

Regional Seismic Hazard Posed by the Mentawai Segment of the Sumatran Megathrust

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Abstract Several lines of evidence have indicated that the Mentawai segment of the Sumatran megathrust is very likely to rupture within the next few decades. The present study is to investigate seismic hazard and risk levels at major cities in Sumatra, Java, Singapore, and the Malay Peninsula caused by the potential giant earthquakes. Three scenarios are considered. The first one is an M_w 8.6 earthquake rupturing the 280 km segment that has been locked since 1797; in the second scenario, rupture occurs along a 600 km segment covering the combined rupture areas of the 1797 and 1833 historical events, producing an M_w 9.0 earthquake; and the third scenario has the same rupture area as the second scenario but with doubled slip amplitude, resulting in an M_w 9.2 earthquake. Simulation results indicate that ground motions produced by the hypothetical scenarios are strong enough to cause yielding to medium- and high-rise buildings in many major cities in Sumatra. It is vital to ensure that the overall strength, stiffness, and integrity of the structures are maintained throughout the entire duration of shaking. However, the ductile detailing in current practice is formulated based on an assumption that ground motions would last from 20 to 40 sec. This has not been tested for longer durations of 3–5 min, expected from giant earthquakes. In Singapore and Kuala Lumpur, only medium- and high-rise buildings, especially those located on soft-soil sites, are at risk. Given that seismic design has not been required in either city, and thus the resulting structures are relatively brittle, it is crucial to investigate their performance under moderate-amplitude, long-duration, ground motions. The present study also points out that shifting the response spectrum toward a longer period range becomes significant for sites located far from potential seismic sources, which should be carefully considered in formulation of future seismic codes.

Introduction

The Sunda arc, extending over 5600 km from the Andaman islands in the northwest to the Banda arc in the east, was formed by the convergence between the subducting Indian–Australian plate and the overriding southeastern Eurasian plate. The Sumatran megathrust of the Sunda arc lies 250 km off the western coast of Sumatra island (Fig. 1), with both the Sumatra and Java islands lying on the Eurasian plate. The convergence is nearly orthogonal to the trench axis south of Java, but it is highly oblique southwest of Sumatra. Based on velocity vectors derived from the regional Global Positioning System (GPS) data, the pole of rotation for the relative motion between the two plates is in East Africa, about 50° W of Sumatra (Larson *et al.*, 1997; Prawirodirdjo *et al.*, 2000). Northern Sumatra is closer to this pole than southern Sumatra; thus, the orientation and magnitude of the relative-motion vector vary significantly along the Sumatran portion of the plate boundary, as shown in Figure 1. Slip vectors of moderate earthquakes along this subduction zone were found to be nearly perpendicular to the strike of the plate boundary

(McCaffrey, 1991, 1992). Most of the strike-slip component of the oblique convergence between the Indian–Australian plate and the Eurasian plate southwest of Sumatra is accommodated by right-lateral slip along the trench-parallel Sumatran fault, lying roughly 250 km northeast of the trench (Fitch, 1972; McCaffrey, 1991, 1992; Sieh and Natawidjaja, 2000). Therefore, the slip along the subduction zone itself has relatively small strike-parallel components.

Five giant earthquakes ($M_w \geq 8.0$) have occurred along the Sumatran megathrust in the last 250 years, releasing the strain accumulated by the convergence between the two tectonic plates. The rupture zones of these earthquakes are depicted in Figure 1. The earliest of these historical events was that of February 1797 (Newcomb and McCann, 1987; Natawidjaja *et al.*, 2006). The earthquake had an M_w of 8.7 and ruptured the 370 km segment from 1° S to about 4° S (Natawidjaja *et al.*, 2006). This was followed by the giant earthquake of 1833 (M_w 9.0), which ruptured a 500 km long segment south of Siberut island, and another one in 1861

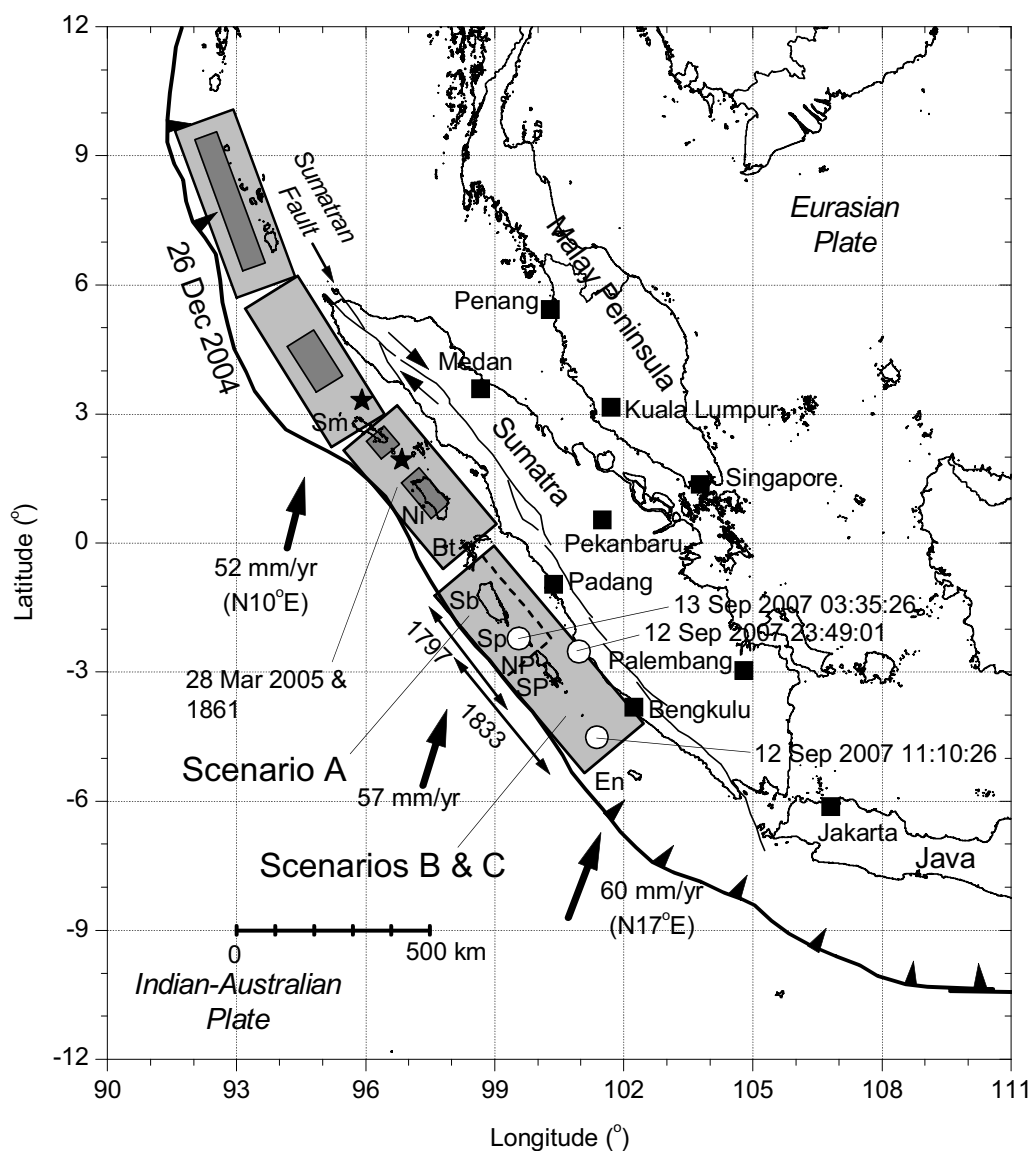


Figure 1. Tectonic setting of the Sumatran megathrust. The rupture areas of the five giant earthquakes with $M_w \geq 8$ are shown by the lightly shaded areas, whereas the asperities are shaded more darkly. The nine major cities in the region are marked by the squares. The islands off the western coast of Sumatra are (from north to south): Sm, Simeulue island; Ni, Nias island; Bt, Batu island; Sb, Siberut island; Sp, Sipora island; NP, North Pagai island; SP, South Pagai island; En, Enggano island. The Mentawai islands comprise the four main islands of Siberut, Sipora, North Pagai, and South Pagai. The rupture planes of scenarios A, B, and C are shown by the rectangles along the Mentawai islands. The epicenters of the southern Sumatran subduction earthquakes, occurring on 12 and 13 September 2007, are depicted by the three circles on the Mentawai islands.

(M_w 8.5) rupturing a 270 km long segment beneath Nias island (Newcomb and McCann, 1987; Zachariassen *et al.*, 1999; Natawidjaja *et al.*, 2006). Since 1861, no giant earthquake with $M_w \geq 8.0$ had occurred along the Sumatran megathrust until 26 December 2004, when the M_w 9.15 Aceh-Andaman earthquake happened (Ammon *et al.*, 2005; Lay *et al.*, 2005; Subarya *et al.*, 2006; Chlieh *et al.*, 2007). This was shortly followed by the M_w 8.6 Nias-Simeulue earthquake on 28 March 2005 (Briggs *et al.*, 2006; Konca *et al.*, 2007), which has a rupture zone coincident with that of the 1861 event.

The ruptures of the 2004 and 2005 events have released a significant portion of the strain accumulated along the megathrust north of the equator, making it unlikely for giant earthquakes to occur again in this segment of the megathrust in the near future. The situation is very different south of 1° S. The megathrust has not ruptured under Siberut island since 1797, and the segment between 2° S and 5° S has not ruptured since 1833. Zachariassen *et al.* (1999) indicate that events similar to the 1833 earthquake might occur about every 265 yr on average, but the December 2004 and March 2005 earthquakes have increased the stress within the Men-

tawai segment of the megathrust (Nalbant *et al.*, 2005). The Mentawai segment is the megathrust beneath the Mentawai islands, comprising four main islands of Siberut, Sipora, North Pagai, and South Pagai. Several lines of evidence outlined in the following discussion further point to the fact that the rupture of this segment is very likely in the near future.

Between about 0.7° S and 2.1° S, the interseismic strain accumulated along this segment of the megathrust has approached or exceeded the levels relieved in 1797 and 1833. This is evidenced by the lack of vintage 1797 and 1833 coral heads in the intertidal zone, which demonstrates that the interseismic submergence has now nearly equaled the coseismic emergence that accompanied those earthquakes (Natawidjaja *et al.*, 2006). Coral microatolls of the Mentawai islands (Natawidjaja *et al.*, 2007) show that subsidence at rates from about 2 to 14 mm/yr has predominated on the islands over the past five decades. This long-lived and rapid subsidence indicates that the megathrust beneath the islands is currently locked and the hanging-wall block, of which the islands are a part, is being carried down with the subducting plate. South of about 2° S, the 1833 microatolls still protrude above the lowest tides, indicating that strain accumulation since 1833 has not compensated the emergence during the 1833 event. Therefore, the deficit of strain relief beneath the Siberut island is greater than that beneath the Sipora and Pagai islands (Natawidjaja *et al.*, 2006). However, the whole segment under the Mentawai islands has been locked since 1833 and has accumulated potential slip of about 10 m, making failure along the whole segment plausible. This is in line with the observed 1797 and 1833 couplet events.

The main objective of the present research is to assess the seismic hazard levels from future rupture of the Mentawai segment at major cities in Sumatra, Java, the Malay Peninsula, and Singapore. This extends the work previously carried out by Megawati and Pan (2002), in which the ground-motion intensity in Singapore due to the rupture of the 1833 event was estimated. The present research is motivated by the fact that the detailed rupture models of the 1797 and 1833 earthquakes have been revealed (Natawidjaja *et al.*, 2006) and the locking condition of the subduction interface along the Mentawai segment has been constrained from recent geodetic and paleogeodetic measurements (Chlieh *et al.*, 2008). This new information allows a better constrain on the credible future rupture scenarios along the

Mentawai segment. The ground motions from this future giant earthquake may affect the whole region within two or three fault lengths, including countries where seismic-resistant design is not currently required by law. Understanding the limitations of the current design practices is therefore necessary to assess the potential hazard and to mitigate the risk to the regional communities. This article highlights problems in current design codes with respect to long-duration ground motions produced by giant earthquakes.

Validation of the Simulation Method Used

The regional seismic hazard is to be estimated based on synthetic seismograms. Because the present study intends to assess the ground-motion intensities from giant earthquakes ($M_w \geq 8.0$), it is important that the simulation method used is capable of reproducing the actual recorded data from earthquakes of similar magnitude. The ground motions recorded in Singapore from the two giant earthquakes in December 2004 and March 2005 are used to validate 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 rupture starts at the hypocenter and propagates radially outward at a certain rupture velocity, triggering each subfault as the rupture front passes its center. 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 (see the Data and Resources section), which is a $2^\circ \times 2^\circ$ global model for the Earth's crust based on seismic refraction data published in the period of 1948–1995. The one-dimensional structure is summarized in Table 1, where the properties of the structure are obtained by taking the averages of the properties of all $2^\circ \times 2^\circ$ grids covering the region.

Table 1

Regional Crustal Structure of Sumatra and the Malay Peninsula

Layer	H (km)	V_P (km/sec)	V_S (km/sec)	ρ (t/m^3)	Q_P	Q_S
Upper crust	9.6	6.0	3.4	2.7	350	175
Middle crust	9.5	6.6	3.7	2.9	500	250
Lower crust	9.1	7.2	4.0	3.1	650	325
Mantle	∞	8.2	4.7	3.4	800	400

H is the layer thickness; V_P is the P -wave velocity; V_S is the S -wave velocity; ρ is the mass density; Q_P is the quality factor of the P wave; Q_S is the quality factor of the S wave.

The Green's function is based on synthetics derived from an elastic wave-propagation model (Koketsu, 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.

Giant Sumatran Earthquakes Recorded in Singapore

The Meteorological Services Division of the National Environment Agency established a network of digital seismic stations in Singapore in September 1996. The network comprises one broadband Global Seismographic Network (GSN) station, four teleseismic stations, and two borehole arrays. The GSN station, situated on a rock-outcropped site, at the center of Singapore island, is equipped with a comprehensive set of sensors to record ground tremors continuously, whereas the other stations operate based on a triggering system.

From the establishment of the seismic array to June 2006, 46 earthquakes with $M_w \geq 6.0$ occurred along the Sumatran subduction zone, and the ground motions were recorded by the GSN station in Singapore. Among these, only two events had $M_w > 8.0$, namely the 26 December 2004 Aceh-Andaman earthquake (M_w 9.15) and the 28 March 2005 Nias-Simeulue event (M_w 8.6). These two giant earthquakes ruptured a combined 1900 km long portion of the fault boundary between the Indian–Australian plate and Eurasian plate (Ammon *et al.*, 2005; Briggs *et al.*, 2006; Chlieh *et al.*, 2007; Konca *et al.*, 2007).

Trial Simulations of Giant Sumatran Earthquakes

Various source-rupture models of the two giant earthquakes have been proposed by Ammon *et al.* (2005), Lay *et al.* (2005), Walker *et al.* (2005), Briggs *et al.* (2006), Chlieh *et al.* (2007), and Konca *et al.* (2007). The slip models derived by Chlieh *et al.* (2007) and Konca *et al.* (2007) for the December 2004 and the March 2005 earthquakes, respectively, are used here because the models are constrained by near-field and far-field GPS data, vertical motion of coral reefs, as well as, teleseismic data. Simplified versions of these source models, given in figure 9 of Chlieh *et al.* (2007) and figure 5d of Konca *et al.* (2007), are implemented in the kinematic ground-motion simulation model to validate its capability to simulate large-magnitude, subduction earthquakes.

The December 2004 event ruptured a 1500 km segment of the curved plate boundary from northern Sumatra (2° N) to the Andaman islands (14° N), releasing a total moment of $6.7\text{--}7.0 \times 10^{22}$ N m (M_w 9.15). The largest slips occurred at the latitudes of 4° N, 7° N, and 9° N (Chlieh *et al.*, 2007). The slip model of Chlieh *et al.* (2007) has three rupture

planes, but only the two southern ones (shown in Fig. 1) are considered in the present simulation, as the northern segment beneath the Andaman islands has smaller slip of less than 5 m and is located relatively farther away from Singapore. The southern plane of the simplified rupture model, measuring 420×160 km, has a strike of N328°E and a dip angle of 12°, whereas the northern one, measuring 460×160 km, has a strike of N340°E and a dip angle of 15°. The high release of energy at 4° N is denoted by the 140×80 km asperity (darker shaded area in Fig. 1), whereas the peaks at 7° N and 9° N form an extended asperity, measuring 360×60 km, on the northern fault plane. The slip on the asperities is equal to 12.5 m, whereas the slip on the surrounding areas is 5 m. The rake angle is taken to be constant, at 110°. The two rupture planes are divided into smaller subfaults of 20×20 km. The seismic energy released by the ruptures of these two planes is equal to 4.79×10^{22} N m (M_w 9.06). The rupture starts at the hypocenter, indicated by the star on the southern rupture plane, and propagates northwestward at a velocity of 2.5 km/sec. The slip velocity is taken to be 0.4 m/sec.

The slip models of the March 2005 earthquake (M_w 8.6), inverted by Briggs *et al.* (2006) and Konca *et al.* (2007), 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 (Fig. 1). Slip on the asperities reaches about 9 m, whereas slip near the trench is only about 3 m. The fault plane has a dip of 10°, and the rake angle is taken to be 90°. The rupture starts at the hypocenter, shown by the star on the rupture plane and propagates bilaterally at a speed of 2.4 km/sec. The slip velocity is taken to be 0.4 m/sec.

The upper panels of Figures 2 and 3 show the ground displacements from the two earthquakes recorded at the GSN station in Singapore, in the north–south (NS), east–west (EW), and up–down (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 reasonably well with the respective recorded values. The slight mismatch in waveforms is to be expected because the actual rupture processes of the earthquakes are very complex (Briggs *et al.*, 2006; Chlieh *et al.*, 2007; Konca *et al.*, 2007), whereas the rupture models used in the simulations are the simplified versions with two asperities.

Running trial simulations ensures that the methodology and the one-dimensional regional crustal structure extracted from CRUST 2.0 (see the Data and Resources section) reproduce, within reasonable estimates, the ground motions from large-magnitude subduction earthquakes. The mismatch in waveforms is acceptable in the view that large ruptures will arise from complex processes, and a slightly generic model has greater applicability for potential earthquakes. The general correlation between the simulated and the recorded waveforms provides enough confidence that the simulation technique can be used for hazard assessment.

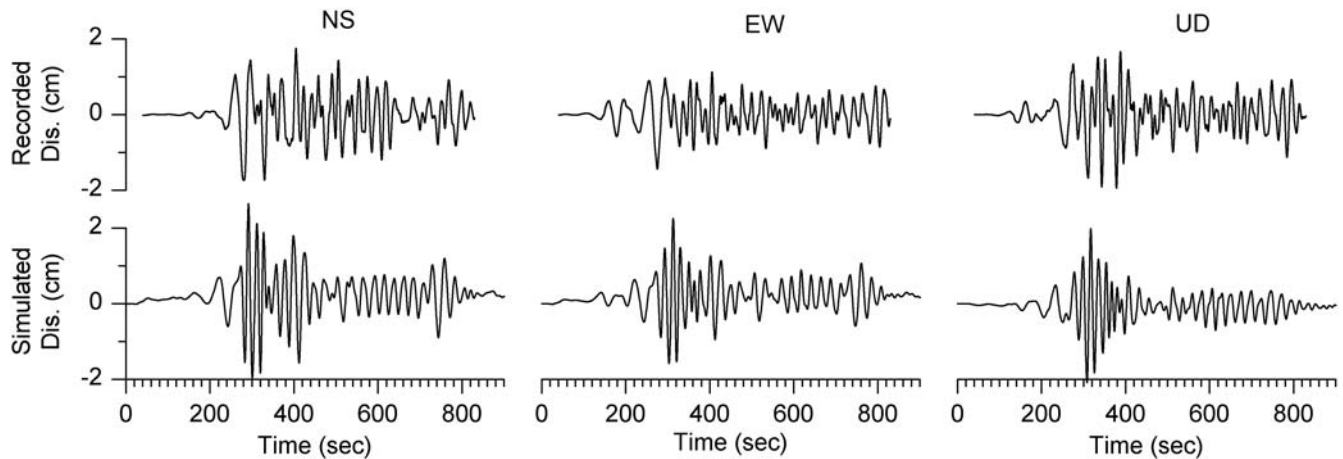


Figure 2. Ground displacements recorded at the GSN station in Singapore from the 26 December 2004 Aceh-Andaman earthquake (M_w 9.15), together with the simulated waveforms.

Seismic Hazard from the Mentawai Segment

Future Rupture Scenarios

The Batu segment of the megathrust, from the equator to about 0.7° S (Fig. 1), last ruptured in 1935, producing an M_w 7.7 earthquake with slip of about 2.3 m over a 70×35 km patch (Rivera *et al.*, 2002). A recent paleogeodetic study (Natawidjaja *et al.*, 2004) shows that the megathrust is slipping aseismically both above and below this narrow patch and that the 1935 patch has been slipping during the past century at about half the rate at which the plate is moving. The accumulated strain, and hence stress, on the Batu segment are probably low, and thus it is likely to be a 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 to 55 km, and it has been locked for, at least,

the past 50 yr (Prawirodirdjo *et al.*, 1997; Bock *et al.*, 2003; Simoes *et al.*, 2004). The dip angle of the subducting interface is about 5° – 8° near the trench and increases gradually to 15° – 20° beneath the Mentawai islands and to 30° below the coastline of Sumatra (Chlieh *et al.*, 2008). In the present study, three segments with increasing dip angles from 8° at the trench to 18° beneath the Mentawai islands and 26° beyond are adopted. The cross section of the subducting interface passing through Siberut island is shown in Figure 4 as the dotted curve, in which the curved megathrust interface is inferred by Chlieh *et al.* (2008) using the locations of hypocenters from the relocated International Seismological Centre (ISC) catalog from 1964 to 1998 (Engdahl *et al.*, 1998). The three-down-dip-segment model has a total width of 200 km, with its lowermost extent at 50 km.

Figure 1 shows a consistent strike of $N320^\circ E$ along the subducting interface beneath the Mentawai islands.

Three future scenarios have been formulated, by varying the length of the segment rupturing and the amplitude of the

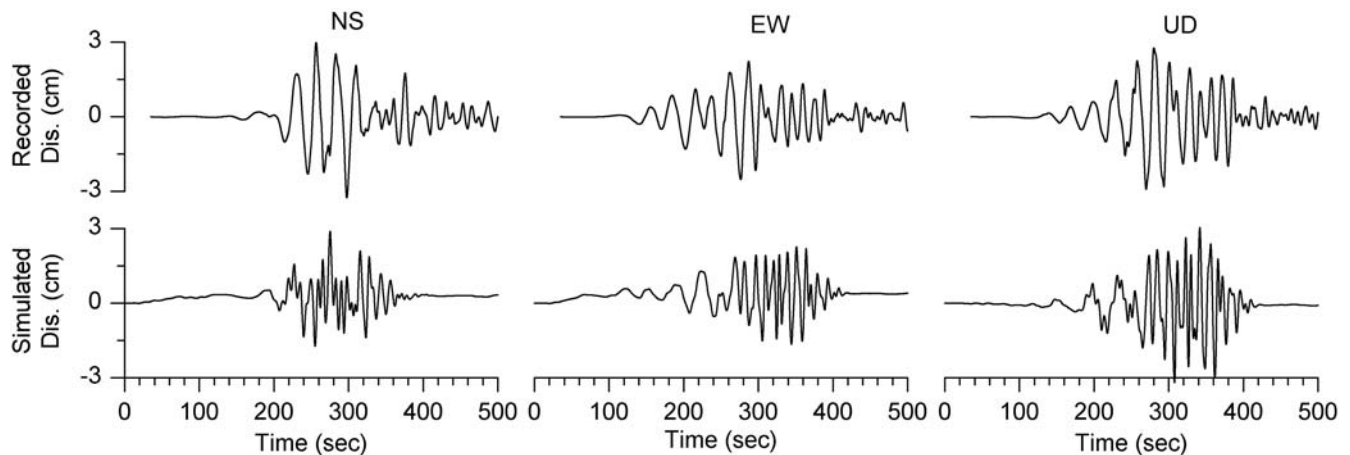


Figure 3. Ground displacements recorded at the GSN station in Singapore from the 28 March 2005 Nias-Simeulue earthquake (M_w 8.6), together with the simulated waveforms.

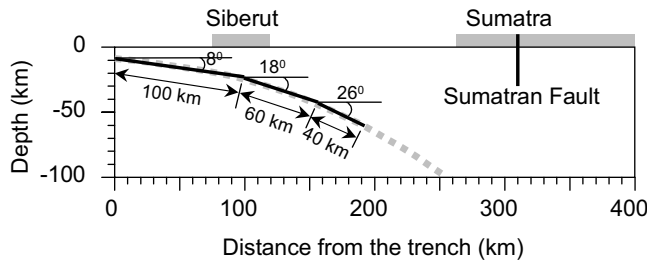


Figure 4. Cross section of the subducting interface passing through Siberut island. The dip angle of the subducting interface is about 5° – 8° near the trench and increases gradually to 15° – 20° beneath the Siberut islands and to 30° below the coastline of Sumatra. In the present study, three segments with increasing dip angles from 8° at the trench to 18° beneath the Siberut island and 26° beyond are adopted. The curved megathrust interface is inferred by Chlieh *et al.* (2008) using the locations of hypocenters from the relocated ISC catalog from 1964 to 1998 (Engdahl *et al.*, 1998).

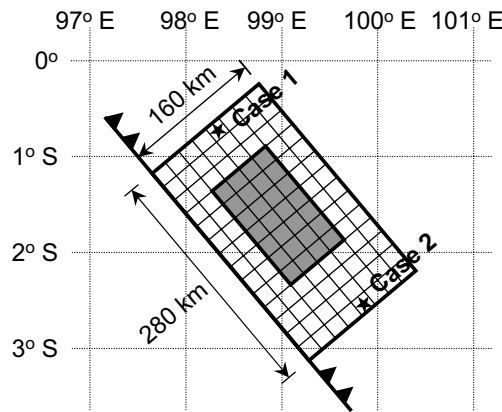
slip. Scenario A, shown in Figures 1 and 5, assumes that the 280 km long segment between 1° S and 3° S ruptures. This is a likely scenario, as the northern portion of the Mentawai segment has been locked since 1797, and the interseismic submergence has equaled the coseismic emergence in the 1797 and 1833 events. The convergence rate between the Indian–Australian plate and the Eurasian plate at this latitude

is about 57 mm/yr at an angle of $N15^{\circ}E$. The trench-normal component of this convergence vector is equal to $57 \text{ mm/yr} \times \cos(35^{\circ}) = 46.7 \text{ mm/yr}$. Thus, the potential slip that has been accumulated since 1797 is equal to 46.7 mm/yr for 210 yr or 9.8 m.

Using geodetic and paleogeodetic measurements, Chlieh *et al.* (2008) show the interseismic coupling on the subducting interface from the equator to 6° S. Two low coupling areas beneath Batu island, at 0.7° S, and at the southern end of Sipora island, at 3° S, are used to demarcate the 280 km long segment in scenario A. A single asperity is indicated by a patch with nearly 100% coupling beneath Siberut island (shaded in Fig. 5a). This has estimated slip of 10 m. The surrounding area, with lower coupling ratios ranging from 20% to 60%, has a slip value of 5 m. The slip along the fault is assumed to arise purely from thrust faulting. This rupture scenario would produce an earthquake with M_w 8.6. Two cases are considered: the rupture starts from the northern edge of the fault in case 1 and from the southern end in case 2.

The second scenario, scenario B, has a 600 km long rupture area, combining the rupture areas of the 1797 and 1833 events. Microatoll observations imply that slip in 1797 did not relieve all strain that had built up in the previous interseismic period, and slip in 1833 relieved more strain than

(a) Scenario A



(b) Scenarios B and C

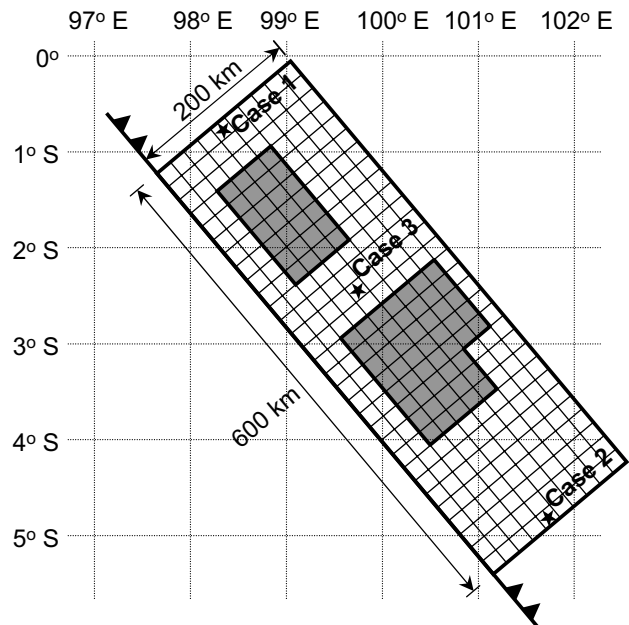


Figure 5. (a) Rupture model of scenario A having one asperity. The slip within the asperity is 10 m and that at the surrounding area is 5 m, producing an earthquake with M_w 8.6. The slip over the fault is pure thrusting. The rupture starts from the northern edge of the fault in case 1 and from the southern edge in case 2. (b) The rupture model of scenarios B and C. The 600 km long rupture plane covers the rupture areas of the 1797 and 1833 historical events combined. The model has two asperities with slip amplitudes of 10 m (scenario B) and 20 m (scenario C). The slip amplitudes in the surrounding area are 5 m (scenario B) and 10 m (scenario C). The rupture may start from the northern edge (case 1), the southern edge (case 2), or near the center (case 3). Scenario B produces an earthquake with M_w 9.0, whereas scenario C produces an M_w 9.2 event.

was accumulated in the years since 1797 (Natawidjaja *et al.*, 2006). Therefore, it is plausible that the segment along the Mentawai islands fails together in the future. Geodetic and paleogeodetic measurements (Chlieh *et al.*, 2008) indicate strong coupling at a large patch south of Sipora island (shaded area in the south, Fig. 5b). Thus, scenario B is hypothesized to have two asperities with potential slip magnitudes of 10 m. Slip in the surrounding area is assumed to be 5 m. This rupture scenario would produce an earthquake with M_w 9.0. The rupture may start from the northern edge (case 1), the southern edge (case 2), or near the center (case 3).

The last scenario, scenario C, has a rupture area identical to that of scenario B, but with 20 m of slip at the asperities and 10 m of slip in the surrounding fault area. This is quite an unlikely scenario as the potential slip accumulated over the past 210 yr is on the order of 10 m. However, slip in the southern segment of the 1833 event (3.5° S– 5° S) may have reached 18 m (Natawidjaja *et al.*, 2006), indicating that the segment relieved strain more than that accumulated in the

preceding interseismic period. Therefore, it is still plausible to have slip of 20 m on the asperities. Scenario C, which would produce an earthquake with M_w 9.2, is put forward as the worst-case scenario that might happen in this region.

The rupture areas of 280×160 km in scenario A and 600×200 km in scenarios B and C are subdivided into smaller subfaults of 20×20 km. The rupture front propagates radially from the hypocenter marked by the stars in Figure 5a,b with a constant velocity, v_r , of 2.5 km/sec. The slip velocity, v_d , is fixed at 0.4 m/sec. These values for rupture velocity and slip velocity are constrained by rupture kinematics studies of the 2004 Aceh-Andaman earthquake (Ammon *et al.*, 2005) and the 2005 Nias-Simeulue earthquake (Konca *et al.*, 2007).

Simulation Results

Figures 6–8 show the ground-motion accelerations simulated at nine major cities in the region, namely Padang, Bengkulu, Pekanbaru, Palembang, Medan, Jakarta, Bengkulu, Palembang, Medan, Jakarta, Singa-

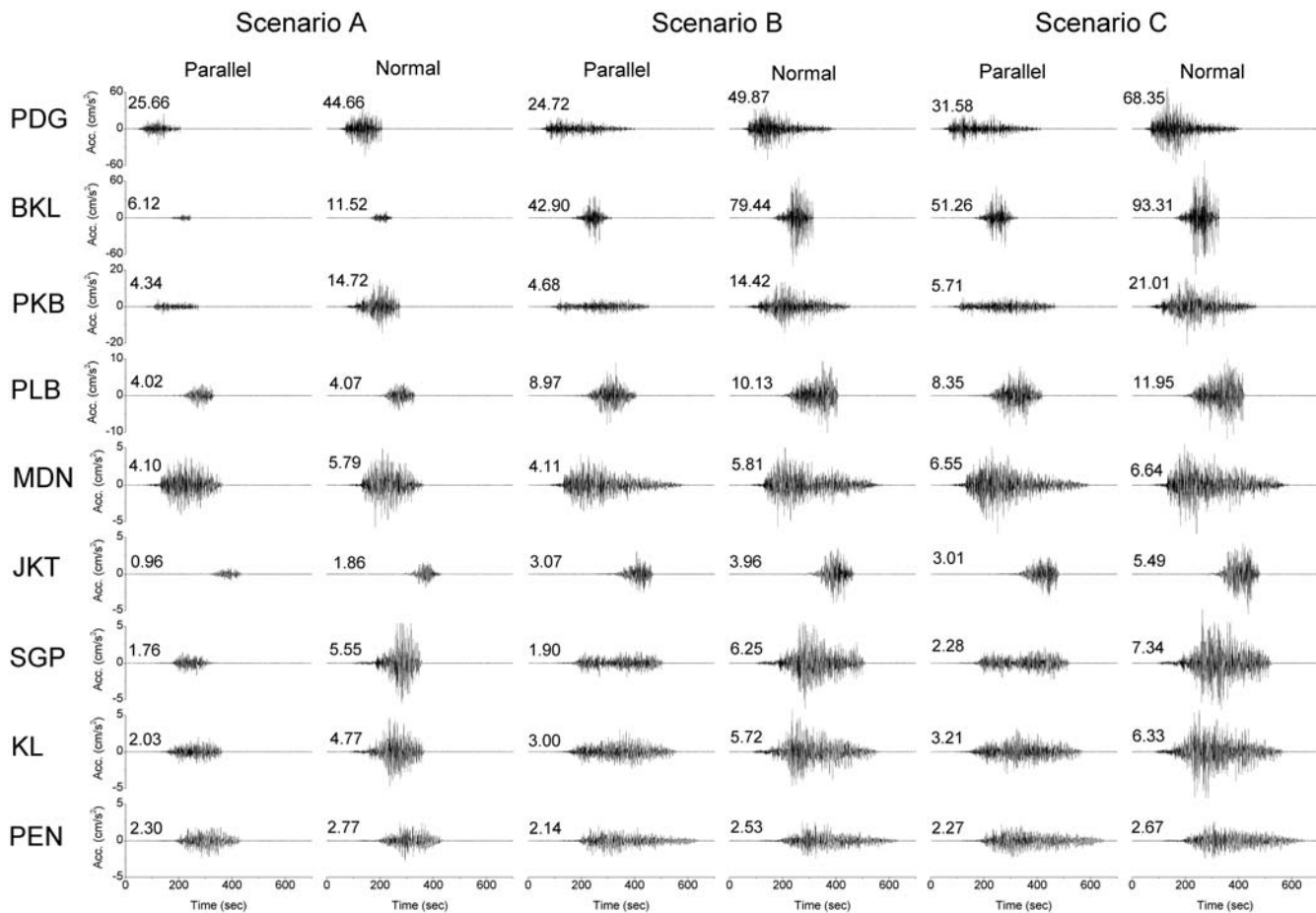


Figure 6. Horizontal ground-motion accelerations simulated at Padang (PDG), Bengkulu (BKL), Pekanbaru (PKB), Palembang (PLB), Medan (MDN), Jakarta (JKT), Singapore (SGP), Kuala Lumpur (KL), and Penang (PEN), for scenarios A, B, and C, in which the hypocenters are located at the northern edge of the rupture plane (case 1). The horizontal ground motions at each station have been aligned in the strike-parallel and strike-normal directions. The time axes for all traces are in the same scale given at the lower side of the figure, where the time 0 sec refers to the time of the initiation of the rupture. The acceleration axis for each station is given on the left-hand side of the figure. The value shown at the beginning of each trace indicates the PGA.

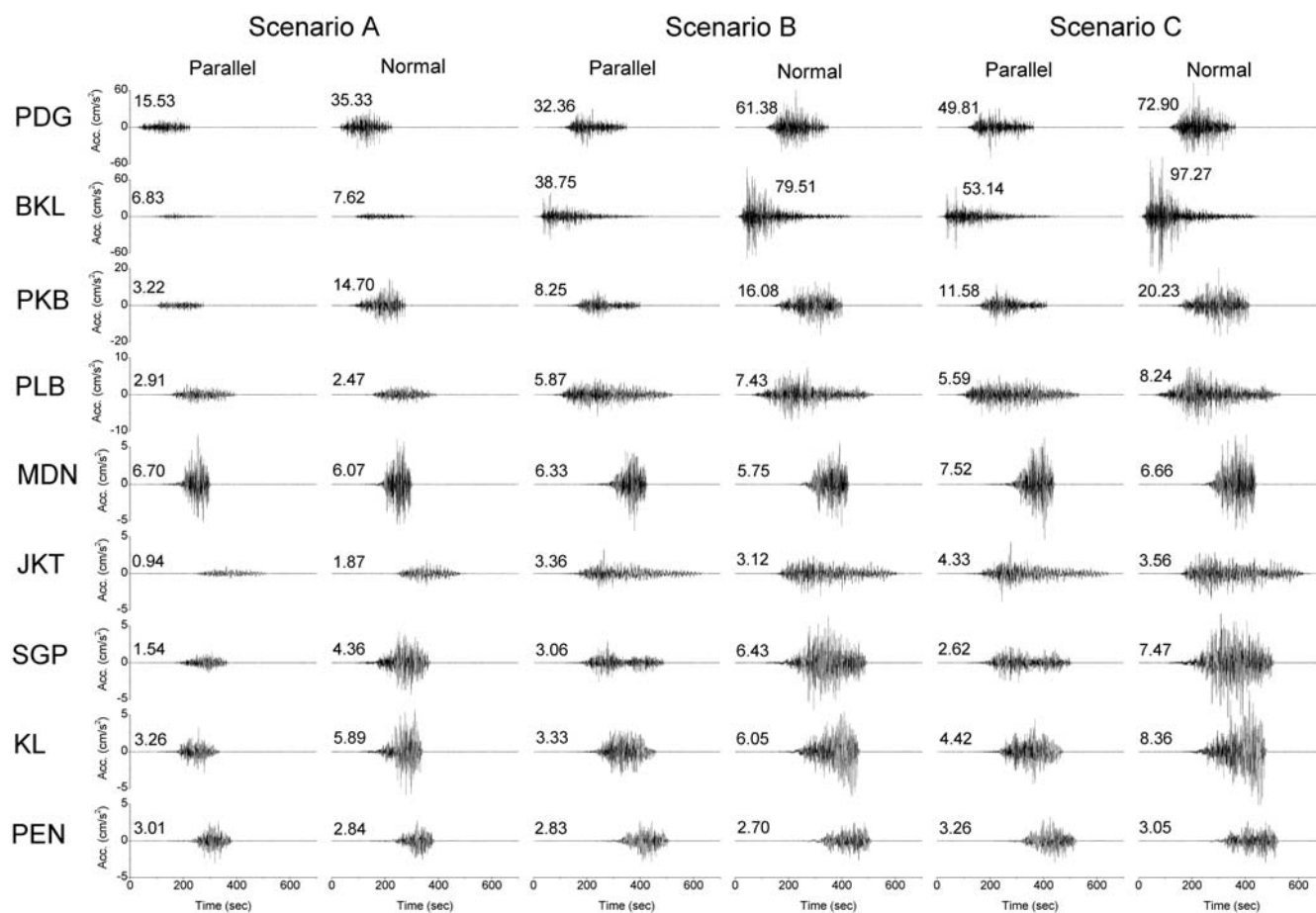


Figure 7. Horizontal ground-motion accelerations simulated at Padang (PDG), Bengkulu (BKL), Pekanbaru (PKB), Palembang (PLB), Medan (MDN), Jakarta (JKT), Singapore (SGP), Kuala Lumpur (KL), and Penang (PEN), for scenarios A, B, and C, in which the hypocenters are located at the southern edge of the rupture plane (case 2). The horizontal ground motions at each station have been aligned in the strike-parallel and strike-normal directions. The time axes for all traces are in the same scale given at the lower side of the figure, where the time 0 sec refers to the time of the initiation of the rupture. The acceleration axis for each station is given on the left-hand side of the figure. The value shown at the beginning of each trace indicates the PGA.

pore, Kuala Lumpur, and Penang. The first six cities are within the territory of Indonesia, whereas Kuala Lumpur and Penang belong to Malaysia. These cities (Fig. 1) lie within two fault lengths from the Mentawai segment and thus may be affected by its rupture. Figure 6 presents the ground accelerations for scenarios A, B, and C, where the respective hypocenters are located at the northern edge of the rupture planes (case 1). Figures 7 and 8 show the ground accelerations for cases 2 and 3, respectively. The upper cutoff frequency of the simulation is 1.2 Hz. The horizontal ground motions at each station have been aligned in the strike-parallel and strike-normal directions. The value shown at the beginning of each trace indicates the peak ground acceleration (PGA) of the waveform. In general, the ground motions in the strike-normal direction are larger than the corresponding strike-parallel components.

Comparing the ground motions resulting from case 1 (Fig. 6) and case 2 (Fig. 7) for each scenario, it appears that the amplitude of the ground motion at a station increases, albeit not significantly, if the rupture propagates toward the

station. This is not the typical forward rupture directivity effect observed in a strike-slip earthquake. Forward rupture directivity effects occur when the rupture front propagates toward the station and the direction of slip on the fault points to the station (Somerville *et al.*, 1997; Megawati and Chandler, 2006). In both cases 1 and 2, the rupture front propagates perpendicular to the slip vector. This pattern of rupture would generate forward directivity pulses confined along the Mentawai islands if the hypocenter was located downdip and the rupture front propagated updip, as was observed in the 1999 Chi-Chi, Taiwan, earthquake (Agaard *et al.*, 2004).

Figures 6–8 show that the ground-motion amplitudes from scenario C (M_w 9.2) are marginally larger than the corresponding amplitudes from scenario B (M_w 9.0).

Discussions

Potential Seismic Risk in Sumatra and West Java

According to the current Indonesian Seismic Code (SNI-1726-2002), the territory of Indonesia is divided into

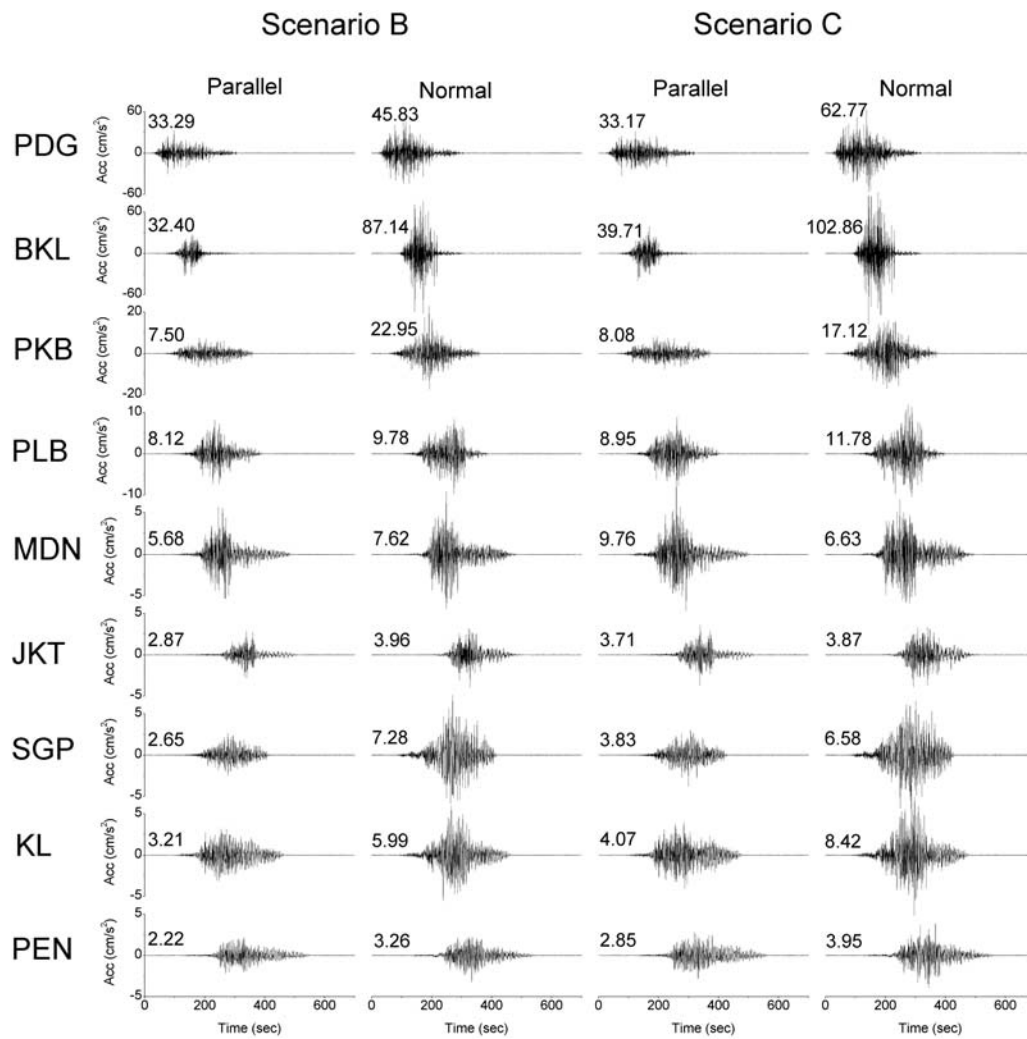


Figure 8. Horizontal ground-motion accelerations simulated at Padang (PDG), Bengkulu (BKL), Pekanbaru (PKB), Palembang (PLB), Medan (MDN), Jakarta (JKT), Singapore (SGP), Kuala Lumpur (KL), and Penang (PEN), for scenarios B and C, in which the hypocenters are located near the center of the rupture plane (case 3). The horizontal ground motions at each station have been aligned in the strike-parallel and strike-normal directions. The time axes for all traces are in the same scale given at the lower side of the figure, where the time 0 sec refers to the time of the initiation of the rupture. The acceleration axis for each station is given on the left-hand side of the figure. The value shown at the beginning of each trace indicates the PGA.

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 PGAs on bedrock with a return period of 500 yr, where zones 1 to 6 are assigned increasing values of 0.03, 0.10, 0.15, 0.20, 0.25, and 0.30g, 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 subsequently to assess the seismic risk of major cities in Sumatra and West Java due to the rupture of the Mentawai segment.

The dotted lines in Figures 9–11 present the pseudo-acceleration response spectra, with 5% damping ratio, resulting from the ground motions simulated for scenarios A, B, and C, respectively. Only the strike-normal components are analyzed as they are larger than the corresponding strike-parallel components. There are two dotted lines in each panel of Figure 9, representing the spectra from cases 1 and 2, whereas the three dotted lines in each panel of Figures 10 and 11 represent the spectra from cases 1, 2, and 3. These spectra from the simulated ground motions are denoted as the demand spectra.

The linearly elastic design spectra with a return period of 500 yr for the six cities in Indonesia are shown in Figures 9–11 as the capacity spectra with $\mu = 1$, where μ indicates the design ductility ratio. As commonly specified in seismic

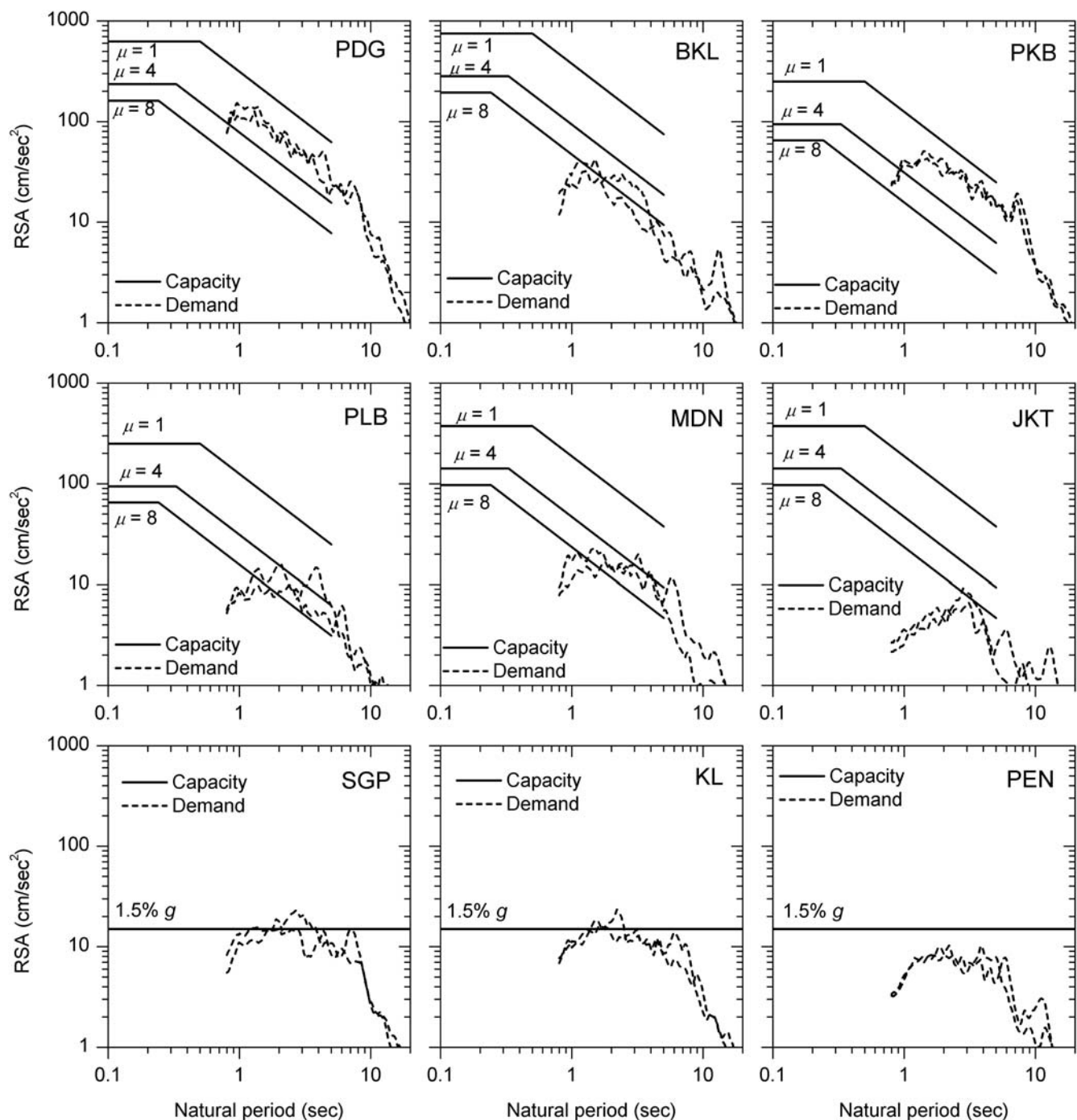


Figure 9. Pseudoacceleration response spectra (5% damping ratio) resulting from the strike-normal components simulated at Padang (PDG), Bengkulu (BKL), Pekanbaru (PKB), Palembang (PLB), Medan (MDN), Jakarta (JKT), Singapore (SGP), Kuala Lumpur (KL), and Penang (PEN) for scenario A (cases 1 and 2). The respective design spectra with ductility ratios, μ , of 1 (linear), 4, and 8 are shown using the solid lines.

codes, it is not economical to design ordinary structures to remain linearly elastic during an earthquake with a long return period of 500 yr. 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 behave in a ductile manner. In other words, the strength, stiffness, and integrity 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 are shown in Figures 9–11.

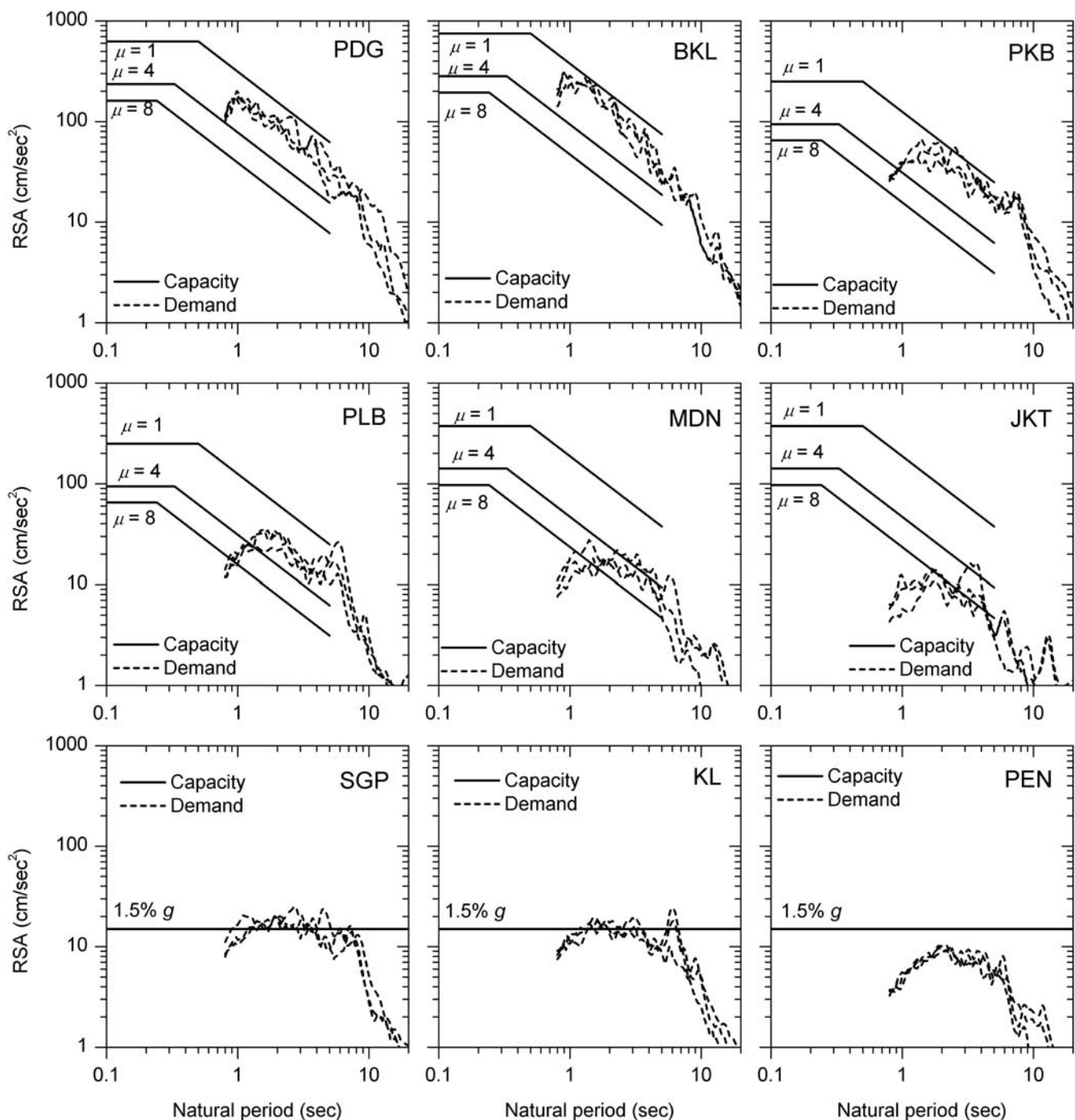


Figure 10. Pseudoacceleration response spectra (5% damping ratio) resulting from the strike-normal components simulated at Padang (PDG), Bengkulu (BKL), Pekanbaru (PKB), Palembang (PLB), Medan (MDN), Jakarta (JKT), Singapore (SGP), Kuala Lumpur (KL), and Penang (PEN) for scenario B (cases 1, 2, and 3). The respective design spectra with ductility ratios, μ , of 1 (linear), 4, and 8 are shown using the solid lines.

Padang and Bengkulu are two major cities located along the high-seismicity region of western coast of Sumatra (Fig. 1). They are situated in the vicinity of the active, right-lateral, Sumatran fault (Sieh and Natawidjaja, 2000) and are also close to the Sumatran megathrust. Bengkulu is located in seismic zone 6, while Padang is in zone 5. It can be seen from Figures 9–11 that the demand spectra ex-

ceed the inelastic capacity spectra ($\mu = 4$) but are lower than the linearly elastic spectra ($\mu = 1$). The notable exception is Bengkulu in scenario A because the city is located 275 km away from the fault. This indicates that medium- and high-rise structures, with natural periods longer than 0.8 sec, in both cities would actually yield if they are designed according to the spectra for the ductility ratio of 4, but they may or

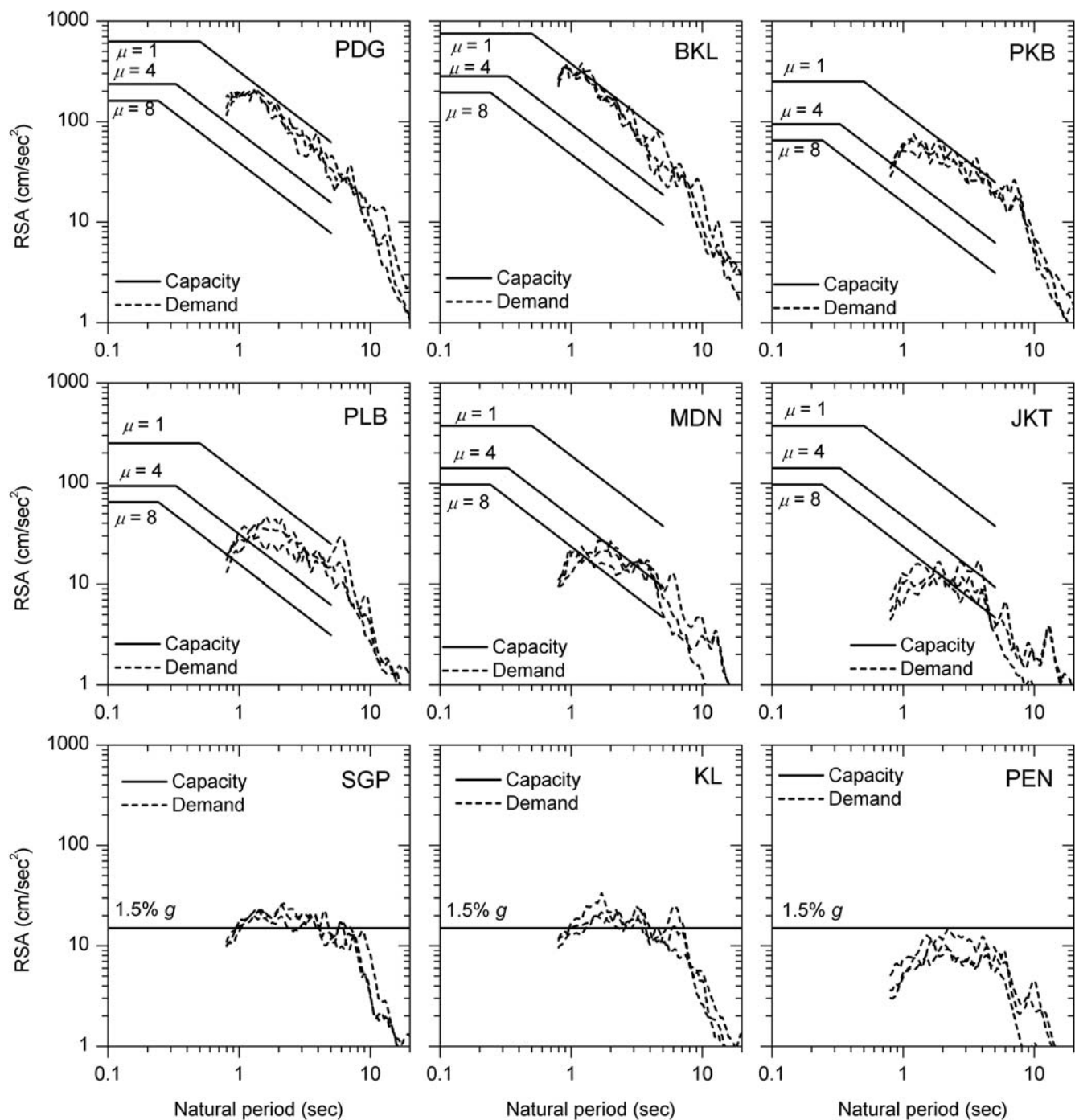


Figure 11. Pseudoacceleration response spectra (5% damping ratio) resulting from the strike-normal components simulated at Padang (PDG), Bengkulu (BKL), Pekanbaru (PKB), Palembang (PLB), Medan (MDN), Jakarta (JKT), Singapore (SGP), Kuala Lumpur (KL), and Penang (PEN) for scenario C (cases 1, 2, and 3). The respective design spectra with ductility ratios, μ , of 1 (linear), 4, and 8 are shown using the solid lines.

may not collapse depending on the ductile behaviors of the structures.

In structural engineering, yielding is usually unavoidable to achieve economical designs to withstand future, rare, earthquakes but collapse of structures should be prevented. There are two measures to prevent collapse: first, the demand ductility ratio should be smaller than the capacity to prevent

excessive lateral deformation, and, second, the structures should be able to maintain their overall strength, stiffness, and integrity 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 (Applied Technology Council [ATC], 1996). The second requirement is more

critical in this case because the ductile detailing as specified in the current seismic codes was 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. Not many experiments, if any, have been carried out to investigate the postyielding performance of structural components subjected to long-duration ground motions from giant earthquakes with $M_w \approx 9$. The ground-motion durations from this level of magnitude may last for about 3–5 min (Figs. 6–8). Therefore, if medium- and long-period structures in Bengkulu and Padang could maintain the ductility capacity for about 3–5 min, corresponding to 200–300 cycles of vibration, they are likely to survive. If the ductile behavior cannot be maintained beyond a few cycles of vibration and disintegration at plastic hinges occurs, the structures may collapse.

The seismic performance of short-period structures with natural periods lower than 0.8 sec is not discussed herewith because this type of structure is more sensitive to the rupture of the nearby Sumatran fault segments, which would produce larger high-frequency ground motions than would the farther subduction earthquakes.

Jakarta and Medan (Fig. 1) are both located in zone 3, which is considered a moderate-seismicity zone. The capacity and demand spectra are compared in Figures 9–11. It shows that the demand spectra barely exceed the capacity spectra ($\mu = 4$). The amplitudes of ground motions generated by the Mentawai earthquakes may be too weak to cause yielding to medium- and high-rise buildings in these cities. Therefore, the seismic risk posed by the Mentawai segment to these two cities is relatively low, simply because they are located far from the rupture zone and the seismic design requirement is relatively high. Note that the main seismic threat to Medan comes from the nearby Sumatran fault and the subduction zone beneath Nias island, whereas Jakarta is more likely to be affected by earthquakes in the subduction zone south of Java and the nearby faults in western Java.

Palembang and Pekanbaru are located in the low-seismicity region of eastern Sumatra (seismic zone 2) and thus have lower seismic design spectra than Jakarta or Medan. Because these two cities are located relatively closer to the rupture zone than Jakarta or Medan, the potential seismic risk to buildings in Palembang and Pekanbaru are higher (Figs. 9–11). It becomes obvious that the potential risk to medium- and high-rise structures with natural periods $T = 0.8$ –3.0 sec in these low-seismicity cities is as high as those in the high-seismicity cities of Bengkulu and Padang.

Potential Seismic Risk in Singapore and the Malay Peninsula

Singapore is located 650 km away from the center of the Mentawai rupture zone; thus, the resulting ground motions

are quite weak. Current building design code for structures in Singapore has been developed largely based on the BS 8110 (British Standards Institution [BSI], 1997), which does not have any provision for seismic loading. It does, however, require that all buildings be capable of resisting a notional, ultimate lateral design load applied at each floor level simultaneously for structural robustness. These static lateral loads are equal to 1.5% of the characteristic dead weight of the structure. The design wind load should not be taken as 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 minimum capacity of the building can therefore be taken as constant at 1.5%g (15 cm/sec²) across the entire natural-period range, as shown in Figures 9–11.

For medium- and high-rise structures, with $T = 0.8$ –5.0 sec, on typical rock sites in Singapore, the demand spectra are slightly larger than the minimum capacity of 1.5%g. However, it does not mean that buildings designed according to current regulations would collapse if hit by the ground motions from the scenario earthquakes. Because of the overstrength of the construction materials, a structure designed against lateral loads equal to 1.5% of the weight of the structure would commonly have a yielding strength larger than the design value. Yet it must be noted that the reliance on the material overstrength as a defense line against seismic excitation is debatable.

The lack of seismic-resistant requirements permits buildings to be designed and constructed with obvious irregularities in horizontal and vertical configurations. Many residential blocks have a long rectangular floor plan, where the elevator shafts and structural walls are placed unevenly at one end of the buildings. This may induce significant torsional effects when subjected to seismic ground motions. Many buildings are allowed to have large openings in the first story, which may result in a soft first story. These types of design and construction practices increase the seismic risk to the building stock in Singapore.

For high-rise structures of more than 30 stories ($T \geq 3.0$ sec), wind design requirements typically supersede the notional lateral load. Thus, the seismic risk to this type of structure is considered lower.

Kuala Lumpur, the capital city of Malaysia, is located at a similar distance from the Mentawai segment as Singapore is. Therefore, the demand spectra in both cities are comparable. The building code used in Malaysia is almost identical to that used in Singapore, and the issues of seismic risk to buildings in Singapore, discussed previously, is also relevant for Kuala Lumpur.

Penang, another major city on the Malay Peninsula, is located farther to the north, and thus, the demand spectra are relatively lower than those in Singapore and Kuala Lumpur. The corresponding risk to the medium- and high-rise buildings in this city is almost negligible.

Effects of Soft-Soil Amplification in Singapore

It should be noted that the demand spectra in Singapore shown in Figures 9–11 are for rock sites. The central and southeastern parts of Singapore island are largely overlain by Quaternary marine clay deposits, and a significant portion of the southern coastal area is reclaimed land (Pitts, 1984). This soft-soil deposits can significantly amplify the weak bedrock motion, as confirmed by recent Sumatran earthquakes where tremors were largely felt by residents of high-rise buildings in these areas and not in other areas with better ground conditions (Pan *et al.*, 2001). Because seismic-resistant design is not required in Singapore, buildings on soft-soil and rock sites are designed against the same lateral loads, resulting in buildings with the same seismic capacity. The seismic risk to structures on soft-soil sites is, therefore, higher than that on firm-soil or rock sites, simply because the seismic hazard level is higher at the soft-soil sites.

Figure 12 shows the soil profile at a site overlain by the marine clay deposit named the Kallang formation, in the southern part of Singapore (Pan and Lee, 2002). This is a typical soft-soil profile in Singapore, having an average shear-wave velocity of the upper 30 m of the site profile, V_{S30} , of 130 m/sec. According to the 2000 edition of the

International Building Code (IBC) (International Code Council [ICC], 2000), this site is classified as soft soil (site class E) based on the value of V_{S30} .

The site response analysis is carried out using the equivalent linear model of the horizontally layered soil deposit, as implemented in the widely used computer program called SHAKE91 (Schnabel *et al.*, 1972; Idriss and Sun, 1992). In the equivalent linear method, nonlinear behavior of soil is accounted for by the use of strain-dependent stiffness and damping parameters. The stiffness of the soil is characterized by the maximum shear modulus G_{max} and a modulus reduction curve, showing how the shear modulus G decreases from G_{max} at larger strain. Damping behavior is characterized by the damping ratio, which increases with increasing strain amplitude. The present study uses the G/G_{max} and damping ratio curves developed by Seed and Idriss (1970) for cohesionless soils and the curves proposed by Vucetic and Dobry (1991) for cohesive soils.

The right-hand column of Figure 12 shows the amplification of the strike-normal component of the horizontal ground motion from scenario B (case 1) as it propagates vertically from the bedrock to the surface. It can be seen that ground motion is only amplified slightly from the bedrock

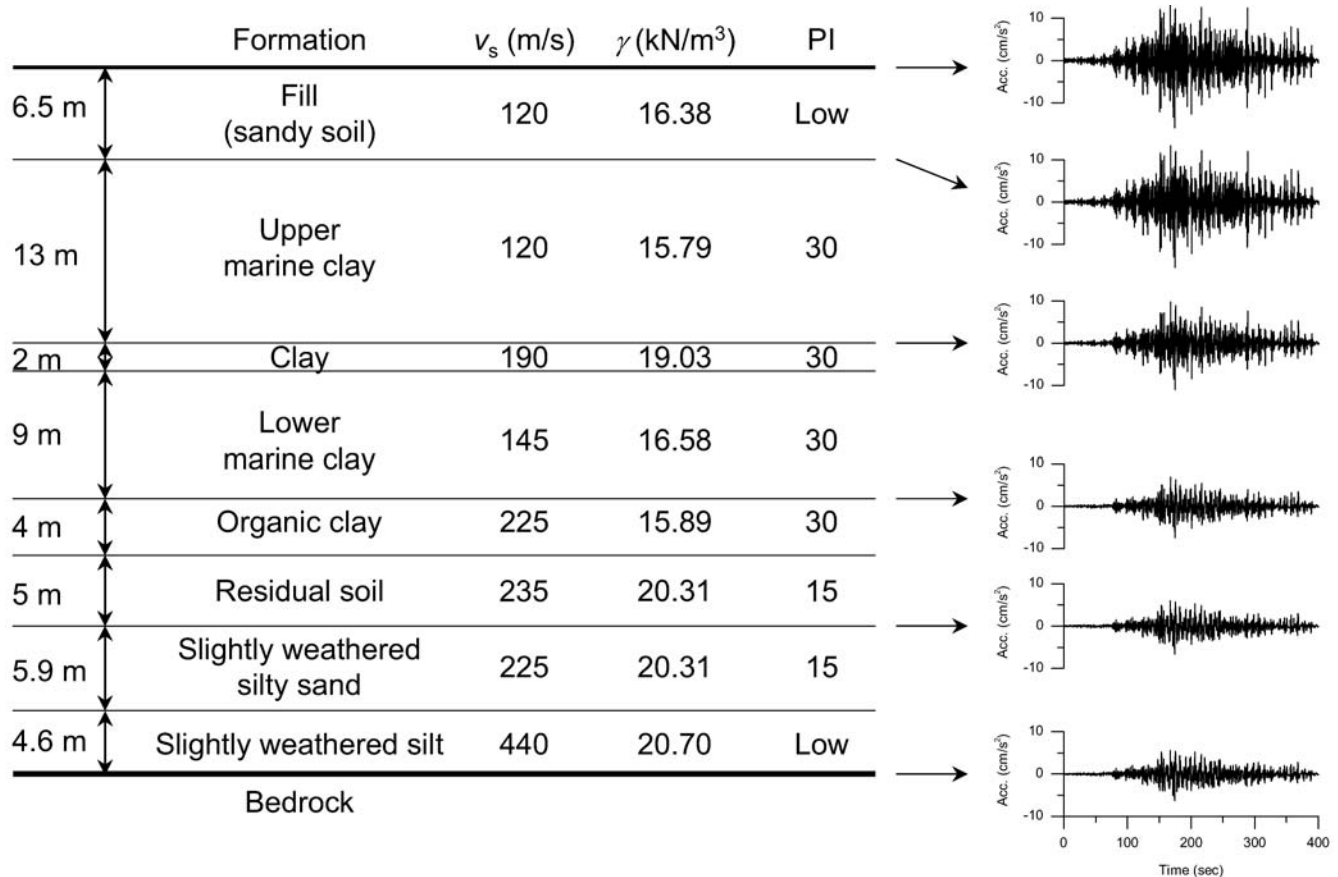


Figure 12. Profile at a typical soft-soil site, overlain by marine clay deposit, in the southern part of Singapore. The traces in the right-hand column show the amplification of the strike-normal component from scenario B (case 1) as it propagates vertically from the bedrock to the surface.

to the depth of 30.5 m, and the amplification becomes significant within the upper 30.5 m of the soil profile.

The response spectra (5% damping ratio) of the ground motions at the three different levels, namely, the bedrock, the depth of 30.5 m, and the surface, are compared in Figure 13a. It is obvious that the upper 30.5 m of the soil profile amplifies the ground motion significantly within the natural period of 0.8–3 sec, whereas the spectral values beyond the natural period of 3 sec are not amplified. The amplification factors, shown in Figure 13b, indicate that the spectral value at $T = 1.2$ sec on the soft-soil site is 4.8 times larger than the corresponding value on the hard-rock site. As a comparison, the spectral amplification factor between site E (soft soil) and site A (hard rock) specified in the IBC 2000 (ICC, 2000) is equal to 4.4 for $T \geq 1$ sec. These site effects bring the maximum value of the spectral acceleration response to 80 cm/sec^2 ($= 8\%g$) at $T = 1.2$ sec. The natural-period range of 1.2–1.8 sec corresponds with the natural periods of common medium- and high-rise residential and commercial buildings in Singapore.

The aforementioned findings indicate that medium- 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 potential rupture of the Mentawai segment. Because seismic design has not been required and providing ductile detailing is not mandatory in current building code, buildings in Singapore have very limited inherent ductility capacity. Further investigations on the postyielding behaviors of nonseismically designed structures are essential for assessing the seismic performance of this type of buildings.

Shape of Design Spectrum

Standard seismic design codes, such as the IBC 2000 (ICC, 2000) and the Indonesian Seismic Code (SNI-1726-2002), specify the design base shear for buildings as

$$V_b = \frac{IC}{R} W,$$

where W is the total dead weight of the structure, R is the strength reduction factor to account for ductility capacity and inelastic performance of structures, and I is the importance factor, which is taken to be 1.0 for ordinary structures. The period-dependent seismic coefficient C depends on the location of the structure, which is characterized by the seismic hazard at the site and the local site condition. The spectral shape of seismic coefficient C is governed by the ordinates of the pseudoacceleration at short period, $A(T_n = 0.2 \text{ sec})$, and that at 1.0 sec, $A(T_n = 1.0 \text{ sec})$. Maps showing these two values of A are usually given in seismic codes.

The typical shape of a seismic design spectrum for a rock site is shown by the solid line in Figure 14, where the corner period T_c indicates the intersection between the constant-acceleration and constant-velocity branches of the spectrum. Because the constant-acceleration branch is defined by $A(T_n = 0.2 \text{ sec})$ and the constant-velocity branch is determined by $A(T_n = 1.0 \text{ sec})$, the corner period T_c always lies between 0.2 and 1.0 sec. The T_c values for rock sites typically range between 0.4 and 0.6 sec. This spectral shape was derived from statistical analyses of numerous ground motions recorded near the epicenters, and thus, it

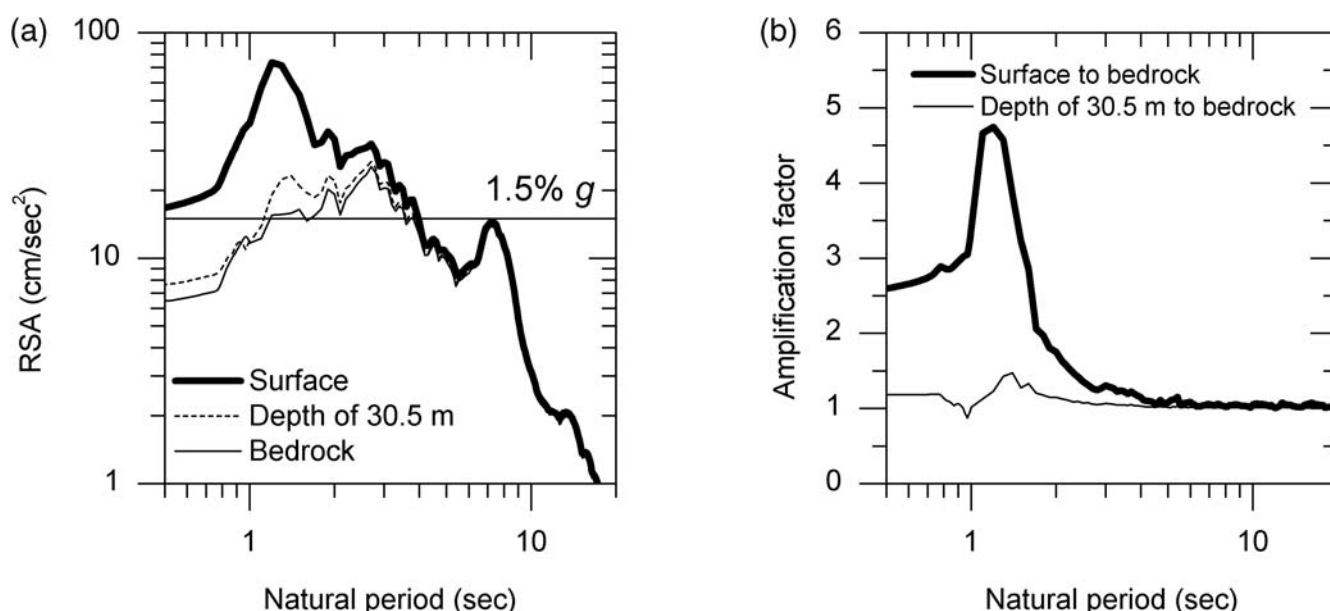


Figure 13. (a) Pseudoacceleration response spectra (5% damping ratio) of the ground motions at the three different levels, namely, the bedrock, the depth of -30.5 m, and the surface. (b) Spectral amplification factors between the surface and the bedrock and between the depth of 30.5 m and the bedrock.

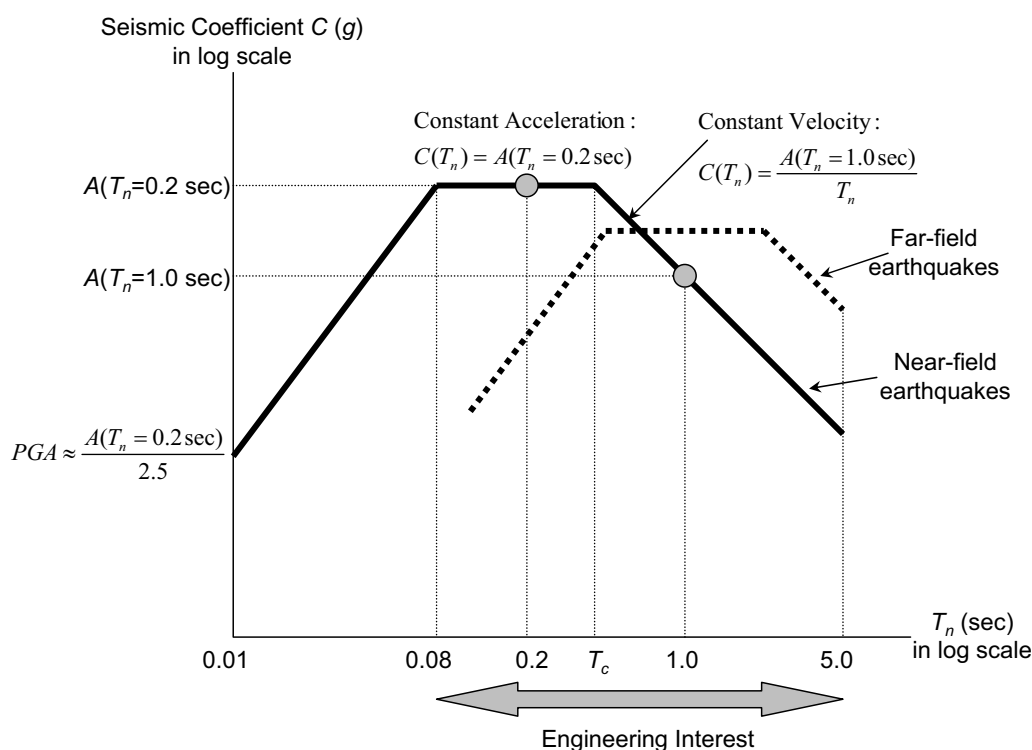


Figure 14. Comparison between the spectral design shapes appropriate for near-field and far-field earthquakes.

is suitable for sites where the seismic hazards are controlled by near-field earthquakes.

Figures 9–11 have shown that the natural-period range for the constant-acceleration branch becomes longer as the distance from the source to the station increases. Comparing the response spectra in Padang and Singapore shows that the range increases from 0.8–1.5 to 1.5–3.5 sec. In both cases, the corner period T_c extends beyond 1.0 sec. This is understandable because the high-frequency components of the ground motions attenuate more rapidly with respect to distance than do the low-frequency components. Therefore, at distant stations the ground motions are likely to be dominated by low-frequency components. This fact implies that the shape of the design spectrum derived from near-field earthquakes, shown by the solid line in Figure 14, may not be suitable for sites where the potential seismic hazard is dominated by large-magnitude, far-field, events because it may underpredict the hazard at long-period range. Unfortunately, this spectral shape with $T_c = 0.5$ sec is currently used for the whole territory of Indonesia, regardless of the local seismicity. For example, the eastern coast of Sumatra (Fig. 1), where the seismic hazard is controlled by distant earthquakes along the Sumatran fault running along the western coast and the subduction zone off the western coast, is assigned the same design spectral shape as the high-seismicity western coast. The implications can be seen in Figures 9–11, where the potential risk to medium- and high-rise structures with $T = 0.8$ –3.0 sec in the low-seismicity cities of Palembang and Pekanbaru are as high as those in the high-seismicity cities of Bengkulu and Padang.

Building authorities in Singapore and Malaysia are currently discussing the incorporation of earthquake-resistant design to existing building codes. It should be understood that the characteristics of ground motions in Singapore and the Malay Peninsula are unique and not the same as those in high-seismicity regions. The shifting of the response spectrum toward longer period range, as discussed previously, should be carefully taken into account in the formulation of future seismic codes.

Southern Sumatran Earthquakes on 12 and 13 September 2007

During the writing of this article, three significant earthquakes occurred in the Mentawai segment on 12 and 13 September 2007. The epicenters of the earthquakes are depicted in Figure 1. According to the Earthquake Center of the U.S. Geological Survey, the first event occurred on the twelfth, at 11:10:26 UTC, with an M_w of 8.4, followed by an M_w 7.8 earthquake at 23:49:01 UTC and an M_w 7.1 earthquake the following day, at 03:35:26 UTC. Although the detailed rupture processes of these earthquakes are still being analyzed by the Tectonics Observatory of the California Institute of Technology, using near-field GPS data and observation of the vertical motion of coral reefs (K. Sieh, personal commun., 2007), initial solutions indicate that the M_w 8.4 event produced between 1 and 4 m of slip on a 250×120 km patch. The M_w 7.8 event occurred at the downdip border of the Mentawai segment and added to strain accumulating within

the segment. The last event of M_w 7.1 may have involved 1 m of slip over a small area of 40×20 km.

These preliminary results show that the northern part of the Mentawai segment remains intact during these series of earthquakes and may have actually suffered an increase in strain from these events. Therefore, the validity of scenario A in the present study is unaffected. The southern part of the Mentawai segment has accumulated potential slip of 8.1 m since 1833 ($174 \text{ yr} \times 46.7 \text{ mm/yr} = 8126 \text{ mm}$). While a portion of the strain accumulated was released in the M_w 8.4 event, this locked fault patch still has potential slip of 4.1–7.1 m. Scenario B, with its projected slip value of 5 m over the southern portion, remains a realistic model.

Conclusions

The 26 December 2004 Aceh-Andaman earthquake (M_w 9.15) and the 28 March 2005 Nias-Simeulue earthquake (M_w 8.6) released a significant portion of the strain accumulated along the Sumatran megathrust north of the equator; thus, there is no immediate danger of a repeating event on the same segment of the megathrust. In contrast, the Mentawai segment, south of 1° S, is very likely to rupture in the near future, as evidence suggests that the interseismic strain accumulated along this segment has approached that released in the historical events of 1797 and 1833. The recent M_w 8.4 southern Sumatran earthquake on 12 September 2007 may have released slip ranging from 1 to 4 m within the southern portion of the Mentawai segment, but it was only a fraction of the 8.1 m of potential slip accumulated since 1833. Three earthquakes having M_w of 8.6, 9.0, and 9.2 have been postulated as potential rupture scenarios within the Mentawai segment. The two smaller scenarios are considered most likely scenarios in the future, whereas the largest scenario is put forward as the worst-case scenario. The analyses of these scenario earthquakes have revealed the following:

1. The ground motions produced by the scenario earthquakes are strong enough to cause yielding to medium-rise structures in Padang, Bengkulu, Pekanbaru, and Palembang, which are major cities in Sumatra, each having a population of over half a million. Because structures are designed to yield in such rare events, it is vital to ensure that the overall strength, stiffness, and integrity of the structures can be maintained throughout the entire duration of shaking. The ductile detailing in the current design code is formulated based on an assumption that typical ground motions would last 20–40 sec and has not been tested against ground motions with duration as long as the 3–5 min expected from these giant earthquakes. It is therefore important to carry out this type of tests to ensure the adequacy of the structural detailing.
2. Seismic risk to medium- and high-rise buildings in Pekanbaru and Palembang, which are located in a low-seismicity region of eastern Sumatra, is as high as the risk in the high-seismicity cities of Padang and Bengkulu. This is due to the shortcoming in the current Indonesian seismic code where the same design spectral shape, having a corner period of 0.5 sec, is used for the whole territory of Indonesia regardless of local seismicity. Although this spectral shape is suitable for high-seismicity regions, where the seismic hazard is controlled by local, strong, earthquakes, it is not appropriate for low-seismicity regions, where the main seismic threat comes from distant earthquakes. Shifting of response spectrum toward longer period range as the distance from the potential seismic source increases should be considered.
3. In Jakarta and Medan, the ground motion from the scenario earthquakes may not be strong enough to cause yielding to the buildings if designed according to the current building code. Instead of the Mentawai segment, Medan is more likely to be affected by the nearby Sumatran fault and the subduction zone beneath Nias island, whereas Jakarta faces threat from earthquakes in the subduction zone south of Java and the nearby faults in western Java.
4. In Singapore and Kuala Lumpur, only medium- 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 structures under moderate-amplitude, long-duration, ground motions.
5. Shifting the response spectrum toward longer period range becomes significant for cities located far from potential seismic sources, and it should be carefully considered in the formulation of future seismic codes for Singapore and Malaysia.

Data and Resources

The ground motions recorded at the GSN station in Singapore were provided by the Meteorological Services Division, National Environment Agency (NEA), Singapore. The same sets of data can also be obtained from Incorporated Research Institutions for Seismology (IRIS; www.iris.edu, last accessed January 2007). The soil profile shown in Figure 12 was obtained from NEA. The global crustal model CRUST 2.0 was obtained from the Institute of Geophysics and Planetary Physics, the University of California, San Diego, <http://mahi.ucsd.edu/Gabi/rem.dir/crust/crust2.html> (last accessed in January 2007).

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12 and 13 September 2007 southern Sumatran subduction earthquakes. The authors have benefited from discussions with Hiroo Kanamori on the rupture velocity and slip velocity of large-magnitude, subduction earthquakes. Felicia Shaw proofread the original manuscript.

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