Recommended Earthquake Loading Model for Peninsular Malaysia

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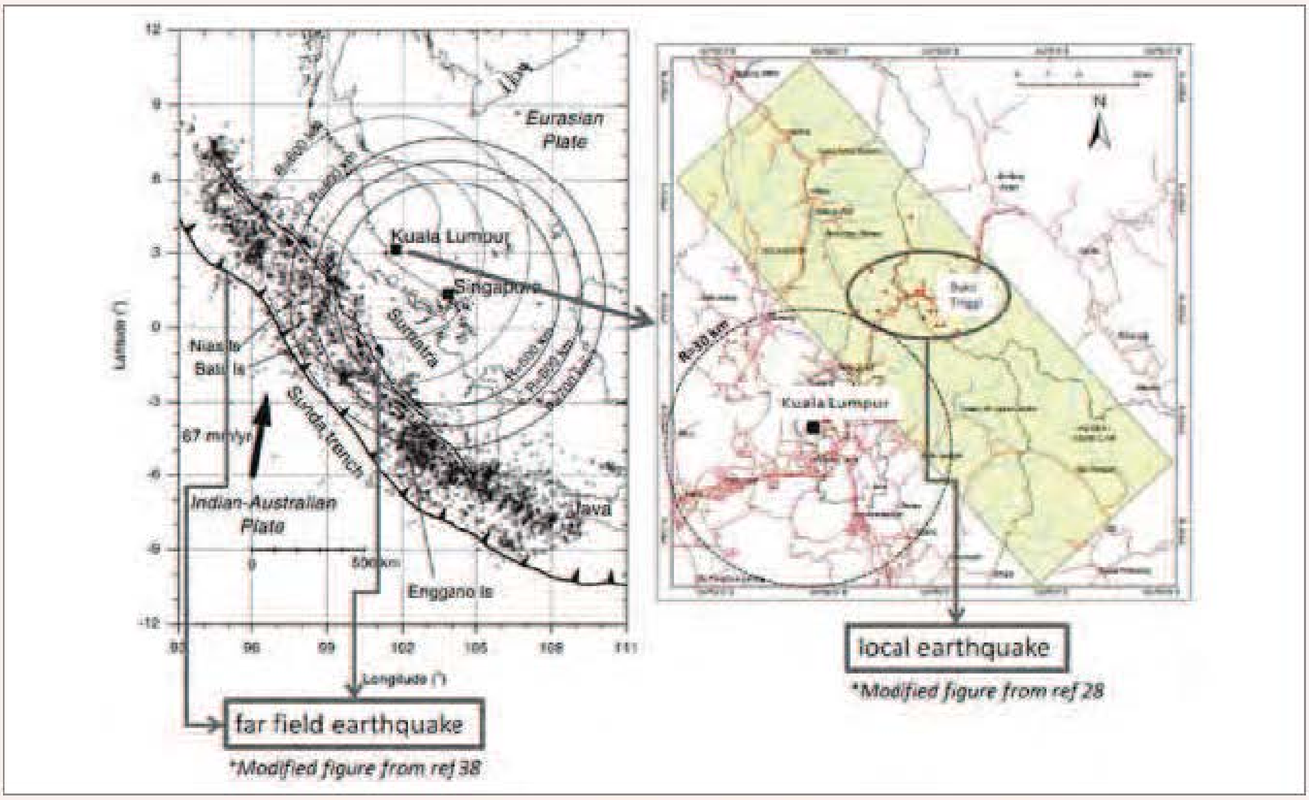
1.0 INTRODUCTION

1.1 Background

Geographically, Malaysia is located outside the *Pacific Ring of Fire* on the stable Sunda plate (a part of the Eurasian plate) and is conventionally perceived as an earthquake free zone. However, in recent years, Malaysia has experienced frequent reports of earthquake tremors generated mainly from the Sumatra fault zone (as shown in Figure 1). The generally increasing rate of earthquake activity in South East Asia in the aftermath of the Sumatra 2004 earthquake has been observed [5], as compiled in the database available from the National Earthquake Information Center (NEIC) of the United States Geological Survey (USGS).

Whilst no structural damage was reported, thousands of people in Malaysia were shaken by the earthquake tremor prompting the inevitable inquiring over the issue of structural safety of buildings in Malaysia [40, 41]. To address this potential threat, the Institution of Engineers, Malaysia (IEM), has formed a Technical Committee on Earthquake and published a position paper in 2007 [12], followed by the publication of a series of articles over the potential implementation of the Eurocodes for structural design [14]. The specific questions to address are whether or not there is a need for seismic design in the nation and whether Eurocode 8 (hereafter abbreviated as EC8) is suitable for providing the framework for codification.

Whilst most of the publicity has been on the Sumatra mega-thrust earthquake, a series of small earthquakes (M 0.3 to 4.2) were recorded by the local seismological network [28] within the Peninsula itself in the Bukit Tinggi area, Pahang, in November 2007. In other words, the threat of potential intraplate earthquakes generated by local inactive faults (including the Bukit Tinggi fault zone, refer to Figure 1) has been underrated. Given this combination of potential threats, it is appropriate to categorise Malaysia as a low-to-moderate seismicity region, similar to Australia, Central and Eastern North America, Northern Europe and South China.



*Modified figure from ref 38

*Modified figure from ref 28

Figure 1: Regional tectonic settings and the potential earthquake threat (far field and local) of Malaysia

The situation has been evaluated seriously by the IEM Technical Committee. A series of technical meetings and symposia were conducted with the participation of invited international experts. Key events include a one-day workshop in June 2010, a two-day symposium and workshop in December 2011 [13] and the upcoming two-day symposium and workshop in April 2013. This paper aims to summarise the research work that has been undertaken in the past 18 months which shall form the basis of the recommended earthquake loading model for Peninsular Malaysia.

1.2 Seismic Hazard Assessment (SHA)

Since 1979, the Malaysian Meteorological Department (MMD) has installed 19 seismological stations in the Peninsula [25]. In addition, hundreds of years of historical data of major far field earthquake events generated from the Sumatra fault zone has become available from the USGS/NEIC database [42]. This has enabled the implementation of the conventional Probabilistic Seismic Hazard Assessment (PSHA) methodology in determining the recurrence rates of various ground motion intensity levels at different locations around the nation. PSHA can be viewed as a statistical method for incorporating the information of seismotectonic features and all historic events in the prediction of a certain ground motion level with a finite probability of occurrence. The most commonly adopted algorithm was initially developed by Cornell (1968) [6] and further coded by McGuire (1976) [26] into a computer programme.

On the contrary, only a limited amount of local earthquake data was recorded from within the Peninsula itself. It is noted that the probabilistic approach would not be reliable in modelling the recurrence rates of local seismic events for the future if local (intraplate) earthquakes are being under-represented in the existing database. This lack of data syndrome is a common issue in many low-to-moderate seismicity regions. In this context, it is considered appropriate to adopt Deterministic Seismic Hazard Assessment (DSHA) as a supplementary or alternative approach of modelling [17].

DSHA was the *de facto* standard approach of seismic hazard modelling during the said period (until the 1980's) when the amount of recorded data was scarce. With an increasing amount of recorded data around the world, the use of PSHA has become more popular. However, recent destructive earthquakes raised concerns over the full reliance of results from PSHA for determining the required level of protection with the built infrastructure. There has been an ongoing debate over this issue in the field of seismology and engineering. Notwithstanding this, PSHA is well recognised in terms of its role in risk management and is undoubtedly an essential tool for assisting policy making by governments and the insurance industry.

From an engineering perspective, the safety of the built infrastructure in countering potential earthquake hazards is the most important consideration in determining the required level of seismic design loadings. It is reasonable to be conservative and take into account uncertainties and unknowns through international benchmarking of seismic design practices, and with particular references to countries in a similar situation. The approach for determining the earthquake loading model should also be tailor-made to address local constraints as well as consider regional specific seismotectonic and geological conditions. It is therefore prudent not to simply adopt a commonly used code of practice for Malaysia.

Ground Motion Prediction Equation (GMPE) (commonly known as attenuation model) is the key component in SHA. GMPE predicts the intensity of ground shaking, based mainly on a given earthquake scenario which is expressed in terms of a Magnitude (M) and Distance (R) combination. Ideally, such a model should be developed based on locally recorded data. References to other generic models can also be made should they be deemed suitable. For far field Sumatra earthquake (both Sunda-Arc subduction and Sumatran fault), the authors adopted two regionally specific models, namely that of CAM [31, 4] models by Megawati and co-workers [19], and a (generic) model developed by Atkinson & Boore (2006) [15, 16]. On the other hand, eight GMPEs as summarised in Ref.[22] have been adopted to assess the attenuation characteristics of ground motions in local earthquake events in Peninsular Malaysia.

1.3 National Annex (NA) to EC8

The long existence of British Standards in Malaysia will be replaced by the Eurocode, with the provision of the National Annex (NA) to take into account local conditions. EC8 (BS EN 1998-1:2004) [8] is the document recommended for the design of buildings against seismic actions. A design Acceleration Response Spectrum (RSA) which is scaled in accordance with the notional Peak Ground Acceleration (PGA) value is stipulated. Importantly, EC8 (Part 1 *Cl. 3.2.2.2 P*) has the flexibility of being adaptable to different spectral shapes. An appropriate design spectrum model for Malaysia has become a crucial matter that is ought to be considered.

In view of the unique pattern of far field and local (background) seismicity that is affecting Malaysia, a hybrid approach of modelling (incorporating results from both probabilistic and deterministic assessments) was discussed and proposed in the workshop that was conducted in December 2011. Due consideration was given to international practices when the proposal was made. The recommendation of this hybrid approach was formally endorsed by all the participants of the workshop where representations from various stakeholders, the local professions and the academia have also been included.

Upon the endorsement, the IEM Earthquake Technical Committee has set up a working group (WG1) to elaborate on the recommended hybrid approach. This article provides a summary of the relevant research work that has been undertaken for the determination of the earthquake loading model for rock sites in Malaysia based on the endorsed approach. This involves the probabilistic assessment of distant seismic hazard as well as the determination of local earthquake scenarios for engineering design purposes. A unified hybrid earthquake loading model for Malaysia as developed in this study is recommended for codification purposes.

The potential effect of amplification by near-surface soil sediments (as represented by the S-factor in EC8) is another important element of considerations in the NA to EC8. The incorporation of the site natural period as an additional parameter for site classification [10, 11] (along with the use of the conventional SPT and shear wave velocity values) has been considered as a more appropriate approach for regions of low and moderate seismicity. This recommendation has also been endorsed by all the participants of the December 2011 workshop. A site-specific design spectrum model has been developed by the authors and will be presented and discussed in the upcoming workshop (which is not included in this article as it only considers the ground motions on bedrock).

2.0 DISTANT SEISMIC HAZARD MODELLING

2.1 Far Field Earthquake Sources

Earthquake hazards from Sumatra have been generated from two major sources (Figure 1): (1) Sunda Arc subduction fault source off-shore of Sumatra; and (2) Sumatran strike-slip fault source.

(1) Sunda Arc subduction fault source off-shore of Sumatra

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.

(2) Sumatran strike-slip fault source

The distance from the 1,500 km long Sumatran strike-slip fault source to Peninsular Malaysia is some 300 to 400 km and is much closer than the distance from the subduction fault source. The magnitude of recorded historical earthquakes generated from this fault source within the Sumatran island is limited to about M7.8.

2.2 Previous Studies

Numerous research groups have contributed to the assessment of the aforementioned far field seismic hazards affecting Peninsular Malaysia. This section provides a brief review of the work done by five major research groups:

1. Lam, Chandler, Tsang, Balendra and co-workers from the University of Melbourne, the University of Hong Kong and the National University of Singapore
2. Megawati, Pan, Koketsu and co-workers from the Nanyang Technological University Singapore and the University of Tokyo
3. Pappin and co-workers from Arup Hong Kong
4. Adnan, Irsyam and co-workers from the University of Technology Malaysia and Institute of Technology Bandung
5. Petersen and co-workers from the United States Geological Survey.

The literature review (presented in the 2011 workshop) provides coverage of some twenty research articles spanning the period 2002 – 2011 [1-3, 7, 9, 16-21, 23, 24, 27, 32, 35-39]. This database features a combination of PSHA and scenario-based DSHA studies. The research methodology and assumptions adopted in the DSHA studies have been clearly explained in Refs.[32, 19]. Numerous representative GMPEs for predicting ground motion levels as functions of magnitude and distance have been developed in these studies. Meanwhile, investigations adopting the PSHA as reported in eight research articles (e.g. [3, 16]), involved the use of a more extensive list of input parameters and modelling assumptions. The analysis output depends on the historical earthquake catalogue, completeness criteria, de-clustering method, source zoning and the use of the logic tree.

Most of the adopted GMPEs are empirically based and were derived from regression analysis of strong motion accelerogram data (e.g. Joyner and Boore, Campbell, Sadigh). Due to the paucity of recorded data for empirical regression analysis (which is common in low and moderate seismic regions including Malaysia), various researchers proposed GMPEs which were developed from studies involving the use of stochastic simulations of the seismological model (e.g. CAM, Atkinson and Boore), and finite-fault ground motion simulations based on the kinematic method (e.g. Ref.[19]). In view of the 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 limited field observations [4].

Two GMPEs reported in the literature have been validated based on benchmarking against ground motion data instrumentally recorded from a long distance. A brief introduction of the two GMPEs is presented below.

(1) Component Attenuation Model (CAM)

The generic CAM was first developed and coded into programme GENQKE for generating synthetic earthquake accelerograms based on stochastic simulations of the seismological model [29, 31]. Even though CAM was initially developed for the prediction 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 [4]. CAM has successfully demonstrated its capability of modelling distant earthquakes affecting Singapore [32, 36, 37].

The mathematical framework of the seismological model underpinning CAM is defined by equation 1:

$$A(f) = CM_0S(f)\ \ G_AA_n(f)\ \ P(f)V_a(f) \qquad \textit{Eq 1}$$

where $CM_0S(f)$ is the "source" component, $G_AA_n(f)$ is the "path" component and $P(f)V_a(f)$ is the "local" component.

A detailed review of the seismological model and stochastic simulation methodology can be found in [31].

(Continued on page 11)

(2) Megawati attenuation relationship

Megawati and co-workers developed an attenuation relationship for modelling ground motions generated from the Sumatran fault source [20] and those from the Subduction fault source [21] in 2007 [39], and was revised in 2010 [19]. Synthetic seismograms which were derived from the analysis of a finite-fault kinematic model have been verified. This attenuation relationship is based on hard rock conditions and site-source distance ranging between 200 and 1,500 km. The use of the developed relationship for making predictions outside this distance range should be treated with caution.

The latest attenuation relationship is defined by equation 2 below:

$$\ln(Y) = a_0 + a_1(M_w - 6) + a_2(M_w - 6)^2 + a_3 \ln(R) + (a_4 + a_5 M_w)R + \varepsilon_{\ln(Y)} \qquad Eq\ 2$$

where all parameters can be obtained from Table IV in Ref. [19].

In addition to the deterministic studies as described above, Pappin and co-workers [15, 16] 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 Megawati (2007) attenuation relationship [39] (i.e. not the most updated one). Based on the earthquake catalogue compiled from the USGS database, the seismic source zone was divided into four categories of seismogenic depth ranging between 50 and 500km, and an earthquake database in which small events (<M5) and aftershocks have been removed. Local seismic hazards were analysed using the attenuation relationship of Atkinson & Boore (2006) which was developed for the mostly cratonic crustal conditions of Eastern North America.

A summary of PGA values, corresponding to a return period (RP) of 475 years (10% probability of exceedance in 50 years) and 2475 years (2% probability of exceedance in 50 years), hereafter rounded off to 500 years and 2,500 years respectively, derived from various studies are presented in Figure 2 along with results from deterministic predictions based on the long distance scenario of M9.3 R530 and the use of CAM (*Eq 1*) and Megawati (2010) (updated) (*Eq 2*) attenuation relationship.

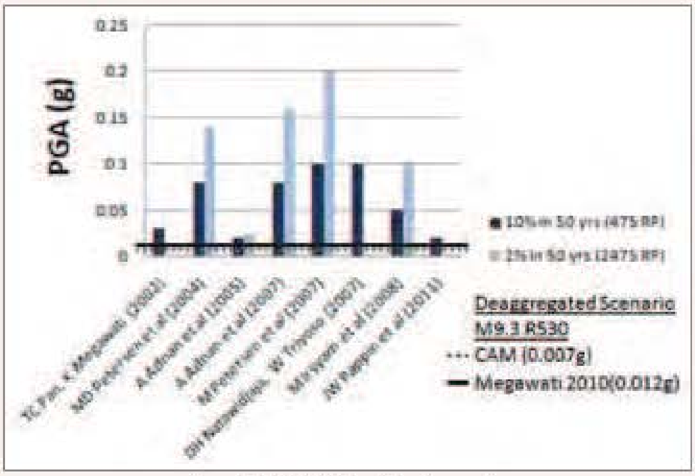


Figure 2: PGA (g) from literature review

Whilst the PGA parameter is conventionally used for scaling a design response spectrum, the response spectral behaviour in the intermediate to long period range is actually represented by response spectral velocity parameter (RSV_{max}) which is a more robust and appropriate parameter for representing the effects of hazards on the built infrastructure.

The developed Uniform Hazard Spectra (UHS) have been de-aggregated into contributory earthquake scenarios [27, 3, 15]. For example, the earthquake scenarios of M8 R400 and M9.3 R530 have been identified to correspond to the mean hazard level for a RP of 2,500 years based on projected events generated from the Sumatran and subduction fault sources respectively. Values of RSV_{max} obtained from the de-aggregation analysis are presented in Figure 3 along with the predictions from CAM (*Eq 1*) and from the Megawati (2010) attenuation relationship (*Eq 2*).

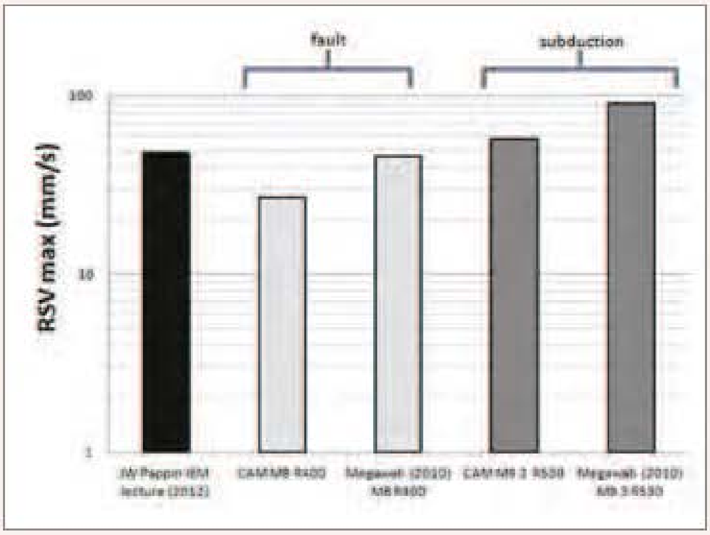


Figure 3: RSV_{max} RP 2500 years on a rock site in Malaysia for Sumatran far field earthquake (fault and Subduction zone)

2.3 Recommended Distant Earthquake Model

In addition to the deterministic studies that have been conducted to model the behaviour of distant earthquakes, comprehensive probabilistic studies have been undertaken more recently to model the aggregated earthquake hazards. The response spectrum produced by the aggregation analysis is known as the Uniform Hazard Spectrum (UHS) in which contributions from multiple fault sources have been taken into account [15, 16]. The attenuation behaviour of the simulated ground motions in the development of the UHS was based on GMPEs developed by Megawati (2007) for the large magnitude distant earthquake and by Atkinson & Boore (2006) for local earthquakes generated from a stable crustal structure. Different parts of the UHS can be identified with very different contributory earthquake scenarios. For example, the short period range of the 2,500-year UHS in Figure 4 is controlled by ground motions generated by moderate magnitude earthquakes whereas the longer period range by the much larger magnitude earthquakes from longer distances.

There is a global trend to benchmark design seismic hazard level to a RP of 2,500 years as opposed to 500 years, in order to achieve a higher level of protection for civil engineering assets. In the low seismicity regions of the United Kingdom a RP of 2500 years has been stipulated in the NA of EC8 for collapse prevention limit state design. Similar design criterion has been adopted in Canada and China. In view of this trend, it is considered that the UHS of Malaysia should be based on a RP of 2,500 years.

It is noted that the UHS model as presented in Figure 4 requires modifications because of subsequent improvements in the accuracies of the regional specific attenuation relationships. For example, the original attenuation relationship of Megawati (2007) [39] has been updated to Megawati (2010) [19]. In parallel with improvements made by the Megawati model, CAM has also been shown to be able to simulate ground motions that match the instrumental field recordings from major events including the Aceh earthquake of 2004 and the Nias earthquake of 2005. To achieve a more robust UHS, the attenuation model has been revised in this study to incorporate both the updated model of Megawati (2010) [19] and the latest development of CAM [32]. A logic tree weighting factor of 0.5 has been allocated to both attenuation relationships in the aggregation analysis.

The modified UHS was obtained by an adjustment procedure comprising the following steps (refer to Figure 4):

a) Three earthquake scenarios, namely (1) M9.3 R530, (2) M9.4 R650 and (3) M9.5 R730 were first identified by calibration analyses to be represented by the original UHS. Earthquake ground motions simulated for these calibrated scenarios based on the use of the (original) attenuation model of Megawati (2007) [39] have been checked to ensure that their respective response spectra were consistent with the UHS at the four reference natural periods of 0.5s, 1s, 2s and 5s.

b) For each of the calibrated earthquake scenarios their respective response spectra were then recalculated using the updated attenuation model of Megawati (2010) [19] along with CAM based on equal weightings. The modified UHS at the reference periods were taken as the geometric mean of results associated with the three calibrated scenarios.

c) Scaling factors at the four reference periods were taken as the ratio of their respective revised and original response spectral values. The period dependent correction factor of the UHS was determined accordingly based on interpolation between the four reference periods.

The (modified) UHS so obtained from the three-step procedure as described is presented in Figure 5 along with scenario specific response spectra of five earthquake events: (1) M9.3 R530 (median prediction simulated by CAM), (2) M8 R300 (median prediction simulated by CAM), (3) M9.3 R635.13 (Aceh earthquake recorded at Ipoh station), (4) M8.7 R500 (Nias earthquake recorded at FRIM Kepong station) and (5) M7.6 R492 (Sumatra fault earthquake recorded at Pusat Sains, Bukit Kiara station).

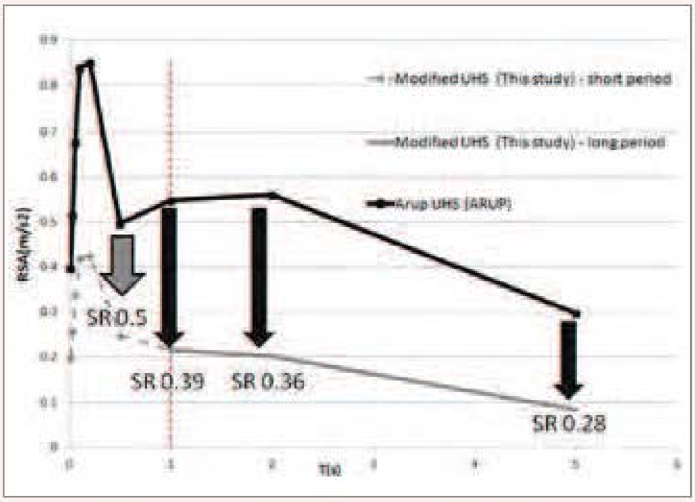


Figure 4: Modified 2500 Return Period UHS by scaling with period-dependant Spectral Ratio (SR)

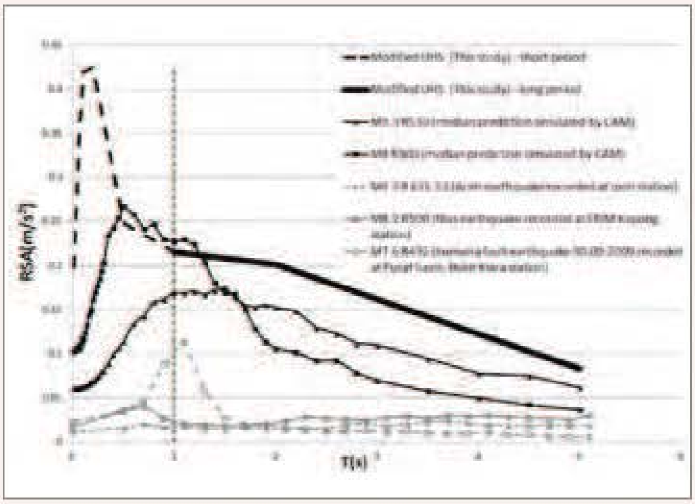


Figure 5: Superimposed modified UHS with 5 distant earthquake events

3.0 LOCAL SEISMIC HAZARD MODELLING

3.1 Local Earthquake Activities

In 2007, the Bukit Tinggi area in Pahang had experienced a series of earthquake tremors. About 24 tremors of magnitude 0.3-4.2 were recorded by MMD over a period lasting for five days [28]. Cracks were detected at the Bukit Tinggi secondary school buildings and the police headquarter at Bukit Tinggi.

The occurrences of earthquake tremors outside Bukit Tinggi have also been documented. Tremors with epicentres located within Peninsular Malaysia were widely felt in the mid 1980's. These tremors have been interpreted as "induced earthquakes" following the filling of the large Kenyir reservoir in Terengganu. 24 weak tremors were reported to have occurred in the period 27.7.1984 – 15.11.1985. Other isolated events have also been located in Jerantut Pahang, Manjung Perak and Kuala Pilah in 2009 [28].

3.2 Scenario-based Modelling and Recommended Local Earthquake Model

In view of uncertainties associated with local earthquake sources and the scarcity of recorded data, results from PSHA are considered to be unreliable for predicting future recurrence rates of earthquakes. In this context, SHA can be undertaken by the alternative scenario-based modelling methodology which is essentially deterministic in nature. This is referred herein as the DSHA approach.

Suitable M-R combinations will have to be predetermined if DSHA is to be used. The "newly discovered" Bukit Tinggi fault has been recorded to have generated earthquakes of up to M4.2. Distance of this identified fault source from Kuala Lumpur and the Klang Valley is around 15km to 60km (Figure 1). Although the M-R combination of M4.2 R15 may well be considered to be the "critical earthquake scenario" in view of what has been recorded in recent times, it is inappropriate to do so simply because a larger magnitude event from the identified fault source cannot be completely ruled out. It is therefore prudent to make reference to seismicity information on a global scale as opposed to restricting the scope of reference to the very limited database of records that has been collected from within the Peninsula to date.

From the global perspective, reference PGA values for RP of 2,500 years have been compiled from the literature for a number of major cities around the world. The level of seismicity around the globe is broadly classified herein into three major zones:

a) **Low** seismic zones: e.g. London (**lower**), Melbourne (**mid**), Hong Kong (**upper**) – <0.25g
b) **Moderate** seismic zones: e.g. Wenchuan (Sichuan), Christchurch (New Zealand) – 0.25g-0.50g
c) **High** seismic zones: e.g. Taiwan, Tokyo, Los Angeles – >0.50g.

A brief introduction of GMPEs has been given in Section 2.2. Eight GMPE models which have been developed independently in different regions around the globe, including two *New Generation Attenuation* (NGA) model (Abraham and Silva (2008), and Campell and Bozorgnia (2008)) [34] which were originally intended for applications in Western and Eastern North America, have been reviewed. Their Response Spectral Displacement (RSD) values have also been collated for comparison in [22]. CAM [30, 31] that has been developed and used by the authors in numerous studies for different countries in the past has also been included as one of the considered GMPEs.

The database of earthquakes used in Lumantarna *et al.* [22] features events of magnitudes in the range M5.5-M6.9, and much of the data were sourced from the PEER NGA database [34], published by the Pacific Earthquake Engineering Research (PEER) Center. RSD values predicted by the considered GMPEs are shown to be more consistent as the magnitude and distance values increase within the considered range: M5.5 R20 – M6.9 R40. The predicted mean Peak Displacement Demand (PDD) values (i.e. maximum value on displacement response spectrum) associated with an array of considered M-R combinations are listed in Table 1. The range of reference distances in the array is based on information shown in Figure 1. The four M-R combinations for the projected local earthquakes correspond with conditions of "low seismic zones" (PGA <0.25g) as defined above in the context of international benchmarking. Thus, every individual M-R combination listed in Table 1 can be aligned with one of the following classification sub-categories: "**lower**", "**mid**" or "**upper**".

In Figure 6, the modified UHS is shown along with the response spectra estimated for a range of local earthquake scenarios. The original UHS model (primarily based on the considerations of distant events) has also incorporated local earthquake scenarios of up to M4.2 [15]. A PGA value of less than 0.04g is predicted for a RP of 2,500 years. Clearly, when it comes to international benchmarking the predicted level of seismic hazard by the presented UHS is somewhat too low for any area with a background seismicity. It is noted that the "lower" classification sub-category within the low seismic zone (in the case for London) is 0.1g which is aligned with the projected scenario of M6 R50.

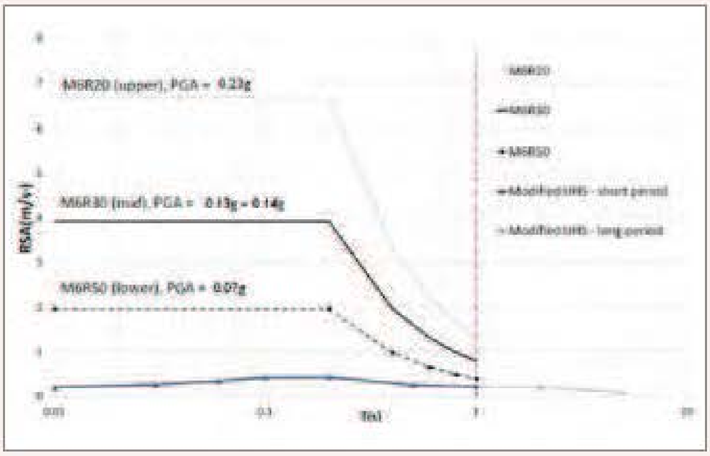


Figure 6: Superimposed modified distant earthquake UHS with RSA (<1s) of 3 selected projected local earthquake scenarios

Table 1: Selected local earthquake scenario based on PDD table [22], with estimated corner period T1, T2 and notional PGA [33]

Bound	Scenario		PDD (mm)	T1 (s)	T2 (s)	RSA_{max} (g)	Notional PGA (g)
	M	R					
Lower	6	50	10	0.2	1	0.20	0.07
Mid	6	30	20	0.2	1	0.40	0.13
	6.5	50	33	0.25	1.25	0.42	0.14
Upper	6	20	34	0.2	1	0.68	0.23

(Continued on page 15)

Irrespective of what has been recorded historically in the area it is considered reasonable to adopt the "mid" classification sub-category and the corresponding projected scenario of M6 R30 which has been identified with the notional PGA values of around 0.13g on rock sites. This level of ground motions can be taken as the basis for defining the design local hazards for the metropolitan area surrounding the capital city of Kuala Lumpur and other major cities. These recommendations are based on international benchmarking and are irrespective of what has been recorded to date in the area over a very limited time span.

4.0 THE UNIFIED EARTHQUAKE LOADING MODEL FOR MALAYSIA

In Section 2 and 3, two design response spectrum models have been developed separately for far field and local earthquake hazards respectively forming a hybrid model. Considerations for distant earthquake hazards are based on the modified UHS for a RP of 2500 years using Kuala Lumpur as reference (i.e. an epicentral distance of 600km is considered). Considerations for local earthquake hazards are based on international benchmarking as described. A design scenario of M6R30 (consistent with the "mid" hazard classification sub-category) has been adopted to model the response spectrum in the natural period range of up to 1s. In summary, the long period range (> 2s) of the response spectrum is controlled by the considerations of distant earthquakes (as represented by the modified UHS) whereas the short period range (<1s) by the projected local earthquake scenarios.

In unifying the two parts of the response spectrum (for distant and local earthquake hazards) there is a transition zone in the period range of 1s-2s. The RSD in the transition zone of this proposed hybrid model features a straight line bridging the two parts of the displacement response spectrum (Figure 7(a)). The same response spectrum is also presented in the conventional acceleration format in Figure 7(b).

4.1 Distance Effects

The general framework of the hybrid model as introduced herein can be extrapolated for use in different cities across Peninsular Malaysia by making use of the "path" component of the seismological model (*Eq 1*), which is principally a function of distance R [31]. The nearest distance of a city to the Sunda Arc subduction fault source off-shore of Sumatra will control the value of PDD which characterises the response spectrum in the long period range. The unified model as presented in Figure 7(a) refers specifically to the capital city of Kuala Lumpur which is identified with distance R = 600 km from the Subduction zone off-shore of Sumatra. The response spectrum for another city such as Penang (R = 400 km) which is closer to the Subduction zone than Kuala Lumpur can be scaled accordingly by the use of the Distance Factor (DF) (refer *Eq 3* and Table 2), which was derived in this study. The RSD value at T = 2s can be scaled using *Eq 4*. The values of DF and the corresponding RSD value at T = 2s of some selected cities can be found in Table 2.

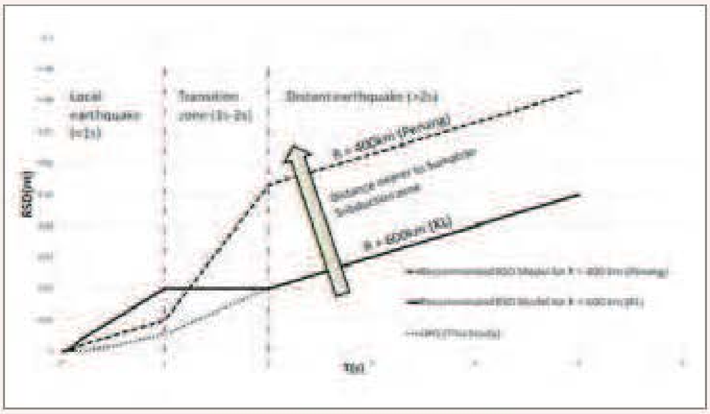


Figure 7(a): The unified RSD model

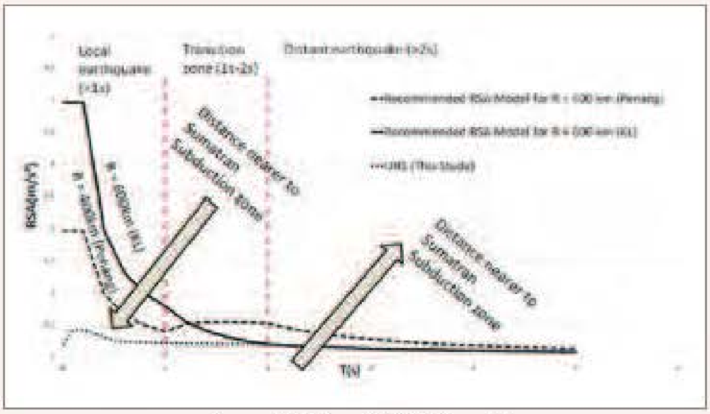


Figure 7(b): The unified RSA model

Distance Factor (DF) = $(600/R)^{2.4}$; R in unit km *Eq 3*

$S_D(2) = 20 * DF \geq S_D(T_D)$; S_D in unit mm *Eq 4*

Table 2: Distance effect of Path Component Attenuation

City	Kuala Lumpur	Penang	Klang, Melaka
R (km)	600	400	500
Distance Factor (DF)	1.0	2.373	1.525
$S_D(2)$ (mm)	20	47	30

For codification purposes, displacement spectral ordinates SD(T) are as defined by *Equation 5-8*, along with the parameters summarised in Table 3, whilst the compatible spectral ordinates of the conventional acceleration response spectrum can be conveniently calculated using *Eq 9*.

RSD

$T \leq T_C$: $S_D(T) = S_D(T_D) * T^2 / (T_C T_D)$ *Eq 5*

$T_C \leq T \leq T_D$: $S_D(T) = S_D(T_D) * T / T_D$ *Eq 6*

$T_D \leq T \leq 2$: $S_D(T) = S_D(T_D) + [S_D(2) - S_D(T_D)] * (T - T_D)$ *Eq 7*

$T \geq 2$: $S_D(T) = S_D(2) + 10 * (T - 2)$ *Eq 8*

RSA

$$RSA = RSD * (2\pi / T)^2 \qquad Eq\ 9$$

In effect, the format of the benchmark design response spectrum model for Kuala Lumpur is consistent with that stipulated in EC8 up to T = 2s. Considering the unique distant hazard in Peninsular Malaysia, location-dependent spectral ordinates would result beyond T = 2s.

Table 3: Values of the parameters describing the design response spectra

Location	$S_D(T_D)$	$S_D(2)$	T_C	T_D
Kuala Lumpur	20	20	0.2	1.0
Others	10	$20 * (600/R)^{24}$	0.2	1.0

4.2 A Comparison with Recorded Data

Three recorded data of far field earthquakes are shown in Figure 5, indicating that the modified UHS is conservative to envelope them. Despite the scarcity of recorded data for local earthquakes (e.g. Bukit Tinggi), the highest recorded data M4.2 is taken as comparison with the unified RSA model of Kuala Lumpur. Data from two MMD stations (1) FRIM Kepong (R = 25 km) sitting on granite foundation and (2) Ulu Yam (R = 16 km) sitting on soft soil foundation are superimposed in Figure 8. It is shown that the unified RSA model is conservative enough for civil protection with a 2,500 year RP.

4.3 A Comparison with EC8

The simulated response spectrum for the large magnitude distant earthquake scenario of M9.3 R530 (which is identified with notional PGA value of 0.095 m/s²) is used to scale the model response spectrum of EC8 Type 1 (for M>5.5) based on the same PGA value as shown in Figure 9(a). Similarly, the simulated response spectrum for the local earthquake scenario of M6 R30 (which is identified with notional PGA value of 1.6 m/s²) is used to scale the model response spectrum of EC8 Type 2 (for M<5.5) as also shown on the same figure. Rock site conditions and a *q* factor of 1.5 as stipulated by EC8 have been adopted in the comparison. It is shown that the shapes of both Type 1 and 2 model spectra are comparable to the respective (scenario specific) simulated response spectra except that the spectral values could have been understated by both EC models in the longer period range depending on the location of the city. The same response spectra are also presented in the conventional acceleration format in Figure 9(b).

4.4 The 1.5% Notional Load

As shown in Figure 9(b), the notion of adopting a nominal horizontal design load of 1.5% gravity load as a simplified format of providing coverage for the seismic design requirement in the Peninsula is proven to be flawed. In view of the non-conservatism of this simple provision, the importance of incorporating proper seismic design requirement for Peninsular Malaysia is now evident.

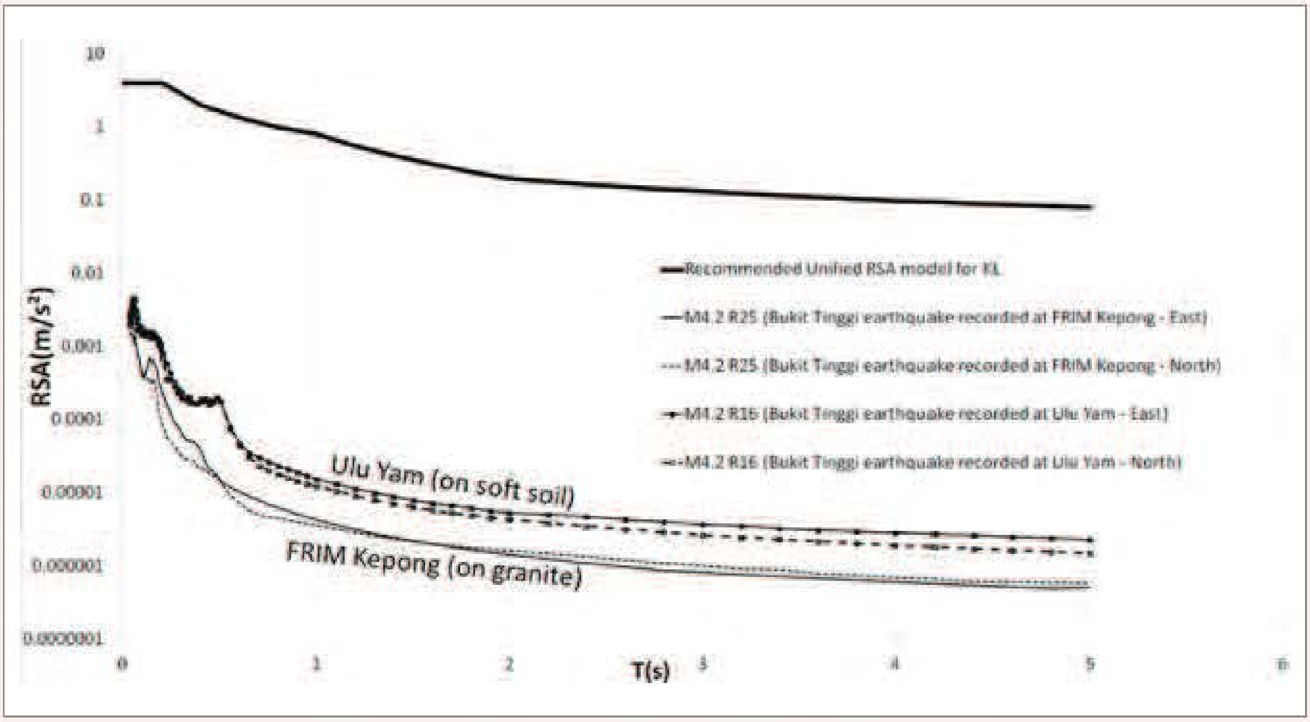


Figure 8: The unified RSA model superimposed with recorded local earthquake data

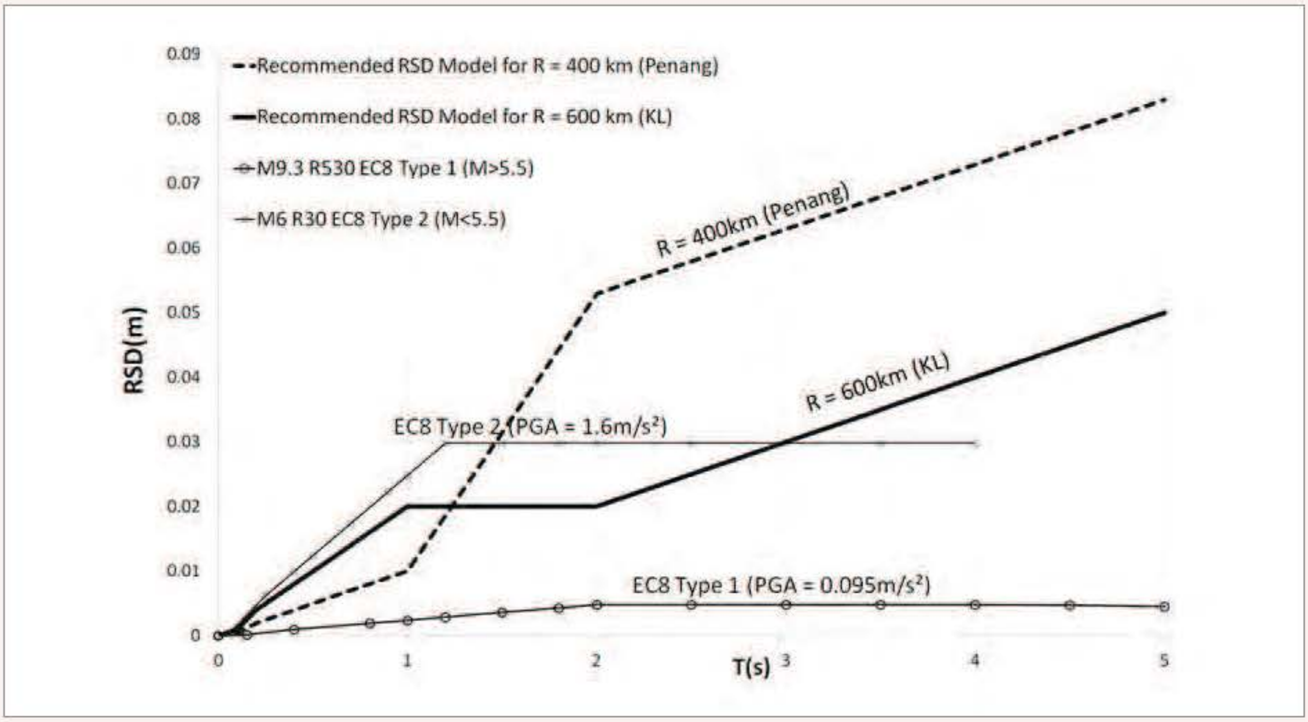


Figure 9(a): The unified RSD model superimposed with EC8 Type 1 and 2

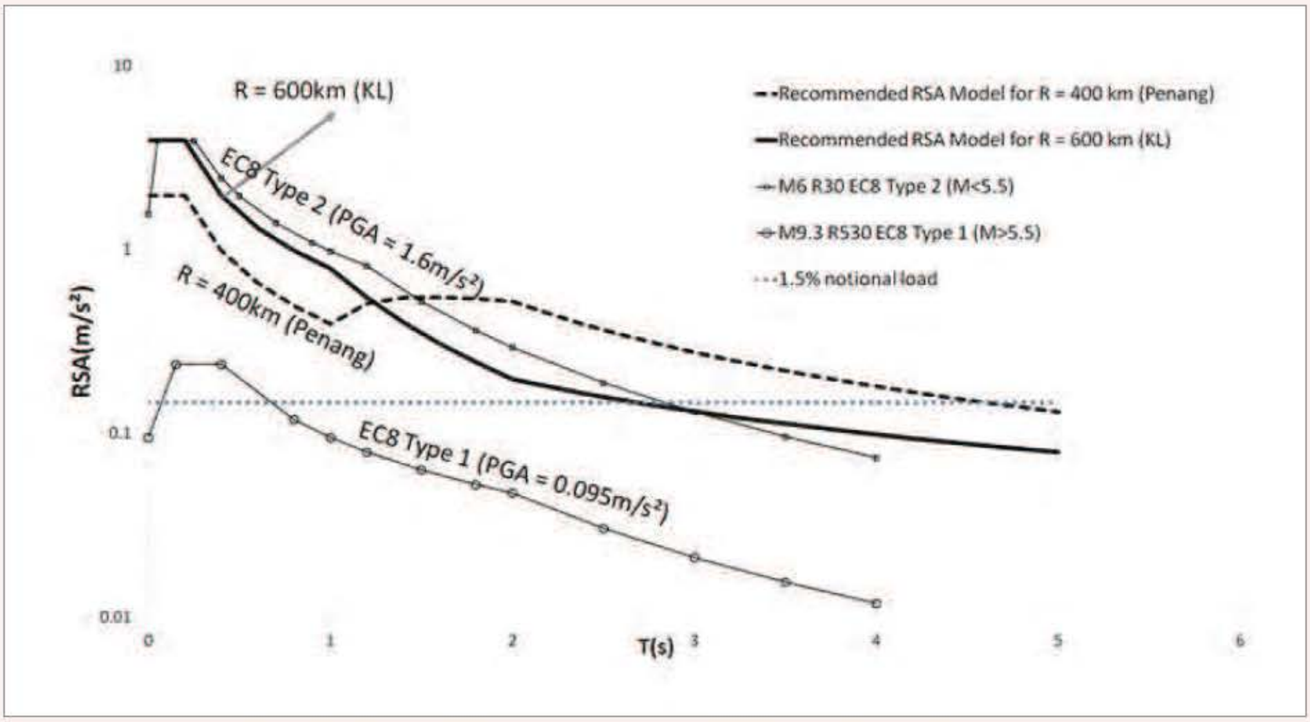


Figure 9(b): The unified RSA model superimposed with EC8 Type 1 and 2, and 1.5% notional load

5.0 SUMMARY AND CLOSING REMARKS

The peninsula of Malaysia is subject to a combination of earthquake threats that can be generated from a multitude of seismic sources. The Sunda Arc subduction source off-shore of the Sumatra Island has been attracting most of the publicity following the aftermath of the phenomenal M9.3 Aceh earthquake event of 2004. Although the level of ground shaking experienced in the peninsula was not of engineering significance in that event, a much higher level of hazard is predicted for a much closer epicentral distance which is deemed possible. Another notable distant fault source is from the

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Sumatran island itself. Although this second fault source is much closer to the Peninsula, its estimated response spectral level in the high period range is not as critical because of its relatively modest upper magnitude limit. Both elements of distant earthquake hazards have been subject to detailed research investigations based on large quantities of seismological data recorded to date from the region. Research findings that have been reported from the literature to date have been associated with these two distant earthquake generating mechanisms. The third potential earthquake source is what is known as background seismicity which refers to local earthquakes generated from within the Peninsula.

Local earthquakes that have been documented to date were only generated from the Bukit Tinggi fault which is located some 15 to 60 km away from the metropolitan area surrounding the capital city of Kuala Lumpur. None of these local earthquake events were of engineering significance because of their low magnitudes. However, given that earthquakes of magnitude 6 are well within the credible limit in regions of low-moderate seismicity (intraplate) areas, the potential hazard that can be generated from local earthquakes can be much higher than what can be inferred from the very limited current historical archives.

The very complex combination of seismic activities affecting the Peninsula means that the generic EC8 (Type 1 and 2) response spectrum models should not be adopted automatically. Thus, the response spectrum model proposed herein has been derived from first principles.

Numerous response spectrum models have been developed from probabilistic, or deterministic, seismic hazard analysis for the region, but most of the data used in these analyses were associated with the two distant fault sources. Because of the infrequent and random nature of local earthquakes, their potential hazard has been under-represented in (the usual) probabilistic evaluation analysis conducted to date. Applying probabilistic analysis in an area which are so lacking in local seismicity data will only produce hazard maps featuring "bull eyes" which are clearly counter intuitive. The disastrous consequence of paying blind faith to results from probabilistic analysis was well demonstrated in the destructive earthquake events in the recent past including the Christchurch Earthquake in the South Island of New Zealand in February 2011.

Hence, a hybrid modelling approach has been adopted to address this shortcoming. In the hybrid model, the part of the response spectrum in the long period range (>2s) is based on the considerations of distant earthquakes. A mega large magnitude (M9.3) earthquake from some 400 to 600km distance has been considered for design purposes. The original UHS model of ARUP has been modified in accordance with predictions from the latest attenuation models for such distant earthquake scenarios. A logic tree approach was employed to take into account contributions from different research groups. The part of the response spectrum in the shorter period range (<1s) was derived from international benchmarking in which seismicity patterns around the world are resolved into the "High", "Moderate" and "Low" seismic zones. The Peninsula on the whole has been ranked as a "low" seismic zone. Seismicity classification sub-categories of "lower", "mid" and "upper" were accordingly defined within the "low seismic zone" category. The seismicity of the capital city of Kuala Lumpur and the surrounding metropolitan area has been assigned to the sub-category of "mid". The earthquake scenario of M6 R30 that is considered to be consistent with this classification has been identified accordingly. Response spectra for this earthquake scenario can be predicted based on GMPE's that have been developed around the globe for local earthquakes. A high level of consistencies amongst the models in their predictions of long period spectral properties offers robustness to the predictions and adds confidence. A transition zone in between the two period ranges is also featured in the hybrid model to complete the construction.

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