Seismic Hazard Modelling for Malaysia

Nelson Lam[1], Hing-Ho Tsang[2], Daniel Looi[3] ,Elisa Lumantarna[1] and John Wilson[2]

[1] *Department of Infrastructure Engineering, The University of Melbourne, Melbourne, Australia.*

[2] *Department of Civil and Construction Engineering, Swinburne University of Technology, Melbourne, Australia.*

[3] *Department of Civil Engineering, The University of Hong Kong, Pokfulam Road, Hong Kong.*

ABSTRACT

Malaysia is to adopt Eurocode 8 (EC8) in the seismic design of building structures. Some members in the authorship of this paper have been researching into the seismic hazard modelling of the region surrounding Malaysia for a long time and have been key contributors to the drafting of the Malaysia National Annex (NA to MS EN1998-1). The draft document has been approved by the Technical Committee who has been granted the charter by the Malaysian government to undertake the task. At the time of writing this paper the draft NA to MS EN1998-1 is undergoing the public ballot process. The purpose of this paper is to explain the principles underlying the derivation of the elastic response spectrum model for all parts of Malaysia: *Peninsular Malaysia*, *Sarawak* and *Sabah*. Topics covered include modelling of distant earthquakes generated from offshore sources and local earthquakes in an intraplate tectonic setting, decisions on zonation, modelling of earthquake recurrences, and ground motion modelling.

Keywords: seismic hazard modelling, intraplate earthquakes, distant earthquakes, Eurocode 8, Malaysia

1. Introduction

The purpose of this paper is to outline and explain the seismic hazard model for different parts of Malaysia which are characterised by very different seismicity conditions. This paper presents arguments surrounding decisions on zonation, earthquake recurrence modelling, ground motion attenuation modelling, and the elastic response spectra as derived from probabilistic seismic hazard analysis (PSHA). The modelling outcomes have been incorporated into the draft National Annex (NA) to *Eurocode 8* (EC8) for Malaysia (MS EN1998-1:2015): *Design of structures for earthquake resistance – Part 1: General rules, seismic actions and rules for buildings*.

Peninsular Malaysia is subject to a combination of earthquake hazards generated from various offshore sources. Most of the seismological studies and hazard modelling undertaken to date have been based on ground motions generated from distant earthquakes because of their high representation in the strong motion database (Balendra *et al.*, 2002; Lam *et al.*, 2009; Megawati & Pan, 2010; Megawati *et al.*, 2005; Pan & Megawati, 2002; Pan *et al.*, 2007; Petersen *et al.*, 2004; Pappin *et al.*, 2011). Whilst potential hazards generated locally can be significant very limited amount of data has been recorded from the monitoring of seismic activities within the peninsula. In view of this unique pattern of combined seismicity a hybrid modelling approach has been adopted to take into account both the distant and local seismic hazards. Thus the seismic hazard model stipulated for the *Peninsular* is a composite model which encapsulates results from PSHA of long distance earthquakes (which characterises the high period behaviour of the response spectrum) and local earthquakes (which characterises the low period behaviour of the response spectrum) based on broad source zone modelling in accordance with global seismicity data. The hybrid approach best capitalises on the benefits of abundant data of distant events, whilst obtaining robust estimates of locally generated hazards based on resourcing global information. Details of modelling of the two types of hazards will be described in separate sections of the paper.

Sarawak is also subject to distant seismic hazard from the *Kelawit* fault and the *Bukit Mersing* fault some 500 kms away from the capital city of *Kuching* but ground motions predicted from these identified fault sources are very mild. Consequently, the response spectrum model for *Sarawak* is essentially based wholly on the considerations of local hazards for the entire period range (covering both low and high period structures). The seismic hazard modelling of the effects of local earthquakes affecting the *Peninsular* and *Sarawak* is undertaken jointly given their similarities in terms of the frequency of earthquake recurrence for these parts of Malaysia.

Sabah is in the proximity of areas of high seismicity, unlike *Sarawak* and *Peninsular Malaysia*. Many fault zones and their focal mechanisms have been identified. These local and regional fault sources include the *Belait* fault zone, *Jerudong* fault zone and *Mulu* fault zone in the south-west near Brunei; the *Crocker* fault zone and *Mensaban* fault zone which lie at the vicinity of *Ranau* and *Kota Kinabalu* in the central-north; the *Labuk bay-Sandakan* basin zone near to *Sandakan*; the *Pegasus* tectonic line near *Lahad Datu*; and the *Semporna* fault in the *Dent-Semporna Peninsula* Zone (JMM & MOSTI, 2009). Thus, the seismic hazard model for *Sabah* in the period range of engineering interests is essentially based on results generated from conventional PSHA of empirical seismicity data based on events occurring within Sabah. However, the higher period part of the response spectrum can be affected by distant offshore sources. References are made to a published *Uniform Hazard Spectrum* (UHS) derived from an earlier studies (Lam *et al.*, 2015b; 2016) but the UHS had to be modified by incorporating the most up-to-date earthquake ground motion attenuation model.

The types of seismic activities characterising the hazards for different parts of Malaysia in the low and high period ranges are summarised in Table 1.

Table 1 Types of seismic activities characterising the hazards for different parts of Malaysia

Part of Malaysia	**Peninsular**	**Sarawak and SW Sabah**	**NE Sabah**
Low period ($T \leq 1.25s$)	wholly controlled by local seismicity	wholly controlled by local seismicity	dominated by local and regional seismicity
High period ($T > 1.25s$)	wholly controlled by distant (offshore) seismicity	wholly controlled by local seismicity	dominated by distant (offshore) seismicity

The seismic actions model to be presented is for ordinary (Type II) buildings which is defined herein as "reference seismic actions", and is based on a notional 475 year return period (RP) being scaled by a factor of 2/3 of the benchmarked 2475 year RP earthquake.

2. Zonation and recurrence modelling of local seismic hazards

2.1 Peninsular, Sarawak and South-western Sabah

This section is concerned with the modelling of the spatial distribution and frequency of occurrences of local earthquakes generated within the low seismicity areas of the *Peninsular*, *Sarawak* and the south-western part of *Sabah* (which does not include the capital city *Kota Kinabalu* nor *Ranau*) and is not to be confused with long distance hazard generated from the island of *Sumatra* or from the subduction fault source off-shore of *Sumatra* which is the subject matter for considerations in a later section of the paper.

A seismic hazard map is to divide a region into zones in order that the spatial distribution of frequency of future earthquake occurrences can be communicated to the designer of future facilities. Such a map is about the predictions of future activities and is not supposed to be a map which merely shows the scientific record of historical activities. Although there are clear differences between these two modelling objectives there is no consensus on how the two types of maps should differ from each other given that what is shown on many seismic hazard maps is mainly reflecting where historical earthquakes have occurred. Hazard maps produced for regions of low seismicity have been recognised to be not robust (Stein *et al.*, 2012).

In the Malaysian context, it has been reviewed from a survey of the literature conducted by the authors that no existing Malaysian seismic hazard maps were able to predict hazards surrounding *Perak* in the northern part of the peninsular where a magnitude 4.1 earthquake occurred in 2013. Prior to the occurrence of this earthquake tremor most of the attention has been drawn to areas surrounding *Bukit Tinggi* where tremors had been recorded. This is one of many examples that local intraplate earthquakes could occur in areas that had no precedents of recognisable earthquake activities. Difficulties with predicting the location of intraplate earthquakes have been recognised by many code drafting bodies in affected countries such as Australia (being wholly away from any tectonic plate boundaries from a long distance).

In Australia, challenges associated with such uncertainties are being attended to through the adoption of a threshold value of Z_{min}=0.08 (where Z is the seismic hazard coefficient and can be interpreted as the notional peak ground acceleration (*PGA*) for design purposes) in order to ensure a minimum level of protection and resilience against earthquake shaking (Wilson *et al*., 2015). A minimum hazard value of 0.08g in Australia is consistent with current hazard specifications in the two largest Australian cities of Sydney and Melbourne (AS1170.4-2007). Neither cities had ever experienced any destructive earthquakes in their respective vicinity in the past and yet the 0.08g threshold has been decided to be necessary for these cities.

In the study for peninsular Malaysia (together with Sarawak and Southwestern Sabah), a broad source zone modelling approach was adopted in order that the recurrence modelling of potentially destructive earthquakes (of magnitude exceeding 5) is predicted directly by the number of M>5 event count (defined herein as N_5). The counting first focused on earthquake events occurring on land in stable continental areas away from the tectonic plate boundaries around the globe. Earthquakes exceeding magnitude 5 were used in the counting process since the records are more complete and the intraplate hazard is contributed mainly by events in the range M5 – M6. For the same reason the event count was based on a period of observation of 50 years. In view of the generally very low rate of occurrence of intraplate earthquakes the number of events counted was normalised to a standard land area of 1,000,000 square kilometres (sq km) which is consistent with conventions adopted by Bird *et al*. (2010) and by Bergman and Solomon (1980). The presented statistics of event counts is not sufficient to indicate an exact global average value. However, it is clear that this global average value is within the range of **5 – 10** M > 5 events occurring in an area of 1,000,000 sq km in the past 50 years, in a 50 year period (Lam *et al.*, 2016). A parameter $\boldsymbol{K_D}$ is introduced herein to represent the rate of recurrence of intraplate events where $\boldsymbol{K_D}$ = **1** refers to five events and $\boldsymbol{K_D}$ = **2** refers to ten events. Amid the uncertainties and lack of adequate local information, it is prudent to err on the safe side. Thus, "**10**" (i.e., $\boldsymbol{K_D}$ = **2**) is a reasonable, and conservative, normalised event count to assume provided that (validated) local data of earthquake occurrence does not infer a higher value.

The rate of seismic activity is conventionally defined using the Gutenberg-Richter magnitude recurrence relationship of the form:

$$\log_{10} \mathrm{N(M)} = a - b\mathrm{M} \quad \text{1a)}$$

$$\text{or } \log_{10} \mathrm{N(M)} = a_5 - b(\mathrm{M} - 5) \quad \text{1b)}$$

where N(M) may be defined as the expected number of earthquakes ≥ M occurring within an area of 1,000,000 km^2 over a 50-year period, and a, a_5 and b are defined as the seismic constants.

For K_D = 1, a_5 = 0.7 or a = 5.2 (being 0.7 + 0.9 x 5) assuming b = 0.9. Similarly, for K_D = 2, a = 5.5. Given these seismological parameters and a suite of representative ground motion prediction equations (GMPEs), PSHA can be undertaken to quantify ground motion intensities in probabilistic terms as described in details in Lam *et al.* (2016) and summarised in the later sections of the paper.

The shortcoming of the broad source zone modelling approach as described is its failure to capture "hot spots" of destructive historical activities. There is the option of superimposing the modelled hazard (for the identified hot spots) on a map showing uniform hazard (that has been derived from the *broad source zone* model) in order that no area is stipulated with a level of hazard which is below a certain hazard threshold. Although this is precisely the concept of "background seismicity" which is already well known the modelling methodology presented herein provides the rationale (and transparency) for quantifying this background hazard level. For the *Peninsula* in particular, and for *Sarawak* and *South-western Sabah,* no such a hot spot which poses a threat to a centre of population has been identified. Consequently, the level of hazard to be stipulated for this part of Malaysia can be based entirely on results derived from the *broad source zone* model.

2.2 Central and Eastern Sabah

The seismicity of Sabah is represented by two zones: (1) a low seismicity zone which is bounded between the border with *Sarawak* and a dividing line located to the south-west of *Kota Kinabalu* (2) the rest of *Sabah* to the northeast of the dividing line (refer Fig. 1 which shows the dividing line). Zone (1) is essentially part of the *Sarawak* zone whereas the level of hazard for zone (2) is to be analysed in accordance with earthquake activities that have been recorded for this part of Sabah. The subject matter of this sub-section is focused upon zone (2) which comprises the eastern and central parts of *Sabah*.

Historical seismic activities in the eastern part of *Sabah* have been attracting much of the attention for the past 30 years. However, similar level of activities (measured in terms of number of *M*>5 events per unit area) have actually been recorded in central *Sabah* (near *Ranau* which is only some 50 km from the capital city of *Kota Kinabalu*). In addition, a major active fault has been identified in the central part of Sabah along with a dense network of fault lines in the south. Although many of the fault lines have been classified as inactive the possibility of a moderate magnitude (*M*>6) earthquake occurring in the area in the future cannot be ruled out.

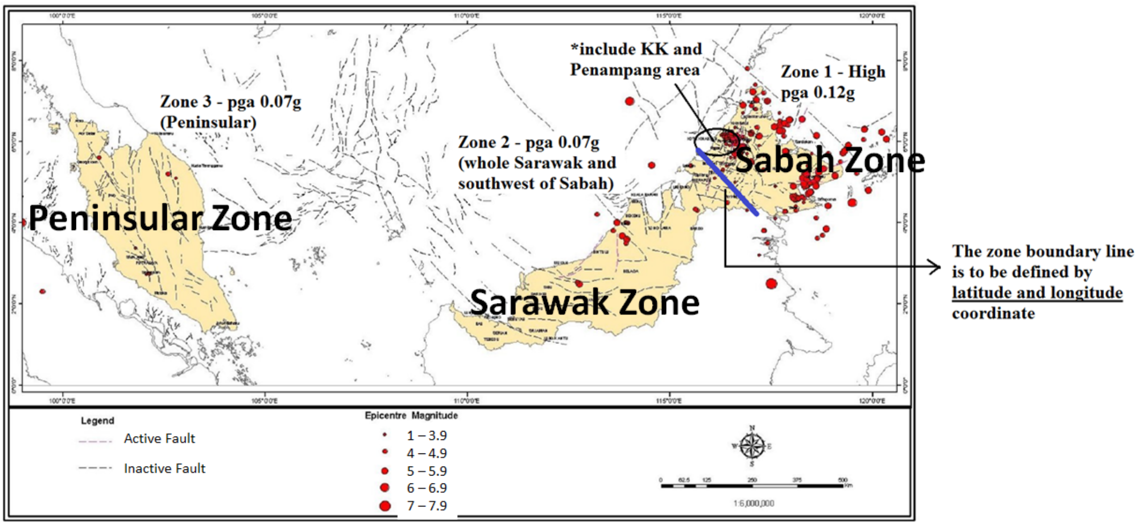


Figure 1 Seismic hazard zonation across the whole of *Malaysia*

The *M*>5 earthquake event count of 4 in the 50 year period over an aggregated land area of 6924 sq.km in *Central Sabah* (Table 2a) is actually consistent with an event count of 5 over an aggregated land area of 8780 sq. km in *Eastern Sabah* (Table 2b) when the number of events has been normalised to the same area of landmass.

In summary, the frequency occurrence of earthquakes in *Central* and *Eastern Sabah* have been shown to be comparable. The statistics presented herein is in support of the rationale of considering the whole of *Central* and *Eastern Sabah* including *Kota Kinabalu* and *Ranau* and the stretch of land between these cities right up to the eastern coast to be of one level of seismic hazard amid lack of data showing the underlying pattern in the spatial distribution of future earthquake activities. The majority of locations in these two parts of Sabah should be classified as areas of moderate seismicity. PSHA for this part of Sabah will be described in details in the next section which shows a reference *PGA* value of 0.12g.

Table 2 Listing of local *M*>5 events in *Central Sabah* and *Eastern Sabah* in the 50 year period 1966 - 2016

Region	Districts	Area (sq. km)	Magnitude of historical earthquakes	Approximate epicentral distance from *Kota Kinabalu* (km)	Year of occurrence
Central Sabah	Kota Kinabalu Ranau Tuaran Kota Belud Total area =	816 3556 1166 1386 6924	M5.3 M5.1 M5.9 M5.3	70 70 60 60	1996 1991 2015 2015
Eastern Sabah	Semporna Lahad Datu Kunak Total area =	1145 6501 1134 8780	M5.0 M6.2 M5.3 M5.6 M5.7	264 270 250 270 300	1976 1976 1976 1984 1994

3. Ground motion modelling of local earthquakes

Once the recurrence behaviour of local earthquakes has been modelled suitable ground motion models have to be selected forming an important part of the PSHA procedure. The great majority of strong motion data which many empirical ground motion prediction equations (GMPEs) are based upon were collected from regions of high seismicity. It is cautioned herein that adapting those GMPEs for use in low-to-moderate seismicity countries like Malaysia must take into account factors controlling the (a) waves generation behaviour at the source of the earthquake in a given tectonic setting and (b) waves modification behaviour of the earth (basement rock) crusts which are not to be confused with the modification behaviour of near-surface sediments. The *Next Generation Attenuation of eastern North American* (*NGA-East*) database comprises 29000 records from 81 earthquake events that were recorded from 1379 stations (PEER 2015/04). This database of earthquakes can be taken to be representative of waves generation behaviour in an intraplate tectonic setting. Ground Motion Models (GMMs) derived from this database is at present the most elaborate database of intraplate. A literature review of seismological studies of ground motion models of *Eastern North America* (ENA) identified some 40 models that were developed in the period 1983-2014. A subset of 22 models were selected based on quality and age of data. Further screening managed to reduce the 22 models into 6 representative models (PEER 2015/04). The acronyms for the six selected published ground motion models (Table 3) are namely: (i) AB95 (ii) SGD02 (iii) A04* (iv) BCA10d (v) BS11 (vi) AB14*.

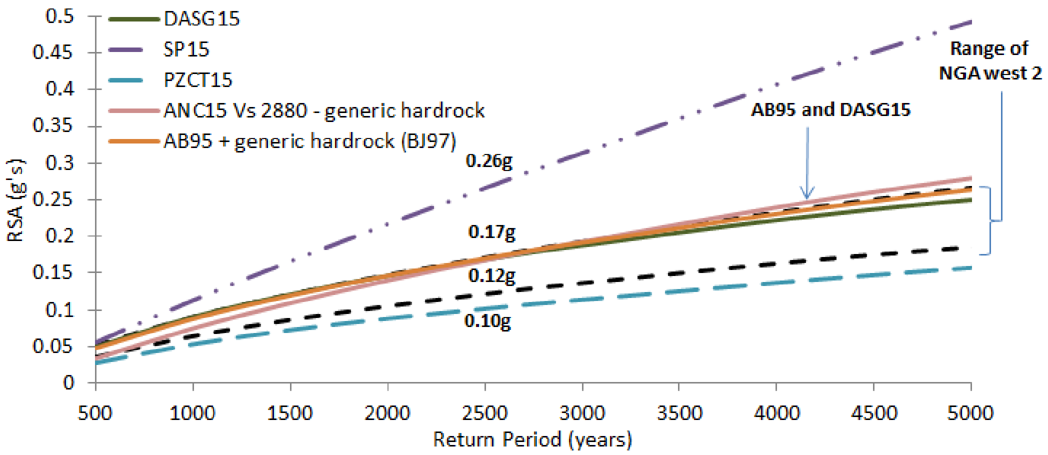
Results of PSHA showing response spectral acceleration (*RSA*) values at 0.3 s and 1.0 s based on a selection of GMMs of *NGA-East* are superposed on the range of predictions based on the GMMs of *NGA-West2* (Figs. 2a – 2b). Clearly, GMMs namely *AB95* and *DASG15* are more robust than the *SP15** and *PZCT15** models in view of inter-model consistencies. An earlier independent review of GMMs developed for use in ENA by Ogweno and Cramer (2014) also ranked *AB95* favourably in view of consistencies between the model predictions and field recordings. Predictions from the *AB95* and the *DASG15* GMMs of *NGA-East* are overall comparable with predictions from the *NGA-West2* and only marginally higher at 0.3s.

The authors had experience of combining the source model of *AB95* with the (non-cratonic) crustal model of *generic rock* (Boore and Joyner, 1997 which is abbreviated herein as BJ97) for predicting ground motions generated by intraplate earthquakes. Simulated *RSA* values for the *non-cratonic* version of *AB95* based on the classical *generic rock* class of Boore and Joyner (1997) is representative of *non-cratonic* regions. Simulated *RSA* values for the *non-cratonic* version of *AB95* based on the classical *generic rock* class of Boore and Joyner (1997) is representative of *non-cratonic* regions. Predictions by the (*non-cratonic*) model are shown in Fig. 3a and 3b to be significantly higher than the upper limit of predictions by the *NGA-West2* models. The *RSA* value of 0.25g at 0.3s is translated to an effective *PGA* of 0.1g for a return period of 2475 years, or 0.07g (2/3 of 0.1g) for a notional return period of 475 years.

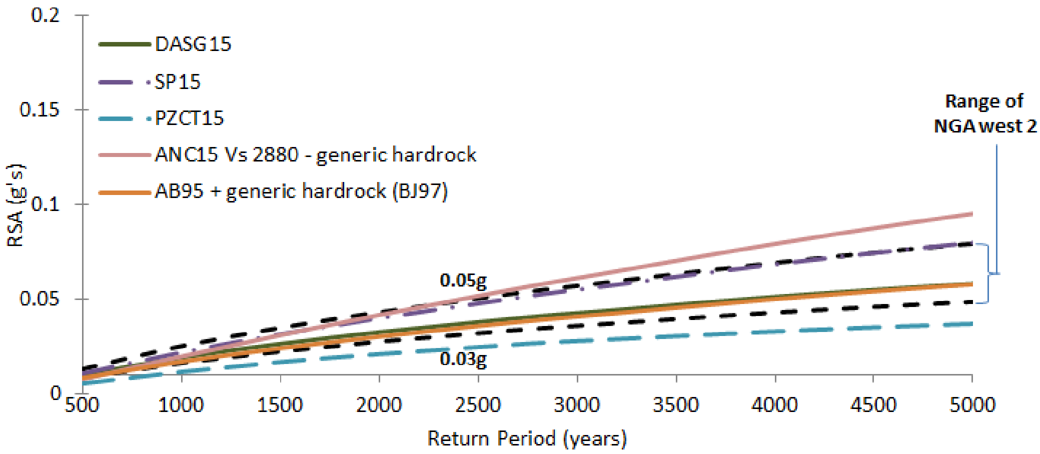
The non-cratonic version of *AB95* has also been used to determine the design response spectrum for Sabah based on modifying PSHA results generated by ARUP (Pappin *et al*., 2011). A higher reference *PGA* value of 0.12g is predicted for a notional return period of 475 years.

Table 3 A selection of ground motion models for use in *tectonically stable regions*

Literature citations	Acronyms in legends	Remarks
Atkinson and Boore (1995)	AB95	BSSA article
Pezeshk, Zandieh, Campbell and Tavakoli (2015)	PZCT15	PEER report 2015/04
Darragh *et al*. (PEER, 2015)	DASG15	PEER report 2015/04
Shahjouei and Pezeskh (PEER, 2015)	SP15	PEER report 2015/04
Al Noman and Cramer (PEER, 2015)	ANC15	PEER report 2015/04
Silva, Gregor and Darragh (2002)	SGD02	PEA report 2002
Atkinson (2004)	A04	BSSA article
Boore, Campbell and Atkinson (2010)	BCA10d	BSSA article
Boatwright and Seekins (2011)	BS11	BSSA article
Atkinson and Boore (2014)	AB14	BSSA article

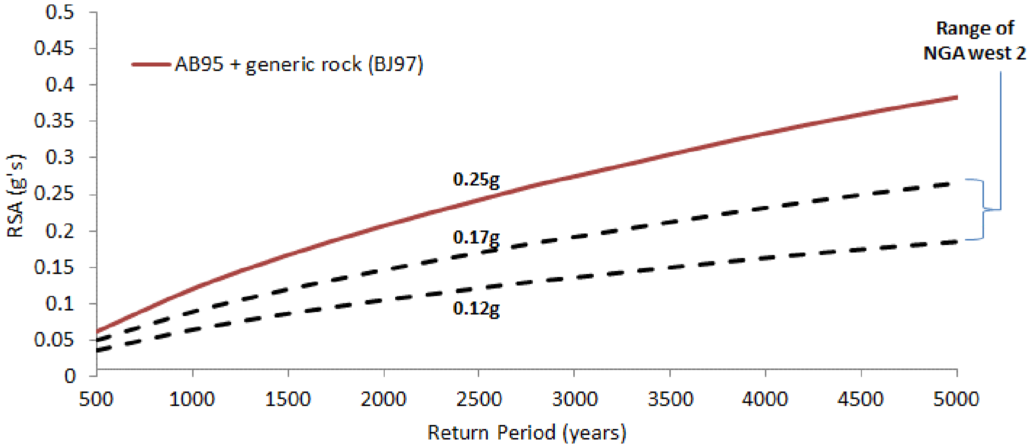


(a) 0.3s period

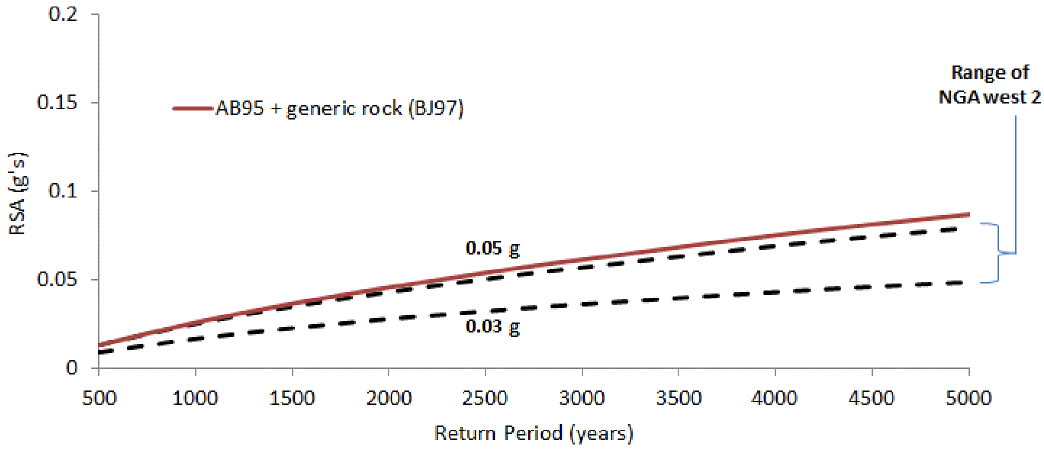


(b) 1.0s period

Figure 2a – 2b NGA-East models (cratonic) overlaid on NGA-West2 models for $\log_{10} N = 5.5 - 0.9M$



(a) 0.3s period



(b) 1.0s period

Figure 3a – 3b Selected NGA-East models (non-cratonic) overlaid on NGA-West2 models for $\log_{10} N = 5.5 - 0.9\, M$

4. Modelling of distant earthquakes

Earthquake hazards from *Sumatra* have been generated from two major sources: (1) Sunda Arc subduction fault source off-shore of *Sumatra*; and (2) *Sumatran* strike-slip fault source (Refer Figure 4). The subduction fault source is formed by convergence between the Indian-Australian plate and the Eurasian plate. Megathrust earthquakes including that of Aceh 2004 (M9.3) and Nias 2005 (M8.7) events were generated from this fault source. The distance from this fault source to *Peninsular Malaysia* is approximately 530 km – 730 km. The Sumatran strike-slip fault source which is located within the *Sumatran* island is 1500 km long and is some 300 – 400 km from *Kuala Lumpur* which is much closer than from the subduction fault source. The magnitude of recorded historical earthquakes generated from this fault source within the *Sumatran* island is limited to around 7.8.

Numerous research groups have contributed to the assessment of the aforementioned far-field seismic hazards affecting *Peninsular Malaysia*. Numerous representative GMPEs for predicting ground motion levels as functions of magnitude and distance have been developed in these studies. The analysis output depends on the historical earthquake catalogue, completeness criteria, de-clustering method, source zoning and the use of the logic tree. A literature review undertaken by the authors provides coverage of some twenty research articles spanning the period 2002 – 2011 (refer a listing of the literature in the review of Looi *et al.*, 2011). This database features a combination of probabilistic and deterministic (scenario-based) hazard analysis (PSHA and DSHA) studies. In view of inconsistencies of the predicted ground motion values from different GMPEs, verification analyses have been undertaken to identify models which give results that match well with instrumented data collected from the field (Chandler & Lam, 2004). Two GMPEs reported in the literature have been validated based on benchmarking against ground motion data instrumentally recorded from a long distance. These two models are: (1) *Component Attenuation Model* (CAM) and (2) *Megawati* attenuation relationship.

CAM was first developed and coded into program GENQKE for generating synthetic earthquake accelerograms based on stochastic simulations of the seismological model of Atkinson & Boore (1995) along with the generic crustal model of Boore & Joyner (1997). Refer also Megawati & Pan (2010) and Lam *et al.* (2000) for more details. Whilst CAM was initially developed for predictions of ground motions generated by local earthquakes, the modelling framework was found to be capable of predicting ground motions generated by large magnitude earthquakes from the far-field. CAM has successfully demonstrated as capable of modelling distant mega-magnitude earthquake events that were generated from the Sunda-Arc subduction source offshore of *Sumatra* and affecting *Singapore* and *Peninsular Malaysia* (Lam *et al.*, 2009; Balendra *et al.*, 2002 and Balendra & Li, 2008). The simulation model of CAM could have been used to quantify the reduction of hazard across the peninsular (from west to east) but it is considered prudent not to do so given that the model has been validated for a site-source distance of up to 600 km. The modelled attenuation of the distant hazard with increasing distance is so gradual that the change in the level of distant hazard across the peninsular is very minor. In perspectives, buildings that are vulnerable to collapse and severe damage in an earthquake is low-rise and medium-rise buildings as opposed to high rise buildings which respond to long distance earthquakes. In other words, the part of the response spectrum in the low period range (and the level of *PGA*) is governed by local hazards anyway. Thus, the long distance earthquake hazard affecting *Peninsular Malaysia* is to be based on one response spectral model.

The Megawati's attenuation relationship for modelling ground motions generated from the *Sumatran* fault source (Megawati *et al.*, 2003) and those from the Subduction fault source (Megawati *et al.*, 2003) was reported in Pan *et al.* (2007) and was revised in Megawati & Pan (2010). Synthetic seismograms which were derived from the analysis of a finite-fault kinematic model have been verified in a manner similar to what has been carried out with CAM. This attenuation relationship is based on hard rock conditions and site-source distance ranging between 200 and 1500 km. The use of the developed relationship for making predictions outside this distance range should be treated with caution.

In addition to the deterministic studies as described above, Pappin *et al.* (2011) conducted PSHA for Malaysia based on historical earthquake data which has been recorded over the past 40 years since 1972, along with the use of the attenuation relationship in Pan *et al.* (2007). Based on the earthquake catalogue compiled from the USGS database, the seismic source zone was divided into four categories of seismogenic depth up to 500 km, and an earthquake database in which small events (*M* <5) and aftershocks have been removed.

The response spectrum produced from PSHA is known as the *Uniform Hazard Spectrum* (UHS) in which contributions from multiple fault sources have been taken into account (Pappin *et al.*2011). The attenuation behaviour of the simulated ground motions in the development of the UHS was based on GMPEs developed by Pan *et al.* (2007). Different parts of the UHS can be identified with very different contributory earthquake scenarios. According to the latest PSHA (Pappin *et al.*, 2011), seismic hazard level varies across the entire *Peninsular Malaysia* (due to the different distances measured from the potential earthquake sources), with Penang indicating the highest hazard. Seismic zoning map could be prepared for the region, but it is considered unnecessary for two reasons: (1) the attenuation behaviour of very long period waves that are characteristics of earthquakes generated from a very long distance is very gradual and (2) the low level of contribution of distant earthquakes to the total hazard in the low to intermediate period range. Thus, the UHS for *Penang* has been selected as the basis of the recommended design spectrum model for the entire *Peninsula Malaysia*.

The UHS model that has been developed initially requires modifications because of subsequent improvements made to the accuracies of the regional specific attenuation relationships. The original attenuation relationship of Pan *et al.* (2007) has been updated to Megawati & Pan (2010). In parallel with improvements made by the Megawati's model, CAM has also been shown to be able to simulate ground motions which match the instrumental field recordings from major events including the *Aceh* earthquake of 2004 and the *Nias* earthquake of 2005.

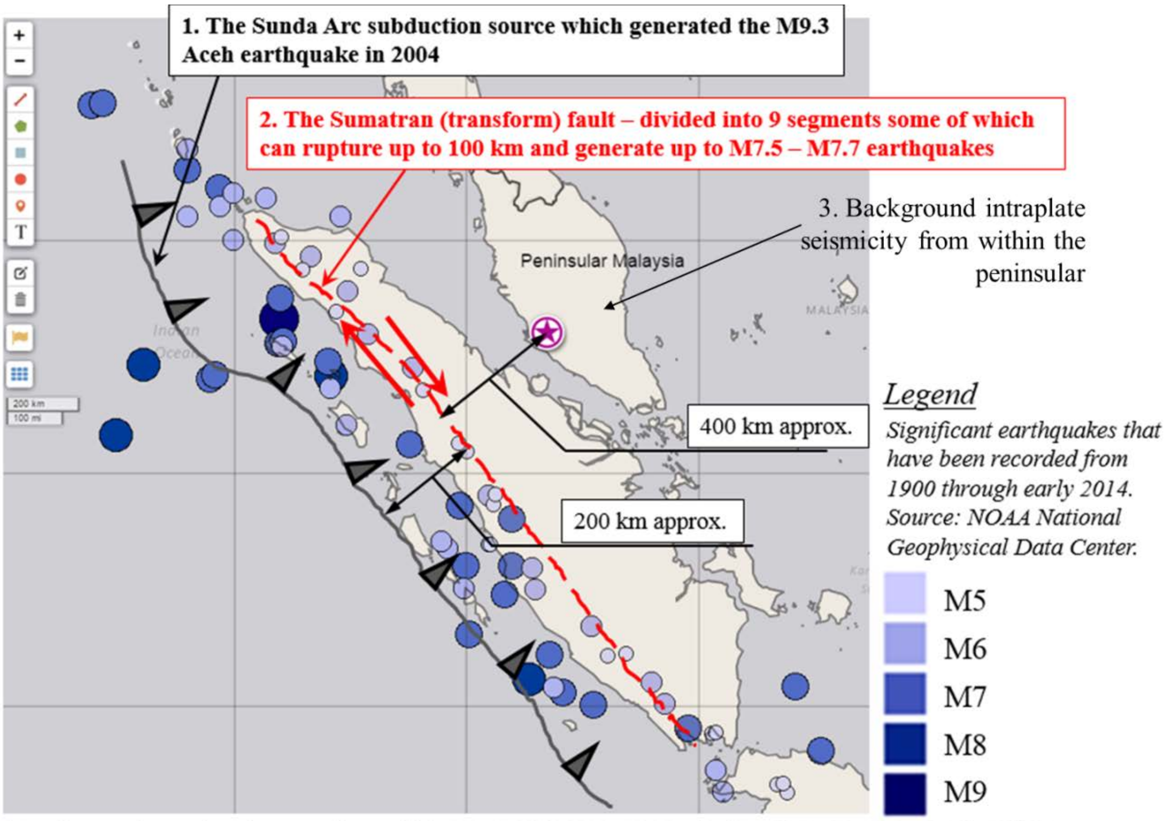


Figure 4 Offshore earthquake generating sources affecting the Peninsular

To achieve a more robust UHS, the attenuation model has been revised in this study to incorporate both the updated model of Megawati & Pan (2010) and the latest development of CAM (Lam *et al.*, 2009). A logic tree weighting factor of 0.5 has been allocated to both attenuation relationships in the aggregation analysis. The modified UHS as presented in Fig. 5 was obtained by an adjustment procedure comprising the following steps:

a) The original UHS (for Penang) was firstly scaled down by a notional factor of 2.0 (Musson, 1999) in order to obtain the median UHS.
b) Seven earthquake scenarios were selected by calibrating the response spectra based on the use of the (original) attenuation model of Pan *et al.* (2007) with the median UHS at three reference natural periods of 1 s, 2 s and 5 s.
c) The response spectra of the calibrated earthquake scenarios were then re-calculated using the updated attenuation model of Megawati & Pan (2010) along with CAM based on equal weightings. The differences in the spectral parameters were represented by the geometric mean of spectral ratios (SR) at the three reference periods amongst the seven calibrated scenarios. The SR for other periods of the UHS were determined accordingly based on interpolation between the three reference periods.
d) The modified UHS was then obtained by scaling the original UHS by the geometric mean SR.

The revised response spectral values in the long period range of 2 s – 3 s based on probabilistic analysis is approximately double the response spectral values based on deterministic (median) predictions as published in Lam *et al.* (2009).

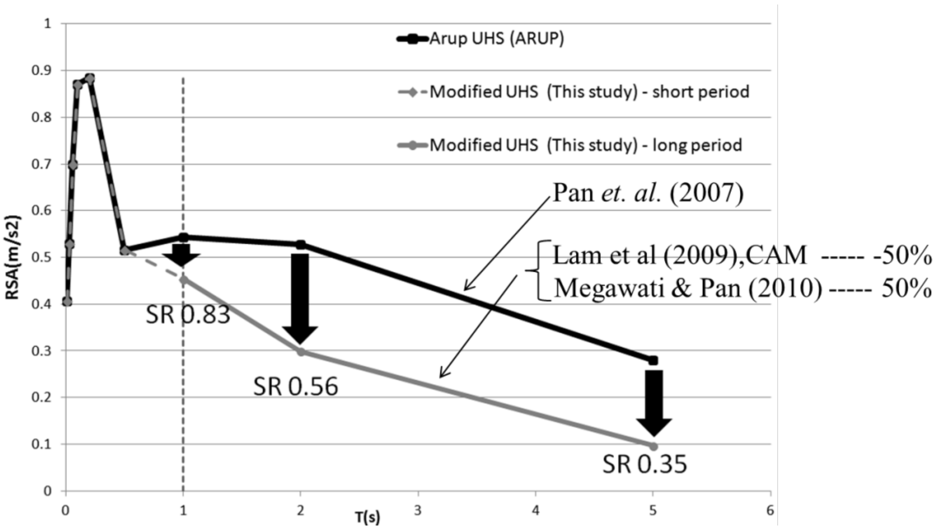
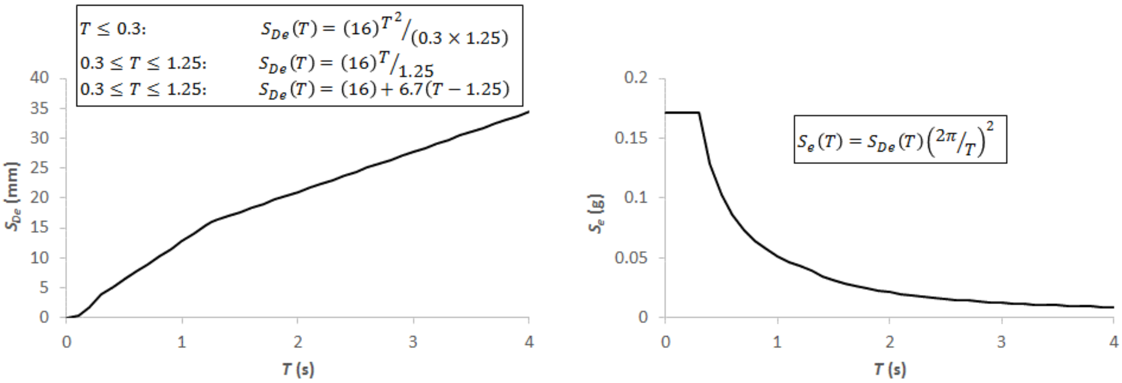


Figure 5 The original and adjusted response spectra representing distant hazard affecting the *Peninsula*

5. Elastic response spectra for different parts of *Malaysia*

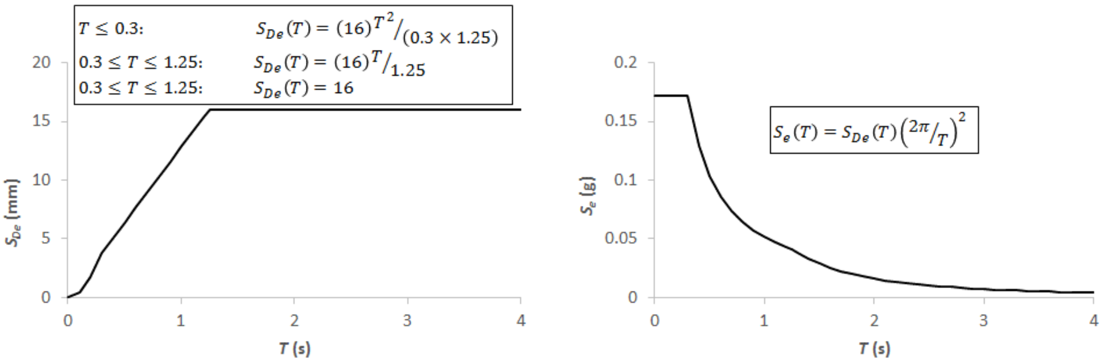
The response spectrum models of Malaysia do not follow the generic EC8 code which stipulates Type 1 and Type 2 spectrum, as per Cl. 3.2.2.2 (2)P of EC8. The model proposed for *Peninsular Malaysia* (Fig. 6a and 6b) is a composite (hybrid) model which encapsulates results from the PSHA of recorded regional earthquakes as well as from the predictions of the local earthquakes based on broad source zone modelling as described in the earlier part of the paper. This approach best capitalises on the benefits of abundant data of distant events, whilst obtaining robust estimates of locally generated hazards.

The response spectrum model for *Sarawak* and *South-western Sabah* (Fig. 7a and 7b) is essentially based on the considerations of local hazards only. The values of *PGA* for the notional 475 year RP and the benchmarked 2475 year RP are 0.07g and 0.1g respectively, as for *Peninsular Malaysia* but differs in the higher period range (>1.25 s) due to different frequency of occurrence of regional seismicity. The response spectrum model for the central and eastern parts of *Sabah* northeast of the dividing line is essentially based on results generated from conventional PSHA based on recorded seismicity data (Fig. 8a and 8b). The values of *PGA* for the notional 475 year RP and the benchmarked 2475 year RP are 0.12g and 0.18g respectively. Refer to the earlier parts of the paper for description of the modelling methodology.



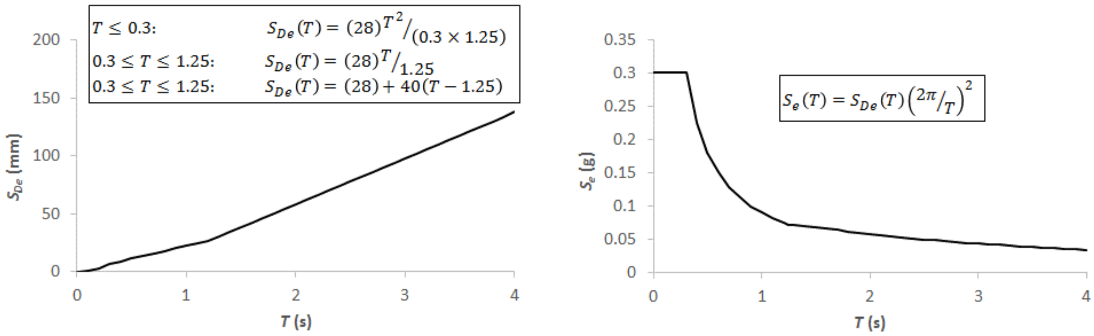
(a) (b)

Figure 6 Elastic Response Spectrum on rock (a) displacement and (b) acceleration for *Peninsular Malaysia* for Type II ordinary buildings (Design *PGA* = 0.07g, RP = 475 years)



(a) (b)

Figure 7 Elastic Response Spectrum on rock (a) displacement and (b) acceleration for *Sarawak* and *South-western Sabah* for Type II ordinary buildings (Design *PGA* = 0.07g, RP = 475 years)



(a) (b)

Figure 8 Elastic Response Spectrum on rock (a) displacement and (b) acceleration for *Central and Eastern Sabah* for Type II ordinary buildings (Design *PGA* = 0.12g, RP = 475 years)

6. Summary

The key challenge of quantifying seismic hazard for Malaysia is in how to (i) quantify the recurrence behaviour of local earthquakes based on the results of a survey of M>5 earthquakes across many countries in five different continents and (ii) select the most suitable ground motion model (GMM) which best represents the seismic environment of Malaysia for conducting probabilistic seismic hazard analysis (PSHA). The additional challenge for modelling the design response spectrum for *Peninsular Malaysia* is in encapsulating both long distance (subduction) earthquakes and local intraplate earthquakes in one response spectrum. Arguments in support of the adopted broad zonation approach in the modelling of local intraplate hazards have also been presented.

7. References

Atkinson, G.M. (2004), "Empirical attenuation of ground motion spectral amplitudes in southeastern Canada and the northeastern United States", *Bulletin of the Seismological Society of America* **94**(3): 1079-1095.

Atkinson, G.M. and Boore, D.M. (2014), "The attenuation of Fourier amplitudes for rock sites in eastern North America", *Bulletin of the Seismological Society of America* **104**(1): 513-528.

Atkinson, G.M. & Boore, D.M. (1995), "Ground Motion Relations for Eastern North America", *Bulletin of the Seismological Society of America* **85**: 17-30.

Australian Standard: AS 1170.4 (2007), Structural Design Actions – Part 4 Earthquake Actions.

Balendra, T., Lam, N.T.K., Wilson, J.L. & Kong, K.H. (2002), "Analysis of long-distance tremors and base shear demand for buildings for Singapore", *Engineering Structures* **24**: 99-108.

Balendra, T. & Li, Z. (2008), "Seismic Hazard of Singapore and Malaysia", *EJSE Special Issue*: Earthquake Engineering in the low and moderate seismic regions of SEA and Australia.

Bergman, E.A. & Solomon, S.C. (1980), "Oceanic intraplate earthquakes: implications for local and regional interpolate stress", *Journal of Geophysical Research* **85**(BI0): 5389-5410.

Bird, P., Kreemer, C. & Holt, W.E (2010), "A long-term forecast of shallow seismicity based on the global strain rate map", *Seismological Research Letter* **81**(2): 184-194.

Boatwright , J. & Seekins, L. (2011), "Regional spectral analysis of three moderate earthquakes in northeastern North America", *Bulletin of the Seismological Society of America* **101**: 1769-1782.

Boore, D.M. & Joyner, W.B. (1997), "Site amplifications for generic rock sites", *Bulletin Seismological Soc of America* **87**: 327-341.

Boore, D.M., Campbell, K.W. & Atkinson, G.M. (2010), "Determination of stress parameters for eight well-recorded earthquakes in eastern North America", *Bulletin Seismological Soc of America* **100**: 1632-1645.

Chandler, A.M. & Lam, N.T.K. (2004). "An attenuation model for distant earthquakes", *Earthquake Engineering and Structural Dynamics* **33**: 183–210.

Eurocode 8 - Design of structures for earthquake resistance. EN 1998-1 Part 1: General rules, seismic actions and rules for buildings.

JMM & MOSTI (2009), *Final report on seismic and tsunami hazards and risks study in Malaysia, Academy of Sciences Malaysia*.

Lam, N.T.K., Balendra, T., Wilson, J.L. & Venkatesan, S. (2009), "Seismic load estimates of distant subduction earthquakes affecting Singapore", *Engineering Structures* **31**: 1230-1240.

Lam, N.T.K., Wilson, J.L. & Hutchinson, G. (2000), "Generation Of Synthetic Earthquake Accelerograms Using Seismological Modelling: A Review", *Journal of Earthquake Engineering* **4**(3): 321-354.

Lam, N.T.K., Tsang, H.H., Lumantarna, E. & Wilson, J.L. (2016), "Minimum loading requirements for areas of low seismicity", *Earthquake and Structures* **11**(4): 539-561.

Lam, N.T.K., Tsang, H.H., Lumantarna, E. & Wilson, J.L. (2015a), "An Alternative Probabilistic Seismic Hazard Assessment Method in Areas of Low-to-Moderate Seismicity", *Procs ASEM15 conf* South Korea.

Lam, N.T.K., Tsang, H.H., Lumantarna, E. & Wilson, J.L. (2015b), "Results of Probabilistic Seismic Hazard Analysis Assuming Uniform Distribution of Seismicity", *Procs 10th Pacific conf Earthquake Engr*, Sydney.

Looi, D.T.W., Hee, M.C., Tsang, H.H. & Lam, N.T.K. (2011), "Probabilistic Approach for Determination of Design Spectrum Model for Peninsular Malaysia: Part One (Background & Methodology) and Part Two (Literature Review)", *Proceedings of 1-day symposium and 1-day workshop on earthquake engineering in Malaysia and Asia Pacific Region*, 6 – 7 December 2011, Armada Hotel Petaling Jaya, Malaysia.

MS EN1998-1:2015 Eurocode 8: Design of structures for earthquake resistance – part 1: General Rules, Seismic Actions and Rules for Buildings

Megawati, K. & Pan, T.C. (2010), "Ground-motion attenuation relationship for the Sumatran megathrust earthquakes", *Earthquake Engineering and Structural Dynamics* **39**: 827-845.

Megawati, K., Pan, T.C. & Koketsu, K. (2003), "Response spectral attenuation relationships for Singapore and the Malay Peninsula due to distant Sumatran-fault earthquakes", *Earthquake Engineering and Structural Dynamics* **32**: 2241-2265.

Megawati, K., Pan, T.C. & Koketsu, K. (2005), "Response spectral attenuation relationships for Sumatran-subduction earthquakes and the seismic hazard implication to Singapore and Kuala Lumpur", *Soil Dynamics and Earthquakes Engineering* **25**: 11-25.

Musson, R.M.W. (1999), "Determination Of Design Earthquakes In Seismic Hazard Analysis Through Monte Carlo Simulation", *Journal of Earthquake Engineering* **3**(4): 463-474.

Ogweno, L.P. & Cramer, C.H. (2014), "Comparing the CENA GMPEs Using NGA-East Ground Motion Database", *Seismological Research Letters* **85**(6): 1377-1393.

Pacific Earthquake Engineering Research Centre (2015), *NGA-East: Median Ground Motion Models for the Central and Eastern North America Region*, PEER Report No. 2015/04 University of California, Berkeley PEER, website: http://peer.berkeley.edu/ngawest/index.html.

Pan, T.C. & Megawati, K. (2002), "Estimation of PGA of the Malay Peninsula due to Distant Sumatra Earthquakes", *Bulletin of the Seismological Society of America* **92**:3: 1082-1094.

Pan, T.C., Megawati, K. & Lim, C.L. (2007), "Seismic shaking in Singapore due to past Sumatran earthquakes", *Journal of Earthquake and Tsunami* **1**(1): 49-70.

Pappin, J.W., Yim, P.H.I. & Koo, C.H.R. (2011), "An approach for seismic design in Malaysia following the principles of Eurocode 8", IEM *Jurutera* Magazine, 22-28.

Petersen M.D., Dewey J., Hartzell S., Mueller C. et al. (2004). "Probabilistic seismic hazard analysis for Sumatra, Indonesia and across the Southern Malaysian Peninsula", *Tectonophysics* **390**: 141-158.

Silva, W.J., Gregor, N. and Darragh, R.B. (2002), "Development of regional hard rock attenuation relations for central and eastern North America", Report to Pacific Engineering and Analysis, El Centro, C.A.

Stein, S., Geller R.J. & Liu M. (2012). "Why earthquake hazard map often fail and what to do about it", *Tectonophysics*. 562-563:1-25.

Wilson J.L., Lam N.T.K. & Gad E.F. (2015). "Hazard Identification and Behaviour of Reinforced Concrete Framed Buildings in Regions of Lower Seismicity", *Proceedings of the 10th Pacific Conference on Earthquake Engineering*, 6 - 8 November 2015, Sydney, Australia.