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On the Selection of Ground-Motion Prediction Equations Compatible with Peninsular Malaysia Region for Sumatran Subduction In-Slab Earthquakes

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Abstract Although Peninsular Malaysia is located in a low-seismicity region, the medium to high rise structures could be vulnerable to distant earthquakes generated by Sumatran fault and Sumatran subduction seismic sources. In addition, seismic design has not been specifically considered in the building design codes of the region. Therefore, it is rational to assess the seismic hazard of the region to apply appropriate seismic designs for the existing and future structures. The most comprehensive method recommended by design codes is Probabilistic method in order to do Seismic Hazard Analysis (i.e. called PSHA). The key component required in any seismic hazard analysis is employing an appropriated set of Ground-Motion Prediction Equations (GMPEs). This paper has attempted firstly to drive new GMPE for Peak Ground Acceleration (PGA) using data recorded in Peninsular Malaysia due to Sumatran subduction in-slab earthquakes. Secondly, the study has presenteda classification among the new derived GMPE and other four GMPEs proposed for subduction in-slab earthquakes of different regions through a comparative study based on the PGAs recorded in Peninsular Malaysia. The goal of the classification was to introduce the GMPEs which were the most compatible with the region. The results of the present study are applicable for seismic hazard analysis in Peninsular Malaysia.

Keywords Ground-motion prediction equation, Sumatran subduction in-slab earthquake, Peninsular Malaysia

1. Introduction

Generally speaking, seismic designs have not been considered in low-seismic regions of Southeast Asia, as these regions have never experienced any severe damages due to earthquakes. Kuala Lumpur, the capital of Malaysia, could be a good example of these regions. Even though it is located in a low-seismic region, it could be vulnerable to distant earthquakes. The active Sumatran seismic sources that could affect this city are located more than 300 km away. The number of felt events is increasing due to the rapid construction of high-rise buildings in this city [1]. Even though earthquakes have never caused any structural damage in Kuala Lumpur, the effects of even a moderate level of ground motion would be enormous because of the large population taking place in the structures that have not been designed for earthquake loads [2].

In view of the Probabilistic Seismic Hazard Analysis (PSHA), Adnan et al. [3] and Petersen et al. [4] obtained the Peak Ground Acceleration (PGA) across Peninsular Malaysia with the values of 20-100 gal and 40-120 gal with 10% probability of exceedance over 50 years (i.e., 475-year return period), respectively. Pan and Megawati [5] calculated the PGA values of 29.5 and 12.7 gal with the same return period for Kuala Lumpur and Singapore, respectively. In a recent study, Nabilah and Balendra [6] found that the PGA in Kuala Lumpur with 10% and 2% probabilities of exceedance over 50 years had the values of 16.5 and 23.4 gal, respectively. One of main reason behind these different results is the selection of unsuitable Ground-Motion Prediction Equations (GMPEs).

Sumatran seismic sources consist of three discrete zones, the Sumatran fault, the Sumatran subduction interface, and the Sumatran subduction in-slab. Since these seismic zones have three different rupture mechanisms, three sets of GMPEs must be derived for the earthquakes generated by these seismic sources.

This paper has attempted firstly to drive new GMPE for horizontal Peak Ground Acceleration (PGA) using data recorded in Peninsular Malaysia due to Sumatran subduction in-slab earthquakes. Secondly, the study has presented a classification among the new derived GMPE and other four GMPEs proposed for subduction in-slab earthquakes of different regions, through a comparative study based on the recorded PGAs in Peninsular Malaysia.

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2. Regional 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. The convergence is nearly perpendicular to the trench axis in south of Java, but it becomes more oblique in southwest of Sumatra. Based on hypocentral distributions and earthquake focal mechanisms, the subducting plate in Sumatra dips less than 15 degrees beneath the outer arc ridge (interface part), and the dip angle steepens to about 50 degrees under the volcanic arc (in-slab part) [7, 8].

The Sumatran fault is 250 km away from the northeast side of Sunda trench. Geological and geophysical studies identify the fault as a seismically active, right lateral strike-slip fault [9].

3. Sumatran Subduction In-Slab Earthquakes Recorded in Peninsular Malaysia

Since 2004, the Malaysian Meteorological Department (MMD) has installed a network of seismic stations in Malaysia. The network is comprised of 28 three-component and real time stations. Twelve seismic stations of this network are located on granite, meta sediment, sandstone and rocky sites (i.e. NEHRP site class B with shear-wave velocity values; 760 m/s < $V_S \leq$ 1500 m/s) in Peninsular Malaysia.

The Sumatran subduction in-slab earthquakes from 2006-2012, recorded by the twelve seismic stations are listed in Table 1. The recorded PGAs were between 0.027-1.700 gal. The 37 records due to 5 Sumatran subduction in-slab earthquakes collected in this study had moment magnitudes ranging from 6.1 to 7.6 and hypocentral distances of 327-904 km.

In the present study, in order to classify earthquakes by type (i.e., interface and in-slab events), the method proposed by Atkinson and Boore [11] that it is related to both the focal depth and focal mechanism was used. The trust worthy epicenters, moment magnitudes, focal depths and mechanisms of collected Sumatran earthquakes were obtained from the Harvard Centroid Moment Tensor (CMT) catalogue [12].

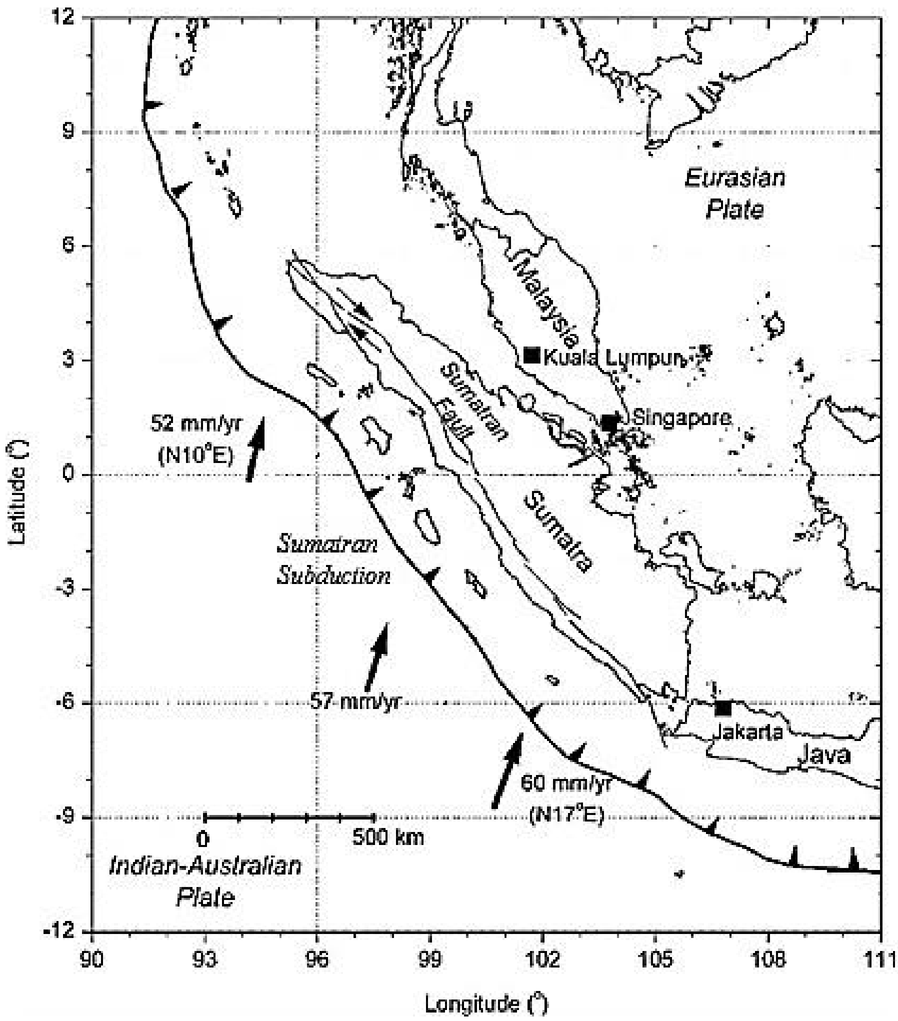

Figure 1. Tectonic setting of Sumatra Island [10]

Table 1. List of Sumatran subduction in-slab earthquakes recorded in Peninsular Malaysia

Date (Time/UTC)	Lat.	Long.	M_W	H^a (km)	Station	NEHRP Site Class	Soil site condition	R_{hypo} (km)
23/06/2012 (04:34:00)	2.98°N	97.77°E	6.1	104.5	BRSM	B	Rock	466.5
					DTSM	B	Rock	464.0
					FRM	B	Rock	441.5
					GTSM	B	Rock	459.0
					IPM	B	Rock	416.0
					JRM	B	Rock	542.3
					KGM	B	Rock	634.0
					KTM	B	Rock	658.0
					KUM	B	Rock	422.9
05/09/2011 (17:55:00)	2.88°N	97.86°E	6.7	94.6	BRSM	B	Rock	454.5
					FRM	B	Rock	430.5
					GTSM	B	Rock	448.5
					IPM	B	Rock	409.9
					JRM	B	Rock	533.0
					KGM	B	Rock	621.0
					KOM	B	Rock	682.7
					KUM	B	Rock	420.0
					PYSM-B0	B	Rock	435.1
30/09/2009 (10:16:00)	0.79°S	99.67°E	7.6	77.8	BRSM	B	Rock	483.7
					FRM	B	Rock	503.8
					GTSM	B	Rock	526.1
					IPM	B	Rock	620.8
					JRM	B	Rock	611.4
					KGM	B	Rock	517.3
					KOM	B	Rock	551.5
					KTM	B	Rock	785.4
					KUM	B	Rock	689.2
					PYSM-B0	B	Rock	475.6
16/05/2006 (15:28:00)	0.01°N	96.98°E	6.8	13.5	IPM	B	Rock	678.5
					KGM	B	Rock	738.9
					KTM	B	Rock	903.7
					KUM	B	Rock	714.7
01/12/2006 (03:58:00)	3.46°N	99.05°E	6.3	208.4	FRM	B	Rock	354.6
					IPM	B	Rock	327.0
					KGM	B	Rock	542.0
					KTM	B	Rock	540.0
					KUM	B	Rock	341.0

H: Focal depth (km)

4. New GMPE for Sumatran Subduction In-slab Earthquakes

Referring to Fukushima and Tanaka (1990) [13], the following attenuation model was selected in order to drive new GMPE:

$$\log(PGA)=aM_W-bR_{hypo}-\log\left(R_{hypo}+c\times10^{aM_W}\right)+d+\varepsilon_{\log(PGA)} \tag{1}$$

where PGA is peak ground acceleration in cm/sec^2, M_W is moment magnitude, R_{hypo} is hypocentral distance in km, and a, b, c, and d are regression coefficients. Performing least-square regression analysis released following equation to predict Sumatran subduction in-slab earthquakes:

$$\log(PGA) = 0.504632M_W - 0.000845R_{hypo} - \log(R_{hypo}) - 0.918416 \qquad \sigma_{\log(PGA)} = 0.1895 \tag{2}$$

5. Classification of GMPEs

The description of the GMPEs are summarized and listed in Table 2. The comparison between the PGAs predicted by the GMPEs and the 37 PGAs recorded on rock sites in Peninsular Malaysia are depicted in Fig. 2.

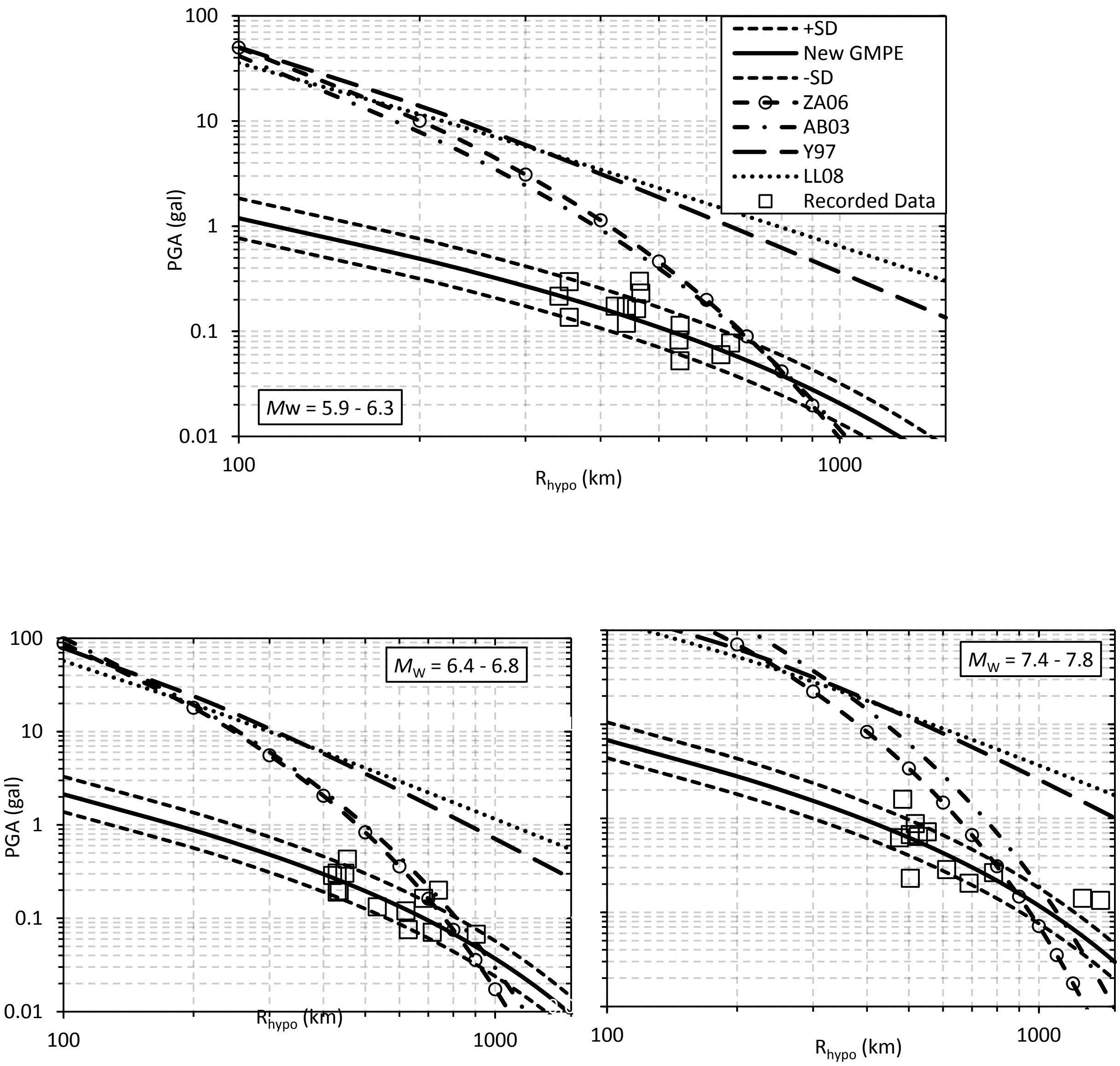

Figure 2. The 37 recorded PGAs due to Sumatran subduction in-slab earthquakes on rock sites (NEHRP site class B) in Peninsular Malaysia, together with the GMPE of this study and other four ones derived for different subduction zones

Table 2. Descriptions of the selected GMPEs

Reference (Model designation)	Model description	M_w range considered	Distance (R) definition and range considered
Present study (New GMPE)	Regression of recorded data from Sumatran subduction *in-slab* earthquakes in Peninsular Malaysia.	6.1-7.6	The hypocentral distance, 327-904km
Zhao et al.[14] (ZA06)	Regression of recorded data mainly from crustal and subduction interface and *in-slab* earthquakes in Japan, with supplementary data from earthquakes in western part of the United States and 1978 Tabas, Iran earthquake.	5.1-8.3	The shortest distance to the rupture plane if fault model is available and otherwise is the hypocentral distance, 25-300km
Atkinson and Boore [11] (AB03)	Regression of real recorded ground motion data from interface and *in-slab* earthquakes occurring in subduction zones of Alaska, Chile, Cascadia, Japan, Mexico, Peru and the Solomon islands.	5.0-8.3	The closest distance to the rupture plane, 10-500km
Youngs et al. [15] (YO97)	Regression of recorded interplate earthquakes from different subduction interface and *in-slab* zones.	5.0-8.2	The closest distance to the rupture plane, 10-500km
Lin and Lee [16] (LL08)	Regression of recorded ground motions from both interface and *in-slab* earthquakes of subduction zones in Taiwan and other foreign regions.	5.3-8.1	The hypocentral distance, 15-630km

Figs. 2 shows that at long distances, Lin and Lee [16] and Youngs et al. [15] equations predicted the largest PGA out of the six models, and the predicted PGAs were significantly larger than the recorded ones. As demonstrated by the figure, the PGAs predicted by Zhao et al. [14] equation were approximately close to the observed data compare to the predicted ones based on the equation proposed by Atkinson and Boore [11]. Refer to the Fig. 2, it could be understood that the PGAs predicted by the New GMPE presented in this study, fit well with the recorded data.

6. Conclusions

One of the most significant components required in any seismic hazard analysis is the selection of a set of appropriate Ground-Motion Prediction Equations (GMPEs). The first objective of this study was to drive a new GMPE for horizontal Peak Ground Acceleration (PGA) using data recorded in Peninsular Malaysia due to Sumatran subduction in-slab earthquakes. As the second objective, the study has presented a classification among the new derived GMPE and other four GMPEs proposed for subduction in-slab earthquakes of different regions, through a comparative study based on the recorded PGAs in Peninsular Malaysia.

The PGAs predicted by the New GMPE and the response spectral acceleration relations provided by Zhao et al. [14], were found to correlate well with the recorded PGAs. As the PGAs collected in this study were recorded with hypocentral distance of more than 327 km, it should be mentioned that the conclusions about the most compatible GMPE for the region are valid only for distances greater than 327 km. The results of the present study in terms of introducing the GMPEs compatible with the region could be applicable in seismic hazard analysis projects of Peninsular Malaysia.

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