京都大学防災研究所年報 第 55 号 B 平成 24 年 6 月
Annuals of Disas. Prev. Res. Inst., Kyoto Univ., No. 55 B, 2012

Proposal for Seismic Resistant Design in Malaysia: Assessment of Possible Ground Motions in Peninsular Malaysia

Sherliza ZAINI SOORIA[(1)], Sumio SAWADA and Hiroyuki GOTO

(1) Department of Urban Management, Kyoto University, Japan

Synopsis

The development of a design motion for seismic resistant design requires ample information on the characteristics of ground motions. This information may be found by analyzing important time-domain parameters, such as the peak ground acceleration (PGA) and peak ground velocity (PGV). However, this is not a straight-forward task for a low seismicity region such as Malaysia because historical data is scarce due to low seismic activities. Thus, alternatively, the characteristics of ground motion at a site may be determined by utilizing established attenuation models. This entails the selection of appropriate attenuation models, which may best represent the seismicity of Malaysia. Another useful method of estimating possible ground motions in Malaysia is by predicting the maximum magnitude earthquakes from available historical data. The maximum magnitude earthquakes can then be used to determine the maximum acceleration and displacement that are expected to occur within inland Malaysia.

Keywords: Low seismicity, Malaysia, seismic resistant design, maximum magnitude earthquake

1. Introduction

Malaysia has been categorized as belonging to the low seismicity group. Consequently, earthquake resistant design has not been given much emphasis until a decade ago when the Malaysian lawmakers (or Members of Parliament) were briefed by the Meteorological Department (MMD), in 2002, on the distant shock waves of the 2001 Gujarat earthquake, which travelled 600 km from its epicenter to rock and cause devastations to many cities in India (Bendick *et al.*, 2001).

Having been affected by both local and distant ground motions, Malaysia has come to realize that seismic hazard in the country is real and has the potential to threaten the public safety and welfare; and may cause damages to properties. Such concern is attributed to the fact that less than one percent of buildings in Malaysia are seismic resistant (Taksiah Abdul Majid, 2009).

Since 2005 the government of Malaysia has taken various efforts, through the Ministry of Science, Technology and Innovation (MOSTI), to assess and address the risk associated with potential earthquake events. Research on reduction of earthquake risk in Malaysia started immediately, and some important publications are macrozonation contour maps based on peak ground acceleration (PGA) at 10% and 2% probabilities of exceedence in 50 years for bedrock of Malaysia (Adnan *et al.*, 2005); and the assessment on the vulnerability of public buildings (Adnan *et al.*, 2006). The Public Works Department of Malaysia (PWD) has also worked closely with academicians of local universities to establish suitable seismic design forces for use in the design of buildings.

For bridge design, the Bridge section of the Civil, Structural and Bridge Engineering Branch of

PWD has incorporated the seismic design requirement in its Terms of Reference (TOR) for Bridges and Viaduct Structures (PWD, 2006). Until recently, PWD has only requested, in a few occasions, for seismic design of bridges in earthquake prone areas, for instance in the Federal Territory of Kuala Lumpur, Penang Island and Selangor.

Of late, clients or end users of high priority (or security) projects have shown considerable concern of the seismic activities in Malaysia, and have started to request that their buildings should account for seismic forces in the design process. These requests require the input from PWD, and hence, motivate the government to expedite the development of seismic design guidelines in Malaysia.

2. Strategy for Developing Seismic Design Guidelines

Developing a seismic design guideline for a low seismicity region such as Malaysia is not a straight-forward task due to of a lack of ground motion records. This makes it difficult to predict maximum expected ground motions appropriate for seismic design, and as such, it is a challenging mission to establish a ground motion model for formulating an earthquake resistant provision for Malaysia.

This section is dedicated to investigating the characteristics of ground motions in Peninsular Malaysia to estimate a suitable design motion for seismic design of bridges.

2.1 Seismicity of Malaysia

A seismotectonic study conducted by the Minerals and Geoscience Department of Malaysia (MGDM) confirms that Malaysia is tectonically situated within the relatively stable Sundaland. Thus, Malaysia belongs to the low seismicity group, except for the state of Sabah, which shows clear rate of crustal deformation (MGDM, 2006). Sabah owes its moderate seismicity condition to the active Mensaban, and Lobou-Loubo fault zones, which have brought about earthquakes that caused light damages to infrastructures, such as roads.

Most people perceive that Malaysia is free from life-threatening seismic crisis. In reality, seismic hazard in Malaysia is irrefutable, with seismic hazard originating from seismically active neighboring countries such as Indonesia and the Philippines. Distant ground motions have been recorded by the Malaysian network of seismic stations, from two most active plate tectonic margins in the world i.e. the Sumatran subduction zone, and the 1650 km long Sumatran fault; and the Philippines plate alike. In general, the impacts of these distant earthquakes, as reported by the local media, include panick-attack among inhabitants of tall buildings, and felt ground motion in high-rise dwelling and office buildings (Pan and Sun, 1996; Pan, 1997; Pan *et al.,* 2001).

Records of felt earthquakes in Malaysia are available for events that began since 1815; however, they are “scanty and poorly correlated” (MOSTI, 2009). The information obtained from the Malaysian Meteorological Department (MMD) indicated that within a period of more than a century, beginning 1909, Peninsular Malaysia has experienced tremors of maximum intensity equivalent to VI, on the Modified Mercalli Intensity (MMI) scale. Between 1984 and 2007, Peninsular Malaysia recorded 35 distant ground motions, which resulted from seismic events in Sumatera. In addition, it has also recorded 32 weak earthquakes, of local origin, of magnitudes ranging from 0.3 to 4.2 M_b (Chai *et al.*, 2011). These weak earthquakes occurred between November 2007 and December 2009 in the Bukit Tinggi area, which is approximately 50 km from Kuala Lumpur. Mustaffa Kamal Shuib (2009) suggests that the earthquake occurrences in the Bukit Tinggi area were the result of “fault reactivation due to stress buildup as a result of the present-day tectonics in the Sundaland”. He further discussed that the weak earthquakes detected at the Bukit Tinggi area indicate that, following the December 26, 2004 Sumatera earthquake, the Sundaland core is deforming.

While Peninsular Malaysia has only experienced weak local earthquakes and been jolted by distant earthquakes from Sumatera, East Malaysia has recorded moderate scale tremors of magnitudes between 3.6 and 6.5 between 1984 and 2007. Since 1897, the state of Sabah has recorded the highest number of ground motions in the country i.e. 77 earthquake events, most of which are of local origin, believed to be contributed by several active faults. The maximum intensity reported was VII on the MMI scale. It is worth noting that an earthquake of scale VII can cause human injuries and property damages. Records of felt earthquake in the state of Sarawak may be traced back from 1874 and until recently, 21 events with magnitude between 3.5 and 5.8 have been observed. Table 1 shows the list of felt earthquakes in Malaysia, and their frequency of occurrences by state, recorded during the period of observation between 1874 and 2010. It is noteworthy that earthquakes from the Philippines and Indonesia have also affected East Malaysia.

Table 1 Frequency and intensity of felt earthquakes recorded from 1874 to 2010

State	Frequency of Occurrence	Maximum Intensity (MMI)
Peninsular Malaysia (1909 – July 2010)		
Perlis	3	V
Kedah	18	V
Penang	41	VI
Perak	24	VI
Selangor	50	VI
Negeri Sembilan	14	V
Malacca	19	V
Johor	32	VI
Pahang	35	III
Terengganu	2	IV
Kelantan	3	IV
Kuala Lumpur/Putrajaya	38	VI
East Malaysia		
Sabah (1897- July 2010)	40 (77)*	VII
Sarawak (1874 – July 2010)	17 (21)**	VI

*Frequency of occurrence recorded as 40 by MMD, but reported as 77 by MOSTI (2009)

**Frequency of occurrence recorded as 17 by MMD, but reported as 21 by MOSTI (2009)

The seismic activities, within Malaysia and around its region for the past 35 years, recorded between 1973 and 2008 are as illustrated in Figure 1. The epicenters of the Bukit Tinggi earthquakes are as depicted in Figure 2. A magnified pictorial of the seismicity of Sabah is as shown in Figure 3. A study conducted by the Minerals and Geoscience Department of Malaysia (MGDM) has confirmed the presence of the Mensaban and Loubo-Loubo active faults, in the Ranau-Kinabalu area, which have contributed to the non-structural damages in the Kundasang High School and the teacher's quarters. Some of these damages are as captured and shown in Figure 4.

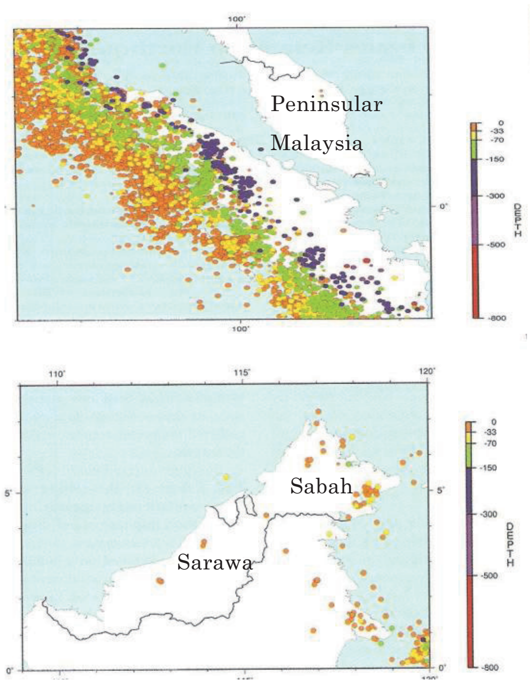

Figure 1 Records of earthquake epicenter in Malaysia and neighboring countries between 1973 and 2008 (adopted from USGS website)

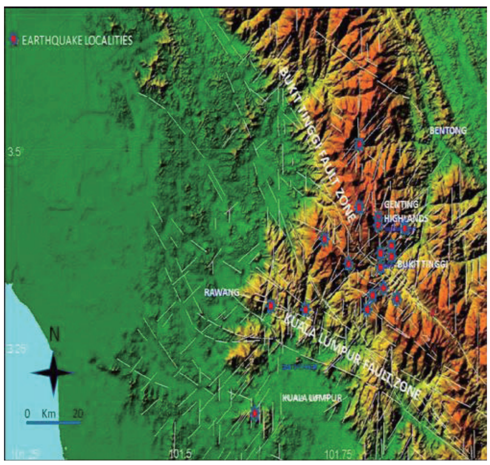

Figure 2 Epicenters of the Bukit Tinggi earthquakes, recorded between 2007 and 2008 (Mustaffa Kamal Shuib, 2009)

Thus, alternatively, the characteristics of ground motion at a site may be determined by utilizing established attenuation models. This entails the selection of appropriate attenuation models, which may best represent the seismicity of Malaysia. Section 3 shall discuss the process of selecting attenuation model(s) for Malaysia.

Another useful method of assessing possible ground motions in Malaysia is by predicting the maximum magnitude earthquakes from historical data. The maximum magnitude earthquakes can then be used to determine the maximum acceleration and displacement that are expected to occur within inland Malaysia.

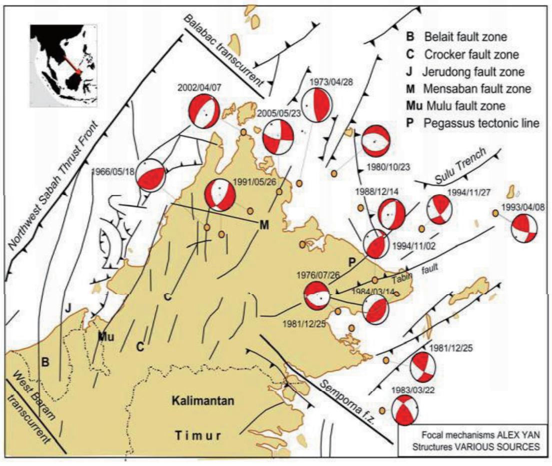

Figure 3 Focal mechanisms of earthquakes in Sabah for the period of 1976 to 2006 (MOSTI, 2009)

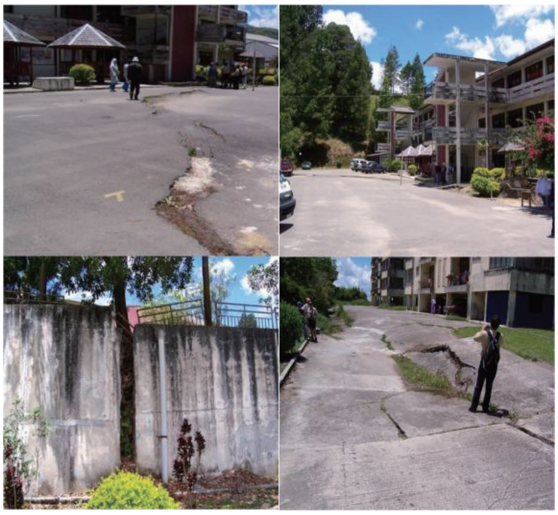

Figure 4 Non-structural damages captured at the Kundasang High School, attributed by the Mensaban and Loubo-Loubo active faults (MOSTI, 2009)

2.2 Assessment of Possible Ground Motions in Peninsular Malaysia

The development of a design motion for seismic resistant design requires ample information on the characteristics of ground motions. This information may be found by analyzing important time-domain parameters, such as the peak ground acceleration (PGA) and peak ground velocity (PGV). However, this is not a straight-forward task for a low seismicity region such as Malaysia because historical data is scarce due to low seismic activities.

3. Selection of Attenuation Models for Earthquakes

In determining the characteristics of ground motions, PGA has become the most widely used parameter, simply because strong motion seismometers record acceleration time-histories. Hence, PGA values can be instantly read off the accelerograms. In addition to using PGA, Chandler and Lam (2004) suggest 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 using PGV. Thus, the selection of attenuation model for Malaysia depends on input parameters such as PGA and PGV derived from locally recorded accelerograms, distance, and magnitude. It is important to mention that the context of discussion within this paper is restricted to PGA and PGV values in reference to rock site conditions.

3.1 Dataset for Study

The Malaysian Meteorological Department (MMD) keeps records of earthquake event dated from more than a century ago. However, compilation of digital ground motion records has only started since 2004. Between May 2004 and July 2007, seismic stations in Malaysia recorded a number of 171 acceleration time-histories, triggered by 15 interplate earthquake events of magnitude $M_w \geq 5.0$ and hypocentral depth of $h_{hypo} \leq 40$ km. Figure 5 illustrates the epicenters of the 15 earthquake events chosen for this study, and their profiles are briefly summarized in Table 2. Data distribution with respect to earthquake magnitudes and source-to-site distances is as demonstrated in Figure 6. It clearly shows that distant ground motions recorded in Malaysia have distances ranging from 450 to 2300 km.

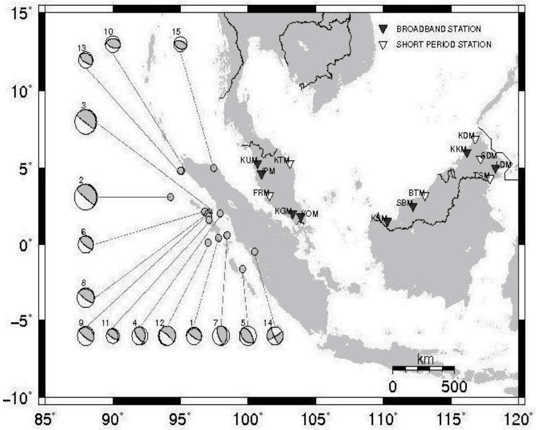

Figure 5 Seismic station network across Malaysia (as in 2007), which recorded 15 earthquake events selected for the study. Epicenters of earthquakes are shown as grey circles, while their focal mechanisms are displayed as black and white “beach ball” symbols.

Table 2 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

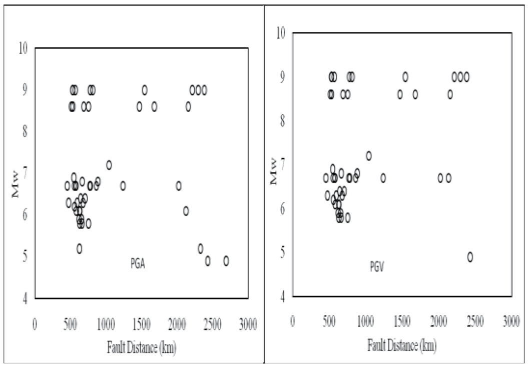

Figure 6 Distribution of data between May 2004 and July 2007. A total of 46 data was available for PGA analysis, whereas 44 data were incorporated in PGV analysis.

The available records were then reduced to 46 accelerograms due to the constraints posed by all four attenuation relationships selected for study.

In this study, only horizontal components of the 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.

3.2 Selection of Attenuation Models

The selection of attenuation model(s), which best describes the seismicity of Malaysia, involves making the comparison between estimated PGA and PGV values with those recorded by the seismic stations. Estimated PGA and PGV values are obtained from attenuation functions, which are presented in an attenuation model. For this purpose, four existing attenuation models have been selected: the 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. The attenuation function is represented by the following expression:

$$\ln Y = f_1 (M_w, r_{hypo}) + f_2 (S) \quad (1)$$

where Y is the horizontal component of PGA or PGV, and

$$f_1 (M_w, r_{hypo}) = c_1 + c_2 (M_w - 6) + c_3 (M_w - 6)^2 - \ln r_{hypo} + c_4 r_{hypo} \quad (2)$$

$$f_2 (S) = c_5 S_{Deep} \quad (3)$$

The values of regression coefficients $c_1, c_2, c_3, c_4, c_5,$ and S_{Deep} are presented in Atkinson and Boore (1995).

Similarly, the Toro *et al.* (1997) attenuation relationship was derived to estimate strong ground motions for 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. The representation of the model is as shown below:

$$\ln Y = c_1 + c_2 (M - 6) + c_3 (M - 6)^2 - c_4 \ln R + c_5 f(R) + c_6 R \quad (4)$$

where Y is the horizontal component of PGA, M = M_w or m_{Lg}, and

$$f(R) = \begin{cases} 0 \text{ for } R \leq 100 \text{ km} \\ \ln (R/100) \text{ for } R > 100 \text{ km} \end{cases} \quad (5)$$

$$R = \sqrt{(r^2_{jb} + c^2_7)} \quad (6)$$

Regression coefficients $c_1, c_2, c_3, c_4, c_5, c_6$, and c_7 are as tabulated in Toro *et al.* (1997).

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 used in this study are distant ground motions with epicenters exceeding 300 km.

Dahle *et al.* established an attenuation model in 1990 for the stable tectonic region of Europe. 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. Estimates of ground motion by this model are represented by the following expression:

$$\ln Y = c_1 + c_2 M_s + \ln R + c_3 r_{hypo} \quad (7)$$

where Y is the largest component of PGA, M_s is earthquake magnitude, and

$$R = \begin{cases} 1/r_{hypo} \text{ for } r_{hypo} \leq 100 \text{ km} \\ (1/100)(100/ r_{hypo}) \text{ for } r_{hypo} > 100 \text{ km} \end{cases} \quad (8)$$

c_1, c_2, and c_3 are regression coefficients listed in Dahle *et al.* (1990).

Si and Midorikawa (1999) derived the attenuation relationship for Japan to predict PGA and PGV values. They treat earthquakes into three types of faulting: crustal, interplate, and intraplate. Attenuation expressions for Si and Midorikawa (1999) model are presented as follows:

$$\text{Log } A = b - \log (X + c) - k X \quad (9)$$

where A is maximum amplitude of PGA (cm/s^2), and PGV (cm/s), and M_w is earthquake magnitude.

$$b = a M_w + h D + \sum d_i S_i + e + \varepsilon \quad (10)$$

$$c = 0.0055 \times 10^{0.50M_w} \text{ for PGA} \quad (11)$$

$$c = 0.0028 \times 10^{0.50M_w} \text{ for PGV} \quad (12)$$

Some of the parameters used in the model are:

D= hypocentral depth (km)
X = shortest distance from hypocenter (km)
S_i = fault type
a, b, c, e, h, and k are regression coefficients

Si and Midorikawa (1999) suggested application of their model with a cutoff fault distance R of 300 km. Although, it is clear that ground motion records for Malaysia represent fault distances larger than 300 km, this model has been included in the analysis mainly to avoid deducing a 'biased' conclusion on PGV characteristics. This is because the comparison for PGV values is provided only by the Atkinson and Boore (1995) model.

The Si and Midorikawa (1999) model was also utilized to compare estimated PGA values with recorded ones. Table 3 lists important ground motion parameters of the selected attenuation models used in the present study.

Table 3 Summary of four attenuation models selected for 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)

3.3 Methodology

The first step in analysis is to determine PGA and PGV values of the 171 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. PGV values were obtained by integrating the accelerograms. At this stage, waveforms for all accelerograms were plotted, and insignificant ones were identified and excluded by introducing resolution values: 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 these values, estimates of source-to-site distances, such as r_{hypo}, r_{jb}, and R were calculated. r_{hypo} is a term commonly used in both the Dahle *et al*. (1990), and Atkinson and Boore (1995) models. Toro *et al*. (1997) used r_{jb} in their model; while Si and Midorikawa (1999) used the term R to define source-to-site distance. The value of r_{hypo} is reasonably easy to estimate by using the familiar expression:

$$r_{hypo} = \sqrt{(r^2_{epi} + h^2_{hypo})} \quad (13)$$

where r_{epi} is the epicentral distance. Campbell (2003), however, suggested that r_{hypo} is a poor representation of distance for "earthquakes with large rupture areas". The distance measure r_{jb} i.e. the closest horizontal distance to the vertical projection of the rupture plane was introduced by Joyner and Boore (1981). Figure 7 shows the various distance measures, which are widely used in characterizing ground motions: r_{rup} or the closest distance to the rupture plane was introduced by Schnabel and Seed (1973), while r_{seis} or the closest distance to the seismogenic part of the rupture plane was first used by Campbell (1987, 2000b).

The distance R is defined as the closest distance from the station or site to the rupture plane. In this study, the values R were derived by considering the source rupture model of the December 26 2004, M_w 9.0 earthquake, proposed by Megawati and Pan (2009). This rupture model was considered because the M_w9.0 earthquake was the largest earthquake recorded in Sumatera in the modern age of ground motion recording.

Reference to Megawati and Pan (2009) has facilitated us to assume a rupture plane located between 2.1ºN and 6.1ºN. The rupture model measuring 410 x 170 km, has a strike of N329ºE and a dip angle of 8º. The rupture plane was subdivided into 6 x 8 grid system, and the shortest distance from the station to the rupture plane can be determined. The present study accounts for PGA and PGV values calculated for rock site conditions because all seismic stations in Peninsular Malaysia are sited on rock areas.

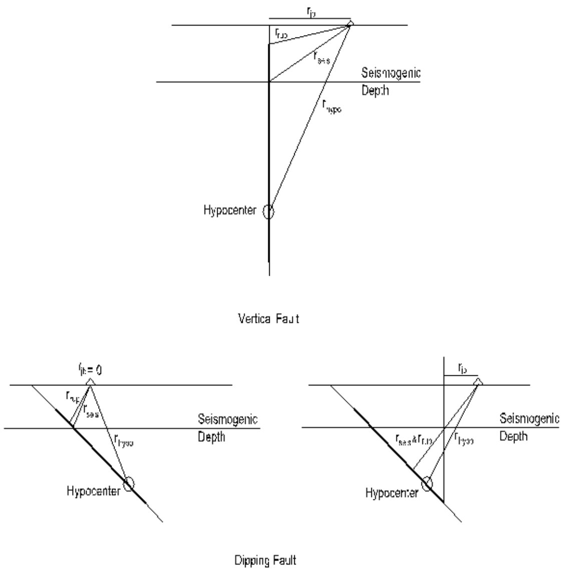

Figure 7 Comparison of distance measures (Abrahamson, N.A. and Shedlock, K.M. 1997. "Overview", Seismol. Res. Lett., 68, 9-23.).

The correlation between recorded and estimated PGA values is presented using all four attenuation models, while comparison of PGV values was examined using the Atkinson and Boore (1995), and the Si and Midorikawa (1999) models.

For analysis purposes, an attenuation model is assumed to give a good estimation of PGA and PGV values, if the observed values fall within the prediction ranges i.e. within the attenuation curve. Further verification of a good agreement between observed and estimated values is confirmed if both the observed and estimated values fall on or very close to the straight line making a 45-degree angle, which run through the axes of the plot.

3.4 Results and Discussion

Following seismic analysis on 15 earthquake events between 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. These correspond 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 as presented in Figures 8 through 15.

3.4.1 Peak Ground Acceleration (PGA)

Figure 8 shows the plots of observed PGA values on the Atkinson and Boore (1995) attenuation curves for magnitudes M_w 6.3 and 6.7. Observation indicates 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 9 indicates that the Toro *et al*. (1997) model predicted earthquakes M_w 6.3 and 6.7 well as observed PGA values fall very close to the attenuation curves. The same trend can be seen in Figure 10, 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 11 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 700 km.

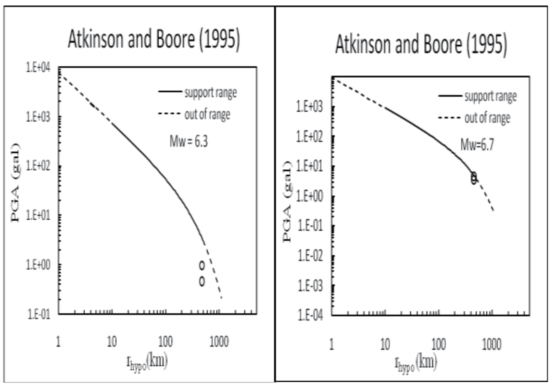

Figure 8 Comparison of recorded PGA with estimated PGA using the Atkinson and Boore (1995) model, for M_w 6.3 and 6.7.

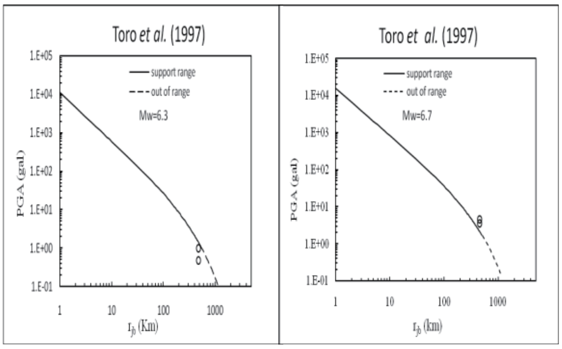

Figure 9 Comparison of recorded PGA with estimated PGA using the Toro *et al.* (1997) model for M_w 6.3 and 6.7.

As suggested by Figures 8 through 11, the selected attenuation models provide relatively good estimates of PGA values for distant ground motions originated in Sumatera. The analysis has shown that recorded PGA values, for earthquake magnitude 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. The results show that the Dahle *et al.* (1990) model estimates PGA values most accurately. Figure 14 shows that the majority of the data points, representing recorded and estimated PGA values, fall on or close to the 45-degree line through the axes. This further confirms that the Dahle *et al.* (1990) model would best represent the attenuation characteristic of ground motions in Peninsular Malaysia.

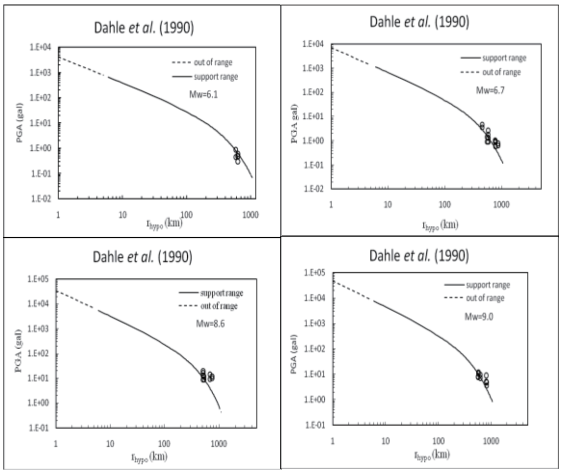

Figure 10 Comparison of recorded PGA with estimated PGA using the Dahle *et al.* (1990) model for M_w between 6.1 and 9.0.

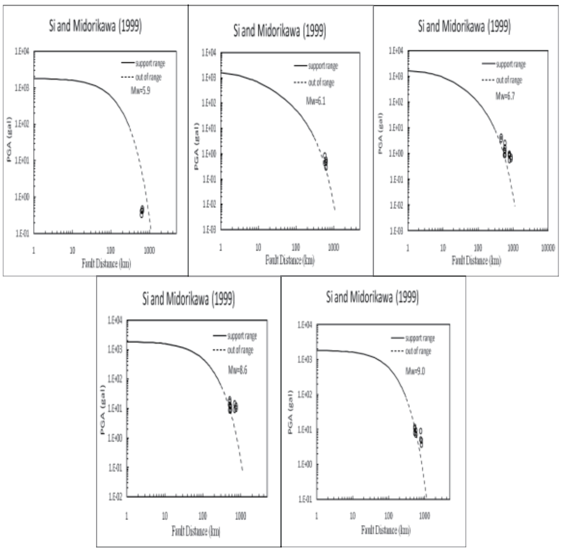

Figure 11 Comparison of recorded PGA with estimated PGA using Si and Midorikawa (1999) model for M_w between 5.9 and 9.0

The 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 700 km. A possible explanation for this is that the Si and Midorikawa (1999) model was developed to predict ground motions for source-to-site distances up to 300 km and as such is out of range for estimating distant ground motions resulting from the Sumatran earthquakes.

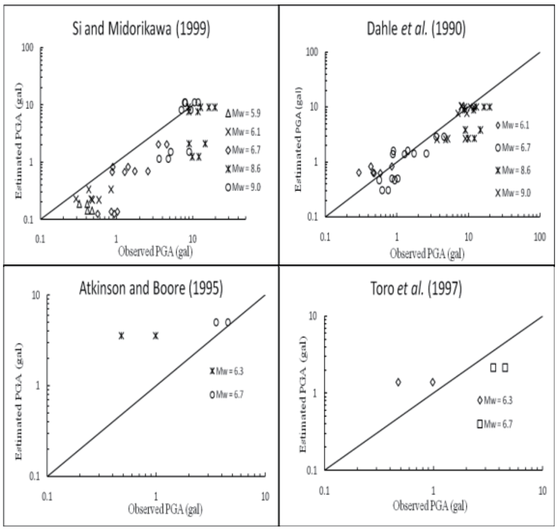

Figure 12 Comparison between estimated and observed PGA values.

3.4.2 Peak Ground Velocity (PGV)

Comparisons of recorded PGV with those estimated using attenuation models of Atkinson and Boore (1995), and Si and Midorikawa (1999) are as demonstrated in Figures 13 and 14, respectively. Results of comparison using the Atkinson and Boore (1995) model in Figure 13 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.

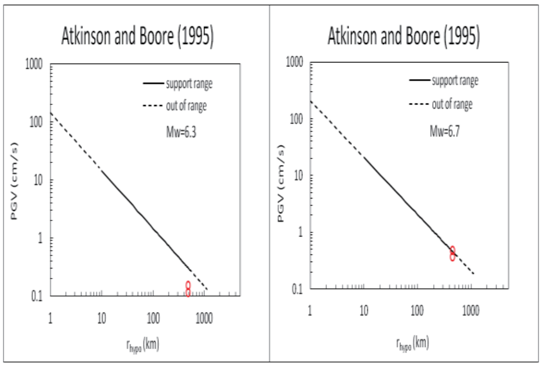

Figure 13 Comparison of recorded PGV with estimated PGV using the Atkinson and Boore (1995) model for M_w 6.3 and 6.7.

Comparison using the Si and Midorikawa (1999) model, as shown in Figure 14, illustrates that the model underestimated PGV values for all earthquake magnitudes under study. Again, as have been discussed earlier in section 3.4.1, a possible explanation for this is that, ground motions recorded by seismic stations in Peninsular Malaysia have source-to-site distances beyond 300 km and therefore, are 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 Sumatera. Figure 15 further supports the deduction whereby the observed and estimated PGV data points lie at the lower portion of the 45-degree line. On the other hand, the comparison of recorded PGV with those estimated using the Atkinson and Boore (1995) attenuation relationship suggested that the Atkinson and Boore (1995) model predicted PGV values well for earthquakes of magnitudes M_w 6.3 and 6.7.

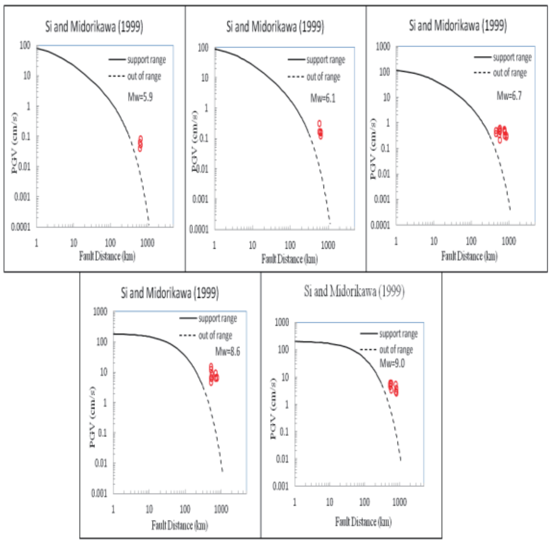

Figure 14 Comparison of recorded PGV with estimated PGV using the Si and Midorikawa (1999) model for Mw between 5.9 and 9.0

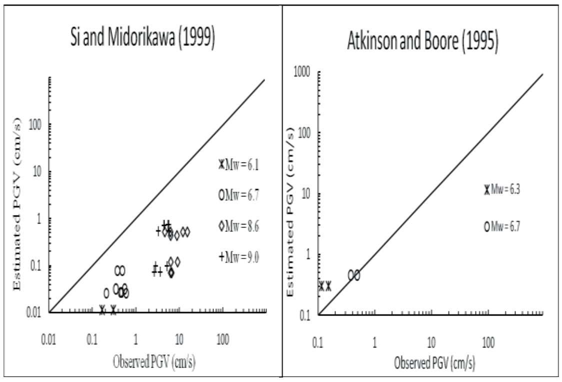

Figure 15 Comparison between estimated and observed PGV values.

4. Maximum Magnitude Earthquake within Inland Malaysia

It is important to assess the maximum magnitude earthquake for a seismic source, as this parameter may dominate the ground motion assessment in low seismicity regions (Bender, 1984). For a country with insufficient historical earthquake data; and a lack of information on geologic structures and recognizable earthquake faults, area sources may be employed to estimate maximum magnitude earthquake. For the case of low seismicity regions, it is assumed that the largest historical earthquake is the minimum value for a maximum earthquake estimate (Tenhaus *et al.*, 2003). This research regards that it is significant to estimate the maximum magnitude earthquake because this value may influence the design earthquake ground motion chosen for an engineering evaluation of structures including bridges.

From section 2.1, it can be identified that the maximum magnitude earthquake observed in Malaysia within a period of 136 years, beginning 1874, is 6.5 M_b, which was recorded in the state of Sabah. At an instance, one may assume a maximum magnitude earthquake as 6.5 M_b, however, to estimate a maximum magnitude earthquake with a return period of 1000 years, it is predicted that larger earthquakes may occur in Malaysia. This is considering the claim of reactivation of the Bukit Tinggi fault due to the occurrences of several earthquakes in Sumatera (Mustaffa Kamal Shuib, 2009). As such, it is assumed that the minimum earthquake magnitude expected in Malaysia is an earthquake, which will result in a surface rupture. Based on the knowledge that an earthquake of magnitude 6.5 and larger is capable of producing surface rupture, it is thus decided that the maximum magnitude earthquake expected for Malaysia shall be 6.5, with a recurrence interval of 1000 years. Note that, as the M6.5 earthquake may be associated with surface rupture, we cannot predict where the earthquake would occur.

It would be interesting to estimate the ground motion at a chosen site, some distance away from a seismic source, for seismic performance assessment. For this purpose, the Samudera Bridge, located 30 km away from the Bukit Tinggi fault, has been chosen for study. The Bukit Tinggi fault is selected on the capacity that it recorded 32 small magnitude earthquakes between November 2007 and December 2009. In section 3.2.4.1, it has been shown that the Dahle *et al.* (1990) attenuation model predicts PGA values in Malaysia most accurately, and thus, the ground acceleration at the Samudera Bridge is estimated using this model. Considering that the Bukit Tinggi fault would generate a 6.5 magnitude earthquake, and assuming a shallow earthquake of 5 km depth, the ground acceleration at the Samudera Bridge, which is sited on rock, is predicted as 135 gal. However, if the earthquake occurs at a nearer location its ground acceleration will be larger.

Another important parameter, which describes the characteristics of possible ground motions, is the peak ground displacement (PGD). This parameter can determine the maximum allowable displacement that a bridge may resist to avoid failure. PGD can be estimated from the peak ground velocity (PGV) attenuation models.

Considering the near fault scenario as described above, the PGV value may be best estimated by using the Si and Midorikawa (1999) model. This model is selected because it accounted for near source data, unlike other attenuation models discussed in this paper, which did not incorporate near source data well.

For these parameters: M=6.5, D=10 km, X=1 km, the PGV value is calculated, using the Si and Midorikawa (1999) model, to be approximately 60 cm/s. PGD can now be estimated as:

$$\omega = 2\pi f \tag{14}$$

where

ω = natural angular frequency (sec^{-1})
f = natural frequency = 1/T (Hz)
T = natural period of structure (sec)

Assume the worst case scenario, whereby the damage anticipated during the 6.5 magnitude earthquake, would occur during the predominant period in the range of 1.5 to 2.0 seconds, as with the case during the 1995 Kobe earthquake. Taking the predominant period as 1.5 seconds will result in ω equivalent to 4.2 sec^{-1}. With PGV of 60 cm/s, and ω = 4.2 sec^{-1}, the peak ground displacement is estimated at approximately 15 cm. Thus, it is safe to deduce that the allowable ultimate displacement for Malaysia is 150 mm.

5. Conclusions

Understanding the attenuation characteristics of ground motions is crucial for optimized seismic hazard assessment or design of seismic resistant structures. For this reason, researchers have heightened their efforts to gather information on earthquake motions over the decades. In earthquake engineering, PGA and PGV are two most important strong motion parameters used in seismic hazard assessment, estimation of acceleration response spectra, and dynamic analysis. PGA has been widely used in studying the characteristics of any strong ground motion, whereas PGV has found its application in estimating possible damage. In addition, PGD is also important to evaluate allowable ultimate displacement to consider non-linear response.

Seismic activities in Malaysia are low, resulting in limited historical data for the development of an attenuation relationship. In addition, developing an attenuation model for Malaysia is a great challenge due to uncertainties in identifying seismic sources within the country. Therefore, an appropriate approach, which can be used to predict the characteristics of ground motions in Malaysia, is by selecting an attenuation model, from a list of established models, which would best describe its seismicity. Section 3.2 has described a methodology for selection of attenuation model(s) for Peninsular Malaysia.

Results of analysis show that attenuation characteristics of ground motions for Peninsular Malaysia can be appropriately represented 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 engineering assessment of structures. In conclusion, 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 for distant earthquakes.

It is also worth noting that estimating a maximum magnitude earthquake within a near inland area is essential to help understand the seismic hazard in a low seismicity region. Engineering evaluation or structural design may refer to this value for future design of both bridges and buildings. In reference to the available historical earthquake data, it is proposed that the maximum magnitude earthquake for Peninsular Malaysia is 6.5. Based on this magnitude, the PGV is estimated at 60 cm/s, and the PGD is calculated as 150 mm.

In summary, it is proposed that the seismic design of structures in Malaysia should account for a maximum magnitude earthquake of 6.5, and that the allowable displacement in structures, due to ground motion, is 150 mm to ensure acceptable performance.

Acknowledgments

The authors are greatly indebted to Mr. Asmadi Abdul Wahab of the Malaysian Meteorological Department for providing data useful for interpretation and analysis of selected ground motions in Malaysia. We are also thankful to the Kyoto University Global Center for Education (GCOE) for giving us the opportunity to enroll in its program and providing us a platform and financial aid to carry out this study.

References

Abrahamson, N.A. and Shedlock, K.M. (1997). Overview*, Seismological. Research. Letters*, 68, pp. 9-23.

Adnan, A., Hendriyawan, A. Marto, and I. Masyhur (2005). Seismic hazard assessment for Peninsular Malaysia using Gumbel Distribution Method. *Jurnal Teknologi* 42(B) Jun 2005: pp. 57-73, Universiti Teknologi Malaysia.

Adnan, A., S. Suradi, P.N Selvanayagam, Z. Darus (2006). Vulnerability of public buildings subjected to earthquake by Finite Element Modelling. *Proceedings of the 6th Asia-Pacific Structural Engineering and Construction Conference (APSEC 2006)*, 5–6 September 2006, Kuala Lumpur, Malaysia.

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

Bender, B. (1984). Incorporating Acceleration Variability into Seismic Hazard Analysis. *Bulletin of the Seismological Society of America* 74, pp. 1451-1462.

Bendick, R., Bilham, Fielding, R. E., Gaur, V., Hough, S.E., Kier, G., Kulkarni, M., Martin, S. and Mukul, M. (2001). The January 26, 2001

Bhuj, India earthquake. *Seismological Research Letters*, 72, 3.

Campbell, K.W. (2003). Engineering models of strong ground motion. In *Earthquake Engineering Handbook.* Chen, W.F. and Scawthorn, C. (Eds), CRC Press, London, chap 5.

Chai, M.F., Zamuna Zainal, D. Ramachandran, Zaty Aktar Mokhtar, Asmadi Abdul Wahab, and Mohd Rosaidi Che Abas (2011). *Study on Hypocenter Relocation of the Local Earthquakes in Malay Peninsular Using the Modified Joint Hypocenter Determination and HYPOCENTER Programs*., Malaysian Meteorological Department, MOSTI, Research Publication 2/2011.

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

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

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

Minerals and Geoscience Department Malaysia (2006). *Study on the seismic and tsunami hazards and risks in Malaysia: Report on the geological and seismotectonic information of Malaysia*, Kuala Lumpur.

Ministry of Science, Technology and Innovation of Malaysia (2009). *Seismic and Tsunami Hazards and Risks Study in Malaysia: Final Report*, prepared by the Academy of Science Malaysia, Kuala Lumpur for the Inter Agency Committee and Tsunami Risk Management, Kuala Lumpur, Malaysia.

Mustaffa Kamal Shuib (2009). The Recent Bukit Tinggi Earthquakes and their Relationship to Major Geological Structures. *Geological Society of Malaysia*, Bulletin 55, Nov. 2009, pp. 67-72.

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

Pan. T.C., and Sun, J. (1996). Historical earthquakes felt in Singapore. *Bulletin of the Seismological Society of America*, Vol. 86, pp. 1173–1178.

Pan, T.C. (1997). Site-dependent building response in Singapore to long-distance Sumatra earthquakes. *Earthquake Spectra*, Vol. 13, pp. 475–488.

Pan, T.C., Megawati, K., Brownjohn, J.M.W. and Lee, C.L. (2001). The Bengkulu, Southern Sumatra, earthquakes of 4 June 2000 (M_w = 7.7) - Another warning to remote metropolitan areas. *Seismological Research Letters*, Vol. 72, pp. 171–185.

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

Public Works Department of Malaysia (2006) (rev. 2008). *Terms of Reference for Bridges and Viaduct Structures*, Public Works Department of Malaysia, Kuala Lumpur.

Schnabel, P.B. and Seed, H.B. (1973). Accelerations in rock for earthquakes in the Western United States. *Bulletin of the Seismological Society of America*, 63, pp. 501-516.

Si, H., and Midorikawa, S. (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, pp. 63-67.

Taksiah Abdul Majid (2009). *Less Than One Per Cent Of Buildings In Malaysia Have Earthquake Preventive Measures*. http://www.bernama.com.my/bernama/v5/newsindex.

Tenhaus, P.C., and Campbell, K.W. (2003). Seismic Hazard Analysis. In *Earthquake Engineering Handbook.* Chen, W.F. and Scawthorn, C. (Eds), CRC Press, London, chap 8.

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

(Received June 8, 2012)

地震活動度を考慮したマレーシアの耐震設計に関する提案

Sherliza ZAINI SOORIA(1)・澤田純男・後藤浩之

(1)京都大学大学院工学研究科都市社会工学専攻

要　旨

耐震設計の高度化をはかるためには，地域の地震動に関する様々な情報が重要である。PGAやPGVのような具体的な観測値が対象地域で十分に得られていれば，統計的に処理をすることでハザードを定量的に的に評価できるが，マレーシアのように地震活動度の低い地域では観測値が不十分なために直接評価することは難しい。そこで、他の地域に対して構築されている距離減衰式のうち，適切なものを選定して援用することを試みる。また，マレーシア全域で過去に発生した最大規模のマグニチュードの地震を想定し，比較的地震活動度の低いマレー半島に対してもこれに対応するPGAやPGDなどを評価するものとする。

キーワード:低地震活動度，マレーシア，耐震設計