

Seismic Hazard of Singapore and Malaysia

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ABSTRACT: This article reviews the seismic hazard studies of low-to-moderate regions like Singapore and Malaysia, and presents a procedure to obtain the seismic demand for buildings in Singapore. The review includes the research on potential seismic sources, attenuation models and soft soil amplification effects. A comparative study of various attenuation models is carried out. In light of the latest two strong earthquakes (2004 Aceh earthquake and 2005 Nias earthquake), the Component Attenuation Model (CAM) is found to predict reliable and more accurate ground motions as far as 600km from potential earthquake sources. It is found that the maximum bedrock spectral acceleration for the worst possible earthquake scenario can be nearly 14 gals. With soil amplification, this could translate to a base shear demand of 10% of the weight of the building.

KEYWORDS: Seismic Hazard, Far field effects of earthquake, attenuation models for rock motion, soil amplification

1 INTRODUCTION

Although Singapore and Malay Peninsula are located on a stable part of the Eurasian Plate, buildings on soft soil are occasionally subjected to tremors due to far-field effects of earthquakes in Sumatra (Balendra et al. 1990). In the last few years, tremors were felt several times in tall buildings in Singapore and Kuala Lumpur, the capital of Malaysia, due to large earthquakes in Sumatra. The mechanism for such tremors is illustrated in Figure 1 (Balendra 1993). The seismic waves, generated from an earthquake in Sumatra, travel long distance before they reach Singapore bedrock. The high frequency earthquake waves damped out rapidly in the propagation while the low frequency or long period waves are more robust to energy dissipation and as a result they travel long distances. Thus the seismic waves reaching the bedrock of Singapore or Malay Peninsula are rich in long period waves, and are significantly amplified due to resonance when they propagate upward through the soft soil sites with a period close to the predominant period of the seismic waves. The amplified waves cause resonance in buildings with a natural period close to the period of the site, and the resulting motions of buildings are large enough to be felt by the residence. In recent years many studies (Balendra et al. 2002, Megawati and Pan 2002, Megawati et al. 2003 and 2005) have been conducted to ascertain whether these motions could cause damage to buildings. This article reviews the state of the art work on: (1) seismicity of potential earthquake

sources responsible for the tremors; (2) the attenuation models to predict the bedrock motions at long distances; (3) soil amplification models to obtain the surface motions, and hence the base shear demand on buildings. Finally, the impact of an earthquake scenario of magnitude 9.5 at 600km away from Singapore is discussed.

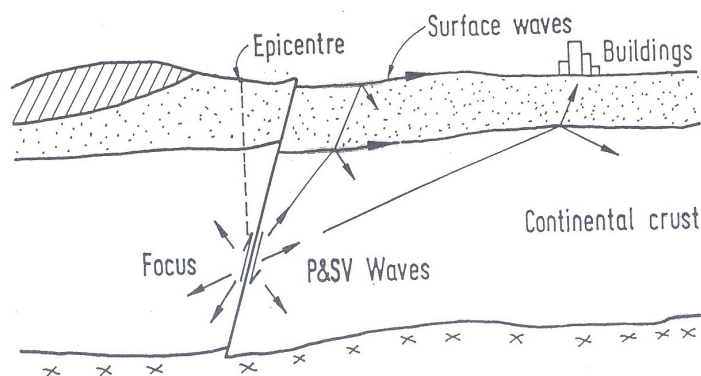


Figure 1. Schematic diagram for far-field effects of earthquakes.

2 POTENTIAL EARTHQUAKE SOURCES AND THEIR SEISMICITY

The earthquakes occurred in Sumatra before 1960's are presented in several catalogs (Gutenberg and Richer 1954; Rothe 1969; Lee et al. 1976, 1978; Abe and Kanamori 1979; Bath and Duda 1979; Abe 1981, 1982; Abe and Noguchi 1983a, 1983b; Dunbar et al. 1992). Since 1964, the Bulletin of the In-

ternational Seismological Centre (ISC) and Preliminary Determination of Epicenters (PDE) catalogs of U.S. Geological Survey provide the listing of major earthquakes. Seismic intensities for earthquakes felt in Singapore are catalogued by Sun and Pan (1996), and those for Malay Peninsula are catalogued by Leyu et. al. (1985). According to these historical records, the earthquakes that influenced Singapore and Kuala Lumpur in Malay Peninsula are originated from two earthquake faults: Sumatran subduction zone and Sumatran strike slip fault as shown in Figure 2.

2.1 Sumatran subduction zone

The Sumatran subduction zone is formed by subduction of the India-Australian plate beneath the Eurasian plate at a rate of about 67mm per year (Hamilton 1979). The nearest location of this subduction zone is about 600km to Singapore. Most of the earthquakes generated in this zone are shallow to intermediate with very unusual deep events. As the subducted slab moves at a shallow angle, the overriding and the subducting plates are strongly coupled in this zone and hence strong earthquakes could occur (Sun and Pan 1995b). According to the historical records in the last 300 years, four great earthquakes have occurred in this zone. Two occurred in the 1800s: moment magnitude (M_w) of 8.75 in 1833 and M_w of 8.4 in 1861 (Newcomb and McCann 1987). And another two occurred in recent years: M_w of 9.3 Aceh earthquake in Dec 2004, which generated the great tsunami that killed over two thousands of people, and M_w of 8.7 Nias earthquake in March 2005. The locations of these four earthquakes including the rupture zones are shown in Figure 3.

The probabilistic seismic hazard analysis of the Sumatran subduction zone was carried out by Sun and Pan (1995a; 1995b). Their research indicated that the recurrence interval of an earthquake with a moment magnitude of 8.5 or larger would be about 340 years, which corresponded to a 14% probability of exceedance within 50 years. Balendra et al. (2002) identified the worst earthquake scenario in this zone as an earthquake of $M_w = 8.9$ at 600 km away from Singapore. Megawati and Pan (2002) identified the 1833 Sumatran subduction earthquake ($M_w=8.75$) as the worst-case scenario earthquake, based on a series of ground motion simulations of potential earthquakes that might affect Singapore. However, these studies were based on earthquake records prior to the two recent strong earthquakes: the $M_w=9.3$ Aceh earthquake in 2004 (focal depth of 30km and 950km away from Singapore) and the $M_w=8.7$ Nias earthquake in 2005 (focal depth of 32km and 600km away). The Aceh earthquake and Nias earthquake

both occurred at the Sumatran sub-duction fault, for which the closest epicentral distance is 600 km away from Singapore. The largest earthquake ever recorded in history was the Chilean earthquake of magnitude 9.5, and the possibility of having earthquakes of this size at this fault was suggested prior to the Aceh earthquake by Zachriassen et. al. (1999).

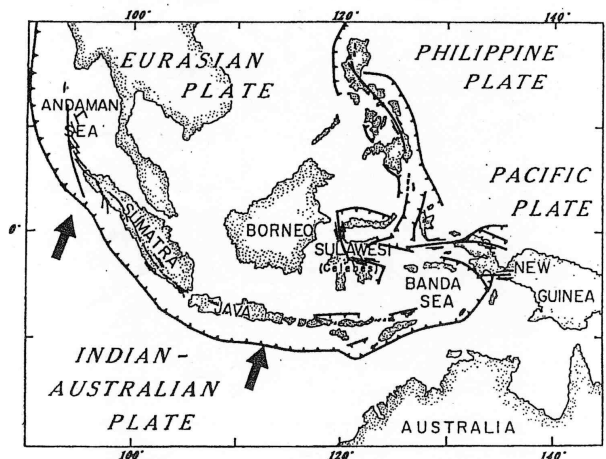


Figure 2. Sumatran fault and subduction of the Indian-Australian Plate into Eurasian Plate (Balendra et al. 2001).

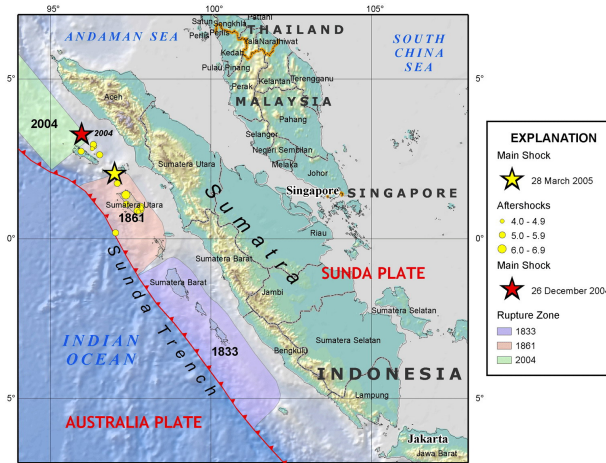


Figure 3. Locations of the four largest earthquakes in Sumatran subduction zone.

2.2 Sumatran strike slip fault

The Sumatran fault (400 km away from Singapore) runs through the entire length of Sumatra with a length more than 1500km. It is a dextral strike slip-fault, which is another source of numerous earthquakes (Katili and Hehuwat 1967). This fault accommodates a larger component of relative plate motion that cannot be accommodated by slip on the thrust-fault interface in the Sumatran subduction zone. In this fault the energy is stored through shear deformation of the rock when the plates on either side of the fault get interlocked while in motion. Lo-

cations of the historical earthquakes in Sumatran fault are shown in Figure 4. According to the historical records, the largest earthquakes occurred in the Sumatran fault are of moment magnitude 7.7 in 1892 and moment magnitude 7.6 in 1943 (Prawirodirdjo et al. 2000; Sieh and Natawidjaja 2000). As it is considered only a limited amount of energy can be stored by the shear interlock, the energy released from this fault is at a relatively lower stress level when compared with the Sumatran subduction zone. As a result, the maximum magnitude of this fault may not exceed a moment magnitude of 7.8 (Merati et al. 2000; Balendra et al. 2002).

pendent of the type of fault mechanism), Lam et. al. (2000b; 2000c) combined a generic source model developed by Atkinson (1993) with a generic crustal model of Boore and Joyner (1997) to construct frequency spectrum of the ground motions using the Component Attenuation Model (CAM) as framework. An appropriate geophysical model for a region of interest could be obtained by examining the crustal characteristics of the region and incorporating them into CAM. A good agreement was achieved between CAM's ground motion prediction and the historical data in Australia (Koo et al. 1999; Koo et al. 2000), the Coastal Region of South China (Lam et al. 1999a, 1999b; Lam et al. 2000a), Shanghai (Luo 2000), and Vietnam (Ngo et al. 2001). For the attenuation relationship in regions near Singapore, a similar approach was adopted to predict the bedrock motions in Singapore (Balendra 2000; Balendra et al. 2002). The attenuation model proposed by Belendra et al.(2002) is elaborated below by including the latest two strong earthquakes (Aceh earthquake and Nias earthquake) for model validation.

The region of interest is south-western region of Eurasian plate, spanning 90° E to 105° E in longitude and -5° S and 25° N in latitude, which include Singapore, Malaysia, Sumatra, Thailand and Burma, and the south-western part of the Sunda Arc. The peak acceleration on bedrock (PRA) is expressed as:

$$PRA(g) = \alpha G \beta \gamma \tag{1}$$

$$\alpha = 0.192g[0.40 + 0.60(M_w - 5)^{1.5}] \tag{2}$$

$$G = \frac{2}{3} \left(\frac{75}{R} \right)^{0.5}; R > 75 \text{ km} \tag{3}$$

$$\beta = \left(\frac{30}{R} \right)^C \tag{4}$$

$$C = 0.009[9.9 - 1.28(M_w - 6)]R^{0.48} \tag{5}$$

$$\gamma = 0.585 \tag{6}$$

where PRA(g) is the peak acceleration on bedrock (in the unit of gravitational acceleration); α the source factor; G the cylindrical attenuation factor which accounts for the crustal wave guide effects; R the epicentral distance in km; β the an-elastic attenuation factor which accounts for energy dissipation along the wave travel path and γ a factor accounts for mid-crust amplification and combined effects of upper crust amplification and attenuation.

Equations 1- 6 were validated (Balendra et al. 2002) using five historical earthquakes in the subduction region of the Indonesian Arc and the Bur-

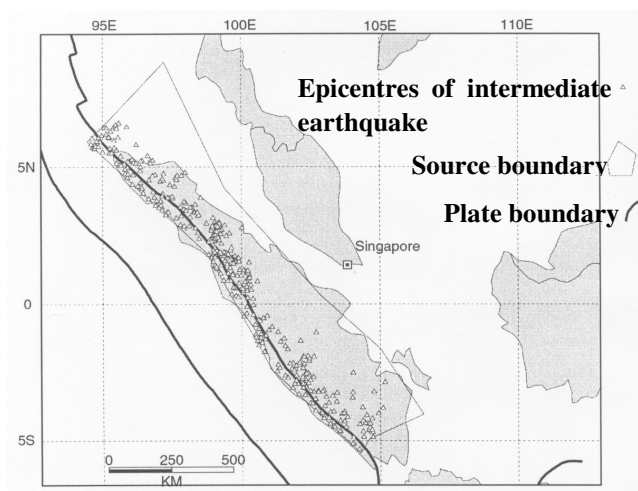


Figure 4. Locations of historical earthquakes in Sumatran fault.

3 ATTENUATION MODELS

The magnitude of ground motion at varying distances from the above earthquake sources is determined from attenuation models. Statistical regression analysis could be used to develop such attenuation models (Ambrasey et al. 1996; Boore et al. 1997; Sadigh et al. 1997; Balendra et al. 1999). However, as there were not enough strong motion data in this region relating the ground acceleration with magnitude and distance, this conventional empirical modeling approach was not feasible. Using the data from other region would not be reliable as the attenuation rate was dependent on the geological characteristics of the region (Balendra et al. 1999). As an alternative approach, attenuation models had been developed from analogue regions which were considered to possess similar seismo-tectonics and geological conditions (Atkinson 1993; Atkinson and Boore 1998). In these attenuation models, the product of a number of components such as source mechanism, radiation mechanism and path modification mechanisms was used to express the motion in the form of Fourier amplitude spectrum. Since the average source characteristics is rather generic (inde-

mese Arc (with the locations shown in Figure 5). The two recent great earthquakes in Sumatra (Aceh earthquake and Nias earthquake) are now included in comparing the peak rock motions in Table 1. The predicted PRA of the Nias earthquake is very close to the measured value, within 15%, implying that the accuracy of the CAM is high for distances up to 600 km. The prediction for Aceh earthquake was not good because the fault rupture was directed away from Singapore and the epicenter was nearly 1000km from Singapore.

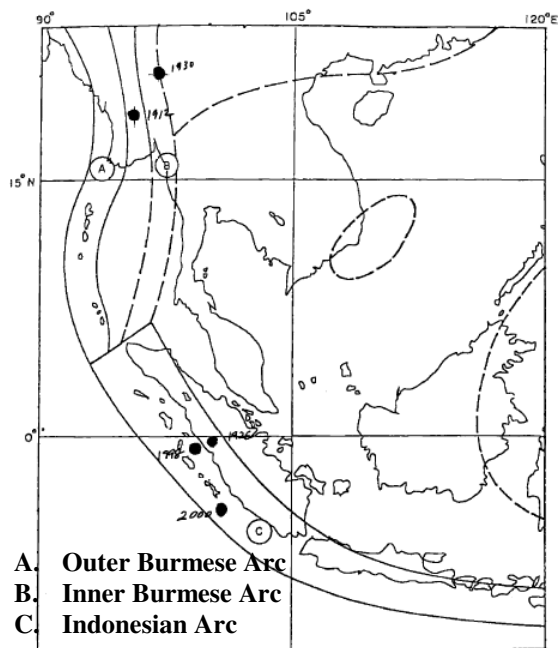


Figure 5. Locations of five Sumatra and Burmese earthquakes.

Table 1. Computed peak rock acceleration and observed field data.

Event	Magnitude		Distance km	Computed gals	Measured gals
	M _L	M _w			
Burma, 1912		8	400	5.5	5-10
Burma, 1912		8	300	12.5	11-14
Burma, 1930		7.2	400	2.4	1-4
Burma, 1930		7.2	300	6	2-10
Sumatra, 1926	6.75		250	11.6	7-14
Sumatra, 1998	6.8		600	0.42	0.31
Sumatra, 2000	7.9		700	0.69	0.36
Aceh, 2004		9.3	950	1.11	0.3
Nias, 2005		8.7	600	3.02	2.62

Note: M_L is Richter scale, M_w is the moment magnitude, 1 gal= 0.1% gravitational acceleration g.

As yet another alternative approach in determining the attenuation model, Megawati and Pan (2002) used an extended reflectivity method to simulate bedrock motions in Singapore due to a hypothesized earthquake (M_w=8.75) in the Sumatran subduction zone. The generated motions had a long duration of 250 seconds and a predominant period between 1.8s and 2.5s. A set of attenuation relationships for Su-

matran-fault segments was derived by Megawati et al. (2003), based on synthetic seismograms, and ground motions were simulated for earthquakes with M_w ranging from 4.0 to 8.0, within a distance range from 174 to 1379 km. Megawati et al. (2005) developed a new set of attenuation relationships for the Sumatran-subduction earthquakes using synthetic seismograms that accounted for the source and path effects. The derived attenuation relationships covered a long distance range from 150 to 1500 km and considered uncertainties in rupture parameters, such as stress drop, strike, dip and rake angles. According to Megawati et al. (2005), the peak acceleration on bedrock (PRA) for the horizontal component is expressed as:

$$\ln(\text{PRA}) = \alpha_0 + \alpha_1 M_w + \alpha_2 M_w^2 + \alpha_3 \ln(R) + \alpha_4 R + \alpha_5 H + \epsilon_H \quad (7)$$

where PRA is the peak acceleration on bedrock (in the unit of cm/s²); R the epicentral distance in km; H the focal depth in km; ε_H the term to account for the variations in the PRA due to the randomness in source parameters (ε_H = 0.4413); α₃ the coefficient representing the geometrical attenuation rate (α₃ = -1); α₄ the coefficient accounting for the anelastic attenuation; (α₄ = -0.001548); other regression coefficients: α₀ = -7.198, α₁ = 2.3691, α₂ = -0.013856, α₅ = -0.08909.

When equation 7 is used to calculate the PRA for the Aceh and Nias earthquakes, the predicted values are 22.13gals (1 gal=0.1% gravitational acceleration g) for Aceh earthquake and 14.13gals for Nias earthquakes, which are several folds larger than the measured ones. Therefore, the CAM's method (equations 1-6) is more reliable and accurate for ground motion prediction up to 600km.

4 SOIL AMPLIFICATION AND BASE SHEAR DEMAND

The bedrock motions can be significantly amplified when the natural period of the soft soil is close to the predominant natural period of the bedrock motions, and can be further enlarged if the building possesses a natural period which is close to the natural period of the site.

Based on the verified CAM model, twelve synthetic bedrock accelerograms for the worst possible earthquake scenario in the Sumatran subduction fault (M_w=9.5, 600 km away from Singapore) and eighteen synthetic bedrock accelerograms for the worst possible earthquake scenario in the Sumatran fault (M_w=7.8, 400km away from Singapore), were generated using a stochastic simulation program named GENQKE (Lam 1999). The average accelera-

tion response spectra at bedrock for these two possible earthquakes (assuming 5% structural damping ratio) are shown in Figure 6. The maximum bedrock spectral acceleration for $M_w=9.5$ earthquake is 13.7 gals and that for $M_w=7.8$ earthquake is 8.4 gals.

In Singapore, the buildings that felt shaking were mostly in the southeastern part of the island, underlain by the Quaternary deposits, namely the Kallang Formation. To obtain the maximum seismic demand due to the worst possible earthquake in Sumatra, a careful selection of the Quaternary deposit soil sites should be carried out. For the worst situations, the predominant period of the bedrock motions, the period of the site and the period of the building must coincide. The bedrock spectra in Figure 6 shows that sites possessing a period of between 1.6s and 1.85s would respond severely to the bedrock motions due to the $M_w=9.5$ earthquake in Sumatran subduction fault, and that sites with a period of 0.7s would resonate to the bedrock motions due to the $M_w=7.8$ earthquake in Sumatran fault. As the natural period of typical buildings in Singapore (15-25 story) is in a range of 0.7s to 1.6s (Balendra et al. 2002), the sites that possess natural periods from 0.7s to 1.85 s would be of interest, and three sites in the Kallang formation on the eastern part of Singapore, located at Marine Parade (MP) with a site period of 0.76s, Katong Park (KAP) with a site period of 1.6s and the Katong area (KAT) with a site period of 1.85s, were selected for investigation. The borehole data for each of these selected sites are given in Balendra et al(2002).

According to the expressions given by Hardin and Drnevich (1972) and Poulos (1991), with the reference shear strain and damping parameters proposed by Lam and Wilson (1999) and initial shear modulus given by Imai and Tonouchi (1982). A 50% plasticity index for clay and 0% for sand were used in the expression. The resulting ensemble averages of the surface acceleration response spectra for 5% structural damping due the worst possible earthquakes are depicted in Figures 7 and 8. From these two figures, it is seen that the maximum spectral acceleration of the $M_w=9.5$ earthquake is 95.8 gals for the site with period of 1.6s to 1.8 s, and that of the $M_w=7.8$ earthquake is 98.9 gals for the site with period of 0.7s. Thus, the maximum elastic base shear that would be induced in a building with a period in the range 0.7 to 1.8 sec due to the worst earthquake scenario is nearly 10% of the weight of the building.

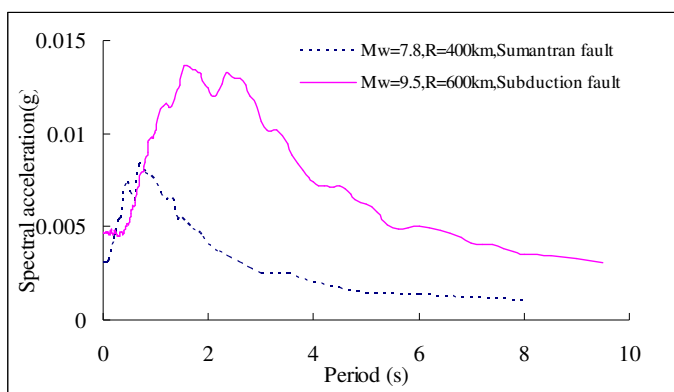


Figure 6. Average acceleration response spectra of the possible worst earthquakes at bedrock ($M_w=9.5$, 600km away from Singapore at the Sumatran subduction fault, and $M_w=7.8$, 400km away from Singapore at the Sumatran fault).

With soil profiles of the selected sites and the bedrock accelerograms generated by GENQKE (Lam, 1999), the computer program SHAKE91(1992) was used to calculate the surface motions, acceleration response spectra at surface and amplification factors. The shear modulus and damping relationship of the soil profiles at the selected sites were calculated ac-

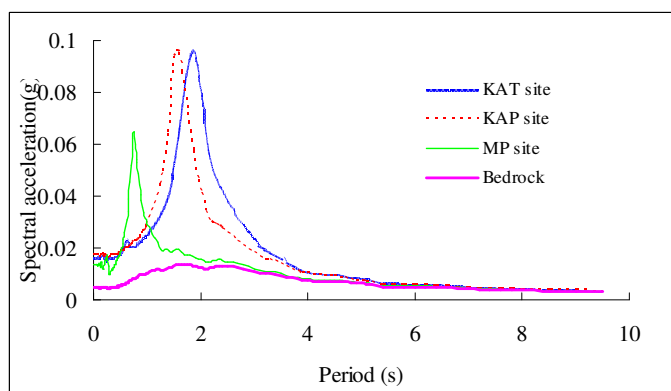


Figure 7. Average surface acceleration response spectra for MP, KAP and KAT sites for structural damping of 5% due to the $M_w=9.5$ Sumatran subduction earthquake.

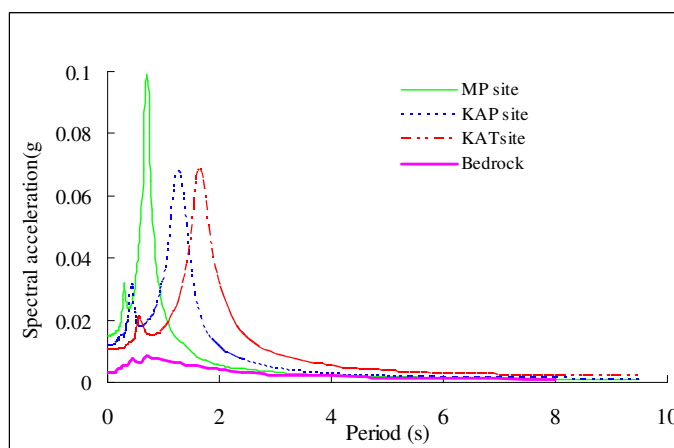


Figure 8. Average surface acceleration response spectra for MP, KAP and KAT sites for structural damping of 5% due to the $M_w=7.8$ Sumatran fault earthquake.

5 CONCLUSION

A state-of-the-art review on seismic hazard study of the regions near Singapore and Malay peninsula has been carried out. The findings are as follows:

(1) According to the historical records, the earthquakes that influence Singapore and Malay Peninsula are originated from two earthquake faults: Sumatran subduction zone and Sumatran fault.

(2) A comparative study of various attenuation models reveals that the CAM model could predict reliable and accurate rock motions for sites as far as 600km from the faults in Sumatra.

(3) The worst earthquake scenario in Sumatran subduction fault is identified as a $M_w=9.5$ earthquake 600 km away from Singapore, and that in the Sumatran fault as a $M_w=7.8$ earthquake 400 km away.

(4) For buildings with period in the range of 0.7 to 1.8 sec, the elastic base shear demand due to the worst earthquake scenarios and soil sites would be nearly 10% of the weight of the building.

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