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Seismicity of Peninsular Malaysia due to intraplate and far field sources

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Abstract. Peninsular Malaysia lying on the stable Sunda Plate has traditionally been considered safe with low to moderate seismicity. However, far field Sumatran mega-earthquakes have been shown to be capable of triggering ground motions felt in high rise structures in the major Malaysian cities while seismic impact from local earthquakes of moment magnitude 3.8 have reportedly induced nominal structural damages to nearby buildings. This paper presents an overview of the recent seismic activities in and around Peninsular Malaysia with reference to prominent earthquakes generated by far field interplate and local intraplate sources. Records of ground motion data and seismic hazard assessment (SHA) results available in the literature have been analyzed and discussed. The peak ground acceleration (PGA) values from historical records for few local intraplate events were observed to be higher than those for the events from Sumatran Subduction Zone. This clearly points to the need for a detailed and comprehensive SHA incorporating both far field and local sources. Such an analysis would contribute the knowledge required for secure and reliable infrastructure design and safeguard the Malaysian people and economy.

Keywords: seismic hazard; peak ground acceleration; far-field sources; intraplate source

1. Introduction

Peninsular Malaysia lies within the Sunda Plate (Fig. 1) - a tectonic region that has historically experienced low to moderate seismicity. The relative seismic stability of the Sunda Plate, evidenced by the scant records of major historical earthquakes, is quite puzzling considering its tectonic set up. Located along the southern edge of the Eurasian Plate, the Sunda Plate is surrounded by tectonically active convergent boundaries, especially the active boundaries running closely along the Sumatran region of Indonesia. The low seismicity experienced by Peninsular Malaysia may, however, be justified as a result of its geological position in the intraplate region (Petersen *et al*. 2004) with the closest plate boundary at about 400 km. Deformations within the Sunda Plate are generally minor, capable of producing only low to moderate seismicity (Baroux and Avouac 1998). Peninsular Malaysia has thus been categorized under the zone of low to

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moderate seismicity.

However, there have been reports of fatalities and documented cases of damages and/or tremors in the major cities of Peninsular Malaysia generated by far field and/or intraplate sources. For example, strong ground motions originating from the far field sources comprising neighboring Sumatran Subduction Zone and Sumatran Fault have been noted for causing tremors in the high rise structures in major cities of Peninsular Malaysia. In the neighboring East Malaysia, the 2015 Sabah earthquake that happened on the morning of 5th June with a moment magnitude, M_w of 6.0 generated by an intraplate (Sunda Plate) fault has raised concerns following the deaths and damages caused in various parts of Ranau and Kota Kinabalu. Table 1 summarizes cases reported in the last decade, starting with the most recent June 2015 Sabah earthquake and ending with the 2004 Sumatra earthquake of M_w 9.1. It is obvious that the prominent earthquakes were generated from two major sources: (a) far-field sources such as Sumatran Subduction Zone and Sumatran Fault, and (b) intraplate sources comprising local faults located within the Peninsula and in Borneo Island. The earthquake effects experienced in the last decade within Malaysia/the Sunda Plate range from minor tremors felt by residents or observed cracks in buildings to human fatalities in the affected areas (see Table 1).

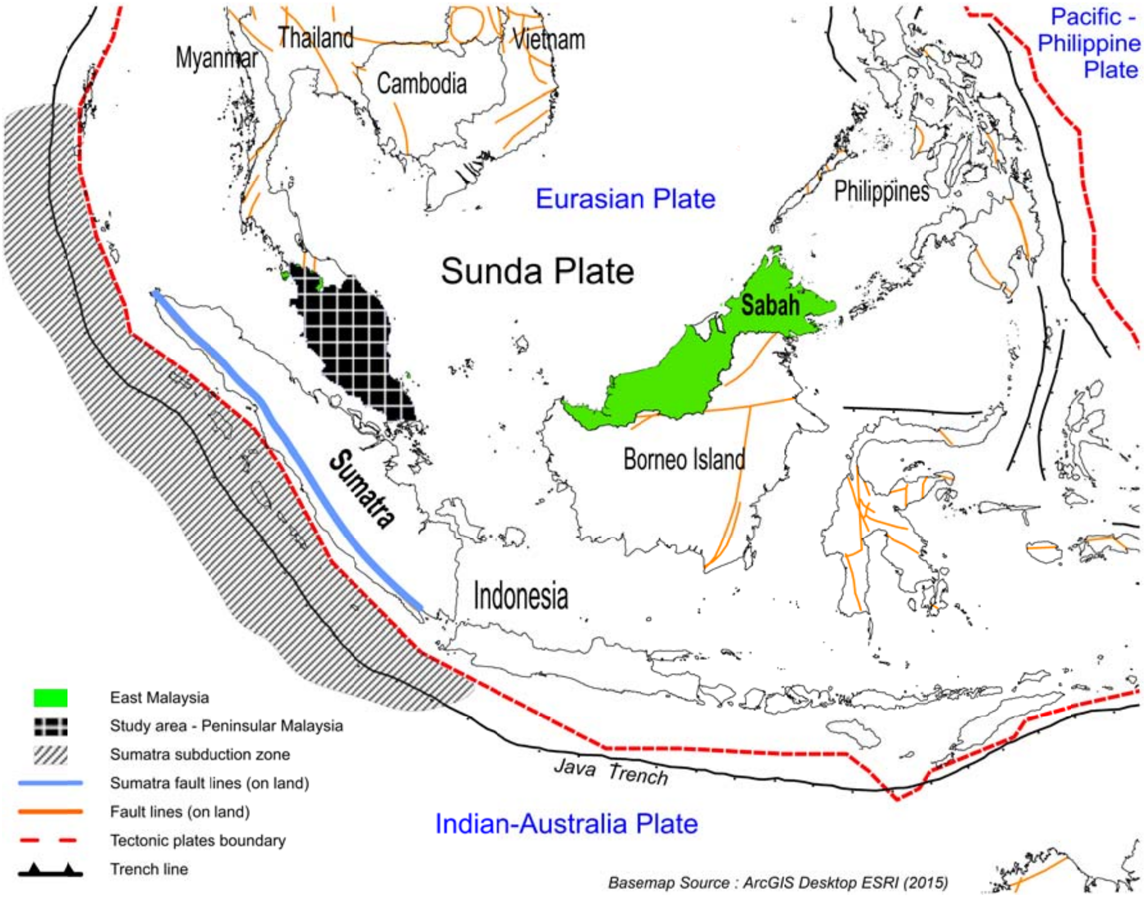

Fig. 1 Tectonic map of the Sunda Plate at the southern edge of the Eurasian Plate, bounded by the Indian-Australia Plate to the south and west and the Pacific - Philippine Plate to the east

Table 1 Cases of seismic damage and tremors reported in Malaysia in the last decade

Date (Time)	Locations affected	Source	Source type	Magnitude	Description of damage	Reference
5/6/2015 MST (07:15:43)	• Ranau • Kota Kinabalu	14 km NW of Ranau, Malaysia	Intraplate	6.0 M_w	• at least18 fatalities reported • rock falls in Mount Kinabalu • disruption of water supply in Ranau-Kundasang area	Straits Times (2015) USGS (2015)
5/9/2011 UTC (17:55:13)	• Kuala Lumpur	Northern Sumatra, Indonesia	Sumatran Fault zone	6.6 M_w	• tremors felt in high rise buildings and residents evacuated • no fatalities	Earthquake-Report (2011)
23/7/2010 UTC (22:51:11)	• Beaufort	Mindanao, Philippines	Interplate	7.6*	• weak shaking felt on the east coast of Sabah located more than 1000 km from the epicenter	The Standard (2013) USGS (2010)
9/5/2010 UTC (05:59:41)	• Northern part of Peninsular Malaysia	Acheh, Indonesia	Sumatran Fault Zone	7.2*	• tremors felt at a fishing village in Kedah • evacuation of residents from several flats in Penang	Sin Chew (2010) USGS (2015)
30/11/2007-14/01/2008 MST (Various times)	• Bukit Tinggi	Bukit Tinggi, Malaysia (50km from Kuala Lumpur)	Intraplate	1.7–3.7 M_w	• tremors felt at nearby villages (<20 km) • hairline cracks on the walls were reported at the nearby police station and school	Shuib (2009) JMG (2011)
26/12/2004 UTC (00:58:53)	• Penang • Kedah • Kuala Lumpur	Northern Sumatra, Indonesia	Sumatra Subduction Zone	9.1 M_w	• tsunamis generated by the earthquake killed more than 60 people in northern Malaysia. • vibrations felt in high rise structures	BBC (2005) USGS (2015)

**type of magnitude not specified*

The 1985 Mexico City earthquake that killed more than 5000 humans and caused extensive damage to the Greater Mexico City with its source located some 350 km away (Pan 1995) serves as a lesson from history on the importance of earthquakes (or strong ground motions) generated by far field sources. In addition, the ground response outcome is also highly dependent on the underlying soil (Raghunandan 2012). In the present context, recurring earthquakes from the

Sumatran sources are potential concerns considering the rapid development of the Malaysian infrastructure with a focus on high-rise constructions and elevated structures. This concern is especially important where the design of the structures has not considered a specified threshold of seismic load, as these structures are susceptible to failure even when subjected to a moderate amount of seismicity-related or other ground motion/vibration (Megawati *et al*. 2005, Lam *et al*. 2009). Occurrence of such a seismic event in highly populated cities and regions such as Kuala Lumpur and Klang valley would be inconceivable in terms of the potential loss of human lives and infrastructure damage. Such considerations of potential seismicity, therefore, serve as a warning and encourage a design approach towards seismic resistant structures. To this end, a thorough knowledge of the seismicity and the current status of seismic hazard assessment for the Peninsular Malaysia region is a prerequisite.

The aim of this paper is to provide an overview of the recent seismic activities in and around Peninsular Malaysia generated by far field as well as intraplate sources. This study further elaborates on the historically recorded ground motion data and the seismic hazard assessments (SHA) for Peninsular Malaysia available in the literature. The ground motion data for this purpose were collected by the Malaysian Meteorological Department via a network of seismic stations consisting of 7 weak and 13 strong motion sensor stations located across Peninsular Malaysia which are illustrated in Fig. 2. A total of 78 earthquake events for the period 2004 to May 2014 with 30 events originating from local intraplate sources (M_w<4.3) and 48 events from the Sumatran region (M_w 5.0-9.1) are considered in the discussion.

2. Earthquake Sources

2.1 Far field sources: Sumatran subduction and Sumatran fault zones

The subduction boundary of the Indian-Australian Plate beneath the overriding Eurasian Plate at an oblique north-west direction moving at a rate of 49 mm/year is one of the most well defined tectonic plate margins, called the Sumatran Subduction Zone (Zachariasen *et al.* 1999). This zone lies on the ocean bed and is located at about 600 km from Kuala Lumpur, the capital city of Malaysia. Historical records over the past three centuries have shown the zone to have generated large magnitude earthquakes (M_w>9.0). The 1833 Sumatra earthquake recorded a magnitude M_w 8.7 (Newcomb and McCann 1987), whilst the more recent 2004 Aceh earthquake is one of the largest magnitude earthquakes ever recorded with M_w 9.1 (refer to Table 1). This latter event was of prime concern for Peninsular Malaysia because the earthquake triggered tsunamis that claimed at least 60 lives in the northern part of the Peninsula and generated ground motions that were felt in the high rise structures of Penang, Kedah, and Kuala Lumpur (BBC 2005).

The Sumatran Fault which lies about 400 km from the Peninsula is more than 1500 km long and runs (the entire length of Sumatra) almost parallel to the convergence plate margin (Sun and Pan 1995, Katili and Hehuwat 1967). Sieh and Natawidjaja (2000) discussed the Fault surface to be highly segmented, which in turn affects the rupture dimensions. This segmented nature perhaps is one of the reasons why the Sumatran Fault has released lower amount of energy in comparison to the Subduction Zone. Balendra *et al.* (2002) estimated that the Fault would not generate earthquakes with magnitude greater than M_w 7.8. However, the incidents of tremors in high rise structures reported in the northern part of the Peninsula and Kedah during the 2010 and 2011 earthquakes, respectively, are not to be neglected (Earthquake-Report 2011, Sin Chew 2010,

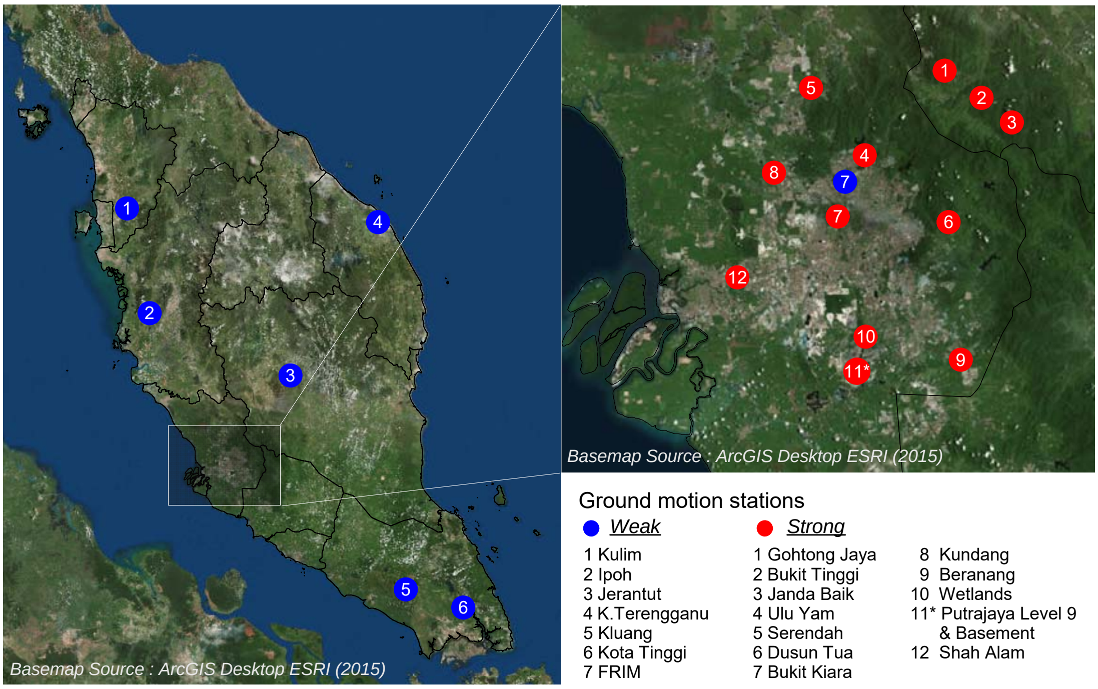

Fig. 2 Locations of seismic stations (weak and strong) within Peninsular Malaysia (MMD 2014)

USGS 2010). The Sumatran Fault region, therefore, is to be treated as capable of producing mega-earthquakes and strong ground motions, and as one of the prime far field sources in the seismic hazard and risk assessments for Peninsular Malaysia.

2.2 Local intraplate sources

Until recently, the Sunda Plate has been considered stable based on the fewer records of major historical earthquakes. However, recent geophysical studies suggest the plate to be deforming gradually. For example, the Global Positioning System (GPS) and Shuttle Radar Topography Mission - Digital Elevation Mapping (SRTM-DEM) measurements have shown distortion of the tectonic plate due to intraplate stress build up in the northwest Peninsular Malaysia region following the 2004 and 2005 mega-thrust earthquakes in Aceh and Nias, respectively (Shuib 2009, Omar and Jhony 2010). Such movements have the potential to activate the intraplate faults, eventually leading to intraplate earthquakes. For example, the local seismic events in Peninsular Malaysia as detected by the Malaysian seismic network indicated the occurrence of significant seismicity at the Bukit Tinggi Fault in 2007, which was suspected by seismologists to be triggered by the Aceh and Nias earthquakes (Chai *et al.* 2011). This event was noteworthy as its intensity of M_w 3.8 was sufficient to trigger tremors felt by the local residents less than 20 km from its epicenter. It is to be noted that a report from the Malaysian Meteorological Department (Chai *et al.* 2011) listed a total of seven such major faults - potential sources of seismicity - in Peninsular Malaysia. The seven major faults are: Bok Bak Fault, Lebir Fault, Terengganu Fault, Bukit Tinggi Fault, Kuala Lumpur Fault, Lepar Fault, and Mersing Fault. The report also mentioned the occurrence of 19 earthquakes with magnitudes up to 3.8 on the Richter scale during the period

2007-2008. It is conceivable that megathrust earthquakes from the far-field Sumatra region have triggered the movement along the local intraplate faults leading to minor earthquakes around Bukit Tinggi (Shuib 2009).

Another important intraplate source are the faults within Borneo Island. The northeastern part of the island, where the state of Sabah lies, is located on the southeast Eurasian plate, bordered by the Pacific-Philippine Plate to the east and Indian-Australian Plate to the south and west (Faisal *et al.* 2011). GPS measurements estimate these three plates to converge in different directions and at varying rates: the Eurasian Plate sliding in the southeast direction at 5 cm/year, whilst the Indian-Australian Plate and the Philippine-Pacific Plate sliding northward at approximately 7 cm/year and 10 cm/year, respectively (Mitchell *et al.* 2000). The relative movements and collision of the three plates would produce high magnitude earthquakes with high recurrence rates. A consequence of the constant interactions among these plates was the formation of a number of sub-plates that deformed internally in a complex pattern, which in turn led to the formation of fault lines found in

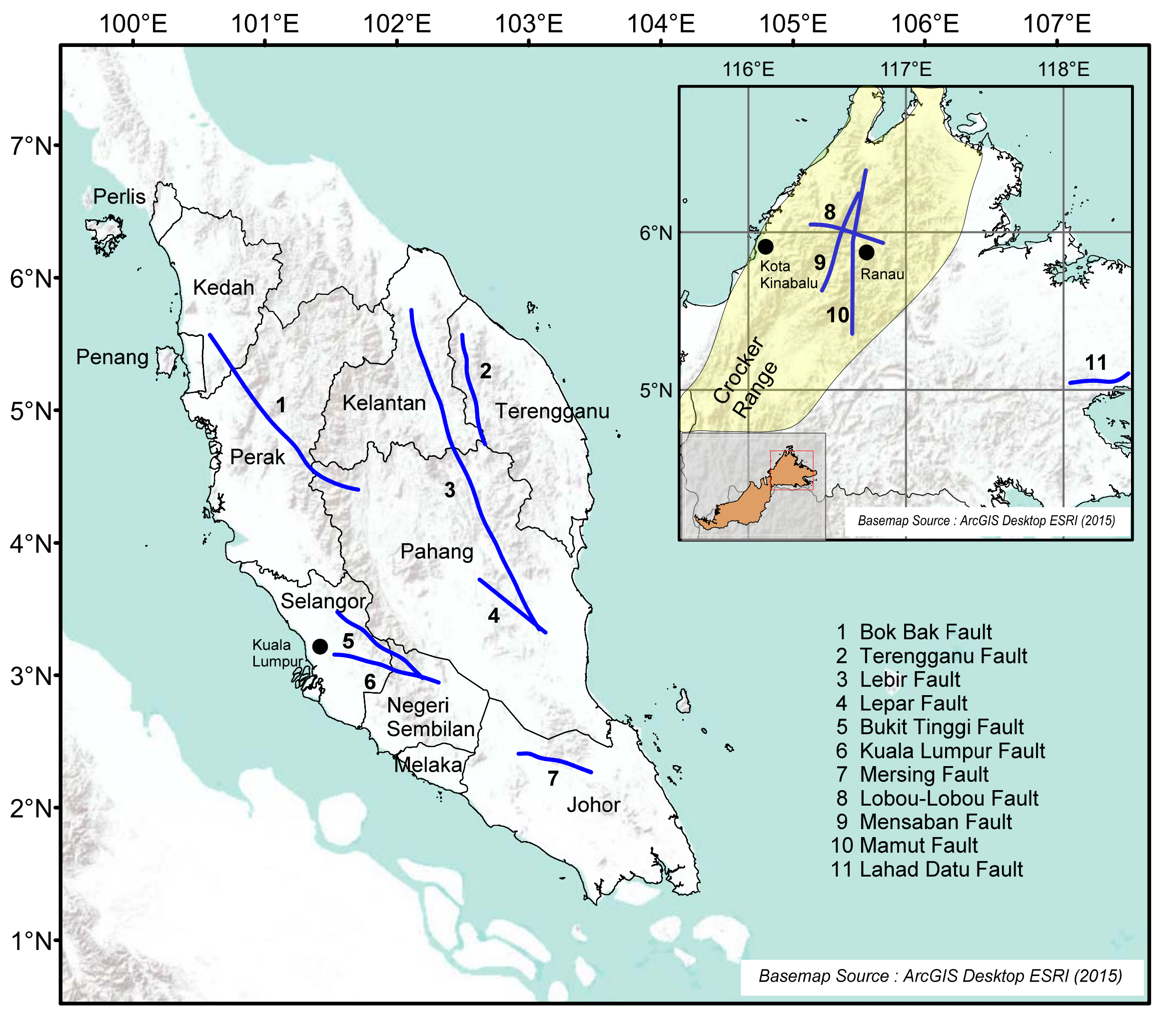

Fig. 3 Major local intraplate fault lines in Malaysia. (JMG 2009)

newspaper reports in the form of active fault lines within Sabah, namely Crocker Fault Zone, Sabah over the centuries (Tan and Lamy 1990). Evidence can be found in the literature and Mensaban Fault, and Lahad Datu Fault (Tongkul 1991) and associated devastating intraplate seismic events. The most noteworthy events include the 1976 Lahad Datu earthquake of 5.8 magnitude on the Richter scale and another 4.5 magnitude earthquake striking Ranau in 1991 that resulted in structural damage of buildings and utilities (Che Abas 2001). Most recently, an earthquake of magnitude M_w 6.0 struck the Sabah region on 6 June 2015 causing 18 fatalities, massive landslides and infrastructure damages (Strait Times 2015).

The foregoing discussion strengthens the scenario that the local intraplate faults are being influenced by the tectonic movements around the Sunda Plate. The seismicity associated with plate boundary movements are likely to activate the intraplate faults and eventually lead to earthquakes with M_w greater than 4.0. Moreover, studies indicate that the Mentawai segment of the Sumatran Subduction Zone is likely to rupture and discharge strong ground motions in the near future (Megawati and Pan 2009, Sieh *et al.* 2008). Finally, a de-aggregation analysis foresees a 10% probability of strike-slip earthquake from the Sumatran Fault happening at approximate M_w 7.5, from Kuala Lumpur within the next 50 years (Nabilah and Balendra 2012, Petersen *et al.* 2004). Based on these factors, the seismicity of the Peninsular Malaysia may be expected to be moderate to high in the near future although not as high as that along the active tectonic boundaries of the Sunda Plate.

3. Ground response data and seismic hazard assessments

3.1 Ground motion records

Table 2 summarizes the ground motion data expressed in terms of peak ground acceleration (PGA) recorded by the seismic stations across Peninsular Malaysia. Although the far field sources are at distances greater than 440 km, the ground motions generated by these far field earthquakes (M_w 6.0-9.1) within the Sumatran Subduction Zone recorded a maximum PGA value of 0.0615 ms^{-2} by the nearest seismic station and an average of about 0.0038 ms^{-2} from all the stations. The vibrations from earthquakes within the Sumatran Fault (M_w 5.0-7.6) show the maximum and average PGA values of 0.0028 ms^{-2} and 0.0033 ms^{-2}, respectively. Notwithstanding the lower M_w values of earthquakes generated by the Sumatran Fault, the average PGA value was observed to be very close to those generated within the Sumatran Subduction Zone. This perhaps relates to the closer distance of the Sumatran Fault system to the recording stations in Peninsular Malaysia. The maximum PGA values for the Sumatran Fault, however, showed a distinct difference when compared to earthquake events from the Sumatran Subduction Zone. This perhaps corresponds to the high magnitude of the earthquake at the source. Surprisingly, the maximum PGA value recorded from the low magnitude (M_w 1.0-4.0) local intraplate earthquake events was 0.0428 ms^{-2}, considerably higher than that for the earthquakes at the Sumatran Fault. This certainly relates to the relatively short source-site distance, thereby highlighting the possibility that these low magnitude earthquakes can cause similar damage/inconvenience to earthquakes from the Sumatran Fault region. Referring to Table 1, these inconveniences may include tremor felt in high rise structures and evacuation of residents. However, occurrence of a slightly higher magnitude earthquake at the intraplate faults will result in moderate to high seismicity in the region and certainly affect the utilities and cause cracks in buildings and structures.

Table 2 Summary of ground motion data recorded by seismic stations across Peninsular Malaysia since 2000

Source	PGA (ms^{-2})			Magnitude at source (M_w)	Distance from source (km)
	Max	Min	Average		
Sumatra Subduction Zone	0.0615	0.00006	0.0038	6.0 - 9.1	440 - 1293
Sumatra Fault Zone	0.0283	0.00006	0.0033	5.0 - 7.6	285 - 1389
Local Intraplate	0.0428	0.00003	0.0016	1.0 - 6.0	6 - 321

Table 3 Earthquakes in Peninsular Malaysia for the period 1977 - 2014 expressed in the MMI scale (MMD 2014, Sooria *et al.* 2012)

Location	State	Number of Recurrence	Maximum MMI
West Coast	Johor	24	VI
	Kedah	22	V
	Kuala Lumpur	47	VI
	Malacca	21	V
	Negeri Sembilan	15	V
	Penang	55	VI
	Perak	30	VI
	Perlis	3	V
	Selangor	65	VI
East Coast	Terengganu	2	IV
	Kelantan	3	V
	Pahang	20	III

The Modified Mercalli Intensity (MMI) scale estimates the damage caused by an earthquake and reflects the actual effect felt on site. Table 3 lists the maximum MMI readings recorded at different locations of Peninsular Malaysia due to seismic events during the period 1977 to 2014. It can be observed from the data that during 1977-2014 the earthquake intensity ranged from III to a maximum of VI. It should be noted that the MMI scale of 'VI' relates to a tremor that has adequate potential to cause movement of heavy objects and startle a person from slumber (USGS 2015). Although Table 3 suggests the region to have experienced low to moderate seismicity during the period, a report by the Mineral and Geoscience Department (JMG 2011) indicated that these vibrations were sufficient to cause minor cracks in the wall of a nearby school in Bukit Tinggi. Another important observation from Table 3 is that the states/provinces located along the west coast of Peninsular Malaysia have been more susceptible to seismic damage. This again can be related to the relatively higher ground vibrations experienced at these places due to their proximity to the Sumatran region. States such as Selangor (which includes Kuala Lumpur and Putrajaya) and Penang recording a high number of felt occurrences testifies to this reasoning. Reports highlighting visible cracks on several buildings in Kuala Lumpur due to the M_w 8.7 Sumatran Subduction Zone earthquakes of 12-13 September 2013 are exceptional evidence of the influence of far field sources (Tan and Razak 2010). As no life-threatening seismic events have occurred in Peninsular Malaysia to date, the common perception is that Peninsular Malaysia is seismically relatively stable. However, the same may not hold true in the future, as we have been reminded by the recent Sabah earthquake of June 2015 in the vicinity and predictions of tectonic rupture of the Mentawai segment of the Sumatran Subduction Zone presented by Megawati and Pan (2009) and Sieh *et al.* (2008).

3.2 Seismic Hazard Assessments (SHAs)

Seismic hazard assessment is customarily based on attenuation models, which formulate the prediction of ground motion as a function of multiple earthquake parameters such as magnitude, distance, and so on (Loi *et al.* 2014). SHA can be conducted using two approaches: deterministic and probabilistic (Baker 2008, Kramer 1996). The usage of conventional deterministic seismic hazard analysis (DSHA) in Peninsular Malaysia has been limited. This method is less desirable as ground motions felt are mostly dictated by distant events, which lead to inaccuracies. Moreover, this method does not treat uncertainties well. Probabilistic seismic hazard analysis (PSHA), on the other hand, is the regular approach used by earthquake researchers in this region (Azmi *et al*. 2013, Nabilah and Balendra 2012, Marto *et al.* 2011, Petersen *et al*. 2007, Adnan *et al*. 2006, Adnan *et al*. 2005, Pan and Megawati 2002). PSHA is more popular as it quantifies and combines uncertainties in the earthquake parameters to estimate the probability of future ground motion at a site. Fig. 4 shows the map of Peninsular Malaysia highlighting the predicted PGA values (in ms^{-2}) corresponding to 2% and 10% probability of exceedance in 50 years using the PSHA. Various authors have predicted different PGA values for major cities such as Kuala Lumpur. PGA values predicted by Nabilah and Balendra (2012) for Kuala Lumpur are at 0.234 ms^{-2} and 0.165 ms^{-2} for 2% and 10% probability of exceedance, respectively. These values were found to be lower when compared with the previous predictions of 0.149 ms^{-2} and 0.074 ms^{-2} for 2% and 10% probability of exceedance, respectively, by Adnan *et al*. (2006).The difference in the PGA values is due to the different PSHA dataset utilized by the researchers. Actual records from strong ground motion data were used by Nabilah and Balendra (2012) whereas Adnan *et al*. (2006) utilized synthetic ground motion for their PSHA. Marto *et al.* (2011) presented even higher PGA values in the ranges of 1.80-3.40 ms^{-2} and 0.090-0.190 ms^{-2} for 2% and 10% probability of exceedance; here the methodology involved different site conditions in and around Kuala Lumpur. These observations clearly suggest the amplification of propagating waves in the course of travel from the Sumatran region towards various parts of the Peninsula depending on the local soil conditions. This behaviour is exactly opposite to that expected by the attenuation model. Similarly, microzonation study for the island of Penang presented by Azmi *et al.* (2013) also showed significantly higher PGA estimations: in the range of 0.255-0.340 ms^{-2} and 0.135-0.200 ms^{-2} for 2% and 10% probability of exceedance, respectively. Site-specific analysis was conducted for different areas within Penang Island and, therefore, PGA value ranges were reported instead of a fixed value. Another important observation of the Azmi *et al.* (2013) study was the higher PGA predictions towards coastal and lowland areas owing to sand and clayey deposits which contribute to higher amplification factors and also may relate to the attenuation model - that is the west coast being at a closer distance to the source would experience higher amplification.

Seismic hazard assessment for the entire Peninsula has also been presented in some of the published literature. The PGA values estimated earlier by Pan and Megawati (2002) are higher (see Fig. 4) compared to the estimates presented by Adnan et al. (2005) and Petersen *et al*. (2007). The reason for this discrepancy may be due to different methodology and attenuation models used in the various studies. An alternative seismic hazard assessment using the Gumbel statistical theory by selecting consistent magnitudes and main shock events was carried out by Adnan *et al*. (2005).

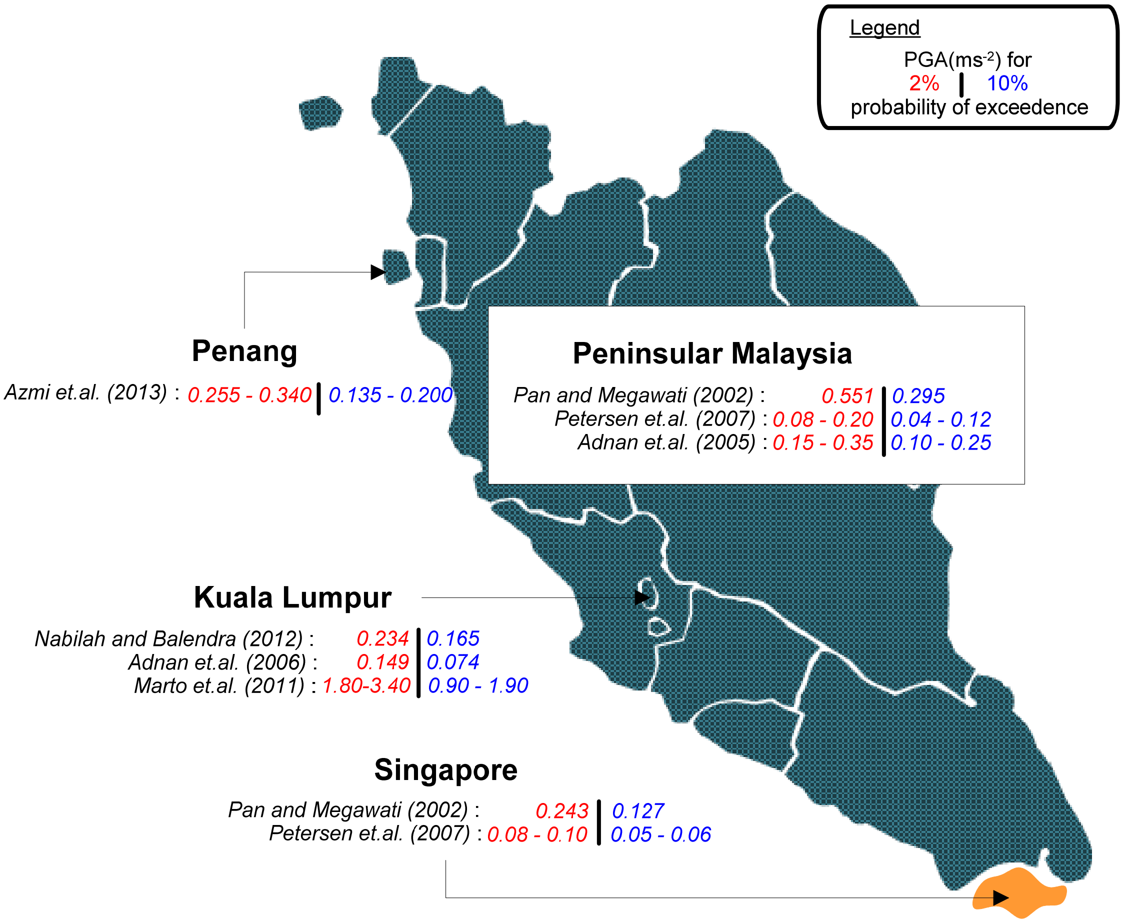

Fig. 4 Map of Peninsular Malaysia showing the predicted PGA values from various sources corresponding to 2% and 10% probability of exceedance in 50 years

The PGA values predicted were twice higher than those predicted by Petersen *et al.* (2007). In addition, Petersen *et al.* (2007) utilized a ground motion prediction equation developed based on earthquakes associated with crustal interplate and intraplate, subduction interface, and deep subduction slabs with appropriate weightage assigned to attenuation models considering the uncertainties. The SHA by Pan and Megawati (2002) and Petersen *et al.* (2007) presented PGA estimates for Singapore as well. An interesting observation from both the studies is that the PGA values for Peninsular Malaysia is higher than that for Singapore which suggests that the northern Sumatran sources to be more active in terms of both intensity and recurrence. In other words, this observation clearly cautions that the Peninsular Malaysia region to have higher impact due to the earthquakes from the Sumatra regions with the west coast being more susceptible. Clearly, further SHA studies using both deterministic and probabilistic approaches for Peninsular Malaysia are important. Moreover, only a limited number of published papers presenting SHA have indicated the use of data from the intraplate earthquakes; the majority have used only interplate earthquake data in the analyses. This is rather crucial as the ground motion records discussed earlier show that the PGA values from local intraplate earthquakes in certain locations to be higher than the PGA values from far field earthquakes. Therefore, we recommend a more detailed SHA incorporating the historical earthquake records from both far field and local intraplate sources is necessary for Peninsular Malaysia.

5. Conclusions

The present paper provides an overview of the seismicity of Peninsular Malaysia by considering and comparing the earthquake sources in and around the region. Our critical analysis of the available literature leads us to summarize the following key aspects of seismicity in Peninsular Malaysia:

• The prominent historical earthquakes of prime concern to Peninsular Malaysia originated from two major sources: (a) far field sources such as the Sumatran Subduction Zone and Sumatran Fault and (b) intraplate sources comprising local faults located within the Peninsula and Borneo Island.

• SHA studies predict higher PGA values towards the coastal and lowland areas due to the shorter source-site distances and the site-specific soil conditions, suggesting that the infrastructure in these regions to be more susceptible to damage due to Sumatran earthquakes.

• The PGA values measured in Peninsular Malaysia from the low magnitude local intraplate earthquakes were observed to be much higher than that of the earthquakes generated by the Sumatran Fault in some cases possibly due to the shorter source-site distance.

• The existing literature on SHA of Peninsular Malaysia predominantly considered the far field earthquakes. However, as noted above, the role of local intraplate earthquakes in dictating the seismicity of the region, especially at short source-site distances, should not be ignored in such analyses. Of immediate requirement, therefore, is a more comprehensive and detailed SHA for Peninsular Malaysia by considering the historical earthquake records from both far-field and local intraplate sources.

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