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Seismic hazard and response spectrum modelling for Malaysia and Singapore

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Abstract. Malaysia and Singapore have adopted Eurocode 8 (EC8) for the seismic design of building structures. The authors studied the seismic hazard modelling of the region surrounding Malaysia and Singapore for a long time and have been key contributors to the drafting of the Malaysia National Annex (NA). The purpose of this paper is to explain the principles underlying the derivation of the elastic response spectrum model for Malaysia (Peninsular Malaysia, Sarawak and Sabah). The current EC8 NA for Singapore is primarily intended to address the distant hazards from Sumatra and is not intended to provide coverage for potential local intraplate hazards. Hence, this paper recommends a reconciled elastic response spectrum for Singapore, aiming to achieve a more robust level of safety. The topics covered include the modelling of distant interplate earthquakes generated offshore and local earthquakes in an intraplate tectonic setting, decisions on zoning, modelling of earthquake recurrences, ground motion and response spectrum. Alternative expression for response spectrum on rock, strictly based on the rigid framework of EC8 is discussed.

Keywords: Eurocode 8; seismic hazard; response spectrum; PSHA; intraplate local earthquake

1. Introduction

This paper outlines and explains the seismic hazard model for different parts of Malaysia (Lam *et al*. 2016b) and its neighbouring country Singapore, which are both characterised by very different seismicity conditions (see Fig. 1). Arguments are presented relating to decisions on zoning, 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, which went through the public ballot process in 2016 (NA-2016). The current NA for Singapore to EC8 (SS EN1998-1:2013), which became mandatory in 2015, intends primarily to address distant hazards, hundreds of kilometres away, arising in Sumatra and is not intended to provide coverage for potential local intra-plate hazards (Lam *et al*. 2015a). Importantly, the latter type of hazard has safety implications for low-rise structures including many of the aged building stock.

1.1 Seismic hazards in Malaysia and Singapore

Peninsular Malaysia and the adjoining country Singapore are subject to a combination of earthquake hazards generated from various offshore sources. Most seismological studies and hazard modelling undertaken to date have been concerned with ground motions generated by distant earthquakes because of their high representation in the strong motion database (Balendra *et al*. 2002, Lam *et al*. 2009, Megawati and Pan 2010, Megawati *et al*. 2005, Pan and Megawati 2002, Pan *et al*. 2007, Petersen *et al*. 2004, Pappin *et al*. 2011). Whilst potential hazards generated locally can be significant, only a very limited amount of such seismic activity data has been recorded in the Peninsula. In view of this unique pattern of combined local and distant seismicity a hybrid modelling approach has been adopted to take into account both types of seismic hazard. Thus the seismic hazard model stipulated for Peninsular Malaysia is a composite model which encapsulates PSHA results from 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 the abundant data on distant events, whilst obtaining robust estimates of

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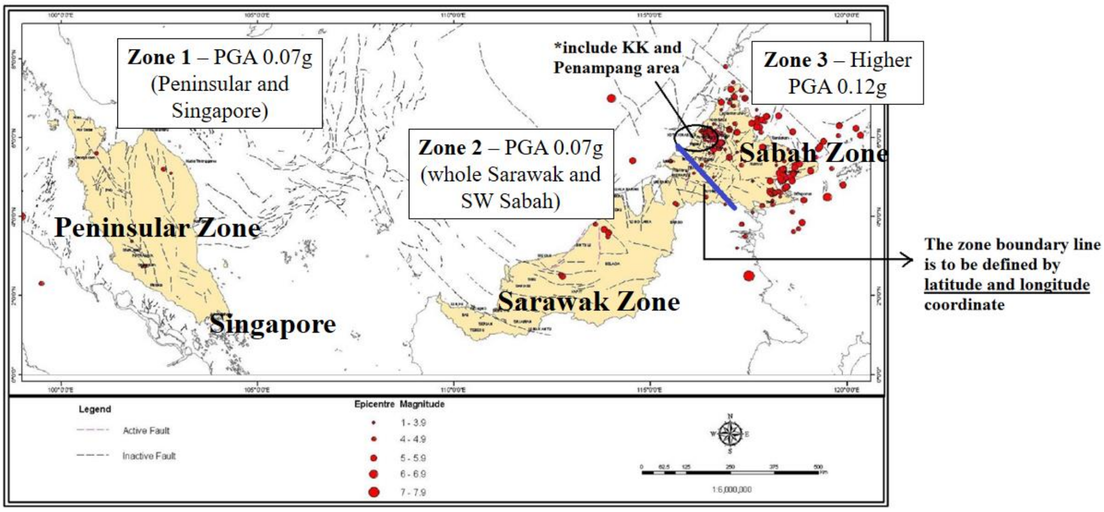


Fig. 1 Seismic hazard zonation across Malaysia and Singapore (proposed by the authors after receiving feedbacks of public comments)

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

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

*SW: South-western (exclude Kota Kinabalu); CNE: Central and North-eastern (include Kota Kinabalu)

locally generated hazards based on global information sources. Details of modelling of the two types of hazard is 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 km away from the capital city of Kuching, but ground motions predicted from these fault sources are very mild. Consequently, the response spectrum model for Sarawak is essentially based wholly on local hazard considerations 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 those two parts of Malaysia.

Sabah is in the proximity of areas of high seismicity, unlike Sarawak, Peninsular Malaysia and Singapore. 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 Kundasang-Ranau fault zone which lie in the vicinity of Ranau and Kota Kinabalu (KK) in the central-north; the Labuk bay-Sandakan basin zone near to Sandakan; the Lahad Datu-Kunak-Tawau fault zone in the east of Sabah; and the Semporna fault in the Dent-Semporna Peninsula Zone (MOSTI 2009). Thus, the seismic hazard model for Sabah in the period range of engineering interest is essentially based on results generated from the conventional PSHA based on empirical seismicity data related to 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 study (Pappin *et al*. 2011) but the UHS had to be modified to incorporate the most up-to-date earthquake ground motion attenuation model.

The types of seismic activities characterising the hazards for different parts of Malaysia and Singapore in the low and high period ranges are summarised in Table 1. The boundary between the low and high period ranges at 1.25 s is representative of the corner period at the beginning of the constant displacement region of magnitude (M) 6.5 earthquake (Lam *et al*. 2000, Lumantarna *et al*. 2012).

The seismic action model to be presented is for ordinary (Type II) buildings which is defined herein as "reference seismic action" and based on a notional 475-year return period (RP) being scaled by a factor of 2/3 of the benchmarked 2475-year RP earthquake. This is not to be confused with an exact 475-year RP earthquake hazard.

2. Zonation and recurrence modelling of local seismic activities

2.1 Peninsular Malaysia, Singapore, Sarawak and South-western (SW) 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 Malaysia, Sarawak and the SW part of Sabah (which exclude the capital city Kota Kinabalu nor Ranau) and is not to be confused with the long distance hazard generated from the island of Sumatra or from the subduction fault source off-shore of Sumatra which is the subject matter of a later section of the paper.

A seismic hazard map divides a region into zones so that the spatial distribution of the frequency of future earthquake occurrences can be communicated to the designer of future facilities. Such a map concerns the predictions of future activity and is not supposed to be a map merely of 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 map should differ from each other given that what is shown on many seismic hazard maps mainly reflects where historical earthquakes have occurred. Hazard maps produced for regions of low seismicity have been recognised as not robust (Stein *et al*. 2012, 2013, Mulargia *et al*. 2017). The credibility of the predictions is further compromised in the case of Malaysia, where a mere 38 years (year 1979 onwards) of complete instrumented records (Che Abas 2001, MOSTI 2009) on a small land area, shows only 2 earthquakes which exceeded magnitude 5 (on 12th February 1994 and 1st May 2004) in Peninsular Malaysia, Singapore and Sarawak combined.

In the Malaysian context, the authors' literature review revealed that no existing Malaysian seismic hazard maps (summarised in MOSTI 2009) were able to predict hazards for the area surrounding Perak, in the northern part of the Peninsula, where a *M*4.1 earthquake occurred in 2013. Prior to the occurrence of this earthquake tremor most of the attention had been focussed on areas surrounding Bukit Tinggi, where tremors had been recorded. This is one of many examples indicating that local intra-plate earthquakes can occur in areas with no recognisable earthquake activity precedents. Difficulties in predicting the locations of intra-plate earthquakes have been recognised by many code drafting bodies in affected countries such as Australia (being wholly distant away from tectonic plate boundaries).

In Australia, the challenges associated with such uncertainties are being met by the adoption of a threshold value of $Z_{\min}$=0.08 (where Z is the seismic hazard coefficient which 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 0.08 g in Australia is consistent with current hazard specifications in the two largest Australian cities of Sydney and Melbourne (AS1170.4-2007). Neither city has ever experienced a destructive earthquake in their respective vicinities in the past and yet the 0.08 g threshold has been decided upon as necessary for those cities.

In the study for Peninsular Malaysia (together with Singapore, Sarawak and SW 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 events. 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 intra-plate hazard is contributed to 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 intra-plate 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 statistics of event counts presented are not sufficient to allow an exact global average value to be determined. However, it is clear that the global average must be within the range of five to ten M>5 events occurring over an area of 1,000,000 sq. km, suitable for a 50-year period prediction (Lam *et al*. 2016a). A parameter *KD* is introduced herein to represent the rate of recurrence of intra-plate events, where *KD*=1 refers to five events and *KD*=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., *KD*=2) is a reasonable, and conservative, normalised event count to assume provided that (validated) local earthquake occurrence data does not infer a higher value.

The rate of seismic activity is conventionally defined using the Gutenberg-Richter magnitude recurrence relationship in the form of Eq. (1a)-(1b)

$$\log_{10} N(M) = a - bM \tag{1a}$$

$$\text{Or } \log_{10} N(M) = a_5 - b(M - 5) \tag{1b}$$

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

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

2.2 Central and North-eastern (CNE) Sabah

The seismicity of Sabah is represented by two zones: Zone 2 is of low seismicity, bounded by the border with Sarawak and a dividing line located to the south-west of Kota Kinabalu. Zone 3 comprises the rest of Sabah from the central part to northeast of the dividing line (see Fig. 1 which shows the dividing line). Zone 2 is essentially part of the Sarawak zone, whereas the level of hazard for Zone 3 is to be analysed in accordance with past earthquake activity records for this part of Sabah. The subject matter of this sub-section is focused upon Zone 3 which comprises the Central, Northern and Eastern parts of Sabah. See Fig. 2 for a listing of M≥5 earthquake events within Zone 3 in the past 52 years since 1966.

Historical seismic activity in the eastern part of Sabah (Lahad Datu, Kunak, Semporna and Tawau) has attracted much attention for the past 30 years. However, similar levels of activity (measured in terms of number of M>5 events per unit area) have actually been recorded in Central

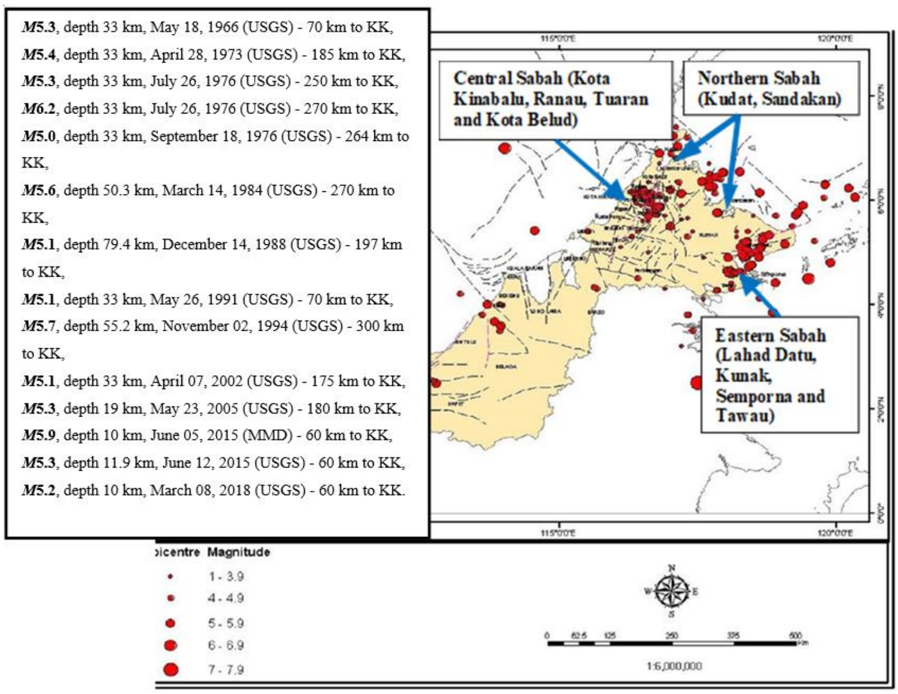


Fig. 2 Seismicity in Sabah between 1966 and March 2018 (inclusive), with details of $M \geq 5$ events included in the textbox

Table 2 Listing of local $M \geq 5$ events in Zone 3 (CNE Sabah) in the 50-year period 1966-March 2018, and analysis of frequency of occurrence

Region	Districts	Area (sq. km)	Magnitude of historical earthquakes	Approximate epicentral distance from Kota Kinabalu (km)	Year of occurrence	Analysis of frequency of occurrence in a normalised area of 10,000 sq. km
North-west and central Sabah	Kota Kinabalu	816	*M*5.3, *M*5.1, *M*5.9, *M*5.3, *M*5.2	70, 70, 60, 60, 60	1996, 1991, 2015, 2015, 2018	5/(8734/10,000) = 5.7
	Ranau	3556				
	Tuaran	1166				
	Kota Belud	1386				
	Penampang	464				
	Tambunan	1347				
	Total area =	8734				
Eastern Sabah	Semporna	1145	*M*5.0, *M*6.2, *M*5.3, *M*5.6, *M*5.7	264, 270, 250, 270, 300	1976, 1976, 1976, 1984, 1994	5/(8780/10,000) = 5.7
	Lahad Datu	6501				
	Kunak	1134				
	Total area =	8780				

*CNE: Central and North-eastern (include Kota Kinabalu)

Sabah (near Ranau which is only some 50 km from the capital city of Kota Kinabalu). Observation of the disposition of historical epicentres shows a clustering around two areas within Zone 3: (a) an area surrounding Ranau which includes the state capital city: Kota Kinabalu, Ranau, Tuaran, Kota Belud, Penampang and Tambunan, (b) an area surrounding Semporna which includes Semporna itself, Lahad Datu, Tawau and Kunak. Analysis of the frequency of occurrence of $M>5$ events in these two areas revealed similar levels of intensity of seismic activity when the earthquake counts had been normalised to an area of 10,000 sq. km. Details of the analysis are summarised in Table 2. The $M>5$ earthquake event count of $N(M>5)=5$ in the 50-year period, over an aggregated land area of 8734 sq. km in North-western and central Sabah is shown to be consistent with an event count of $N(M>5)=5$ over an aggregated land area of 8780 sq. km in Eastern Sabah when the value of $N(M>5)$ had been normalised to a common area of 10,000 sq. km (see Table 2). In summary, the frequency occurrence of earthquakes in Zone 3 (Central and Eastern Sabah) have been shown to be comparable.

Despite the observed clustering of earthquake activities in the past 38 years, much of Zone 3 in Sabah should be considered as one block and the stretch of land separating Ranau and Semporna should be considered as possessing similar level of earthquake activity generating potential, as the two areas have very limited data (in a mere 38-year period of instrumented earthquake recording) (Che Abas 2001, MOSTI 2009). The northern part of Sabah (e.g., Kudat and Sandakan) had experienced some *M*5 earthquakes in the past and hence it is included into the same block in Zone 3. This approach to modelling is warranted because of the major active fault identified in the central part of Sabah along with the dense network of fault

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 (in PEER 2015)	PZCT15*	PEER report 2015/04
Darragh *et al*. (in PEER 2015)	DASG15	PEER report 2015/04
Shahjouei and Pezeskh (in PEER 2015)	SP15*	PEER report 2015/04
Al Noman and Cramer (in 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

*Models labelled with an asterisk feature a geometrical attenuation factor of $R^{-1.3}$ within about 50 km site-source distance as opposed to the conventional factor of R^{-1}.

lines in the south (Tongkul 2016).

In summary, the whole of CNE Sabah including Kota Kinabalu and Ranau and the stretch of land between these cities right up to the eastern coast is of one level of seismic hazard and can be classified as areas of moderate seismicity. PSHA for this part of Sabah is described in detail in the next section, which gives a reference PGA value of 0.12 g.

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 as 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 that adapting those GMPEs for use in low-to-moderate seismicity countries like Malaysia and Singapore must take into account factors controlling the: (a) wave generation behaviour at the source of the earthquake in a given tectonic setting and (b) wave modification behaviour of the earth (basement rock) crusts which are not to be confused with the modification behaviour of near-surface sediments. The discussions below in Section 3 are mainly referenced to the previous work in Lam *et al*. (2016a).

3.1 Peninsular Malaysia and Singapore (Zone 1), Sarawak and SW Sabah (Zone 2)

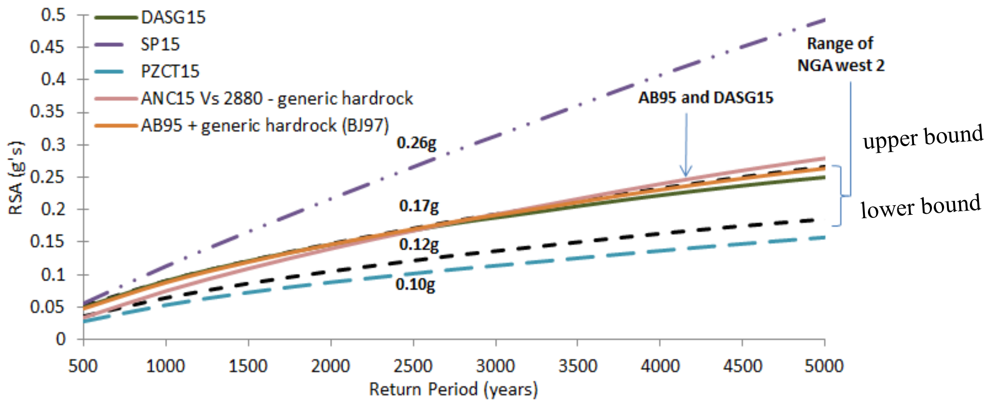
In this relatively stable region of Malaysia (Peninsular, Sarawak and SW Sabah) and Singapore, the ground motion models intended for use in stable (intraplate) regions such as eastern North America should be adopted. The Next Generation Attenuation of the eastern North American (NGA-East) database comprises 29000 records from 81 earthquake events recorded from 1379 stations (PEER 2015/04). This database of earthquakes can be taken to be representative of seismic wave generating behaviour in an intra-plate tectonic setting. Ground Motion Models (GMMs) based on this database, have the merit of deriving from the most elaborate existing database of intra-plate events. A literature review of the seismological studies of ground motion models for Eastern North America (ENA) identified some 40 models developed in the period 1983-2014. A subset of 22 models was selected based on quality and the age of the data. Further screening reduced those 22 to 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*.

PSHA results 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 (Fig. 3). 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 the consistencies shown with model predictions and field recordings. Overall, predictions made by the AB95 and the DASG15 GMMs of NGA-East are comparable with predictions from the NGA-West2 and only marginally higher at 0.3 s.

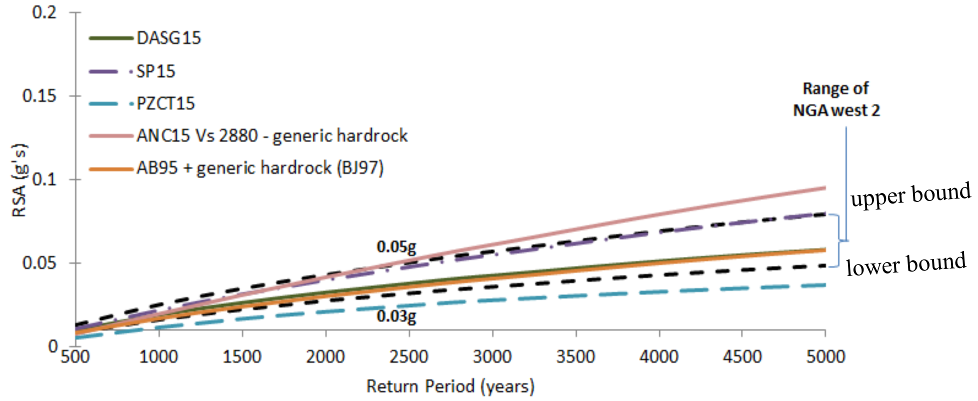
The authors had experience of combining the source model of AB95 with the (non-cratonic) crustal model of generic rock (Boore and Joyner 1997, which is abbreviated herein as BJ97) for predicting ground motions generated by intra-plate earthquakes. Simulated RSA values for the non-cratonic version of AB95, based on the classical generic rock class of Boore and Joyner, (1997) are representative of non-cratonic regions. Predictions by the (non-cratonic) model are shown in Fig. 4 to be significantly higher than the upper limit of predictions by the NGA-West2 models. The RSA value of 0.25 g at 0.3 s is translated to an effective PGA of 0.1 g for a return period of 2475 years, or 0.07 g (2/3 of 0.1 g) for a notional return period of 475 years.

3.2 CNE Sabah (Zone 3)

PSHA for various areas within Sabah was undertaken by ARUP (Pappin *et al*. 2011). The conclusions drawn from the sub-section 2.2 results obtained for Kota Kinabalu specifically were called up to represent the region considered in this sub-section. Results obtained in the

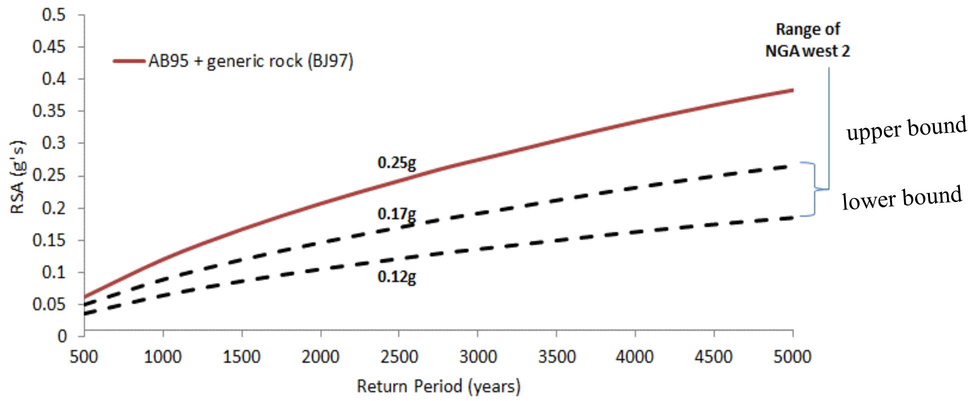


(a) 0.3 s period

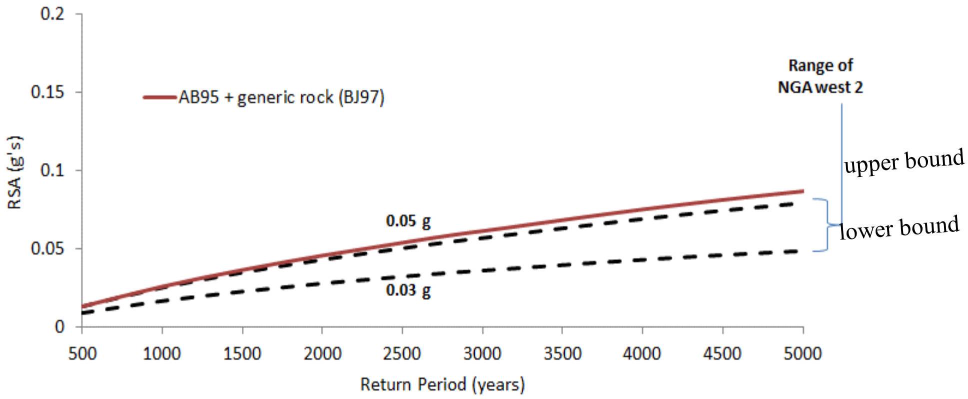


(b) 1.0 s period

Fig. 3 Selected ENA (cratonic) models overlaid on NGA-West2 models for $\log_{10} N$=5.5-0.9M



(a) 0.3 s period



(b) 1.0 s period

Fig. 4 ENA (non-cratonic) model (AB95 + BJ97) overlaid on NGA-West2 models for $\log_{10} N$=5.5-0.9M

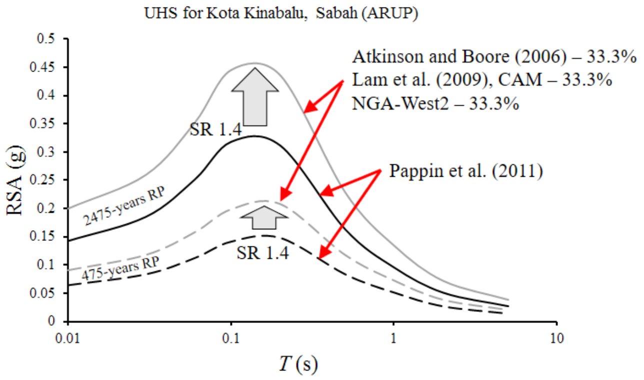


Fig. 5 Adjusted uniform hazard response spectrum on rock based on the original spectrum recommended by Pappin *et al*. (2011)

earlier study are summarised in Fig. 5, showing a maximum response spectral acceleration value of 0.15 g and 0.32 g at return periods of 475 years and 2475 years, respectively.

The Ground motion models considered relevant for this part of Sabah are those of: (i) Atkinson and Boore (2006) which was adapted from the initial study by ARUP and is codenamed herein as AB06 (ii) Atkinson and Boore (1995) but modified for non-cratonic conditions as described above and is codenamed herein as CAM, an acronym for Component Attenuation Model (Lam *et al*. 2000), and (iii) the 2nd edition of the Next Generation Attenuation Model for the tectonically active region of western North America and is codenamed herein as NGA-West2. Items (i) and (ii) are for modelling intra-plate earthquakes which typically occur infrequently, whereas item (iii) is for modelling inter-plate earthquakes. It is noted that AB06 gives predictions that are close to the lower bound of NGA-West2. Thus, ground motion models representing a diversity of conditions in tectonic and crustal terms, have been incorporated into the study because of the Sabah conditions.

It can be shown that CAM gives response spectral predictions at 0.2 s which are two times that of AB06 (i.e., spectral ratio, SR=2.0) whereas the upper bound of NGA-West2 gives predictions which are 1.4 times that of AB06 (i.e., spectral ratio, SR=1.4). The quoted SR values can be inferred from Fig. 3(a) and 4(a) An equal weighting factor of 33.3% are used on the ground motion models considered, i.e.: AB06, CAM and upper bound of NGA-West2 resulting in a resultant SR of 1.4 (being 1×0.333+2×0.333+1.4× 0.333). The maximum response spectral acceleration value of 0.32g, as shown in Fig. 5 is accordingly increased to 0.45g. The notional peak ground acceleration value is accordingly 0.18g of a return period of 2475-year (being 0.32 g divided by 2.5) and 0.12 g at a notional return period of 475-year (being 2/3 of 0.18 g).

4. Modelling of distant earthquakes

Earthquake hazards arising in Sumatra are from two major sources: (1) the Sunda Arc subduction fault source off-shore of Sumatra; and (2) the Sumatran strike-slip fault source (see Fig. 6). The subduction fault is formed by convergence of the Indian-Australian plate with the Eurasian plate. Megathrust earthquakes including that of the Aceh 2004 (M9.3) and Nias 2005 (M8.7) events were generated by this fault source. The distance from this fault to Peninsular Malaysia and Singapore is 530 km-730 km. The Sumatran strike-slip fault, located within the Sumatran island is 1500 km long and some 300-400 km from Kuala Lumpur, i.e., much closer than the subduction fault source. The magnitudes of recorded historical earthquakes

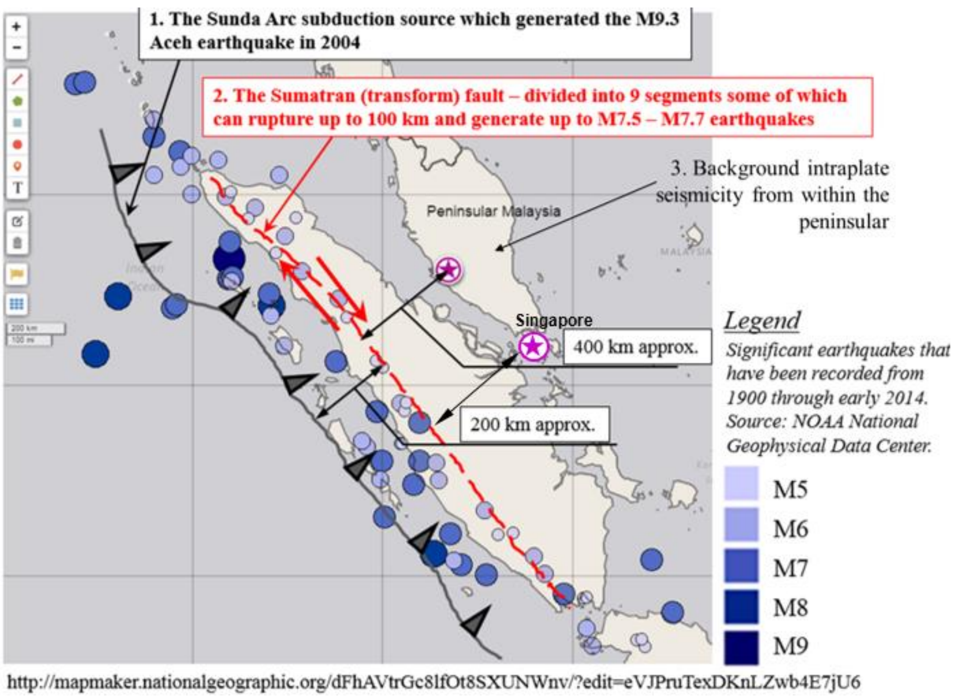


Fig. 6 Offshore earthquake generating sources affecting Peninsular Malaysia and Singapore

generated at this latter fault source have been limited to around *M*7.8.

Numerous research groups have contributed to the assessment of the above far-field seismic hazards affecting Peninsular Malaysia and Singapore. Numerous representative GMPEs for the prediction of ground motion levels as functions of magnitude and distance have been developed in those studies. 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 the inconsistencies in predicted ground motion values from different GMPEs, verification analyses have been undertaken to identify those models which give results that match well with instrumented data collected from the field (Chandler and 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) the Component Attenuation Model (CAM) and (2) the Megawati's attenuation relationship.

CAM was first developed and coded into the program GENQKE which generates synthetic earthquake accelerograms based on stochastic simulations of the seismological model of Atkinson and Boore (1995) along with the generic crustal model of Boore and Joyner (1997). See Lam *et al*. (2000) for more details. Whilst CAM was initially developed to predict 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 (Chandler and Lam 2004). CAM has been successfully demonstrated as capable of modelling distant mega-magnitude earthquake events generated at the Sunda-Arc subduction source, offshore of Sumatra, affecting Singapore and Peninsular Malaysia (Lam *et al*. 2009, Balendra *et al*. 2002, Balendra and Li 2008). The CAM simulation model 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 rate is so gradual at a long distance from the source, that the change in hazard level across the width of the Peninsula is small. In perspective, buildings that are vulnerable to collapse and severe damage in an earthquake are low-rise and medium-rise 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 hazard sources anyway. Thus, the long distance earthquake hazard affecting Peninsular Malaysia and Singapore, is to be based on the one response spectral model for all areas.

The Megawati's attenuation relationship when modelling ground motions generated at the Sumatran fault source (Megawati *et al*. 2003) and those from the Subduction fault source (Megawati *et al*. 2005) were reported in Pan *et al*. (2007) and revised in Megawati & Pan (2010). Synthetic seismograms derived from the analysis of a finite-fault kinematic model have been verified in a manner similar to that for the CAM. This attenuation relationship is based on hard rock conditions and site-source distances ranging between 200 and 1500 km. The use of the relationship developed, for predictions outside this distance range, should be treated with caution.

In addition to the deterministic studies described above, Pappin *et al*. (2011) conducted PSHA for Malaysia based on historical earthquake data which recorded over the past 40 years since 1972, 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 maximum earthquake magnitude was assigned for different areas and depths in Pappin *et al*. (2011).

The response spectrum produced from a PSHA is known as a Uniform Hazard Spectrum (UHS) in which contributions from multiple fault sources are 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 associated with very different contributory earthquake scenarios. According to the latest PSHA (Pappin *et al*. 2011), seismic hazard levels vary across Peninsular Malaysia (due to the different distances from potential earthquake sources), with Penang posessing the highest hazard. A 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 characteristic of earthquakes generated a very long distance away 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 Peninsular Malaysia. Singapore is located right next to the Peninsula, hence the design spectrum model for a distant earthquake is similar to that of Peninsular Malaysia.

The UHS model developed initially required modifications because of subsequent improvements made to the accuracies of region specific attenuation relationships. The original attenuation relationship of Pan *et al*. (2007) has been updated to that of Megawati and Pan (2010). In parallel with improvements made by Megawati's model, CAM has also been shown able to simulate ground motions which match the instrumented field recordings of major events including the Aceh earthquake of 2004 and the Nias earthquake of 2005 (Lam *et al*. 2009).

In this study, to achieve a more robust UHS, the attenuation model has been revised to incorporate both the updated model of Megawati and 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 presented in Fig. 7 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

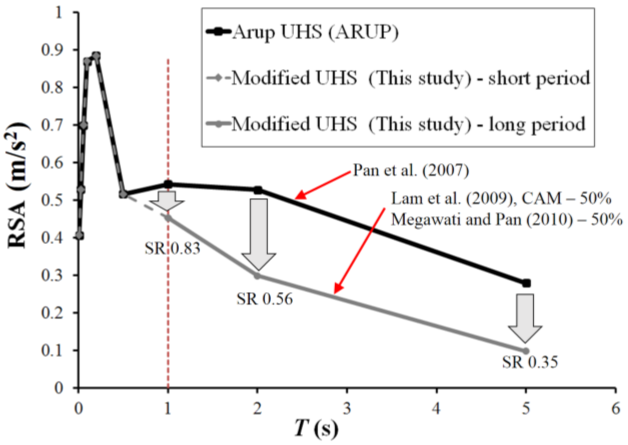


Fig. 7 The original and adjusted uniform hazard response spectra on rock representing distant hazard affecting the Peninsular Malaysia and Singapore

calibrating the response spectra based on 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.

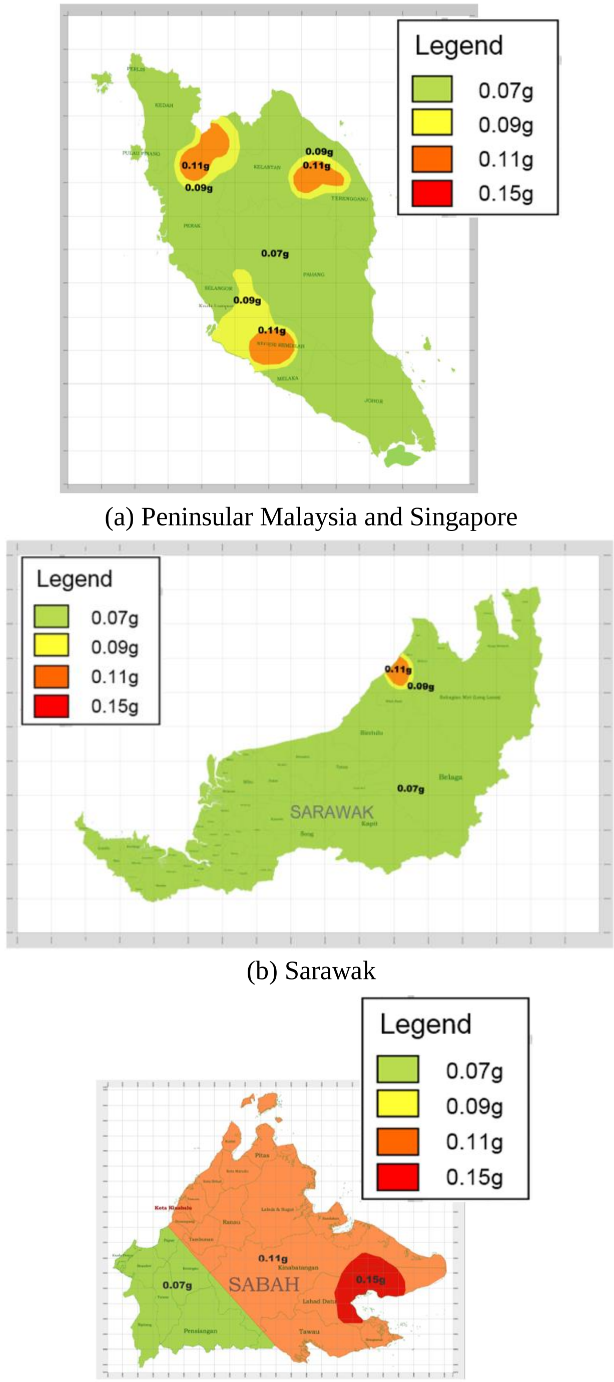
c) The response spectra of the calibrated earthquake scenarios were then re-calculated using the updated attenuation model of Megawati and Pan (2010) along with CAM based on equal weightings. The differences in the spectral parameters were represented by the SR geometric means, at the three reference periods, from amongst the seven calibrated scenarios. The SR for other UHS periods were determined accordingly, by interpolating 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-5 s based on probabilistic analysis, is approximately double the response spectral values based on deterministic (median) predictions as published in Lam *et al*. (2009).

5. Proposed seismic hazard featuring minimum loading for adoption in design

Any country located in a low or moderate seismic region should impose, it is recommended, a minimum loading, to constrain the seismic hazard estimates particularly if the land area is not sufficiently large to have captured a statistically meaningful database of records of destructive earthquakes from within the country. Nevertheless, the option exists of superimposing the modelled hazard (for the identified hot spots) on a map showing uniform hazard zones (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. For the Peninsular Malaysia and Sarawak, hotspots can be identified (Adnan 2017, NA-2017). For SW Sabah, no such hot spot, posing a threat to a centre of population, has been identified. For Singapore, being small in land area, no major event has occurred in history, consequently the level of local intra-plate earthquake hazard to be stipulated, can be



(a) Peninsular Malaysia and Singapore

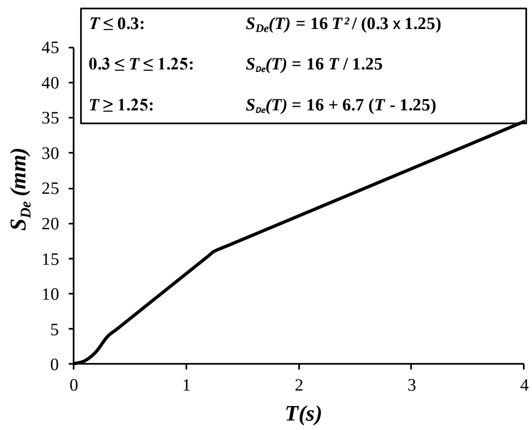
(b) Sarawak

(c) Sabah

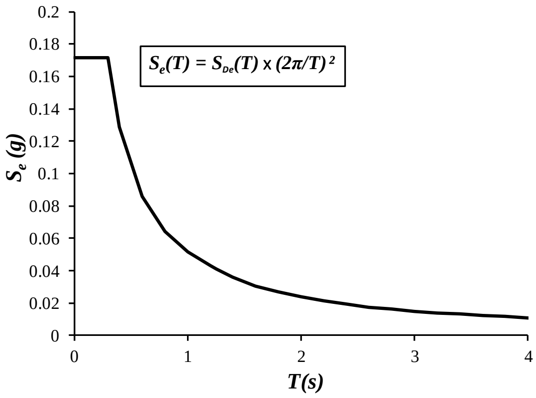
Fig. 8 Proposed seismic hazard contours featuring a minimum reference PGA value for adoption in design

based entirely on the results derived from the broad source zone model.

To address the modelling of uncertainties, a seismic zonation map with hot spots (Fig. 8) which features a minimum reference PGA value of 0.07 g for Peninsular Malaysia, Singapore, Sarawak, and SW Sabah (excluding Kota Kinabalu), and 0.12 g for CNE Sabah (including Kota Kinabalu) is proposed to provide a precautionary minimum reference PGA value for those areas, even though more than the conventional PSHA would indicate.

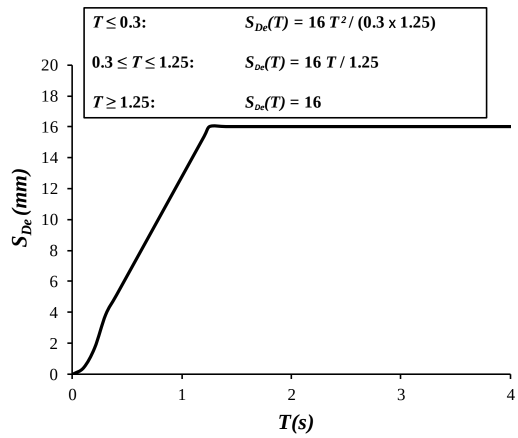


(a) displacement format

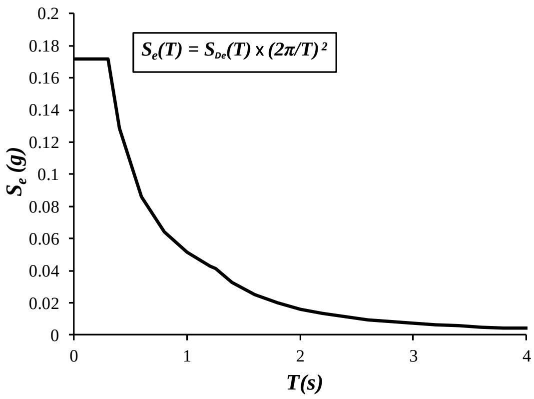


(b) acceleration format

Fig. 9 Elastic response spectrum on rock for Peninsular Malaysia for importance Class II ordinary buildings (similar for Singapore) (Design PGA=0.17 g/2.5=0.07 g, notional RP=475 years)



(a) displacement format



(b) acceleration format

Fig. 10 Elastic response spectrum on rock for Sarawak and SW Sabah for importance Class II ordinary buildings (Design PGA=0.17 g/2.5=0.07 g, notional RP=475 years)

6. Elastic response spectra on rock

6.1 Peninsular Malaysia and Singapore (Zone 1)

The response spectrum models of Malaysia do not follow those of the generic EC8 which stipulates Type 1 and Type 2 spectrum, as Cl. 3.2.2.2 (2)P of EC8. The model proposed for Peninsular Malaysia (in Fig. 9(a)-(b)) is a composite (hybrid) model which encapsulates results from the conventional PSHA of recorded distant earthquakes, as well as from the probabilistic predictions of the local earthquakes based on broad source zone modelling (Zone 1) as described above. This approach makes good use of the abundant distant events data, whilst obtaining robust estimates for locally generated hazards. Singapore is located at the south of the Peninsula, so the response spectrum model for Peninsular Malaysia should also be applicable to Singapore, given that no major event has occurred in the vicinity of Singapore in history.

The PGA values for the notional 475-year RP and the benchmarked 2475-year RP are 0.07 g and 0.1 g respectively. It should be noted that the short corner period (known as T_B in EC8) is not defined for the spectrum in Fig. 9(b) which has a flat plateau (similar in Fig. 10(b) and 11(b)). The maximum RSA value of 0.17 g is not to be confused with the notional PGA of 0.07 g (being 0.17 g divide by 2.5).

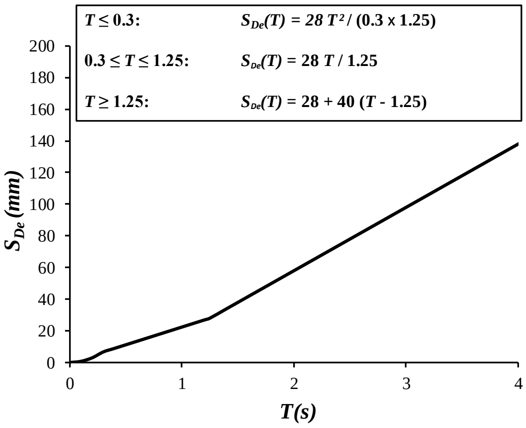
6.2 Sarawak and SW Sabah (Zone 2)

The response spectrum model for Sarawak and SW Sabah (Fig. 10(a)-(b)) is essentially based on the considerations applying to local intraplate hazards only (Zone 2). The values of PGA for the notional 475-year RP and the benchmarked 2475-year RP are 0.07 g and 0.1 g respectively, as for Peninsular Malaysia, but differs in the higher period range (>1.25 s) due to different frequency of distant earthquake events.

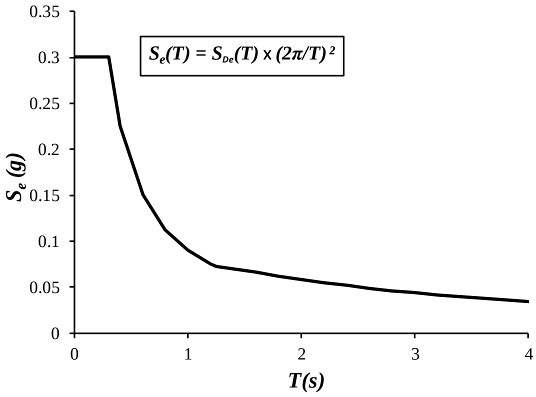
6.3 CNE Sabah (Zone 3)

The response spectrum model for the CNE Sabah (northeast of the dividing line) is essentially based on conventional PSHA analysis based on recorded seismicity data (Fig. 11(a)-(b)). The values of PGA for the notional 475-year RP and the benchmarked 2475-year RP are 0.12 g and 0.18 g respectively. See above for a description of the modelling methodology.

6.4 Alternative expression for elastic response spectrum on rock



(a) displacement format



(b) acceleration format

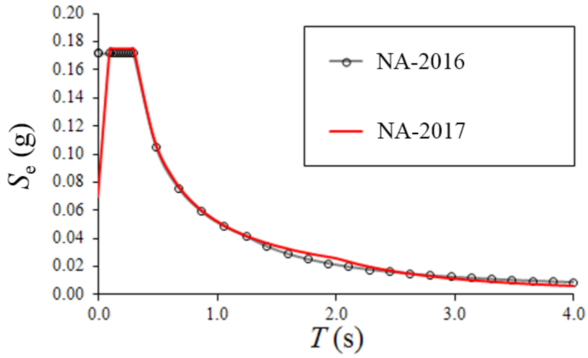
Fig. 11 Elastic response spectrum on rock for CNE Sabah for Importance Class II ordinary buildings (Design PGA=0.30 g/2.5=0.12 g, notional RP=475 years)

Table 4 Summary of elastic response spectrum for ground type A in NA-2017

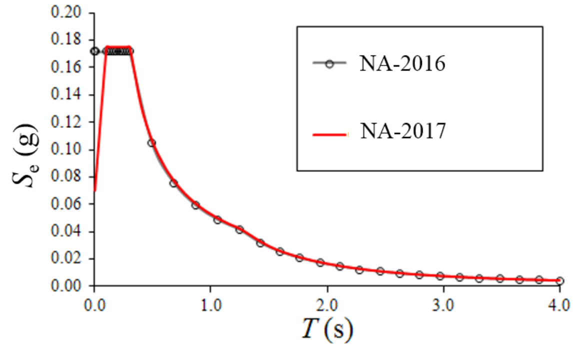
Location	T_B^* (s)	T_C^* (s)	T_D^* (s)
Peninsular Malaysia (applicable to Singapore)	0.1	0.3	2.0
Sarawak (and SW Sabah)	0.1	0.3	1.25
Sabah (CNE)	0.1	0.3	4.0

*Definition in EC8, where T_B: lower limit of the period of the constant spectral acceleration branch; T_C: upper limit of the period of the constant spectral acceleration branch; T_D: value defining the beginning of the constant displacement response range of the spectrum.

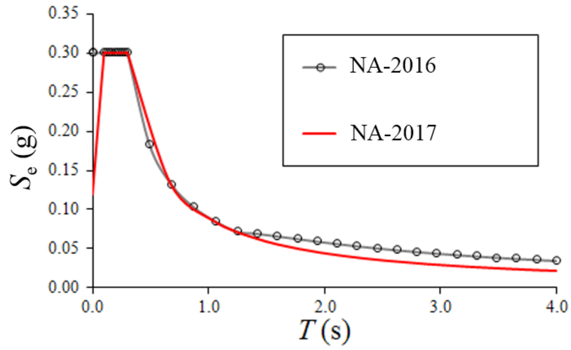
The response spectrum models discussed above were originally formulated in displacement format (NA-2016, draft Malaysia NA to EC8 in the first public ballot in April 2016) and can be conveniently converted into acceleration format by following fundamental principle (see Fig. 9(b), 10(b) and 11(b)). Nonetheless, alternative expression strictly based on the rigid framework of EC8 can be compromised. Table 4 shows the summary of ground type A of the latest draft Malaysia NA to EC8 which went through the second public consultation process in October 2017 (NA-2017). Fig. 12 shows the comparison of the elastic response spectrum on rock for Peninsular Malaysia and



(a) Peninsular Malaysia (applicable to Singapore)



(b) Sarawak (and SW Sabah)



(c) Sabah (CNE)

Fig. 12 Comparison of elastic response spectrum on rock in NA-2016 and NA-2017

Singapore, Sarawak and SW Sabah, and CNE Sabah based on the acceleration converted from displacement format recommended in NA-2016 and the rigid EC8 format written into NA-2017.

7. Conclusions

This paper explains the approach taken in the draft NA for Malaysia to EC8 to quantify the design seismic hazard for a low-to-moderate seismicity region like Malaysia and Singapore. The study first identified the seismic activities, which have occurred in the vicinity of, and locally within, the landmass, and categorised the types of seismic activities into low and high period response spectra ranges. The modelling of local intraplate hazard was presented based on the broad source zone model according to Lam *et al.* (2016a), which resulted into three zones, Zone 1 for

Peninsular Malaysia and Singapore, Zone 2 for Sarawak and Southwestern (SW) Sabah, and Zone 3 for Central, Northern and Eastern (CNE) Sabah. Conventional PSHAs on distant earthquakes and an updated UHS for Peninsular Malaysia and Singapore is presented. A hybrid design response spectrum for Peninsular Malaysia (and Singapore) encapsulating both long distance (Sunda Arc subduction and Sumatran fault) earthquakes and local intra-plate earthquakes, based on different probabilistic modelling approaches, is proposed. It is noted that the current NA for Singapore, to EC8, is primarily intended to address distant hazards arising in Sumatra. The hybrid model, therefore, provides a reconciled elastic response spectrum for Singapore, aiming to achieve a more robust level of structural safety. The minimum earthquake loading model (based on a broad source zone), applicable to low to moderate seismic risk geographical zones in conjunction with conventional PSHA results for hot spots are synchronised into one map to take account of the few, if any, earthquake records for relatively small areas. The design response spectra for Peninsular Malaysia and Singapore, Sarawak and SW Sabah, and the rest of CNE Sabah derived in the NA-2016 and NA-2017 were discussed.

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