

POTENTIAL SEISMIC HAZARDS OF SUMATRA, THE MALAY PENINSULA, AND SINGAPORE

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ABSTRACT

Several evidences have shown that the rupture of the Mentawai segment within the Sumatran megathrust is very likely in the next few decades. The degree of destruction that can be caused by this earthquake with a potential M_w of 9.0 has been witnessed in the recent earthquakes on 26 December 2004 (M_w 9.2) and 28 March 2005 (M_w 8.7). The main objective of the present research is to estimate the seismic hazard levels at several major cities in Sumatra, Java, Singapore and the Malay Peninsula due to the possible rupture of this megathrust segment, and to understand the potential risks to civil engineering structures in the cities. The regional seismic hazard is estimated by a means of ground-motion simulations using a kinematic model, which has been validated by simulating successfully the ground motions recorded during the two recent giant earthquakes. The results of the simulations indicate that the ground motions produced by the hypothetical earthquake are strong enough to cause yielding to medium-rise structures in Bengkulu and Padang, two major cities along the western coast of Sumatra. Since structures are designed to yield in such a rare event, it is important that the overall strength and stiffness can be maintained throughout the entire duration of shaking. The performance of the ductile detailing specified in the current design code has not been tested against long-duration ground motions of about 4 minutes as expected from this giant earthquake. In Singapore and Kuala Lumpur, only medium-rise and high-rise structures, especially those located on soft soil sites, are at risk. Given that seismic design has not been required in Singapore and Malaysia, and thus the resulting structures are relatively brittle, it is crucial to investigate the performance of such non-ductile structures under moderate-amplitude, long-duration, ground motions.

Keywords: Sumatra, Singapore, subduction earthquake, seismic hazard, synthetic seismogram

INTRODUCTION

The Sunda arc, extending over 5,600 km from the Andaman islands in the northwest to the Banda arc in the east, was formed by the convergence between the Indian-Australian plate and the south-eastern Eurasian plate. The Sumatran megathrust of the Sunda arc lies 250 km off the western coast of the Sumatra island (Figure 1). Five giant earthquakes ($M_w \geq 8.0$) have occurred along the Sumatran megathrust in the last 250 years, to release the strain accumulated in the convergence between these two tectonics plates. The rupture zones of these earthquakes are depicted in Figure 1. The earliest historical earthquake whose magnitude has been carefully analyzed occurred in February 1797 (Newcomb and McCann, 1987; Natawidjaja *et al.*, 2006). This earthquake had an M_w of 8.7 and ruptured the 370-km segment starting from 1° S to about 4° S (Natawidjaja *et al.*, 2006). This earthquake was followed by two giant earthquakes, namely the 1833 earthquake (M_w 9.0) rupturing the 500-km segment south of the Siberut island and the 1861 earthquake (M_w 8.5) rupturing the 270-

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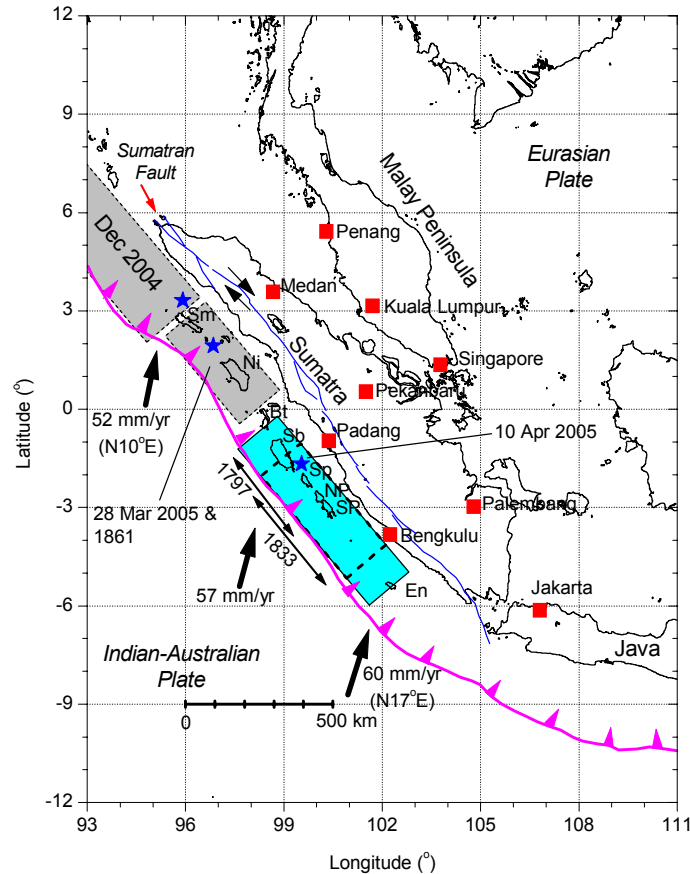


Figure 1. Tectonic setting of the Sumatran megathrust. Sm = Simeulue island, Ni = Nias island, Bt = Batu island, Sb = Siberut island, Sp = Sipora island, NP = North Pagai island, SP = South Pagai island, and En = Enggano island. The Mentawai islands comprise four main islands of Siberut, Sipora, North Pagai and South Pagai.

km segment beneath the Nias island (Newcomb and McCann, 1987; Zachariassen *et al.*, 1999; Natawidjaja *et al.*, 2006). From 1861, no giant earthquake had occurred along the Sumatran megathrust until 26 December 2004, when the M_w 9.2 Aceh-Andaman earthquake happened (Ammon *et al.*, 2005; Lay *et al.*, 2005; Subarya *et al.*, 2006). Three months later, this giant earthquake was followed by the M_w 8.7 Nias-Simeulue earthquake on 28 March 2005 (Briggs *et al.*, 2006). The rupture zone of the 2005 event coincides with that of the 1861 event.

The ruptures of the 2004 and 2005 events may have released a significant portion of the strain accumulated along the megathrust north of the Equator. It is, therefore, unlikely that such giant earthquakes will occur again in the near future, north of the Equator. The situation is very different for the segments south of 1° S. The megathrust has not ruptured under the Siberut island since 1797, and the segment between 2° S and 5° S has not ruptured since 1833.

The main objective of the present research is to estimate the seismic hazard levels in several major cities in Sumatra, Java, the Malay Peninsula, and Singapore, due to the future rupture of the segment south of the Siberut island. This so-called Mentawai segment stretches along the islands of Siberut, Sipora, North Pagai and South Pagai (Figure 1). The adequacy of the current design codes in Indonesia, Malaysia and Singapore, will be discussed in the present paper.

VALIDATION OF THE SIMULATION METHOD USED

Ground-Motion Simulation Method

The ground-motion simulation method used in the present study follows a kinematic method, in which the source rupture is represented using a finite-fault model. The fault plane is subdivided into several subfaults and each subfault is treated as a point source. The sum of the seismic moments of all subevents should equal the seismic moment of the target event. The rupture starts at the hypocenter and propagates radially outward at a certain rupture velocity, triggering each subfault as the rupture front passes its centre. The ground motions at an observation point produced by the ruptures of individual subfaults are summed with time lags to account for rupture propagation on the fault plane.

The crustal structure representing the whole region of Sumatra and the Malay Peninsula is extracted from the global crustal model CRUST 2.0 (<http://mahi.ucsd.edu/Gabi/rem.dir/crust/crust2.html>), which is a recent $2^\circ \times 2^\circ$ global model for the Earth's crust. The Green's function is based on synthetics derived from elastic wave-propagation model (Kohketsu, 1985), which provides proper phasing of body and surface waves. The source time function of the slip on each subfault is approximated by a ramp function with a source duration of $t_r = L_s/v_r + t_d$, where L_s is the length of the subfault, v_r is the rupture velocity, and t_d is the rise time of the local dislocation. The rise time t_d is equal to D_s/v_d , in which D_s is the slip amplitude and v_d is the slip velocity. The source duration t_r is to reflect the effects of rupture propagation within the subfault and the dislocation rise time.

Since the objective of the present study is to estimate the ground motions from a giant earthquake ($M_w = 9.0$), it is important that the simulation method used in the present study is capable of simulating the actual data recorded during the 26 December 2004 Aceh-Andaman earthquake (M_w 9.2) and the 28 March Nias-Simeulue event 2005 (M_w 8.7).

Trial Simulations of Large-Magnitude Earthquakes

The source-rupture models of the two recent giant earthquakes have been studied recently (Ammon *et al.*, 2005; Lay *et al.*, 2005; Briggs *et al.*, 2006; Walker *et al.*, 2005). The simplified versions of these source models are implemented in the kinematic ground-motion simulation model to validate the capability of the model to simulate large-magnitude, subduction earthquakes.

The December 2004 event ruptured 1300 km of a curved plate boundary, where the region of the largest slip extended from about 3°N to 7°N and included substantial slip across the entire megathrust width (Ammon *et al.*, 2005; Lay *et al.*, 2005). In the present paper, only the rupture of this southern portion is considered as the northern segment beneath the Andaman islands was relatively farther away and thus generated only very weak motions in Singapore. The rupture model used follows the inversion result of teleseismic waves and regional seismograms, as shown in Figure 5c of Ammon *et al.* (2005). The rupture area of 600 km along the strike and 240 km downdip is divided into 90 subfaults of $40 \text{ km} \times 40 \text{ km}$. The rupture has three asperities at 4°N , 5°N and 6°N . The slips at these asperities are around 12 m, while areas surrounding the asperities have slips of about 5 m. The seismic energy released by the rupture of this 600-km segment is equal to $4.52 \times 10^{22} \text{ N.m}$ (M_w 9.04). The rupture starts at the hypocenter, indicated by a star in Figure 1, and propagates northwestward at a velocity of 2.5 km/sec.

The slips of the March 2005 earthquake (M_w 8.7) have been studied by Briggs *et al.* (2006), Walker *et al.* (2005), and Ammon *et al.* (2005), revealing that the slips involve an area of about 400 km along the strike and 180 km downdip, with two asperities at a depth of about 20 km beneath the Nias and Simeulue islands. The slips at the asperities reach about 10 m, while the slips near the trench are only about 3 m. The rupture starts at the hypocenter, shown by a star in Figure 1, and propagates bilaterally at a speed of 2.7 km/sec.

The uppermost panels of Figures 2 and 3 show the ground displacements from the two earthquakes recorded in Singapore, in the NS, EW and UD directions. The simulated ground motions are aligned in the second row of each figure. Both amplitude and duration of the simulated ground motions agree

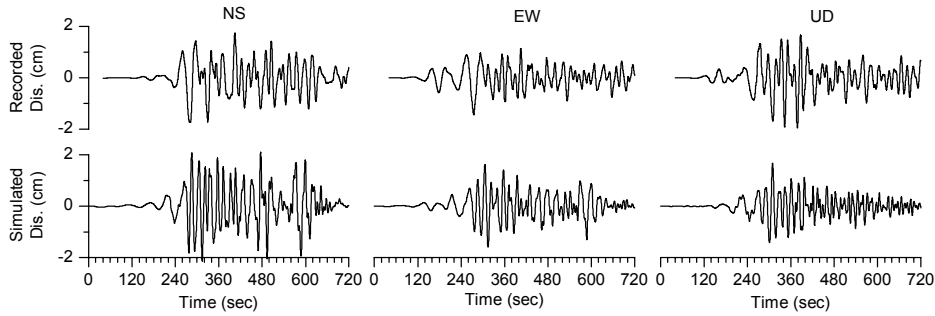


Figure 2. Recorded and Simulated ground displacements in Singapore from the 26 December 2004 earthquake.

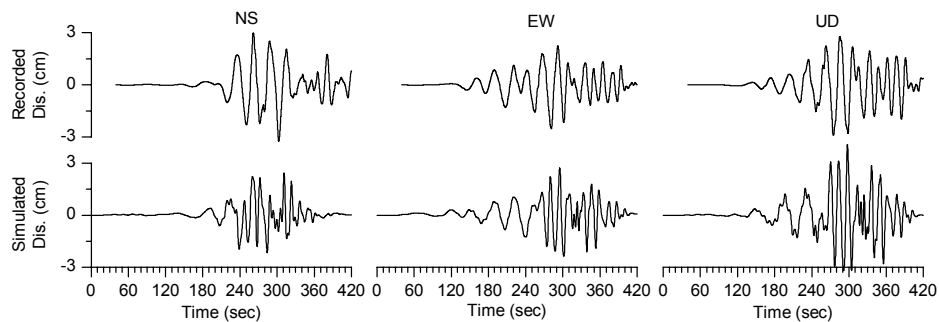


Figure 3. Recorded and Simulated ground displacements in Singapore from the 28 March 2005 earthquake.

reasonably well with the corresponding recorded values. The simulated ground motions for the two giant earthquakes do not match every wrinkle of the recorded ground motions because the actual rupture processes of the earthquakes are very complex (Ammon *et al.*, 2005; Lay *et al.*, 2005; Briggs *et al.*, 2006; Walker *et al.*, 2005), while the rupture models used in the simulations are the simplified versions with three and two asperities, as described above. The objective of these trial simulations is to ensure that the simulation method used and the one-dimensional regional crustal structure extracted from CRUST 2.0 can both be used to reasonably estimate the ground motions from large-magnitude subduction earthquakes. No attempt was made to match every wrinkle of the recorded motions by modifying the source rupture models because, in reality, it is impossible to predict precisely the rupture processes of future earthquakes. The general match between the simulated and the recorded waveforms provides enough confidence that the simulation technique can be used to predict the ground motions at major cities in the region, due to the future rupture of the Mentawai segment.

SEISMIC HAZARD FROM THE MENTAWAI SEGMENT

Rupture Model

The Batu segment of the megathrust, from the Equator to about 0.7° S, last ruptured in 1935, producing an M_w 7.7 earthquake with a slip of about 2.3 meters over a $70 \text{ km} \times 35 \text{ km}$ patch (Rivera *et al.*, 2002). Recent paleogeodetic study (Natawidjaja *et al.*, 2004) shows that the megathrust is slipping aseismically both above and below this narrow patch, and the 1935 patch has been slipping during the past century at about half the rate at which the plate is moving. Therefore, the accumulated strains and hence stresses on the Batu segment are probably low, and thus it is likely to be the northern barrier to the future rupture of the Mentawai segment (Natawidjaja *et al.*, 2006).

Geodetic measurements and paleogeodetic records of interseismic deformation along the Mentawai segment suggest that the depth of the downdip end of the locked zone varies from about 40 km to 55 km, and it has been locked for at least the past 50 years (Prawirodirdjo *et al.*, 1997; Bock *et al.*, 2003; Simoes *et al.*, 2004). The dip angle of the megathrust along the Mentawai segment is estimated as 15° based on previous geological investigations (Natawidjaja *et al.*, 2006). In the present study, the downdip length of the fault along the Mentawai segment is taken to be 180 km, and with the dip angle of 15° the depth of the downdip end is 46.6 km.

Natawidjaja *et al.* (2006) revealed that the rupture of the 1833 event (M_w 9.0) started from 2° S and extended as far south as about 5° S. This rupture of about 450-km long is marked by the dotted line in Figure 1, and it is used as the rupture area of the scenario earthquake. The rupture area of $450 \text{ km} \times 180 \text{ km}$ is subdivided into 90 subfaults of $30 \text{ km} \times 30 \text{ km}$. To be realistic, the rupture is assumed to have two or three asperities with equal probability, where the total area of the asperities is confined to be 22% of the total rupture area. The slip contrast, which is defined as the ratio of the average slip in the asperity area to the average slip in total rupture area, is fixed at 2.0. The individual asperities are randomly located along the fault plane without overlap. The rupture initiation may take place at any arbitrary location along the fault plane, but not within the asperities. The average slip of the asperity areas is computed to be 18.2 m, while that of the other subfaults is 6.5 m. This maximum slip of 18.2 m agrees with the recent study on source parameters of the 1833 event using coral microatolls (Natawidjaja *et al.*, 2006). The rake angle of the slip is random and is confined between 80° and 110° as the slip is expected to be mainly thrust faulting. The rupture propagates radially from the hypocenter with a constant velocity v_r , which may vary from 2.4 to 3.0 km/sec for different rupture models. The slip velocity v_d ranges from 0.3 to 0.5 m/sec. Twenty random rupture models are generated based on these parameters, and the upper cut-off frequency of the simulations is 2.0 Hz.

The seismic hazards and risks at nine major cities, namely Bengkulu, Padang, Medan, Pekanbaru, Palembang, Jakarta, Singapore, Kuala Lumpur and Penang, are to be assessed in this study. The first six cities are within the territory of Indonesia, while Kuala Lumpur and Penang belong to Malaysia. The locations of these cities are indicated in Figure 1, and they are all within two fault lengths from the Mentawai segment and thus may be affected by the future rupture of the segment.

Simulation Results

The seismic hazards at the nine cities are represented by the pseudo-acceleration response spectra (5% damping ratio), which correspond directly with the design spectra in many seismic codes. The horizontal ground motions are aligned in the fault-parallel and fault-normal directions. Since the fault-normal component is typically larger than the fault-parallel component, the former is used to represent the horizontal ground motion.

Figure 4 shows the response spectral accelerations (RSA) at the nine cities due to the scenario earthquake (M_w 9.0). The ground motions at each city are computed for the twenty different rupture models described above, and thus the variation of the acceleration response spectra in Figure 4 is due to these different models. Each panel in Figure 4 represents the hazard at each city, where the shaded area indicates the range between the envelopes of the maximum and minimum spectra. The distribution of the spectral values agree with the lognormal distribution, where the solid line shows the median spectrum (50-percentile spectrum), and the pair of dashed lines mark the median-minus-one-standard-deviation (16-percentile) and median-plus-one-standard-deviation (84-percentile) spectra. The typical values of the standard deviation of $\ln(\text{RSA})$ vary between 0.3 and 0.5 across the natural period range of 0.5 – 50 sec.

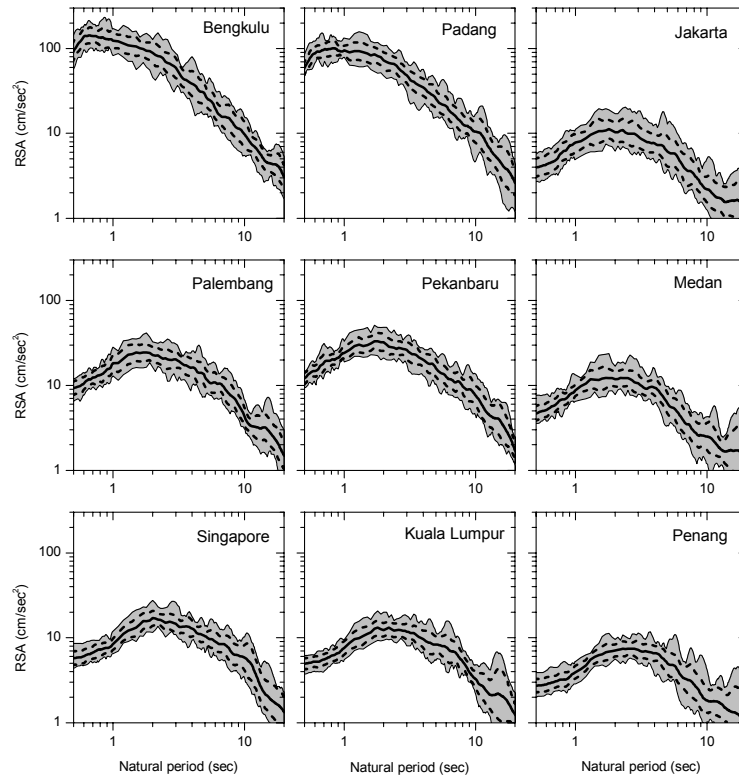


Figure 4. Response spectral accelerations (RSA) with 5% damping ratio, in the fault-normal direction, in the nine major cities, due to the hypothetical M_w 9.0 earthquake along the Mentawai segment.

DISCUSSION AND CONCLUSION

Potential Seismic Risks in Sumatra and West Java

According to the current Indonesian Seismic Code (SNI 03-1726-2002), the territory of Indonesia is divided into six seismic zones, where Zone 1 indicates regions with the lowest seismic hazard and Zone 6 refers to regions with the highest seismic hazard. The division of the zones is based on the expected peak ground accelerations on bedrock with a return period of 500 years, where Zones 1 to 6 are assigned increasing values of 0.03 g, 0.10 g, 0.15 g, 0.20 g, 0.25 g and 0.30 g, respectively. The seismic design spectrum for each zone is then determined based on the corresponding PGA. Although the amplitudes of the design spectra for different zones vary, the shapes of the spectra are identical where the corner period between the constant-acceleration and the constant-velocity branches in each spectrum is fixed at 0.5 sec for rock sites. The design spectra of different zones are discussed below to access the seismic risks of major cities in Sumatra and West Java due to the rupture of the Mentawai segment.

Padang and Bengkulu are two major cities located along the high-seismicity region of the western coast of Sumatra (Figure 1). They are situated in the vicinity of the active, right-lateral, Sumatran fault, and are also close to the Sumatran megathrust. Bengkulu is located in Seismic Zone 6, while Padang is in Zone 5. The linearly-elastic design spectrum with a return period of 500 years for Bengkulu is shown in Figure 5 by the line marked by $\mu = 1$, where μ indicates the design ductility ratio. As commonly specified in seismic codes, it is not economical to design ordinary structures to remain linearly elastic during an earthquake with a return period of 500 years. Structures may be allowed to yield in this rare event, so that the required strength of the structures can be reduced to a more economical level. Depending on the types of structural systems used, the allowable ductility ratio may range from 4 to 8. The reduction of the required strength should, however, be compensated by providing ductile detailing at the potential plastic hinges within the structure, so that the structure can

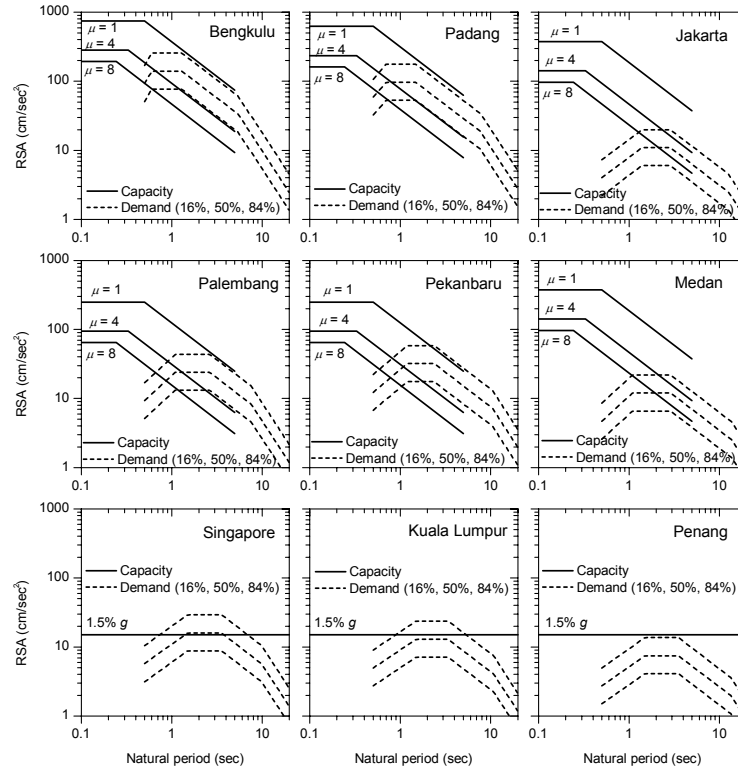


Figure 5. The capacity and demand spectra in the nine major cities for the hypothetical M_w 9.0 earthquake along the Mentawai segment.

behave in a ductile manner. In other words, the strength and stiffness of the structure should be maintained after yielding throughout the whole duration of ground shaking. The corresponding design spectra with ductility ratios of 4 and 8, for Bengkulu are depicted in Figure 5. Structures should then be designed using these spectra, thus they are denoted as capacity spectra in Figure 5.

The demand spectra in Bengkulu due to the potential rupture of the Mentawai segment with $M_w = 9.0$ are represented by the response spectra shown in Figure 4. The median spectrum is approximated using a series of straight lines indicating the increasing spectral acceleration, the constant spectral acceleration, constant spectral velocity and constant spectral displacement, shown by the dotted line marked “demand spectrum (50%)” in Figure 5. The median-minus-one-standard-deviation (16-percentile) and median-plus-one-standard-deviation (84-percentile) demand spectra are also shown in the figure. Note that a standard deviation $\sigma_{\ln(RSA)} = 0.6$, rather than the smaller standard deviations depicted in Figure 4, is used here. The standard deviations of 0.3 to 0.5 in Figure 4 are smaller than the standard deviations of existing attenuation relationships, which usually range from 0.4 to 0.8 (Abrahamson and Shedlock, 1997). This is understandable because the standard deviation in the present simulations accounts for the randomness in the source parameters only, while the standard deviations for the attenuation relationships include the randomness in both source and path. To take into account the randomness of the path in the present study, a value of 0.6 is adopted.

For structures with short natural period of 0.5 sec (corresponding to 5-storey buildings), it can be seen that there is a 12% probability that the structures will yield if they are designed according to the spectrum for a ductility ratio of 4. Therefore, the probability for the structures to actually yield is low though they are designed to yield during a rare earthquake. For structures with natural periods shorter than 0.5 sec, the probability of yielding is even lower as the capacity spectrum increases with the decrease of natural period and vice versa for the demand spectrum. Therefore, the expected degree of damage to properly designed, short-period, structures ($T \leq 0.5$ sec) on rock sites in Bengkulu due to the M_w 9.0 earthquake is negligible.

For structures with medium natural period ($T = 1$ sec), the probability of yielding to actually occur increases to 75% and 97% if they are designed according to the spectra for ductility ratios of 4 and 8, respectively. In structural engineering, yielding is usually unavoidable to achieve economical designs to withstand future, rare, earthquakes, but collapse of structures should be prevented. They are generally two requirements to prevent collapse: firstly, the demand ductility ratio should be smaller than the capacity to prevent excessive lateral deformations, and, secondly, the structures should be able to maintain their overall strength and stiffness after yielding throughout the entire duration of shaking by providing ductile detailing at the potential plastic hinges. The first requirement can be checked using the standard iterative procedures, such as ATC-40 (ATC, 1996). The second requirement is more critical in this case because the ductile detailing as specified in the current seismic codes is typically formulated based on laboratory tests and mathematical modeling of structural components subjected to short-duration ground motions usually recorded during major and strong earthquakes ($M_w = 6.5 - 7.5$). The typical durations of these ground motions are less than 20 sec, and very few have durations up to 40 sec. Very few experiments, if any, have been carried out to investigate the post-yielding performance of structural components subjected to long-duration ground motions from giant earthquakes with $M_w \geq 9$. The ground-motion durations from this level of magnitude may last for about 4 minutes. Therefore, if medium-period structures in Bengkulu could maintain the ductility capacity for about 4 minutes, corresponding to 200 – 300 cycles of vibration, they are likely to survive. If the ductility capacity cannot be maintained beyond one minute and disintegration at plastic hinges occurs, the structures may collapse.

Padang is located in Seismic Zone 5, and thus the capacity spectrum is one grade lower than that of Bengkulu. However, the demand spectrum shown in Figure 5 is also lower than the corresponding spectrum in Bengkulu, thus the probability of yielding is comparable to that in Bengkulu.

Jakarta and Medan (Figure 1) are both located in Zone 3, which is considered as a moderate-seismicity zone. The capacity and demand spectra are presented in Figure 5. It is obvious that the amplitudes of ground motions generated by the Mentawai earthquakes are too weak to cause yielding to structures with natural periods shorter than 2 sec in the two cities. Therefore, the seismic risks posed by the Mentawai segment to these two cities are relatively low, simply because they are located far from the rupture zone and the seismic design requirement is relatively high. The seismic risk to long-period structures ($T = 2 - 4$ sec) indicated by the probability of yielding is relatively higher than that of shorter-period structures ($T < 2$ sec). Since the majority of buildings in Jakarta and Medan are medium-rise and low-rise structures ($T < 2$ sec) and the requirement for wind design for tall buildings may supersede the seismic design, the seismic risks to building stocks in these two cities are considerably low.

Palembang and Pekanbaru are located along the low-seismicity, eastern coast of Sumatra (Seismic Zone 2), and thus have lower seismic design spectra than Jakarta or Medan. Since these two cities are located relatively closer to rupture zone than Jakarta or Medan, the potential seismic risks to buildings in Palembang and Pekanbaru are higher than those in the previous two cities (Figure 5). It becomes obvious that the potential risks to long-period structures with $T \geq 2$ sec in these low-seismicity cities are as high as those in the high-seismicity cities of Bengkulu and Padang.

Potential Seismic Risks in Singapore and the Malay Peninsula

Singapore is located 650 km away from the centre of the Mentawai rupture zone, thus the resulting ground motions is quite weak. Current building design code for structures in Singapore has been developed largely based on the BS 8110 (BSI, 1997), which does not have any provision for seismic loading. It, however, requires that all buildings be capable of resisting a notional ultimate horizontal design load applied at each floor level simultaneously for structural robustness. These static horizontal loads are equal to 1.5% of the characteristic dead weight of the structure. The design wind load should not be taken less than this value. Given the moderate design wind speed of 30 m/sec in Singapore, the notional horizontal load is generally greater than the wind loading for most medium-rise buildings.

Thus, the notional lateral load is usually the governing lateral load for design. The capacity of the building can therefore be taken as constant at 1.5% g (15 cm/s²) across the entire natural period range, as shown in Figure 5. The demand spectra are plotted in the same figure. It is obvious that structures with short natural periods ($T \leq 0.5$ sec) are barely affected as the capacity is much higher than the demand. For M_w 9.0 earthquake, structures with $T = 1$ sec have a 30% probability that the demand is higher than the capacity, and structures with $T = 2$ sec have a higher probability of 54%. Therefore, there is a 54% probability that the demand base shear exceeds the capacity base shear for structures with natural periods ranging from 1.5 to 3.5 sec (Figure 5). This natural period range coincides with the natural periods of many medium-rise and high-rise structures in the city. Since seismic design has not been required and providing ductile detailing is not mandatory in the current building code, the structures are expected to have very limited inherent ductility capacity. Further investigations on the post-yielding behaviors of non-seismically designed structures are essential for assessing the seismic performance of buildings in Singapore.

It should be noted that the demand spectra shown in Figure 5 are for rock sites in Singapore. The central and southeastern parts of the Singapore island are largely overlain by Quaternary marine clay deposit, and part of the coastal area is reclaimed land (Pitts, 1984). This soft soil deposit may significantly amplify the weak bedrock motion, as evidenced in the fact that ground tremors from recent Sumatran earthquakes were largely felt by residents of high-rise buildings in these areas and not by those living in other areas with better ground conditions (Pan *et al.*, 2001). Therefore, the seismic risk to structures on soft soil sites is higher than that on firm-soil or rock sites because the lateral design loads are the same regardless of the local soil conditions. For illustration, if the soil-amplification factor within natural period range from 1.5 to 3.5 sec is taken as 2.0, the probability that the demand is higher than the capacity will increase from 54% to 90% for the M_w 9.0 earthquake. It can be concluded that medium-rise and high-rise structures founded on soft-soil sites in the central and southeastern districts of the city have the highest seismic risk with regard to the potential rupture of the Mentawai segment.

Since Kuala Lumpur and Penang, two major cities on the Malay Peninsula, are located farther from the Mentawai segment than Singapore, the demand spectra for these cities are lower than that for Singapore. The building code in Malaysia is essentially identical with that used in Singapore, thus the seismic risks for Kuala Lumpur and Penang are lower than that of Singapore. The seismic risk for medium-rise and high-rise structures in Kuala Lumpur is slightly lower than that of Singapore, while the risk to similar structures in Penang is almost negligible.

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