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Incorporating the local faults effects in development of seismic ground-motion hazard mapping for the Peninsular Malaysia region

Abdollah Vaez Shoushtari[a], Azlan Bin Adnan[a,*], Mehdi Zare[b]

[a] Department of Structure and Materials, Faculty of Civil Engineering, Universiti Teknologi Malaysia, 81310 Skudai, Johor Bahru, Malaysia
[b] Department of Engineering Seismology, International Institute of Earthquake Engineering and Seismology (IIEES), 26 Arghavan Street, Tehran 19395/3913, Iran

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ABSTRACT

The probabilistic seismic ground-motion hazard maps for the Peninsular Malaysia region have been developed by the present study. Despite the earlier seismic hazard maps for this region, which were proposed only based on far-field Sumatran seismic sources, this study has attempted to present the new maps using the combination of the local faults within the region, Sumatran fault, and Sumatran subduction source zones. The composite earthquake catalogue of the study region has been extended to cover an area limited by 10°S–10°N Latitude and 90°–110°E Longitude with the period from 1900 to 2014. The seismic source zones were categorized into subduction and fault sources. Line, area, and background source models were used to model the seismic sources with variable characteristics along them. In order to consider the epistemic uncertainty, logic-tree framework was used to incorporate basic quantities such as different source modelling, maximum magnitudes, and ground-motion prediction equations (GMPEs). The hazard maps are presented over a 12.5 km grid in terms of peak ground acceleration (PGA) for 10 and 2% probabilities of exceedance in 50 years corresponding to 475 and 2475 years return periods (RP), respectively. The proposed new hazard maps give the expected ground motions based on the extended earthquake catalogue, upgraded seismic source parameters, and more compatible GMPEs than applied in the development of previous hazard maps. The estimated PGAs on rock site condition across the Peninsular Malaysia region for RP475 and 2475 years are in the range of 1.0–10.0%g and 2.0–20.0%g, respectively. The horizontal elastic acceleration response spectra on different soil site conditions have been also presented for the region of interest following the principles of Eurocode 8 through the calculated uniform hazard spectra.

1. Introduction

Peninsular Malaysia is located on the stable Sunda plate, as a part of the Eurasian plate, outside the Pacific Ring of Fire. Therefore, it has been perceived conventionally that the region is an earthquake free zone. However, there are some reports that state that Peninsular Malaysia has experienced several earthquake-induced tremors mainly due to Sumatran seismic sources. Although no structural damage has been reported in the region, many people in Peninsular Malaysia have felt the shake induced by earthquake tremors (The Star Online, 2004, 2011). The 2011 Tohoku earthquake in Japan with moment magnitude (**M**) 9.1 is an example of overseas regional megathrust subduction earthquakes with remarkable influence on sites which were far from the epicenter. Takewaki et al. (2011) reported that most of the super high rise buildings in the major cities of Japan such as Tokyo and Osaka with epicentral distances (R_{epi}) of about 385 and 760 km away, respectively, were seriously shaken by the earthquake-induced long-period ground motions. Soil site effect is another parameter that could cause serious damage by amplifying the low amplitude, long-period ground motions induced by far-field excitations. For example, the devastating 1985 Michoacán earthquake with **M**8.0 caused serious damage in Mexico City, which was about 400 km away from the earthquake epicenter. The disaster was due to the amplification of incoming earthquake waves by the soft soil layer on the ground surface (Seed et al., 1988). Regarding to the aforementioned concepts, the medium to high rise buildings of Peninsular Malaysia and the surrounding region have shaken due to the far-field earthquakes generated by the Sumatran seismic sources (Nabilah and Balendra, 2012; Pan, 1995; Pan et al., 2001; Pan and Sun, 1996). In addition, since November 2007, a series of small earthquakes with **M** of 2.1 to 4.4, recorded by the local seismic stations operated by the Malaysian Meteorological Department (MMD), have occurred within the Peninsular Malaysia region. The epicenter of these local earthquakes were mostly located in the Bukit Tinggi area (Minerals and Geoscience Department Malaysia, 2012). However, the hazards and

* Corresponding author.
E-mail addresses: vsabdollah3@live.utm.my (A. Vaez Shoushtari), azlanadnan@utm.my (A.B. Adnan), mzare@iiees.ac.ir (M. Zare).

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threats that could be induced by the potential intraplate earthquakes due to the local active faults such as Bukit Tinggi and Kuala Lumpur faults have been underrated. As a result, given this combination of the far-field Sumatran earthquakes and the potential local intraplate earthquakes, it is reasonable to categorize Peninsular Malaysia as a low to moderate seismic region. Therefore, new seismic ground-motion hazard maps incorporating potential hazards posed by the both Sumatran and local active faults will absolutely be useful for structural engineers as a provision during seismic design stage.

In view of previous probabilistic seismic hazard assessment (PSHA) studies, Pan and Megawati (2002) calculated the peak ground acceleration (PGA) values of 29.5 and 55.1 gal (or cm/s^2) on rock site for Kuala Lumpur with 10 and 2% probabilities of exceedance (PE) in 50 years, respectively (i.e., corresponding to a return period (RP) of 475 and 2475 years, respectively). Petersen et al. (2004) and Adnan et al. (2006) obtained the PGA on bedrock across Peninsular Malaysia with the values of 30–120 and 20–100 gal with 10% PE in 50 years, respectively. A new set of U.S. Geological Survey (USGS) seismic hazard maps for Southeast Asia was developed by Petersen et al. (2008). Referring to the developed hazard maps, the PGA value with RP475 years on rock site for Kuala Lumpur was estimated to be around 50 gal. In 2011, Pappin and his co-workers proposed an approach for seismic design in Malaysia and calculated the PGA value of 19.62 gal on rock site of Kuala Lumpur with RP475 years (Pappin et al., 2011). Delfebriyadi (2011, 2012) presented the probabilistic seismic hazard maps on rock site condition for Peninsular Malaysia. The obtained PGA values across the Malay Peninsula region were 50–90 and 180–200 gal with RP475 and 2475 years, respectively. Nabilah and Balendra (2012) found that the PGA on bedrock in Kuala Lumpur with RP475 and 2475 years had the values of 16.5 and 23.4 gal, respectively. In a recent study, Loi et al. (2018) suggest mean PGA values of 6–42 and 12–70 gal across Peninsular Malaysia on bedrock at 10% and 2% PE in 50 years, respectively. It should be noted that the results of the aforementioned studies are only based on the distant Sumatran seismic sources and the local faults located inside the Peninsular Malaysia region and the earthquakes generated by them are not considered by these probabilistic studies.

This study presents the new probabilistic seismic ground-motion hazard maps and the elastic acceleration response spectra for the Peninsular Malaysia region considering the both local faults within the region and the far-field Sumatran seismic sources. The Frankel (1995) approach with crustal fault and subduction zone models were applied in the present new PSHA study for the region of interest. The new seismic hazard results are presented based on the extended earthquake catalogue, upgraded seismic source parameters, and selection of appropriate ground-motion prediction equations (GMPEs). A Logic-tree framework is used to tackle the epistemic uncertainties in the hazard definition. The outcome seismic hazard contour maps present the geometric-mean horizontal component PGA on rock site of the Peninsular Malaysia region for return periods of 475 and 2475 years. The recommended horizontal 5%-damped elastic acceleration response spectra on four different ground types have been proposed following the principles of Eurocode 8 (EC8) (BS EN 1998-1:2004) in order to develop the future seismic design provisions of the study region.

2. Peninsular Malaysia and its surrounding tectonic setting

The Sumatra and Java Islands in the Indonesian archipelago are on the Eurasian plate which rests on top of the subducting Indian-Australian plate (Fig. 1). The Indian-Australian and the Eurasian plates converge to form the Sunda trench, and the islands are located a few hundred kilometers from the trench. The convergence is nearly perpendicular to the trench axis south of Java, but it becomes more oblique southwest of Sumatra. Based on hypocentral distributions and earthquake focal mechanisms, the subducting plate in Sumatra dips less than 15°beneath the outer arc ridge (interface part), and the dip angle steepens to about 50°under the volcanic arc (intraslab part) (Newcomb and McCann, 1987; Fauzi et al., 1996). The moderately shallow dip angle between the overriding and the subducting plates results in a strong coupling that generates large earthquakes in the region (Megawati et al., 2005).

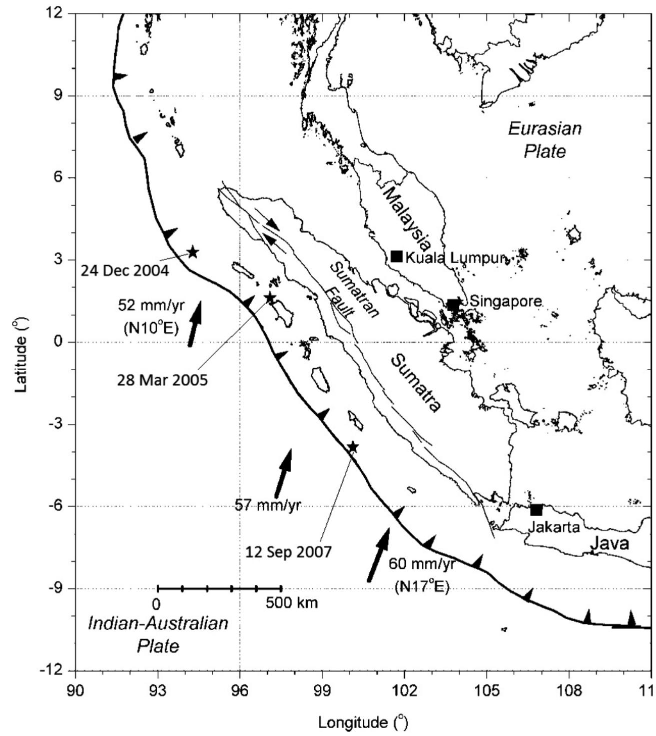

Fig. 1. Tectonic setting of Sumatra Island, together with the epicenters of 3 recent significant Sumatran subduction interface earthquakes - modified figure from Megawati and Pan (2010).

Releasing the strain accumulated by the convergence between the two plates has resulted in six very large earthquakes (**M** ≥ 8.0) along the Sumatran subduction interface zone in the last 250 years. The earliest of these earthquakes occurred in February 1797 with **M**8.7 and a rupture length of 370 km (Newcomb and McCann, 1987; Natawidjaja et al., 2006). The next was the great 1833 earthquake with **M** estimated to be between 8.8 and 9.2 followed by another earthquake in 1861 (**M**8.5) with rupture lengths of 500 and 270 km, respectively (Natawidjaja et al., 2006; Newcomb and McCann, 1987; Zachariasen et al., 1999). After 1861, no further earthquakes with **M** ≥ 8.0 occurred along the Sumatran interface zone until 26 December 2004, when the Aceh earthquake with **M**9.1 occurred (Chlieh et al., 2007; Subarya et al., 2006; Ammon et al., 2005; Lay et al., 2005). Next was the **M**8.6 Nias earthquake on 28 March 2005 which had a rupture length that matched to that of the 1861 event. The latest large earthquake occurred along the Sumatran megathrust (interface) on 12 September 2007 with **M**8.5 (Briggs et al., 2006; Konca et al., 2007).

The Sumatran fault is 250 km away from the northeast side of the Sunda trench. Geological and geophysical studies identify the fault as a seismically active, right lateral strike-slip fault (Sieh and Natawidjaja, 2000). The Sumatran fault has a sinusoidal overall shape. It is 1650 km long and it runs along the western side of the Sumatra Island, coinciding with the Bukit Barisan mountain chain. The Sumatran fault is highly segmented compare to other great strike-slip faults. The fault has caused numerous major earthquakes, but because it is highly segmented, the magnitude of the earthquakes are approximately limited to 7.5–7.7 with rupture lengths no more than 100 km (Sieh and Natawidjaja, 2000).

In accordance to the geological map of Peninsular Malaysia published by the Mineral and Geoscience Department of Malaysia (JMG),