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RESEARCH

Development of elastic design response spectra with emphasis on far-source earthquakes for low to moderate seismic region

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Abstract

The development of design response spectra is crucial for earthquake design of structures. However, there are disagreements from the engineering community on the suitability of design values proposed by the existing design code which underestimates the long-period responses for flexible soils, typical of far-source earthquakes. This study uses soil response analysis to investigate the effect of near and far sources' earthquakes on the response spectral acceleration of Malaysia in three seismically different regions, namely Peninsular Malaysia, Sabah and Sarawak. 1923 borehole data have been collected and analysed under 5 near and 4 far sources earthquakes, subjected to the intensity from the probabilistic seismic hazard analysis. The results show that for Peninsular Malaysia, the far-source earthquake will govern the response at a period of more than 1 s, indicating its importance for structures with long periods such as tall buildings. It is also found that the corner period T_C is slightly higher than the code recommended and is dependent on the soil property, while T_D is significantly higher for far-source earthquakes due to the larger magnitudes. The finding of this research shows that the Eurocode 8 supplemented by the Malaysian National Annex (MS-EN1998-1, 2017) can be used to design structures in Malaysia, with some adjustments to the longer period motion for Peninsular Malaysia. Finally, it is recommended to perform an enhanced analysis for important structures of long periods to ensure their loadings are not underestimated.

Keywords Response spectral acceleration · Code · National Annex · Far-source earthquakes

Introduction

Malaysia is located on a stable Sunda plate, surrounded by countries of high seismicity, namely Indonesia and the Philippines. Based on the probabilistic seismic hazard analysis (PSHA) conducted, Malaysia is a country of low to moderate seismicity, depending on the region. Malaysia consists of 3 geographically different regions, namely Peninsular Malaysia, Sabah, and Sarawak as shown in Fig. 1. The seismic threats in Peninsular Malaysia are from local and far-source earthquakes, while Sabah and Sarawak are mainly from local earthquakes.

Recently, Malaysia adopted Eurocode 8 (EN, 2004) for the seismic design of structures. However, the seismicity of the region is much different from the recommended values in the code, triggering the need to develop Malaysia National Annex (MS EN, 2017) for the regional design values. Due to the lack of recorded regional data for local and far-source earthquakes, the development of response spectra based on statistical analysis is not possible and could cause large over predictions of the potential hazard (Gao et al., 2021).

The seismic hazard in Malaysia is coming from two main sources, (1) near-source earthquakes of small to moderate magnitudes (maximum 5.3 M_w for Peninsular Malaysia and Sarawak, and 6.5 M_w for Sabah) with epicentral distances ranging from 5 to 30 km, and (2) far-source earthquakes from strike-slip and subduction zones with large magnitudes (7–9.2 M_w) and distances (200 to 500 km). The former causes larger amplitude at smaller periods, while the latter

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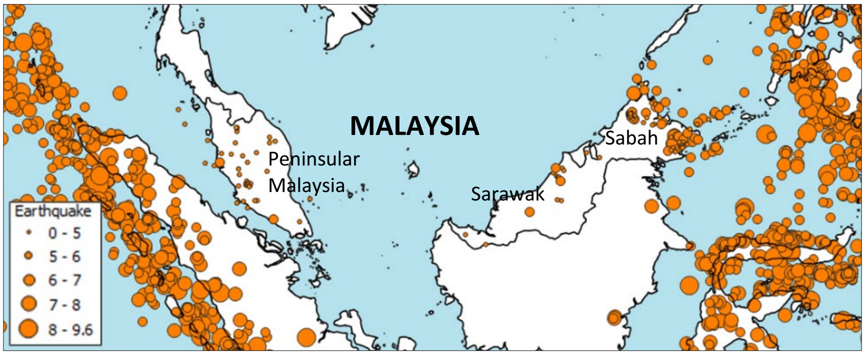


Fig. 1 Past earthquakes around Malaysia

controls the maximum displacement range at the higher periods. The effects of the sources on the seismic demand must be investigated due to the unique nature of this region. Tremors from far-source earthquakes have been felt especially in Peninsular Malaysia (example: 6.1 M_w West Sumatra earthquake on 25 February 2022). The need to distinguish and emphasise the importance of far-source earthquake effects must be done to ensure the proper design of medium to high-rise buildings.

Far-source earthquakes

The far-source long-period earthquake is characterised by its later-arriving surface waves, having long-period motion (Dai et al., 2019). The long-period motion tends to attenuate slowly at a longer distance due to the path effect. In the paper by Koketsu and Miyake, (2008), the velocity time-history of far-source long-period earthquakes exhibits a longer duration compared to the near-source long-period earthquakes. In addition, the values of the velocity response spectra of the far-source earthquake are comparable to the near-source earthquake, despite the smaller amplitude of the former. The 1968 Tokachi-Oki earthquake in Japan with 8.2 M_w is an example of such an earthquake, where the predominant period is 2.5 s and the motion was measured in a high-rise building 650 km from the epicentre. As highlighted by Dai et al., (2019), near-source earthquakes are earthquakes with an epicentral distance of fewer than 50 km. In their study, there is no clear definition of far-source earthquake as the far-source long-period ground motions were selected based on visualisation of the waveforms of the velocity–time series. However, it is implied that earthquakes with distances of more than 100 km are taken as far-source earthquakes (Saman et al., 2021).

The motion of far-source long-period earthquakes can also be amplified due to the site condition, causing the greatest effects to the medium to high-rise structures (1 to 10 s periods). The effect of far-source long-period motion on flexible soil is evident in the case of the famous Michoacan earthquake in 1985. Mexico City, located 400 km from the epicentre, is heavily damaged compared to locations that are much closer to the epicentre. The field report by EEFIT (Booth et al., 1986) concluded that the motion amplified by the local site condition is very large, even though the motion attenuated by the distance is considered to be harmless. The amplification is found to be 10 times of rock site, at a period of about 2 s. Nabilah et al. (2019) in their research, discovered that sites with soft, flexible soil yield higher spectral acceleration at longer periods, and up to 2 to 3 times larger than that recommended by Eurocode 8.

Soil response in Eurocode 8 and its application in low to medium seismic regions

Soil classification

The soil classification in Eurocode 8 (EN, 2004), EC8, is quite descriptive, which takes into account the soil profile for limited depths of soil. EC8 uses the average shear wave velocity of the top 30 m of soil ($V_{s,30}$), where the classification generally goes from stiff (soil A) to soft (soil D) soil as given by other seismic codes. Soil type E, on the other hand, deals with shallow soft soil (soil C or D) underlain by bedrock, which will cause large amplification due to the impedance contrast between bedrock and the overlain soil. However, soil classification based on $V_{s,30}$ might not represent the actual soil behaviour, which could lead to errors in the determination of earthquake loads for deep soil conditions (Barani et al., 2008; Looi et al., 2021; Pitilakis et al., 2004).

For areas with low to moderate seismicity, direct shear wave velocity measurement using the in situ test is very rarely conducted, if any. Hence, an indirect measurement through a standard penetration test (SPT) is used. These tests are usually terminated when the number of blows exceeded 50 within 15 cm depth for three consecutive times. Usually, the soil test rarely reaches bedrock due to the high soil depth.

Design response spectrum

Compared to the International Building Code (International Code Council, 2000), EC8 uses a response spectrum to determine the seismic force at a particular building period. The parameters involved are the soil amplification factor (S) and corner periods (T_B, T_C, and T_D). T_B and T_C denote the period of constant spectral acceleration, T_C and T_D denote the constant spectral velocity region while the period longer than T_D is the constant spectral displacement region (Fig. 2). EC8 specifies two different response spectra, depending on the types of earthquakes an area is subjected to. Type 1 elastic response spectrum (Fig. 3.2 in EC8) is to be used for earthquakes with magnitudes larger than 5.5, while Type 2 spectrum (Fig. 3.3 in EC8) is for smaller earthquakes (magnitudes less than 5.5). It could be observed that the response spectra of larger earthquakes have smaller amplification (S factor), and the corner periods are higher compared to the smaller magnitude earthquakes. This is due to the non-linear soil response for stronger ground motion, causing smaller amplification, while the frequency content of larger earthquakes is typically smaller and causes a shift in the corner periods.

The findings by Booth and Lubkowski, (2012) suggest that the corner period (T_D) in EC8 is low, which could underpredict the displacement demand of long-period structures. In addition, the response spectra for soil types C and D are much lower compared to NEHRP (2011) values, underestimating the long-period responses, typical of far-source earthquakes. Based on the study by researchers (Looi et al., 2021; Nabilah & Balendra, 2012), the response spectra in EC8 need to be adjusted to take into account the effects of both near and far-sources' earthquakes unique in this region. Compared to the existing spectra in EC8, the Type 2 curve could fit the near-field earthquakes in this region for Peninsular Malaysia and Sarawak. However, the far-source earthquake having a large magnitude at higher distances is of low amplitude, possibly causing larger amplification, especially at longer periods.

Malaysia adopted the EC8 for seismic design in this region. There has been a long debate on the determination of parameters to be used for its National Annex (MS EN, 2017), NA, due to the low to medium seismicity of this region. In the past, there has been a disregard for the earthquake effects on the design of buildings in Malaysia. Thus, the introduction of EC8 was extensively discussed among practising engineers on its applicability and design values. This paper aims to evaluate the applicability of the values in EC8 and the accompanying NA to Malaysia, considering different seismicity in the three regions (Peninsular Malaysia, Sabah, and Sarawak). The response spectra of different soil conditions were compared to the soil response analysis conducted based on soil data collected across Malaysia subjected to near and far sources' earthquake motions, as well as suitable existing ground motion models (GMM). The response spectra were also compared to the GMM suitable in this region. Finally, some recommendations were given to the NA to improve the estimation based on the results.

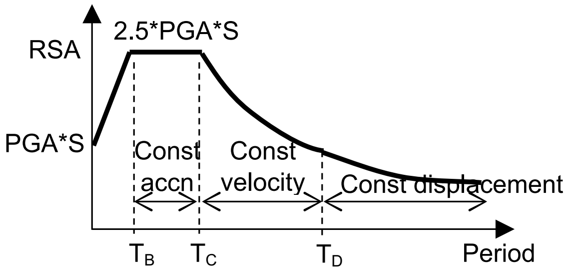


Fig. 2 Response spectral acceleration according to EC8

Research significance

The effects of far-source earthquakes on the design of structures of low to medium seismicity regions have been studied by many researchers (Muin et al., 2020; Pan et al., 2006; Su et al., 2015). However, a consensus on the values and limits to be used has not been achieved, with considerable arguments from the engineering communities on its suitable values and rationale. This study attempts to distinguish between the far-source and near-source earthquakes and perform the soil response analysis to observe the significant differences between them. Further comparing with the existing GMM proves that the consideration for large magnitude, far-source earthquakes is of high importance in regions with low seismicity which will govern the design of high period structures such as tall buildings. Through this research, the Malaysia National Annex could be updated considering the far-source seismicity to better design structures. Structures of medium to high periods will be designed for these earthquakes, which tremors have been felt frequently in the Peninsular Malaysia region, especially in the city centres. Moreover, the results from this analysis could convey valuable information for other areas with similar seismicity as Malaysia, and the recommendations could be implemented accordingly.

Existing ground motion models

In areas of low to medium seismicity, there is an apparent lack of earthquake data that could be used to estimate the acceleration response for the region. Consequently, 1-D soil response analysis could be conducted using worldwide earthquake data, however, cannot be verified from past events in this region. Due to this, the ground motion models (GMMs) developed by researchers around the world could be implemented to obtain the approximate response of structure against specific magnitude and distance earthquakes. Most of the GMMs developed were to obtain the peak ground acceleration and velocity (PGA and PGV, respectively) for the region, rather than the response spectral acceleration (RSA). **Table 1** tabulated the available GMMs for PGA and RSA developed in the past 20 years relevant to this region, with recommended application ranges. The RSA in Table 1 was developed for a 5% damping ratio.

From the available GMMs in Table 1, Campbell and Bozorgnia, (2014) is found to best represent the seismicity of this region due to the wide ranges of earthquake magnitude and distance, with consideration of many important parameters and soil types. Hence, this model will be used as the basis to compare the statistical analysis, ensuring a better representation of the response spectra of this region.

Soil response analysis

For small vibration, soil analysis is assumed to be linear. Each soil layer is assigned a shear modulus and material damping ratio. As the soil layer is modelled as a horizontal layered system, the analysis can be reduced to a simple 1-D wave propagation problem. However, when soil is subjected to large vibration, soil properties can be extremely non-linear. Thus, the change in shear modulus and damping ratio with shear amplitude needs to be accounted for. Hence, the modification of the linear analysis can be used, which is termed equivalent linear analysis. In this method, the linear analysis with dynamic soil properties is performed in an iterative manner consistent with an 'effective' shearing strain induced in the soil later. These soil properties are determined from empirical curves by various researchers, based on laboratory studies.

The soil response analysis in Malaysia is conducted separately for the three regions namely Peninsular Malaysia, Sabah, and Sarawak due to the different geological conditions and earthquake hazards. For the soil response analysis, soil investigation data in the form of borehole logs were collected to obtain the soil types and SPT values, and the estimation of the static and dynamic soil properties. Next, suitable time-history data were collected to represent the seismic load in the area based on the seismic hazard analysis conducted by previous literature. Finally, equivalent linear soil response analysis is conducted for all the soil types and earthquake records, using DEEPSOIL (2021) capable of performing equivalent linear and non-linear site response analyses. The acceleration response spectra for different soil types were later compared with EC8 and the GMM.

Data collection and analysis

For areas with low to moderate seismicities, in situ shear wave velocity measurement is rarely conducted. Due to the unavailability of shear wave velocity data from field testing,

Table 1 GMMs available for the region of interest

Reference	Predicted values	Magnitude (M_w)	Distance (km)	Other parameters	Comment
Youngs et al. (1997)	PGA, RSA on rock, shallow and deep soils	5–8.2	10–500	Depth, source type (interface/intraslab)	Recorded ground motions of worldwide subduction earthquakes
Lam et al. (2022)	PGA, PGV, RSA on rock	Not specified	Not specified (compared with 300–400 km eq)	Crustal thickness	Using Component Attenuation Model for near- and far-source earthquakes in Hong Kong
Megawati et al. (2005)	PGA, PGV, RSA on rock	4.5–8	150–1500	Focal depth	Derived the GMM based on the synthetic seismograms for Sumatran-subduction earthquakes
McVerry et al. (2006)	PGA, RSA for soil	5.08–7.23 (up to 7.09 for RSA)	6–400	Depth, fault mechanism, hanging wall, site class	Based on New Zealand data for crustal and subduction zone earthquakes
Campbell and Bozorgnia (2014)	PGA, PGV, RSA on soil	3.3 to 7.5–8.5, depending on source mech	0–300	Fault type, hanging wall geometry, shallow site resp., basin resp., depth, fault dip, anelastic attenuation	Updated the GMM based on new earthquake data (California and worldwide)

the SPT values obtained from borehole data were converted using the relationship by Imai and Tonouchi (1982) as given in Eq. (1). This relationship is used as it gives the best estimate for Malaysia soil, as described by many researchers (example Jusoh et al., 2020). The test is terminated when the number of blows reaches 50 within 15 cm depth for three consecutive times. For these cases, the number of blows is extrapolated using the relationship in Eq. (2):

$$V_s = 96.9N^{0.314} \tag{1}$$

$$\text{SPT correlation, N} = \frac{(\text{no of blows})}{(\text{penetration length})} * 300\text{mm} \tag{2}$$

Based on EC8, the soil is classified into soil types A to E, based on the average shear wave velocity of top 30 m ($V_{s,30}$), SPT blow count, and the values of the undrained shear strength. Rather than the description of the stratigraphic profile outlined in EC8, the soil classifications will be based on the $V_{s,30}$ of soil which also includes the deep soil condition. Soil type A refers to rock sites with $V_{s,30}$ exceeds 800 m/s, type B with $V_{s,30}$ between 360 and 800 m/s, type C with $V_{s,30}$ between 180 and 360 m/s, and soil type D for very weak soil with $V_{s,30}$ less than 180 m/s. Soil type E, on the other hand, refers to dense to weak soil overlain by bedrock, to take into account the high impedance factor between them. The average shear wave velocity of the top 30 m soil is calculated using Eq. (3). The shear wave velocity of bedrock is assumed to be 800 m/s:

$$V_{s,30} = \frac{30}{\sum \frac{h_i}{V_i}} \tag{3}$$

Table 2 Number of data according to soil type

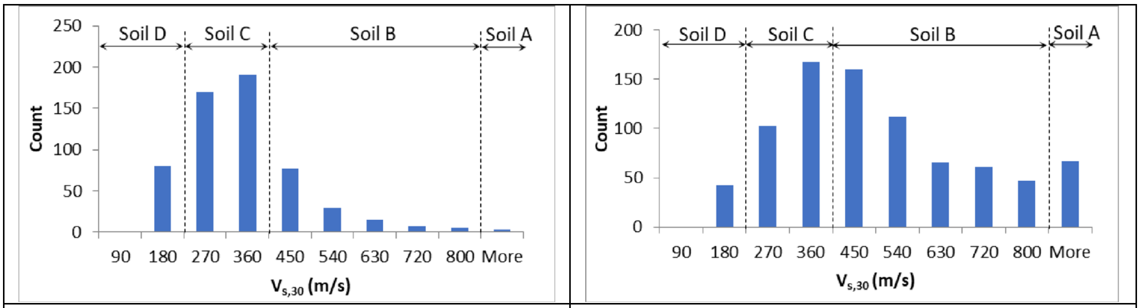
Region	A	B	C	D	E
Peninsular Malaysia	5	133	344	79	16
Sabah	73	440	251	43	19
Sarawak	10	70	325	95	20

In total, 1923 soil data were collected and segregated according to the soil classes in EC8 and shown in Table 2, with the graphical distribution shown in Fig. 3. In general, Peninsular Malaysia and Sarawak show similar soil data trends, with more data collected for soil class C, whereas more data of very dense soil (type B) were collected for Sabah.

The shear modulus reduction, $G/G_{\max}$ and soil damping ratio, were taken from Vucetic and Dobry, (1991), Seed and Idriss (1970), and Schnabel et al. (1972) based on the type of soil. For a detailed description, refer to the research by Nabilah et al. (2019).

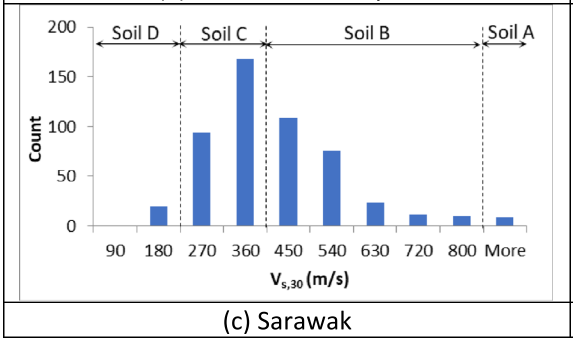
Development of earthquake time-history

The probabilistic seismic hazard analysis (PSHA) conducted by other researchers for Peninsular Malaysia, Sabah, and



(a) Peninsular Malaysia

(b) Sabah



(c) Sarawak

Fig. 3 Distribution of the soil data collected for every region. **a** Peninsular Malaysia, **b** Sabah, and **c** Sarawak

Table 3 Magnitude-distance of earthquakes for each region

Region	Source	*M*	*R* (km)	PGA (g)
Peninsular Malaysia	Near source	4.5–5.5	0–50	0.1
	Far source	6.0–8.0	250–350	0.01
Sabah	Near source	6.0–6.6	0–50	0.17
	Far source	6.0–8.0	300–500	0.01
Sarawak	Near source	4.0–5.5	0–50	0.1
	Far source	6.0–8.0	300–500	0.01

Table 4 Earthquake time histories used for each region

Earthquake	Year		*R* (km)	Mechanism	$V_{s,30}$ (m/s)
All					
Near-source (local) earthquake					
Anza-02	2001	4.92	28.8	Normal	845
51182810	2007	4.6	45.6	Strike-slip	1252
14295640	2007	4.26	32.8	Strike-slip	1100
10403777	2009	4.42	47.1	Strike-slip	1043
40238431	2009	4.39	42.1	Strike-slip	847
Far-source earthquake					
Chi-Chi, Taiwan	1999	7.62	160	Reverse	806
Hector Mine	1999	7.13	186	Strike-slip	1016
San Fernando	1971	6.61	108	Reverse	Hard rock
MYG01212**	2011	7.3	252	n/a	902
Sabah					
Near-source (local) earthquake					
Coyote Lake	1979	5.7	10.7	Strike-slip	1428
Morgan Hill	1984	6.2	14.9	Strike-slip	1428
Chi-Chi, Taiwan (4)	1999	6.2	39.3	Strike-slip	804
Chi-Chi, Taiwan (4)	1999	6.2	69.0	Strike-slip	845
Parkfield-02	2004	6	5.3	Strike-slip	907

All data from PEER ground motion database (USGS, 2022) except: **K-NET (National Research Institute for Earth Science & Disaster Resilience, 2022)

Sarawak was referred to in this study (Harith et al., 2017; Shoushtari et al., 2018). The resultant PGA and the deaggregation analysis based on a 10% probability of exceedance in 50 years were used as the input ground motion in this analysis, as shown in Table 3. The deaggregation analysis provides the corresponding magnitude and distance of the effecting earthquakes while the hazard curve gives the PGA of the corresponding earthquake source at different hazard levels. As there are different sites corresponding to each region, the magnitude and distance are given in a range of values that are generally affecting the area.

Earthquake time-history from other regions with magnitude and distance similar to the earthquake in Malaysia is scaled to the required PGA value. Around 4 to 5 time-history earthquake data are collected for each earthquake source for every region which corresponds to earthquake magnitude (*M*) and distance (*R*) ranges as given in Table 3. Due to the unavailability of strong-motion data in this region, worldwide data of earthquake records are collected and scaled to the appropriate PGA value. The PGA value in this region is considered to be small to moderate, with less than 0.2 g. Table 4 shows the modified earthquake time-history used for near (local) and far sources' earthquakes for all the regions. For Sabah, a different set of records were used for the near-source (local) earthquake due to its higher magnitude.

The average response spectra of both earthquake sources are normalised to the PGA of near-source earthquakes which controls the design in all cases. The PGA of the far-source earthquakes in Peninsular Malaysia and Sabah are 3.9 and 10 times smaller than that of the near source, respectively. The normalised response spectra of the input motion are given in Fig. 4 for each region, based on the near and far-source earthquakes. From Fig. 4, it is evident that the far-source earthquakes will affect Peninsular Malaysia for larger periods than the other regions.

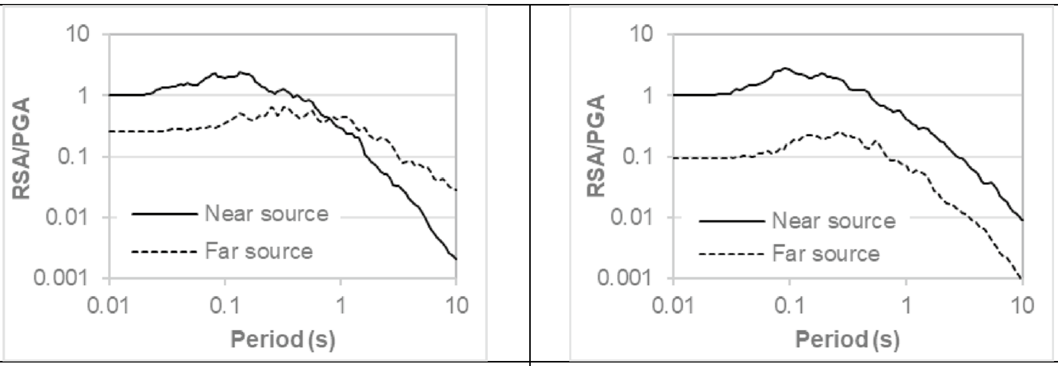
Results and discussion

From the equivalent non-linear ground response analysis conducted for the soil columns, the average of the responses for each soil class was calculated for 5% damping.

Comparison with the GMM

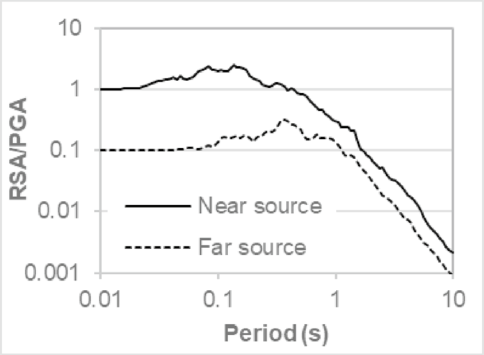
Due to the significant contribution of far-source earthquakes to the seismic hazard in Peninsular Malaysia, the analysis results were compared to the GMM by Campbell and Bozorgnia, (2014) (herein referred to as Cam14) for verification and investigation of its suitability. The Cam14 model is found to be capable of capturing the behaviour of near and far-source earthquakes in this region while considering many other factors that affect the shape of the response spectrum.

The comparison of the normalised response spectrum for different soil types is shown in Fig. 5 for soil types A to D. As shown, the response spectra for soil type A are very similar for both analysis and the GMM. For the GMM, there is a slight dip in the response at around 0.1 s period for the far-source earthquake. This reduction at 0.1 s period becomes more significant as the soil becomes more flexible, while the amplification at longer periods (1 s) increases due to the soil dynamic property. As observed from many past earthquake



(a) Peninsular Malaysia

(b) Sabah



(c) Sarawak

Fig. 4 Normalised average input RSA for near and far-source earthquakes for **a** Peninsular Malaysia, **b** Sabah, and **c** Sarawak (normalised to the PGA of the near-source earthquake)

events, the long-period component of the far-source earthquakes was amplified by the high period of the underlying soil, causing large motions at the period of around 2 to 4 s in the flexible soils.

For all soil types, it is shown that the far-source earthquake controls the response of the buildings with periods exceeding 1 s (tall buildings). This is evident based on the analysis and GMM, where both consistently give a larger response for the far-source earthquake after 1 s, even though the amplification varies. For the other regions (Sabah and Sarawak), the near-source earthquakes control the motion at all significant periods (between 0.01 and 10 s, further discussions in “Comparison with Eurocode 8 and Malaysia National Annex”).

Effect of far-source earthquakes on the response spectrum

The shape of the response spectrum is described by a few parameters, namely the soil amplification factor and corner periods. In EC8, the corner periods T_C and T_D denote the constant spectral velocity region while for a period longer than T_D is the constant spectral displacement region as shown in Fig. 2. For each soil analysis, the maximum response acceleration (A), velocity (V), and displacement (D) were calculated, and the corner periods were determined based on Eqs. (4) and (5):

$$T_C = 2\pi\left(\frac{V}{A}\right) \tag{4}$$

$$T_D = 2\pi\left(\frac{D}{V}\right) \tag{5}$$

The effect of earthquake sources on the corner periods (T_C and T_D) is shown in Fig. 6 for ranges of shear wave velocities. The soil was classified as soil A to E according to EC8, with different markers as given in the figure. It should be noted that according to EC8, the near-source (local) earthquake in Peninsular Malaysia follows the Type 2 curve while the far-source earthquake is of Type 1. In Fig. 6, the values recommended by EC8 according to the respective earthquake types are represented by red lines. The response spectrum for near-source earthquakes shows an observable correlation between the shear wave velocity and corner periods T_C and T_D for all soil types. The more flexible soils (soils C and D) yield higher values of corner periods compared to the harder soil (soils A and B), due to the higher soil periods. The values of T_C and T_D are slightly lower than that recommended by EC8 for Type 2 earthquakes, especially for soils A and B (hard to very hard soil).

As expected, the values of the corner periods for far-source earthquakes are higher than that of the near-source.

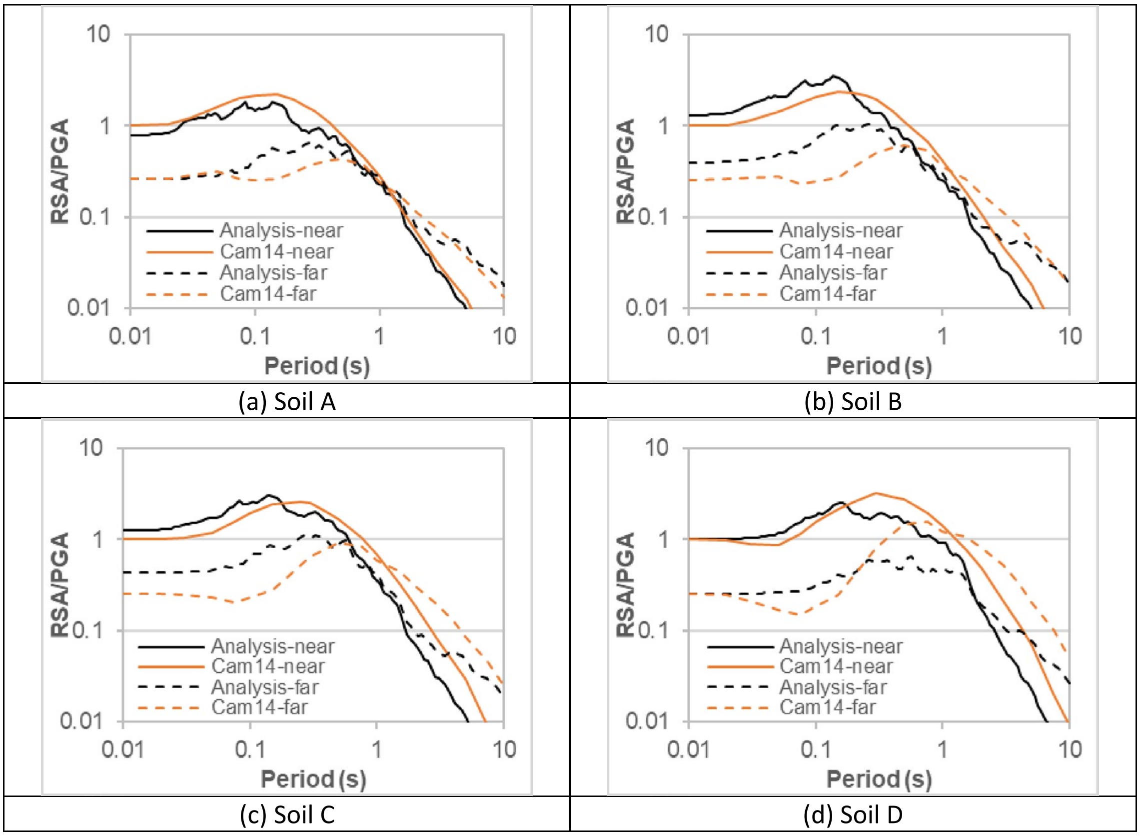


Fig. 5 Normalised response spectra for Peninsular Malaysia considering near and far sources. **a** Soil A, **b** Soil B, **c** Soil C, **d** Soil D

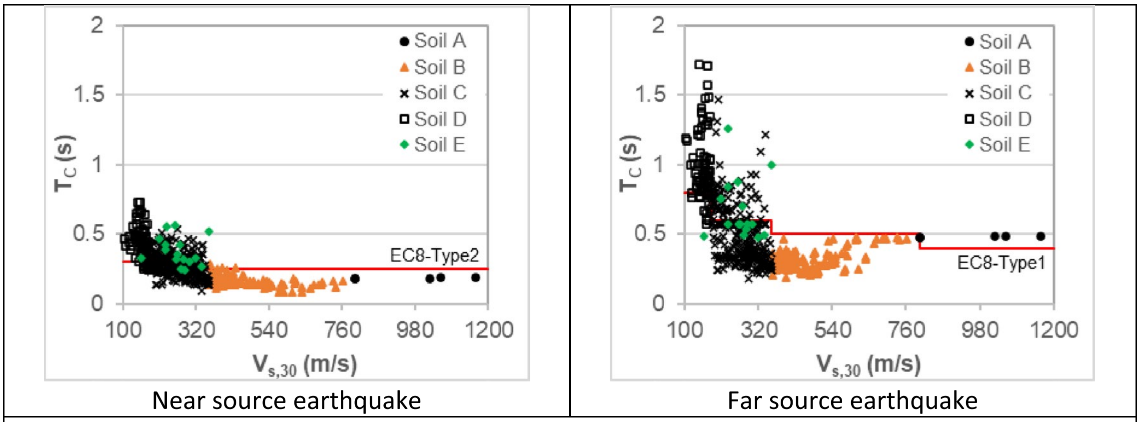
This is due to the larger magnitude and distance of the earthquake which resonates with the higher soil period, resulting in amplification at the higher periods. From the analysis, it is observed that T_C could reach up to 1.5 s, especially for the weaker more flexible soils (soil D). The average values from the analysis are generally higher than that recommended by EC8 (Type 1) except for soil B. From Fig. 6a, the value of T_C increases with decreasing of the soil shear wave velocity, which is apparent for both near and far sources' earthquakes.

The value of T_D is very much dependent on the earthquake magnitude, reflected by the different values recommended by EC8 for Types 1 and 2 earthquakes. Few expressions have been developed for T_D of large earthquakes based on regression analysis, namely by Lam et al. (2000) and Faccioli et al., (2004), as shown in Eqs. (6) and (7), respectively. Equation (6) predicts consistent results for a magnitude (M) less than 6, while Eq. (7) predicts a higher value to match the observation from the Chi-chi earthquake with a magnitude of 7.6. These equations are not reflective of the different soil conditions:

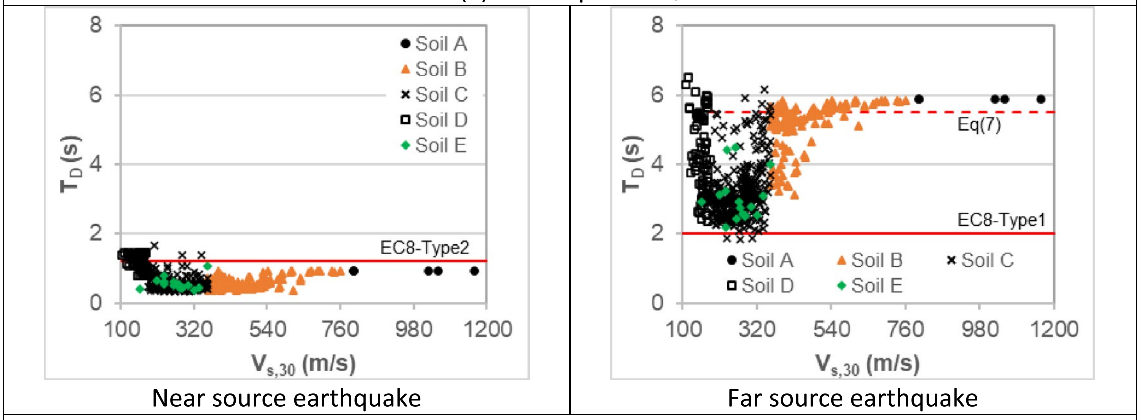
$$T_D = 0.5 + \frac{M - 5}{2} \tag{6}$$

$$T_D = 1.0 + 2.5(M - 5.7) \tag{7}$$

For T_D, there is no observable relation between shear wave velocity and the corner period for the far-source earthquake, and the values are highly inconsistent. For the hard soil (soil A and B), the value of T_D is higher compared to that of the weaker soil, especially for soil C subjected to far-source earthquakes. This is, however, contrary to the general findings, as more flexible soil tends to amplify the motion similar to its resonance frequency. The reason could be due to the significantly high peak velocity response in the softer soils (soil C and D) as shown in Fig. 6a, causing that to control the motion compared to the displacement. Nevertheless, the values obtained for T_D are generally higher than the EC8 recommended value of 2 s across all soil classes. However, the predicted values are comparable to Eq. (7) for $M = 7.5$ earthquakes, as shown in Fig. 6b. Compared to the Type 1 earthquake, the far-source earthquake for Peninsular Malaysia is of large magnitude, with an even larger source-to-site distance. Thus, the motion has a larger maximum RSV and RSD compared to near-source motions, resulting in a significantly higher T_D value. This shows that for a region that is highly affected by the far-source earthquakes, the value of T_D has to be



(a) Corner period T_C



(b) Corner period T_D

Fig. 6 Average shear wave velocity versus corner period **a** T_C and **b** T_D, for near and far-source earthquakes in Peninsular Malaysia

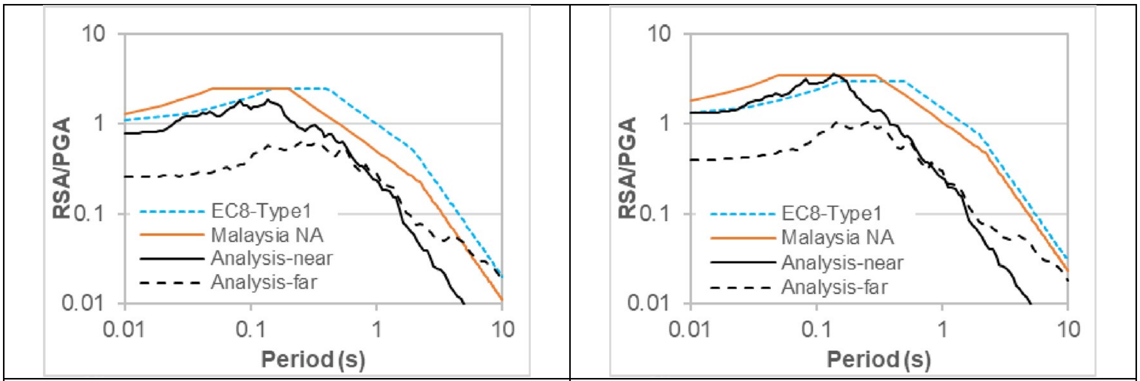
increased to better represent the higher motion at larger periods. As specified by Lumantarna et al. (2010), the peak ground velocity and its associated values are dependent on the stress drop, which is not considered in this study.

Comparison with Eurocode 8 and Malaysia National Annex

Figures 7, 8, and 9 compare the normalised RSA to the design response spectra in EC8 and the Malaysia National Annex (NA) for Peninsular Malaysia, Sabah, and Sarawak, respectively. As shown in Fig. 7, the EC8 is able to cover the long-period motion of the earthquake across the whole soil type, especially type A (Fig. 7(a)). However, it should be noted that for very tall buildings with periods longer than 5 s, wind load usually will govern the design, especially in the low seismicity regions. In comparison, the NA covers the short periods better (Fig. 7a–c) for the harder soil (types A–C). Although it was previously discussed that the corner periods for far-source earthquakes are inherently higher than that recommended by the EC8, the smaller intensity (PGA) of the far-source in comparison to the near-source earthquake resulted in an almost envelope of the RSA at periods of lower than 1 s. Hence, the application of EC8 with the consideration of the National Annex will be appropriate for the design of buildings in this region.

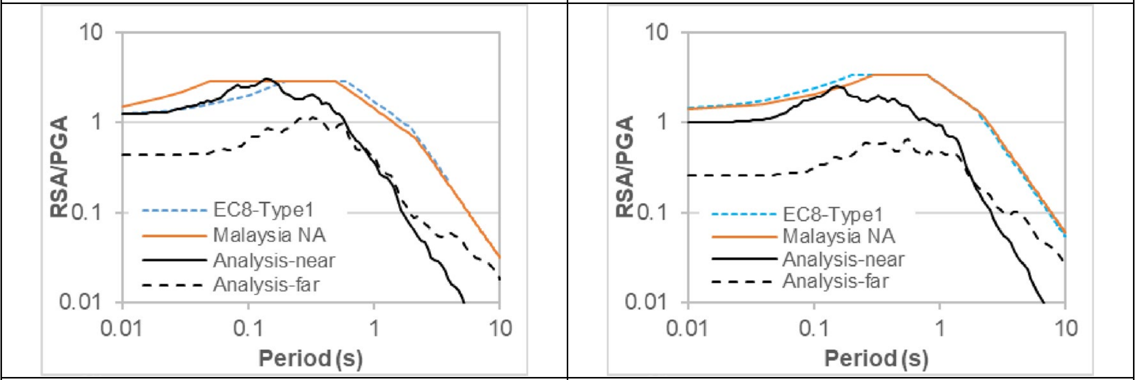
For Sabah, the GMM closely resembles that of Type 1 earthquakes in EC8, with maximum effect from the near-source earthquake due to its proximity and large magnitude throughout the whole period range. In this region, the far-source earthquakes do not affect the motion with considerably low RSA throughout the periods, and safe to be excluded from the analysis. However, both EC8 and the NA underestimate the motion at lower periods, especially for soil A–C (Fig. 8a–c).

Theoretically, due to the smaller magnitude of the local earthquake in Sarawak, the response spectrum will closely resemble the Type 2 earthquake in EC8 (Najar et al., 2022). However, it is observed from the analysis that the earthquake for this region is a combination of both Type 1 and Type 2 earthquakes in EC8, as reflected in the NA. The results were also compared to the GMM (Cam14) for the near-source earthquake. From the analysis, it is found that the GMM



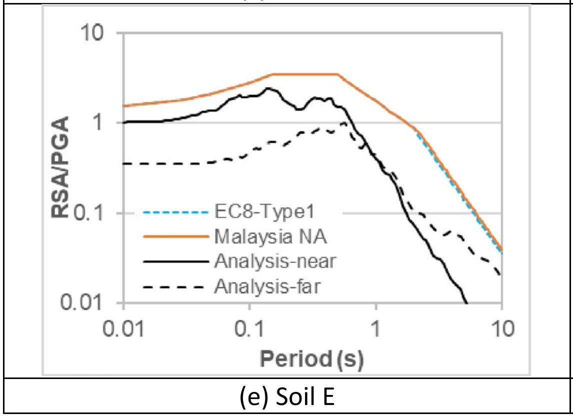
(a) Soil A

(b) Soil B



(c) Soil C

(d) Soil D

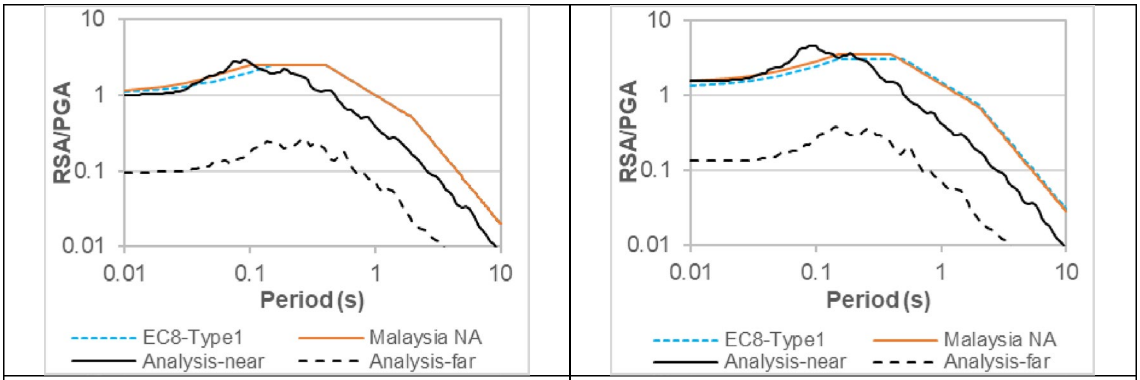


(e) Soil E

Fig. 7 Comparison of normalised response spectra for different soil types in Peninsular Malaysia. **a** Soil A, **b** Soil B, **c** Soil C, **d** Soil D, **e** Soil E

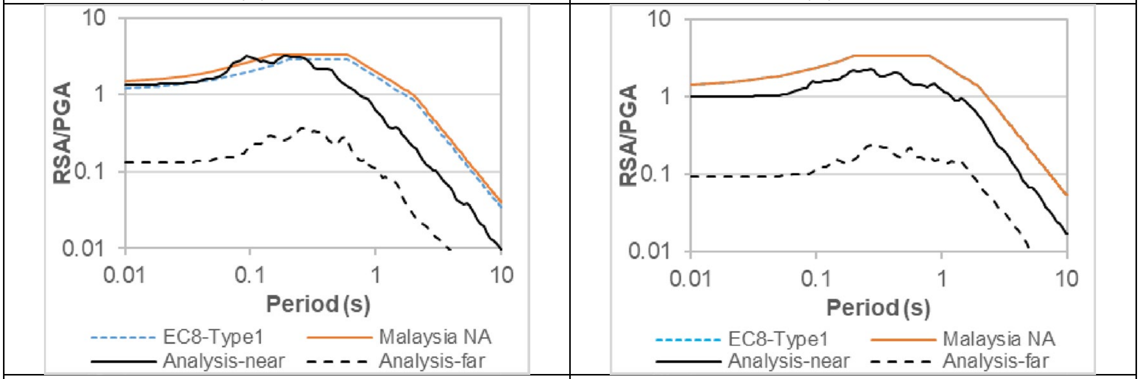
underestimates the motion of hard soil at higher periods while overestimating the motion of the soft soil (type D).

In general, it is found that the EC8 with the supplementary National Annex is suitable to be used to design structures in Malaysia. For the region susceptible to far-source earthquakes (Peninsular Malaysia), care should be taken to analyse important structures of high periods such as tall buildings. In addition, the influence of stress drop could be incorporated using regional data recorded in this country.



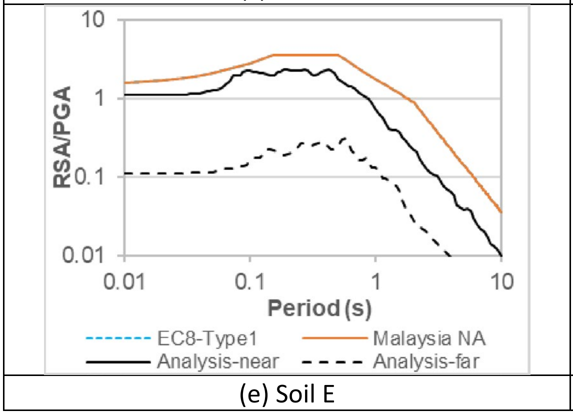
(a) Soil A

(b) Soil B



(c) Soil C

(d) Soil D



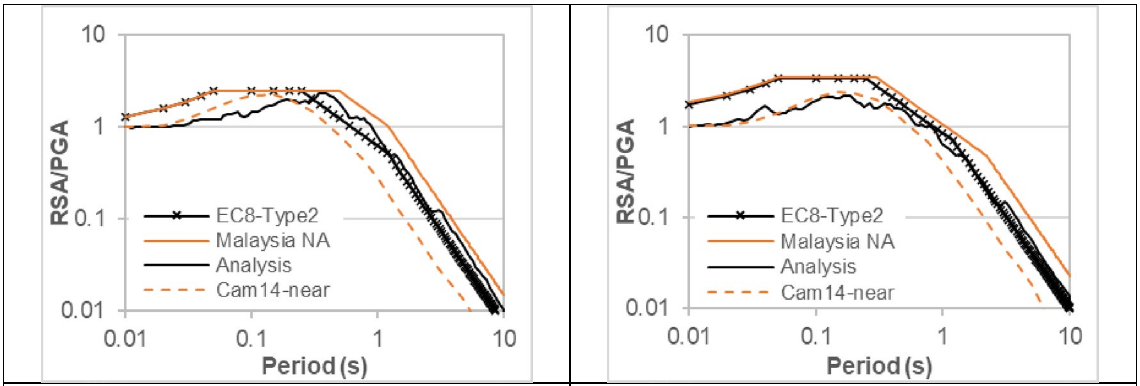
(e) Soil E

Fig. 8 Comparison of normalised response spectra for different soil types in Sabah. **a** Soil A, **b** Soil B, **c** Soil C, **d** Soil D, **e** Soil E

Conclusions

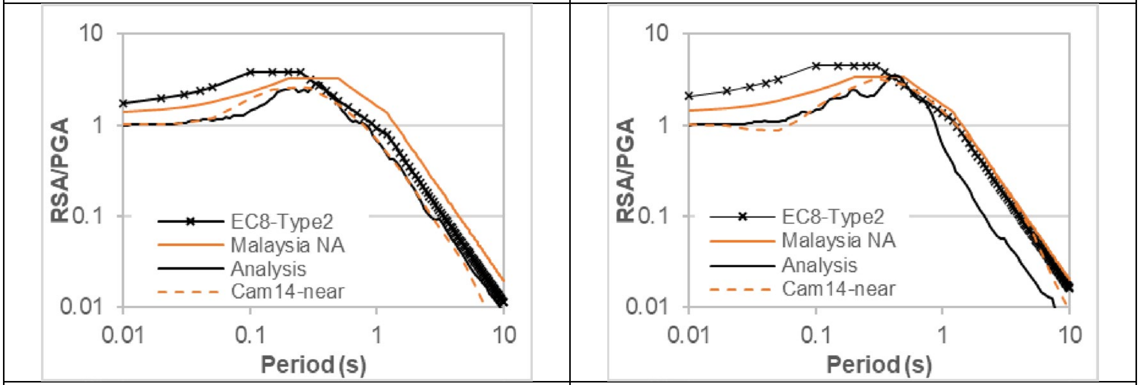
Soil response analysis has been conducted on 1923 soil data of types A to E according to Eurocode 8 in three regions namely Peninsular Malaysia, Sabah and Sarawak. The analysis was based on the deaggregation analysis considering earthquakes affecting these regions, specifically the near and far sources' earthquakes. The conclusions from this research are as follows:

- The corner periods, namely T_C and T_D are highly dependent on the earthquake magnitude and soil type. T_C is found to be slightly higher than the value recommended by EC8, with its values increasing as the soil shear wave velocity ($V_{s,30}$) decreases. For the far-source earthquake particularly in Peninsular Malaysia, the T_D value shows inconsistencies, with a significantly large value of around 6 s at higher $V_{s,30}$, and a lower value at $V_{s,30}$ of 200 to 400 m/s. The effect of stress drop could be a major factor affecting the results and should be incorporated in future studies.
- A comparison with the GMM by Campbell and Bozorgnia, (2014) shows that this model can be used for this region for both near and far sources' earthquakes. How-



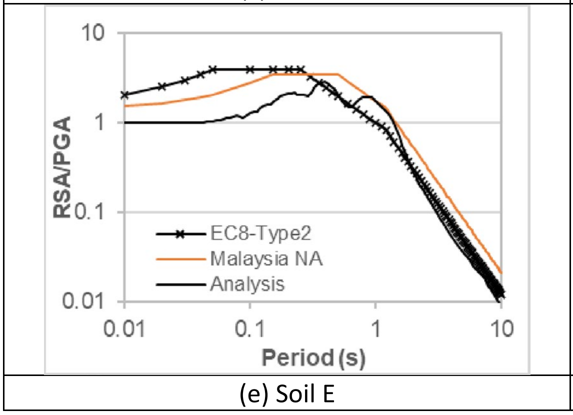
(a) Soil A

(b) Soil B



(c) Soil C

(d) Soil D



(e) Soil E

Fig. 9 Comparison of normalised response spectra for different soil types in Sarawak. **a** Soil A, **b** Soil B, **c** Soil C, **d** Soil D, **e** Soil E

ever, the GMM tends to overestimate the motion at larger periods and underestimate it at lower periods.

- For areas of low seismicity, the response of structures is dependent on the earthquake sources. Particularly in Peninsular Malaysia, the near-source earthquake governs the structural response at lower than 1 s, and far-source earthquake at periods beyond that. In contrast, Sabah is highly influenced by the near-source earthquakes, while the far-source earthquake is considerably smaller and was enveloped by the former. Hence, care should be taken to analyse important high period structures in the low seismic regions considering far-source earthquake data.
- The Eurocode 8 with the supplementary National Annex is shown to be adequate and can be used for the design of buildings in this region, however, some adjustments can be made for the longer periods in Peninsular Malaysia.

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Availability of data and materials The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Ethical approval and consent to participate Not applicable.

Consent for publication All the authors consent for publication.

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