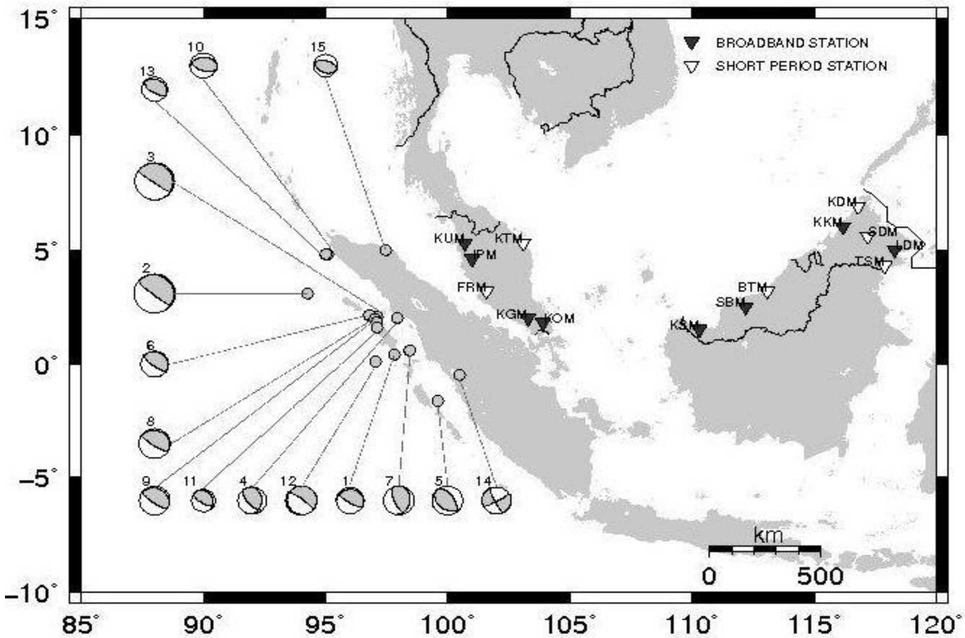

Figure 1 : Strong motion network across Malaysia (as in 2007) which recorded 15 earthquake events selected for the study. The epicenters of earthquakes under study are shown as grey circles while their focal mechanisms are displayed as black and white “beach ball” symbols.

From 150 available ground motion records, 46 data were selected for analysis of PGA, whereas only 44 records can be incorporated for the analysis of PGV. This is because waveforms with background noises have been excluded and only records, which are applicable to support distance range recommended by selected attenuation relationships, have been accounted for. Furthermore, insignificant waveforms, which exist within the available dataset, have been removed by applying resolution values for PGA and PGV.

Between May 2004 and July 2007, 15 interplate earthquake events of magnitude $M_w \geq 5.0$ and shallow hypocentral depth, $h_{hypo} \leq 40$ km were recorded. Out of these 15 events, three were shallow strike-slip events, which occurred along the Sumatran fault, while the remaining 12 events occurred within the subduction zone. The hypocenters of all 15 events were adopted from the National Earthquake Information Center (NEIC) of the United States Geological Survey (USGS) and the MMD. Figure 1 illustrates epicenters of the 15 earthquake events chosen for this study and their profiles are briefly summarized in Table 1. Data distribution with respect to earthquake magnitudes and source-to-site distances is demonstrated in Figure 2, which clearly shows that distant ground motions recorded in Malaysia have distances ranging from 450 to 2300 km.

Table 1: Profile of 15 earthquake events recorded between May 2004 and July 2007.

Ref. Number	Date	M_w	Latitude (°)	Longitude (°)	Source Depth (km)	Number of Recordings
1	2004/05/11	6.1	0.415	97.8	21	4
2	2004/12/26	9.0	3.295	95.982	30	9
3	2005/03/28	8.6	2.085	97.108	30	8
4	2005/04/03	6.3	2.022	97.942	36	3
5	2005/04/10	6.7	-1.644	99.607	19	5
6	2005/04/28	6.2	2.132	96.799	22	1
7	2005/05/14	6.7	0.587	98.457	34	2
8	2005/05/19	6.9	1.989	97.041	30	1
9	2005/07/05	6.7	1.819	97.082	21	2
10	2005/10/11	5.9	4.82	95.098	30	2
11	2006/02/06	5.2	1.607	97.101	26	1
12	2006/05/16	6.8	0.093	97.05	12	2
13	2006/12/17	5.8	4.815	95.018	36	3
14	2007/03/06	6.4	-0.493	100.498	19	2
15	2005/07/21	5.2	5.003	97.456	30	1

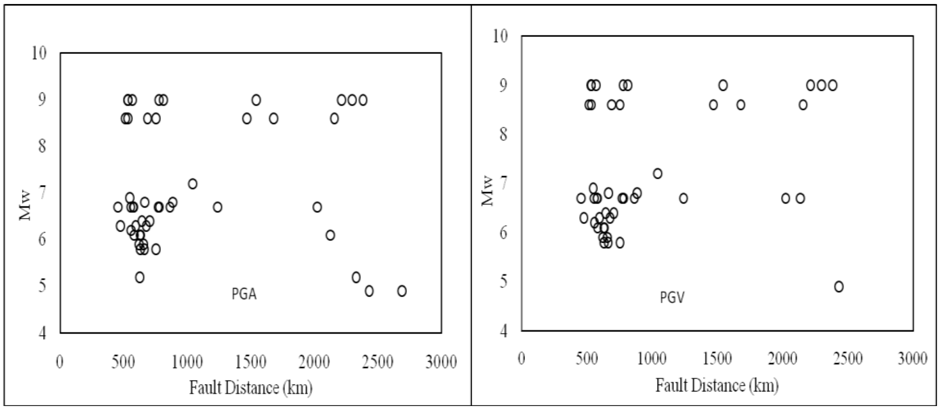

Figure 2 : Distribution of data between May 2004 and July 2007. A total of 46 data was available for PGA analysis, whereas 44 data were incorporated in PGV analysis.

3.0 Attenuation Models

Four established attenuation models have been selected for comparison purposes owing to the fact that none has ever been derived for Malaysia due to lack of data for such a development. These attenuation models are those established by Atkinson and Boore (1995), Toro et al. (1997), Dahle et al. (1990), and Si and Midorikawa (1999). Their selections were based on the types of tectonic environment i.e. for shallow crustal earthquakes and subduction zone; and source-to-site distance.

The Atkinson and Boore (1995) attenuation relationship was developed, using the stochastic method, for tectonically stable, low seismicity regions of Eastern North America (ENA). The model provides expressions to estimate PGA and PGV values and is intended for applications within r_{hypo} of 10 to 500 km, and for M_w ranging from 4.0 to 7.25.

Similarly, Toro et al. (1997) attenuation relationship was derived to estimate strong ground motions in ENA. It only provides expressions to estimate PGA values, which are applicable for M_w between 4.5 and 8.0; and Joyner-Boore distance, r_{jb} of up to 500 km.

Due to the constraints posed by the Atkinson and Boore (1995) and the Toro *et al.* (1997) models, it is obvious that these models are able to represent only four percent of the field data. This is due to the fact that majority of the data for Malaysia were generated by distant earthquakes exceeding 300 km.

An attenuation relationship for stable tectonic region of Europe was established by Dahle *et al.* in 1990. It incorporated worldwide database from 56 intraplate earthquakes in North America, Europe, China and Australia. This model gives expressions to predict PGA values for earthquake magnitudes between 3.0 and 6.9 and is applicable for source-to-site distances of up to 1000 km. Thus, the Dahle et al. (1990) model can represent 71 percent of the observed data.

The attenuation relationship for PGA and PGV, which was derived for Japan by Si and Midorikawa in 1999 treats earthquakes into three styles of faulting, namely crustal, interplate and intraplate. Although the attenuation model suggests a cutoff fault distance, R, of 300 km this model was primarily chosen to compare PGV values against those estimated using the Atkinson and Boore (1995) model. This model was also utilized for comparing recorded PGA with estimated ones. A summary of selected attenuation relationships used in the present study is as listed below, in Table 2.

Table 2 : Summary of four attenuation models selected for the study

Region	Types of Earthquake	M_w	Supporting range (km)	Literature Reference
Stable Continental Region	Shallow crustal earthquake in ENA	4.0-7.25	r_{hypo} 10-500	Atkinson & Boore (1995)
	Shallow crustal earthquake in ENA	4.5-8.0	r_{jb} 1-500	Toro et al. (1997)
Stable tectonic region of Europe	Intraplate worldwide	3.0 –6.9	r_{hypo} 6-1000	Dahle et al. (1990)
Active Tectonic Region of Japan	Crustal, intraplate and interplate	5.8 -8.2	R 0-300	Si & Midorikawa(1999)

4.0 Methodology

The first step in analysis is to determine recorded values of PGA and PGV from 150 available accelerograms. For this purpose, horizontal components of ground motions were processed with a band-pass filter between 0.1 and 50 Hz for PGA while PGV values were obtained by integrating the accelerograms. At this stage, waveforms for all accelerograms were plotted and insignificant ones were excluded by introducing appropriate resolution values for both PGA and PGV, these being 0.2 gal for PGA and 0.05 cm/s for PGV.

What follows next is the determination of estimated PGA and PGV values using expressions given by each attenuation model. However, prior to calculating estimated PGA and PGV values, estimates of source-to-site distances such as r_{hypo}, r_{jb}, and R were calculated. The term r_{hypo} is commonly used in both the Atkinson and Boore (1995) and the Dahle *et al*. (1990) models; r_{jb} in the Toro *et al*. (1997) model; and R is the term used in the Si and Midorikawa (1999) model. Values of r_{hypo} and r_{jb} were reasonably easy to estimate by using established expressions (Campbell, 2002). However, those of R were derived by considering the source rupture model of the M_w 9.0 earthquake, which occurred on December 26, 2004, by adopting the procedures laid out by Megawati and Pan (2009). Reference to Megawati and Pan (2009) facilitates us to assume a rupture plane located between 2.1ºN and 6.1ºN. The rupture model measuring 410 x 170 km, which has a strike of N329ºE and a dip angle of 8º was further subdivided into 6 x 8 grid system, and R is defined as the closest distance from the station or site to the rupture plane. The present study accounts for PGA and

PGV values calculated for rock site conditions as all seismic stations in Malaysia are sited on rock areas.

The correlation between recorded and estimated PGA values is presented using four attenuation models, namely the Atkinson and Boore (1995), the Toro *et al.* (1997), the Dahle *et al.* (1990), and the Si and Midorikawa (1999) models; whereas comparison between recorded and estimated PGV values is examined using the Atkinson and Boore (1995), and the Si and Midorikawa (1999) models.

A good estimation of PGA and PGV values, by the attenuation models, can be concluded if the observed values fall within the prediction ranges i.e. the attenuation curves. Further verification as to whether a good agreement exists between observed and estimated values can be confirmed if both observed and estimated values fall on or very close to the straight line making a 45-degree angle with the axes of the plot.

5.0 Results And Discussion

Following seismic analysis on a selection of 15 earthquake events from May 2004 and July 2007, it was revealed that minimum value of PGA is approximately 0.3 gal corresponding to the March 6, 2007 M_w 6.4 earthquake, recorded in the E-W direction at station KUM. Minimum PGV value of 0.05 cm/s was recorded by the October 11, 2005 M_w 5.9 earthquake in the E-W direction at station IPM, 656 km from the epicenter. Maximum PGA and PGV values are 20 gal and 15 cm/s respectively, corresponding to the March 28, 2005 M_w 8.6 earthquake recorded in the N-S direction at FRM station near Kuala Lumpur, located approximately 515 km away from the fault plane. Comparisons between recorded and estimated PGA and PGV values are presented in Figures 3 through 10.

5.1 Peak Ground Acceleration

Figure 3 shows the plots of observed PGA values on the Atkinson and Boore (1995) attenuation curves for magnitudes M_w 6.3 and 6.7. It can be observed that the Atkinson and Boore (1995) attenuation model estimated the data well for both earthquakes since observed data fall within the prediction range. Similarly, Figure 4 indicates that the Toro *et al*. (1997) model predicted earthquakes M_w 6.3 and 6.7 well as observed PGA values fall near the attenuation curves. The same trend can be seen in Figure 5 whereby most of the observed PGA values lie on or clustered around the Dahle *et al.* (1990) attenuation curves for earthquakes M_w 6.1, 6.7, 8.6 and 9.0. Observation on Figure 6 indicates that the Si and

Midorikawa (1999) model estimated PGA values fairly well, within the first order, for earthquake magnitudes M_w 5.9, 6.1, 6.7, 8.6 and 9.0, up to a distance of 700km.

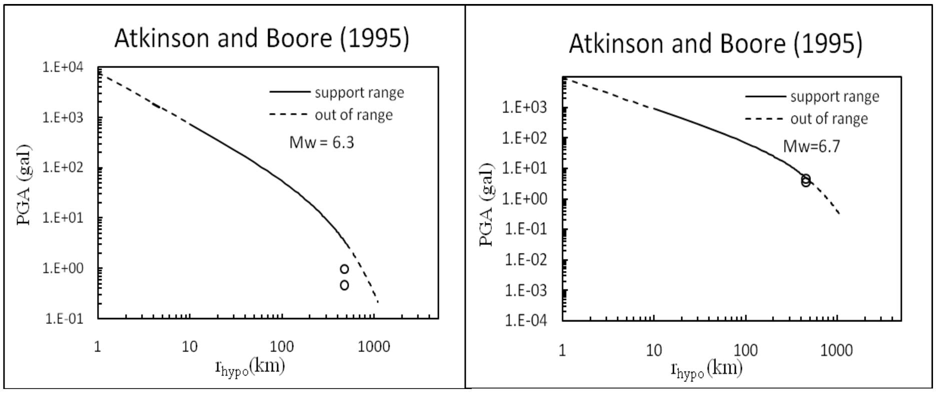

Figure 3 : Comparison of recorded PGA with estimated PGA using the Atkinson and Boore (1995) model, for M_w 6.3 and 6.7.

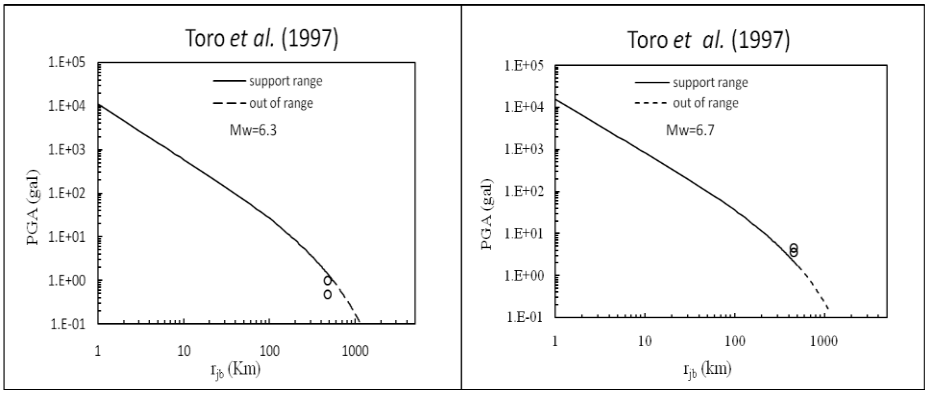

Figure 4 : Comparison of recorded PGA with estimated PGA using the Toro *et al.* (1997) model for M_w 6.3 and 6.7.

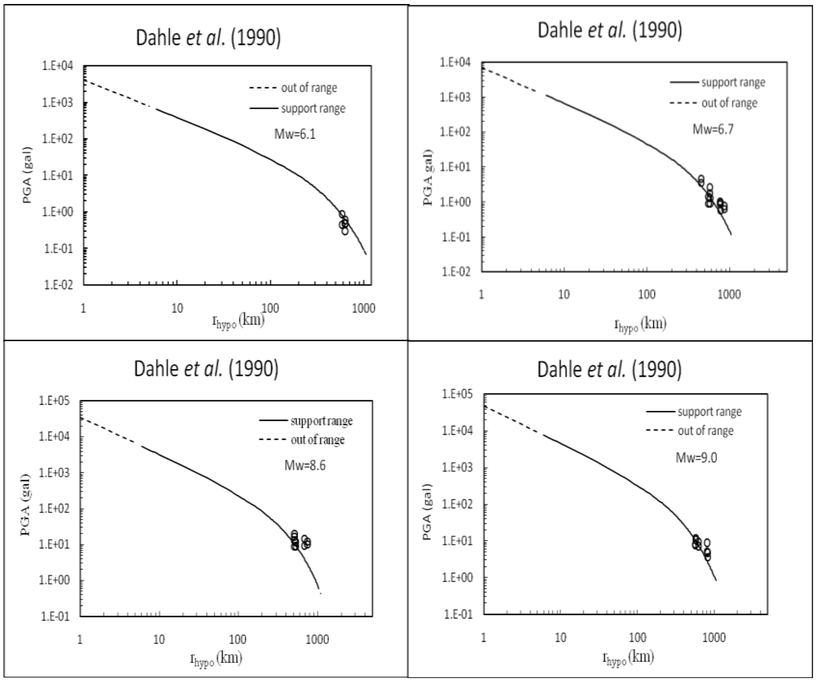

Figure 5 : Comparison of recorded PGA with estimated PGA using the Dahle et al. (1990) model for M_w between 6.1 and 9.0

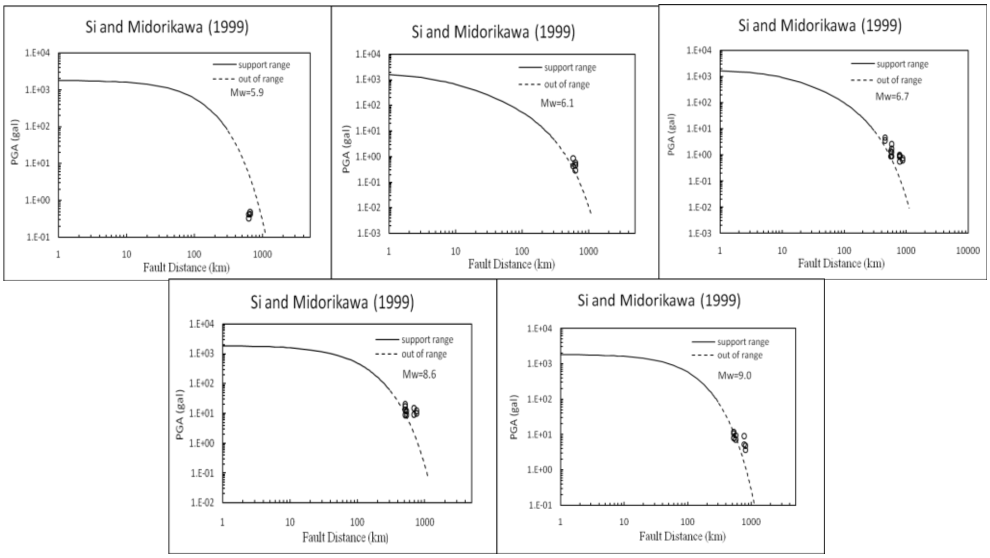

Figure 6 : Comparison of recorded PGA with estimated PGA using Si and Midorikawa (1999) model for M_w between 5.9 and 9.0

As suggested by Figures 3 through 6, selected attenuation models provide reasonably good estimates of PGA values for distant ground motions originated in Sumatra. The analysis has shown that recorded data for earthquakes M_w between 5.9 and 9.0 seem to agree well with the values predicted using the Atkinson and Boore (1995), the Toro et al. (1997) and the Dahle et al. (1990) models, with Dahle et al. (1990) model being the most accurate. This is further supported by the results shown in Figure 7 whereby data points of both recorded and estimated PGA values fall on or close to the 45-degree line through the axes.

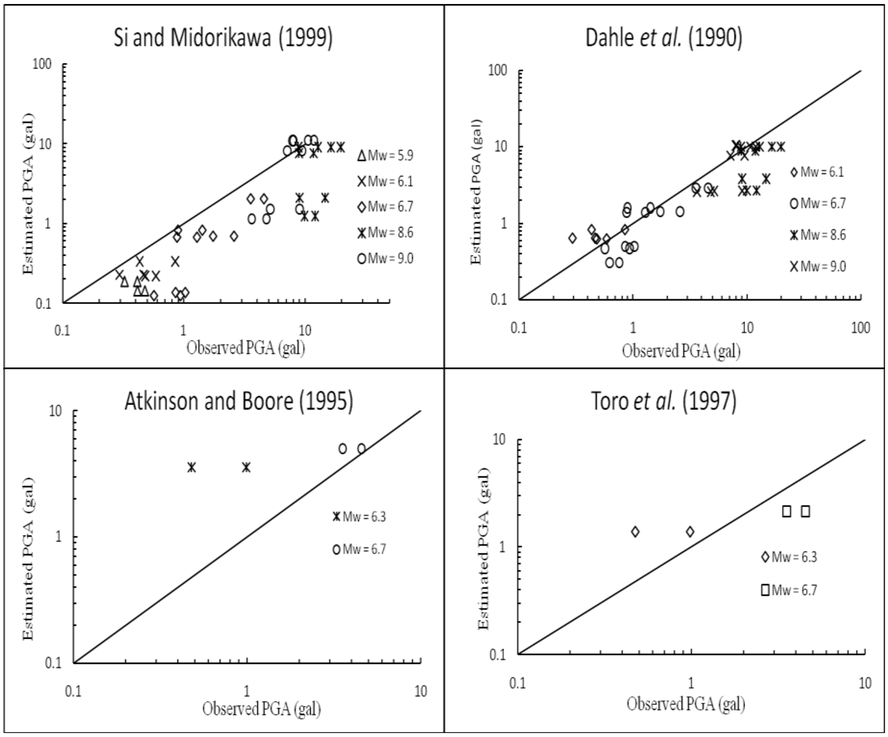

Figure 7 : Comparison between estimated and observed PGA values.

Si and Midorikawa (1999) model, on the other hand, only gave good PGA predictions for earthquake magnitudes Mw 5.9, 6.1, 6.7, 8.6 and 9.0, for distances up to 700km. A possible explanation for this is that Si and Midorikawa (1999) model was developed to predict ground motions for source-to-site distances up to 300km and as such is out of range for estimating ground motions resulting from the Sumatran earthquakes.

5.2 Peak Ground Velocity

Comparisons of recorded PGV with those estimated using the Atkinson and Boore (1995) and the Si and Midorikawa (1999) attenuation models are demonstrated in Figures 8 and 9 respectively. Results of comparison using the Atkinson and Boore (1995) model in Figure 8 show that the model predicted the Sumatran earthquakes well since recorded values fall very close or on the attenuation curves for both M_w 6.3 and 6.7 earthquakes.

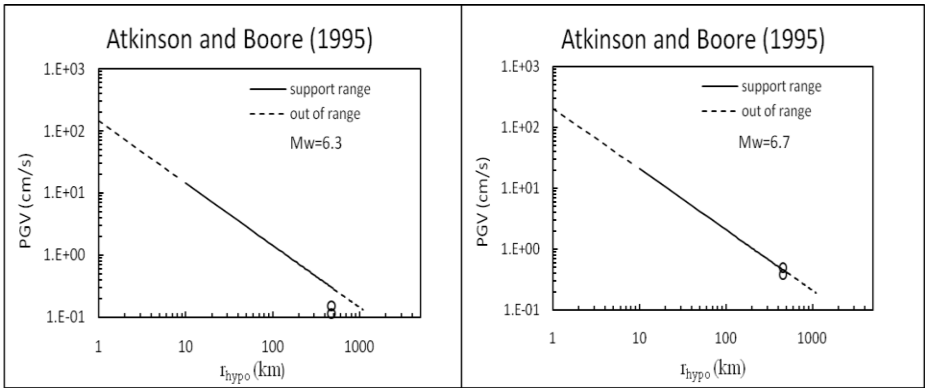

Figure 8 : Comparison of recorded PGV with estimated PGV using the Atkinson and Boore (1995) model for M_w 6.3 and 6.7

Comparison using Si and Midorikawa (1999) model as shown in Figure 9 illustrated that the model underestimated PGV values for all earthquake magnitudes under study. Again, as have been discussed earlier in section 5.1, a possible explanation for this is that ground motions recorded in strong motion stations in Malaysia have source-to-site distances beyond 300 km and are therefore out of range for this model. The Si and Midorikawa (1999) model was developed using near-field strong ground motions of the seismically active region of Japan and therefore is not appropriate to represent distant ground motions of Sumatra.

Figure 10 further supports the suggestion that Si and Midorikawa (1999) model underestimated PGV values for distant earthquakes of Sumatra. Comparison between observed and estimated PGV values using Atkinson and Boore (1995) attenuation relationship, on the other hand, suggested that it predicted PGV values well for earthquakes of magnitudes Mw 6.3 and 6.7.

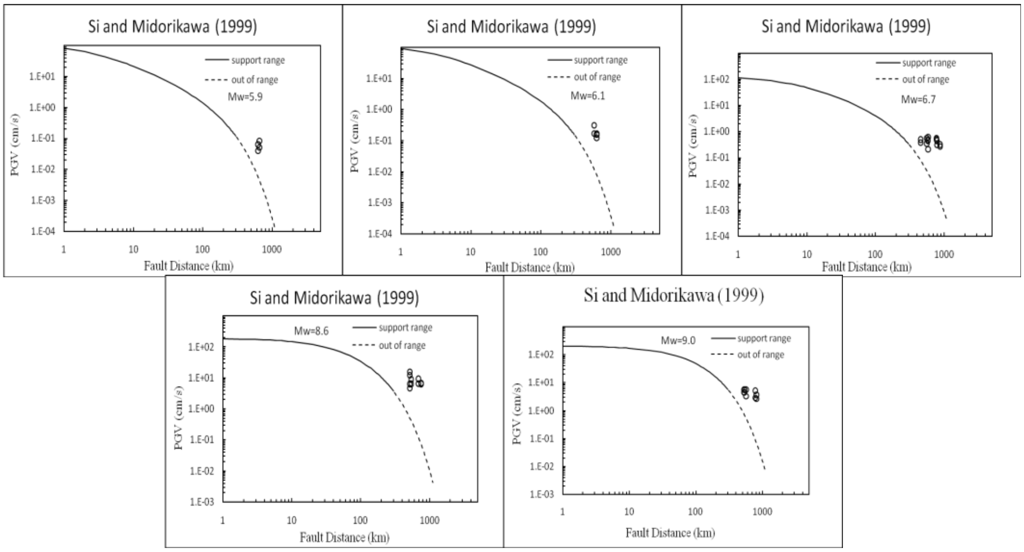

Figure 9 : Comparison of recorded PGV with estimated PGV using the Si and Midorikawa (1999) model for M_w between 5.9 and 9.0

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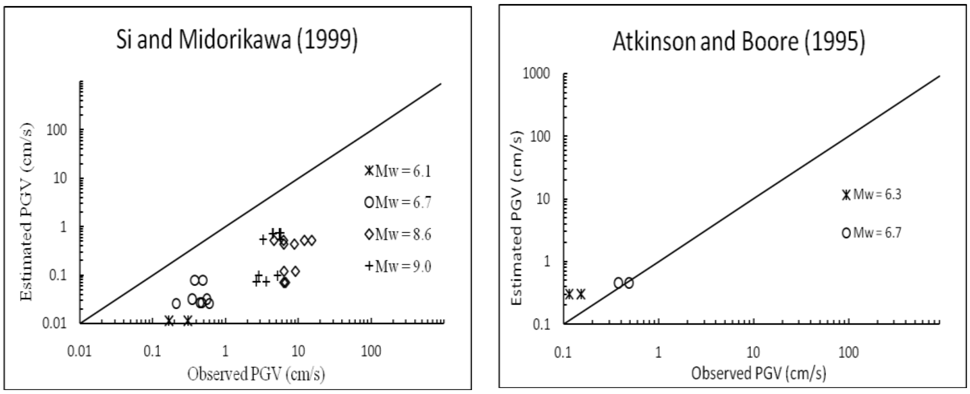

Figure 10 : Comparison between estimated and observed PGV values

6.0 Conclusion

Understanding the attenuation characteristics of ground motions is essential for application in seismic hazard assessment or the development of seismic design motion. For this purpose, PGA has been widely used in studying the characteristics of any strong ground motion, whereas PGV has found its application in understanding characteristics of distant ground motion. For the case of Malaysia, where historical data is scarce and seismic activities are low, a suitable approach utilized to investigate the characteristics of ground motions is by way of comparing recorded with estimated PGA and PGV values.

Results of analysis show that attenuation characteristics of ground motions for Peninsular Malaysia can be appropriately described by attenuation models established for stable tectonic region, used herein. As such, these models may be used to estimate or predict ground motion amplitudes across Peninsular Malaysia, for application in seismic hazard assessment, seismic design or assessment of structures. It can be concluded, from the study, that the Dahle *et al.* (1990) model best represents the attenuation characteristics of ground motion in terms of PGA, while the Atkinson and Boore (1995) model may appropriately estimate ground motion in terms of PGV.

It is also significant to point out that although much emphasis have been given by many literatures to characterize strong ground motions based on peak ground acceleration, peak ground velocity is yet another important parameter to consider in the analysis of strong ground motions.

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References

Atkinson, G.M., and D.M. Boore (1995). New ground motion relations for Eastern North America. *Bulletin of the Seismological Society of America* **85**, 17-30.

Campbell, K.W. (2003). Engineering models of strong ground motion. In *Earthquake Engineering Handbook.* Ed Chen, W.F. and Scawthorn, C., CRC Press, London.

Chandler, A., and N. Lam (2004). An attenuation model for distant earthquakes. *Earthquake Engineering and Structural Dynamics* **33**, 183-210.

Dahle, A., H. Bungum, and L.G. Dvamme (1990). Attenuation models inferred from intraplate earthquake recordings. *Earthquake Engineering and Structural Dynamics* **19**, 1125-1141.

Megawati, K., and T-C. Pan (2009). Regional seismic hazard posed by the Mentawai segment of the Sumatran Megathrust. *Bulletin of the Seismological Society of America* **99**, 566-584.

National Earthquake Information Center Database. USGS. http://neic.usgs.gov/.

Petersen, M.D., J. Dewey, S. Hartzell, C. Mueller, S. Harmsen, A.D. Frankel, and K. Ruskstales (2004). Probabilistic seismic hazard analysis for Sumatra, Indonesia and across the Southern Malaysian Peninsular. *Techtonophysics* **390**, 141-158.

Si, H., and S. Midorikawa (1999). New attenuation relationships for peak ground acceleration and velocity considering effects of fault type and site condition. *Journal of Struct. Constr. Eng.*, AIJ **523**, 63-67.

Toro, G.R., N.A. Abrahamson, and J.F. Schneider (1997). Model of strong ground motions from earthquakes in Central and Eastern North America: Best estimates and uncertainties. *Seismological Research Letters* **68**, 41-57.