A RECONNAISANCE REPORT
ON
THE 2007 SINGKARAK LAKE (SOLOK) EARTHQUAKE
WITH
AN EMPHASIS ON THE SEISMIC ACTIVITY OF SUMATRA FAULT
FOLLOWING 2004 and 2005 GREAT OFF-SUMATRA EARTHQUAKES

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CONTENT

1 INTRODUCTION

An intraplate earthquake struck West Sumatra Province of Indonesia on March 6, 2007, killing 73 people and caused heavy damage in the cities of Solok, Payah Kumbuh, Batusangkar and Simabur. Most affected areas are Padang Pariaman, Bukittinggi, Agam, Batusangkar, Tanah Datar, Padang Panjang, Solok, Limapuluh Kota, Padang, and Payakumbuh .Two large events with a moment magnitude of 6.4 and 6.3 occurred at an interval of two hours. Before the largest event occurred at 10:49, the region was shaked by a smaller earthquake with a magnitude of 4.7.

Following the 2004 and 2005 great off-Sumatra earthquakes, it was pointed out that Sumatra Fault Zone (SFZ), which is more than 1900km long, may be activated. Within this respect, the earthquake of March 6, 2007 occurred in Singkarak Lake along the Sumatra Fault Zone might have some significant implications on the near future seismic activities along this fault zone. The recent studies concerning Sumatra Fault Zone by Natawidjaja (2002) and Aydan (2007) imply that there are a number of seismic gaps along the segments of Sumatra Fault Zone, which may be interpreted as sources of potential earthquakes. Some of these segments may produce intraplate earthquakes with a magnitude ranging between 7.4 and 7.8, which may cause tremendous damage and the loss of huge number of lives. The author pointed out a potential seismic gap in a lecture on March 2, 2007 at the Technology Faculty of Andalas University in Padang City and the earthquake occurred about 5 days after this lecture (Aydan, 2007a).

The author visited the epicentral area between Bukit Tinggi and Solok in July, 2007. The village called Sumpur near the north end of Singkarak Lake was visited and ground ruptures in this village can be clearly observed about 5 months after the earthquake. Although most of damaged structures were cleaned up, the damage to the epicentral area can be easily recognized in many places.

This earthquake induced many slope failures in sceneric Sianok Valley. This valley was created by cutting through pyroclastic flow deposits from nearby Volcanoes by Sumatra Fault. Furthermore, there is a non-supported underground shelter built by Japanese Imperial Army in 1942 in the same geological formation. While there were many extensive slope failures along the valley, the damage to the underground shelter was almost none, which may be of great value for understanding the behaviour of underground openings during earthquakes.

This reconnaisance report is written with a sole purpose of pointing out the importance of earthquake hazard and risk due to intraplate plate earthquakes in Sumatra Island as well as other parts of Indonesia, since more emphases were given to off-shore tsunamigenic earthquake hazard and risk. Furthermore, Indonesia lacks the strong motion network, which is one of the most important items in earthquake resistant design. Since 2004 Aceh earthquake too many proposals for seismic and strong motion monitoring were put forward and it has been more than 3 years and we still see no strong motion records. This earthquake, which was called Solok earthquake, will be called Singkarak Lake Earthquake in this report as it occurred in Singkarak Lake and affected an elongated area from Bukit Tingi to Solok.

(a) Location of the earthquake (from Reuter)

(b) Affected districts and major transportation facilities (re-arranged from OCHA)

Figure 1.1 Location of the earthquake and affected districts and transportation facilities

2 TECTONICS

2.1 Tectonics of Indonesia

Indonesia forms the southeastern extremity of the Euro-Asian lithospheric plate. The northward-moving Indo-Australian and the westward-moving Philippine Sea plates bound Indonesia and it is certainly one of the most complex active tectonic zones on earth (Figure 2.1). The rate of subduction is some centimeters per year; for example, it is 6.0 cm per year in the West Java Trench at 0°S 97°E (azimuth 23°); 4.9 cm per year in the East Java Trench at 12°S 120°E (azimuth 19°); and 10.7 cm per year in New Guinea at 3°S 142°E (azimuth 75°). Figure 2.2 shows the inter-seismic deformation rates in and around Indonesia (Aydan 2007b). As noted from this figure, the Indonesian part of Euro-Asian lithospheric plate tends to rotate clock-wise.

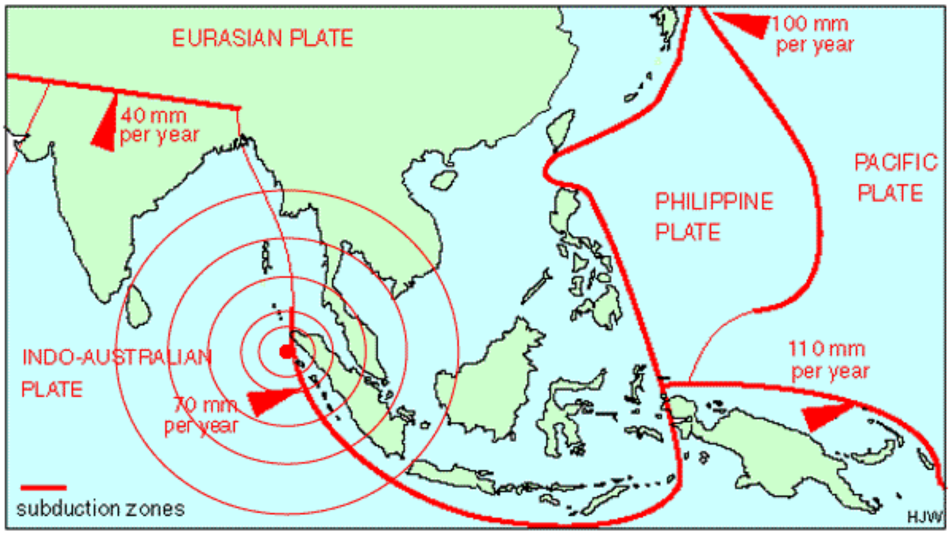


Figure 2.1 Plate tectonics of Indonesia

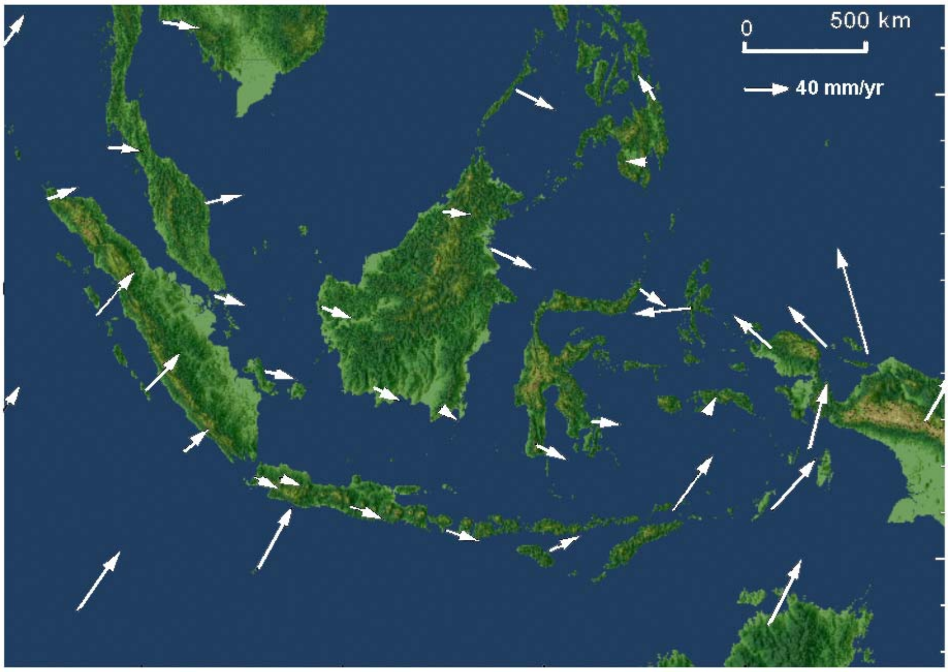


Figure 2.2 Inter-seismic annual deformation rates in Indonesia (from Aydan 2007b)

2.2 Tectonics of Sumatra

In the region of Sumatra Island, the Indo-Australia plate moves toward the northeast at a rate of about 6 cm/year relative to the Euro-Asian plate (Figure 2.3). This results in oblique convergence at the Sunda trench. The oblique motion is partitioned into thrust-faulting, which occurs on the plate-interface and involves slip directed perpendicular to the trench, and strike-slip faulting. Strike-slip faulting occurs several hundred kilometers to the east of the trench and involves slip directed parallel to the trench. This fault is named Sumatra fault, which passes through the entire island. The fault is divided into three sections, namely, southern, central and northern sections. The fault is thrust type with a dextral sense. Sumatra Fault System (SFS) probably dates from the Middle Miocene and the opening of the Andaman Sea, although the relative motions of the major plates have changed little since the Middle Eocene. The SFS runs the entire length of the Barisan Mountains, a range of uplifted basement blocks, granitic intrusions, and Tertiary sediments, topped by Tertiary-Recent volcanics. Studies of Mesozoic outcrops in central Sumatra suggest that the SFS has a displacement of approximately 150km in this area. It is however noted that strike slip deformation is distributed over a geographically wide area outside the present active trace of the SFS.

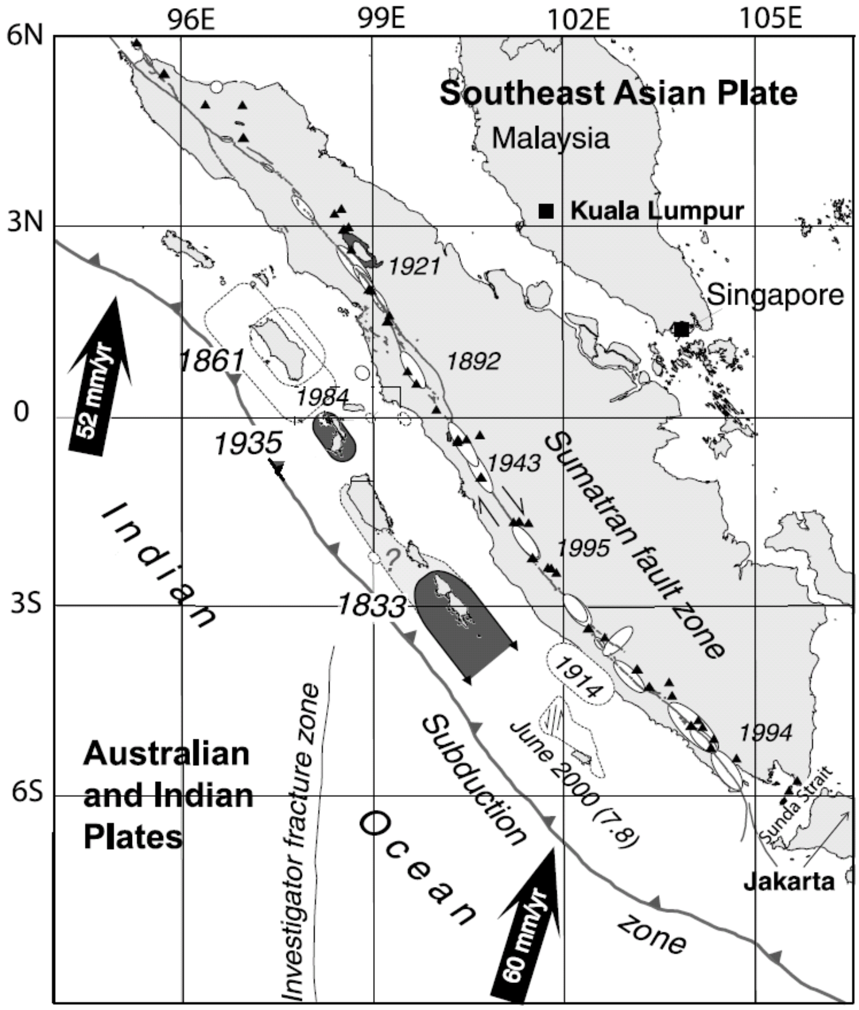
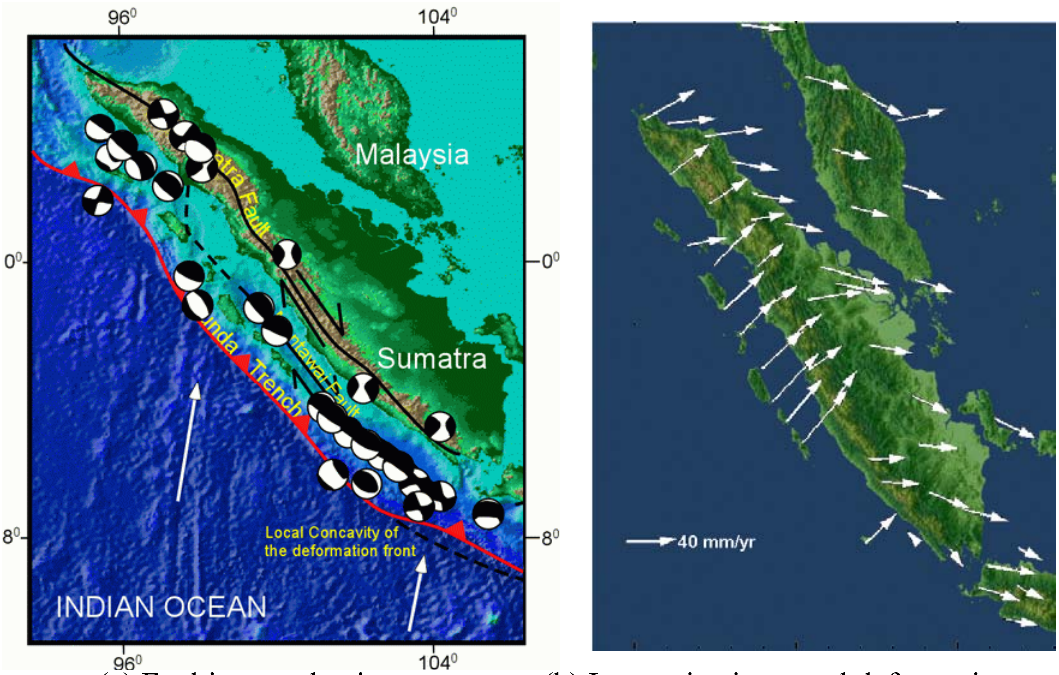


Figure 2.3: Seismo-tectonics of Sumatra Island (from Natawidjaja et al. 2004)

Most of the fault plane solutions indicate the dominant faulting mode is thrust type with a slight dextral or sinistral lateral strike-slip sense in the subduction zone (Figure 2.4(a)) Nevertheless, dominant strike-slip faulting is observed within the Euro-Asian plate between the southern tip of Sumatra Island and Nicobar Island. The fault plate solutions indicate dextral strike-slip sense of deformation for faults trending NW-SE.

Figure 2.4(b) shows the annual crustal deformation rate in/around Sumatra Island. As noted from the figure, the direction of deformation rate vectors differs in the west side and east side of Sumatra fault. While deformation vectors are oriented towards NE in the western side of the fault while they are eastward in the eastern side. In view of Figure 2.2, it seems that Sumatra Island tends to rotate clock wise in conjunction with Euro-Asian plate.



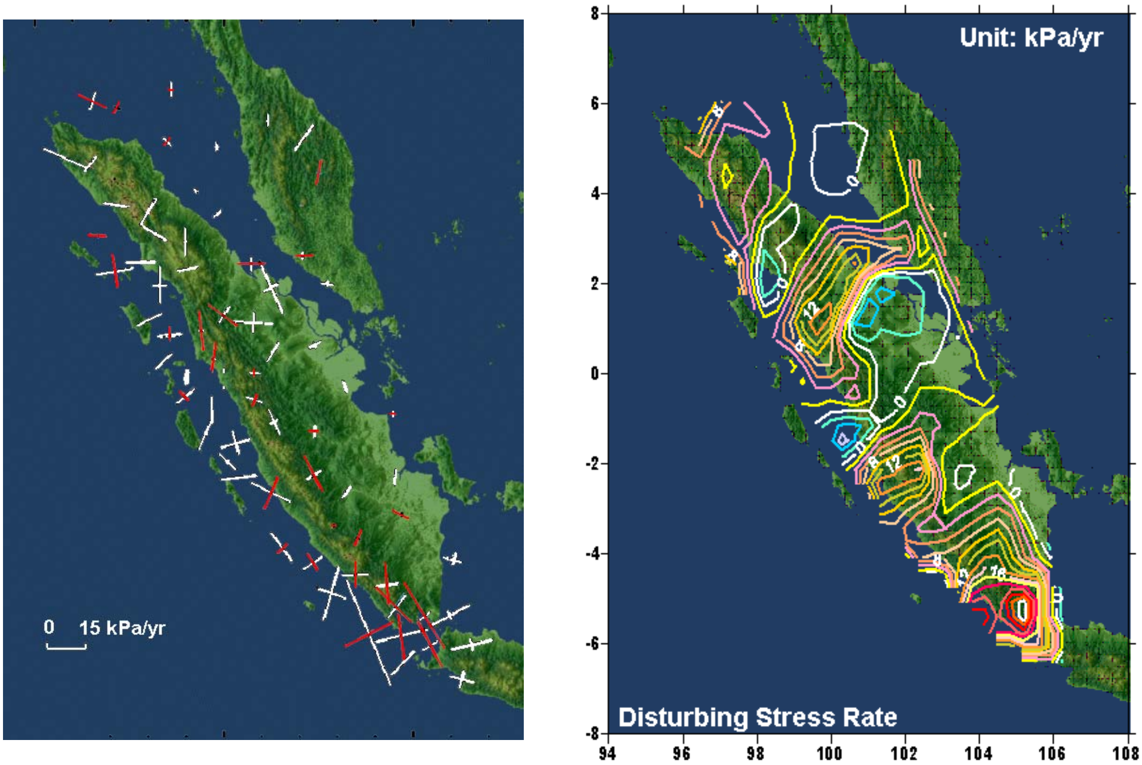
(a) Faulting mechanisms (b) Inter-seismic crustal deformation rates

Figure 2.4 Faulting mechanism and inter-seismic crustal deformation rates in Sumatra Island and its close vicinity

Sieh and Natawidjaja (2000) presented a detailed description of tectonics of 1900km long Sumatra Fault. They identified 19 segments, which are identified by names of rivers or sea, and indicated the possibility of sub-segments for each major segment. The longest and shortest segments are 220km and 35km long. As noted from Figure 2.3, there are many unbroken parts along the Sumatra fault, According to the segmentation of Sieh and Natawidjaja (2000) and seismic gap concept, the segments with high possibility of future earthquakes are Sunda (150km), Kumering (150km), Dikit (60km), Sumpur (35km), Burumun (115km), Tripa (180km), Aceh(200km) and Seulimeum (120km). Although it is pointed out that data is lacking for the last three segments, the expected moment magnitudes of earthquakes for these three segments would range between 7.4 and 7.8. The largest earthquake with a surface magnitude of 7.7 occurred on Angkola segment south of the 2007 Solok earthquake (Sieh and Natawidjaja, 2000)). In view of this observational fact, the estimated magnitudes are quite reasonable. Nevertheless, the intra-plate earthquakes are more destructive than the offshore earthquakes due to differences in ground shaking characteristics, distance as well as permanent continuous or discontinuous ground deformations.

Another important issue is the return period of earthquakes. Since many faults exhibit a stick-slip behaviour, it may be possible to estimate their return period on the basis of mechanical models for stick-slip phenomenon. The return period depends upon the rigidity of continental plate, frictional properties and subduction or relative sliding velocity. The experimental data indicate that the return periods may not always be the same even for the same fault. Nevertheless, if the rigidity of the overriding plate is low and relative slip is slow, the return periods become longer. The slip data during the earthquakes along Sumatra fault is also scarce. Sieh and Natawidjaja (2000) report a 450cm relative sliding for the 1892 earthquake with a surface magnitude of 7.7 on Angkola segment, which was initially reported to be 200cm. The slip rate at various segments of the Sumatra fault ranges between 11 mm/yr to 27mm/yr. If the slip rate is assumed to be constant in time, the earthquakes for a 450cm relative slip may range between about 160 to 400 years. The data on the past seismicity of Sumatra fault is also still lacking and this aspect of the region still needs further investigations and studies.

In a very recent study by (Aydan 2007b) on crustal deformation and straining of Sumatra Island using the GPS deformation rates, it is found that there are three high stress rate concentration regions along the Sumatra Fault. These sections are associated with fault segments named by Sieh and Natawidjaja (2000), which are Sianok, Sumpur, Barumun, Angkola, Toru, Dikit, Ketaun Sunda, Semangko and Kumering segments (Figure 2.6). It is pointed out that tensile stress rate along the first section implies the reduction of normal stress on the Sumatra fault, which may lead the sliding of that segment in years to come. The recent 2007 Singkarak Lake (Solok) earthquake may be a part of this rupture process.



(a) Principal stress rate (b) Disturbing stress rate contours

Figure 2.5: Annual principal stress rates and disturbing stress rate contours

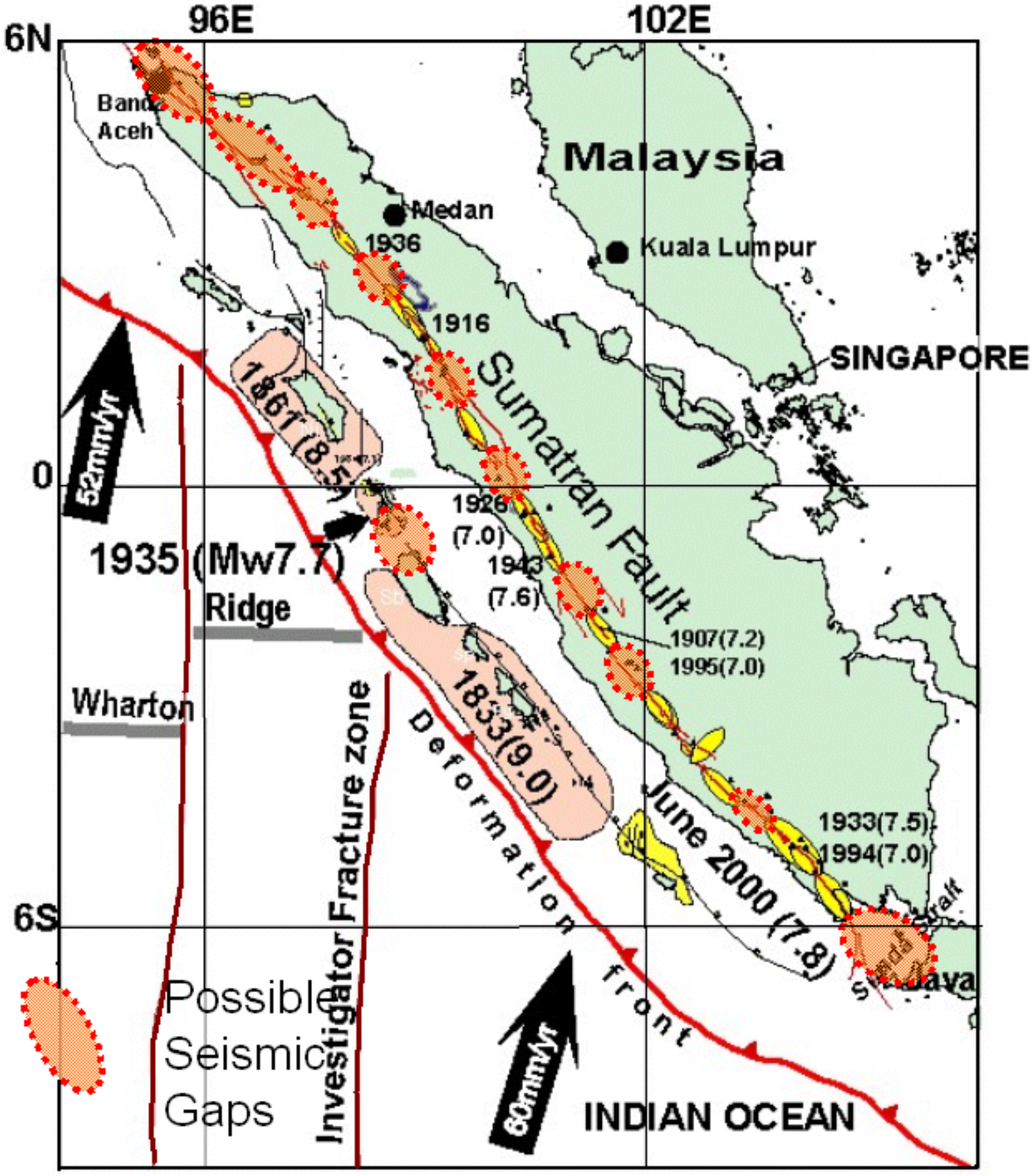


Figure 2.6. Possible seismic gaps along Sumatra Fault Zone (SFZ)

3 REGIONAL GEOLOGY AND TECTONICS

This area is called the Padang Highland. A geologica1 sketch map of the area is shown in Figure 3.1, which was compiled by Sato (1991) from the 1250000 quadrangle geologic maps published by the Geological Survey of Indonesia. This area consists of pre-Tertiary basement rocks, Tertiary sedimentary and volcanic sequences and Quaternary volcanic rocks. The pre-Tertiary units are exposed mainly to the northeast of the Sumatran Fault zone, which extends through Bukittinggi, Lake Singkarak and Solok whereas its southwestern side is largely covered by Quaternary volcanic rocks. Volcanoes in this area reach nearly 3000m in altitude. The pre-Tertiary sedimentary sequences mainly of Permian to Triassic age are dominated by sandstone shale and limestone with local occurrences of intermediate volcanic rocks. They are intruded by granitoid plutons, which show elongated exposures trending northwest southeast. A similar trend is also recognized in the Tertiary coa1 bearing Ombilin Formation located to the east of Solok. The main tectonic features of the region are dextral Sumatra Fault Zone and a thrust fault in the east. The Sumatra Fault Zone is segmented and the volcanoes exist at the ends of each segment. Furthermore, there are sinistral faults of smaller scale and they are conjugate to the main strand of Sumatra Fault Zone. The sedimentary rocks are folded and the fold axis is aligned northwest and southeast direction.

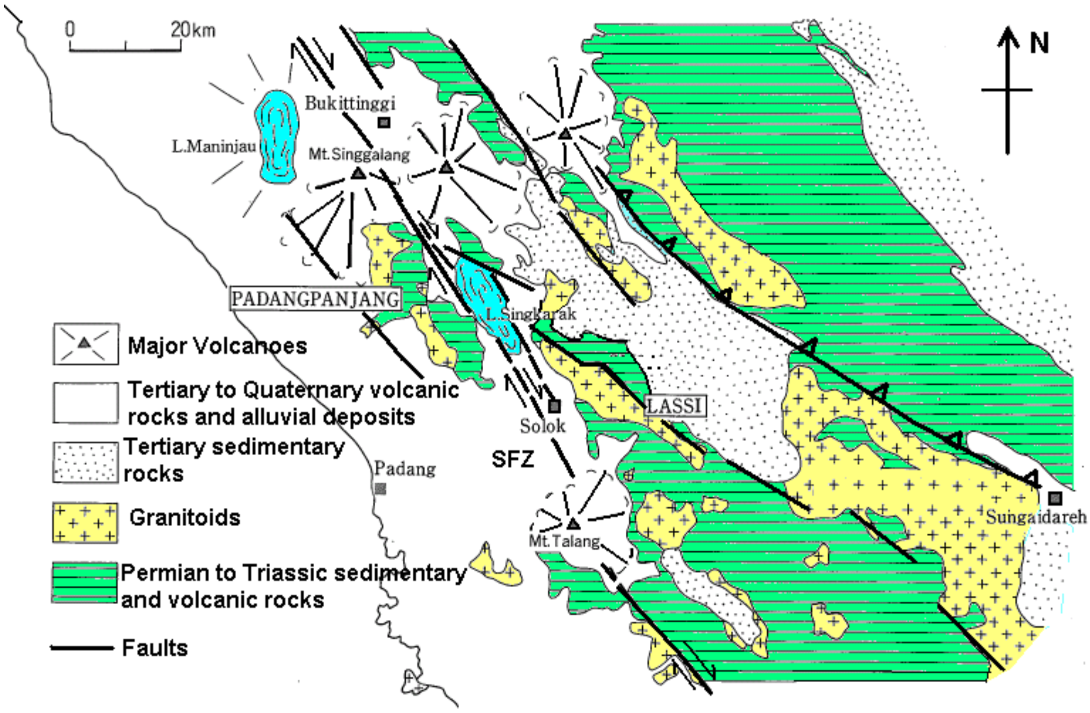


Figure 3.1 Geology and tectonic features of Padang Higland (modified from Sato, 1991).

The epicenter of the earthquake is located near the NW end of Singkarak Lake in at the middle part of West Sumatra Province. This region is called Singkarak basin and covers an area of approximately 1135 km^2. The basin belongs to two districts (kabupaten) Kabupaten Tanah Datar in the northern half and Kabupaten Solok in the southern half.

The lake has an area of 107.8 km^2, being approximately 21 km long and 7 km wide. The maximum depth of the lake is 268m. The natural outlet for excess water is the Ombilin river which flows eastward to the Strait of Malacca. A hydroelectric project however has diverted most of the lake outflow to the Anai river which flows westward into the Indian Ocean near Padang.

Geological Research and Development Centre prepared geological map of the region on scale 1:250,000. Singkarak Basin is an elongated basin from Mt Marapi in the north and Lake Danau Di Bawah in the south (Figure 3.2). It's a part of the depression zone of Sumatra Fault Zone, bound by mountainous area of Bukit Barisan in the west, and tertiary folds in the east. Alluvial deposits of clay, sand and gravel and andesite detritus from the volcanoes cover the relatively flat depression area around and south of the lake. The major underlying rocks in Singkarak Basin are volcanic rocks. Several parts in the western and northwestern part of the basin are metamorphic rocks. The plain area to the south of the lake is alluvium. Of the volcanic rocks in Singkarak Basin, both the upstream most areas in the north and in the south are breccia andesit, in the northern part being associated with Mt Marapi, while the southern most part associated with Mt Talang (Figure 3.1) The Lake is in a tectonically active area. Field evidences suggest that the lake results from a damming process by volcanic material produced by the Marapi-Singgalang-Tandikat volcanoes in the north and by the products from the Talang volcano in the south.

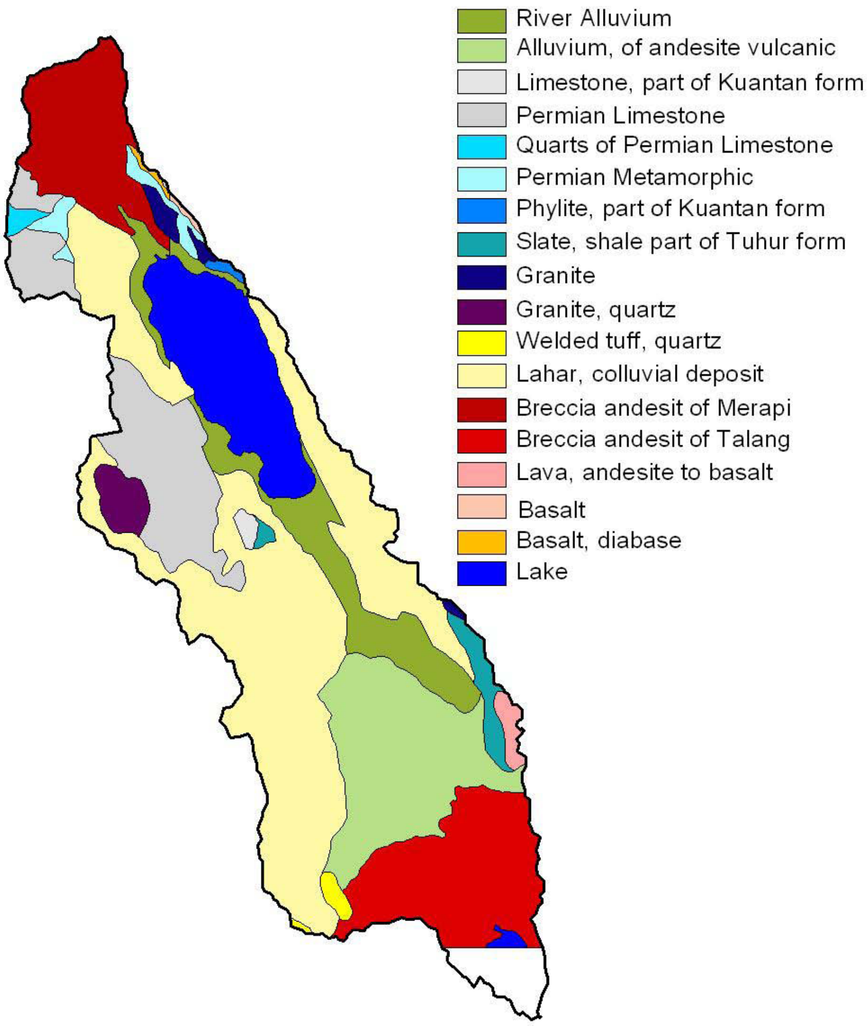


Figure 3.2 Geological Map of Singkarak Basin.

The author did some observations in a quarry just north of Singkarak Lake. Figure 3.3 shows views of the fractures in a quarry and a fault surface with striations. The fractures are almost steeply inclined. However, their dipping direction is about 85^{o}SW. The striations are almost horizontal. Nevertheless, they have slight normal component. In other words, the sense of deformation implies slight trans-tension type movements. Figure 3.4 shows the inferred focal mechanism solution for the striations in the quarry proposed by Aydan (Aydan and Kim, 2002, Aydan 2007b). The strike of the fractures is slightly different from the general trend of the SFZ.

Figure 3.3. Views of the fractures and the striations in Batipuh quarry in the north of Singkarak Lake

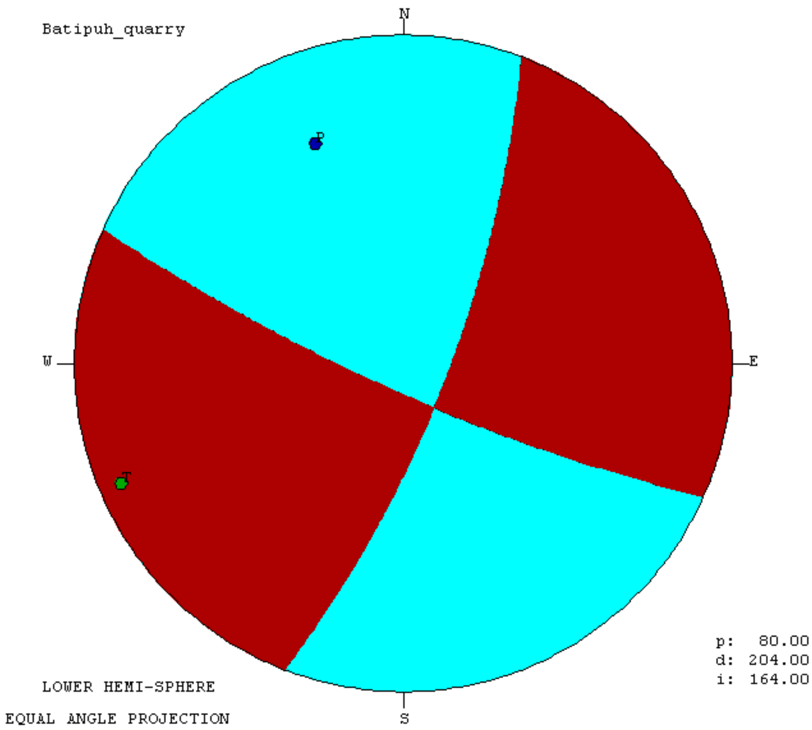


Figure 3.4. Inferred focal mechanism solution for the striations in Batipuh quarry.

4 CHARACTERISTICS OF THE EARTHQUAKE

4.1 Fundamental Characteristics

The earthquake took place as two large shocks on March 6, 2007. The first event was at 10:49 with a magnitude of 6.4 and the second event with a magnitude of 6.3 was two hours later at 12:49 on the same day. It is of great interest that the overall sequence of the earthquake follow the pattern of 1926 and 1943 events. There was a pre-shock at a distance of 55km southwest of the epicenter area. The fundamental source parameters of the first shock are given in Table 4.1. Figure 4.1 shows the focal plane solutions by USGS and HARVARD. Both institutes estimated the faulting as strike-slip faulting. If the first plane NP1 is taken the causative fault, this will coincide with the general trend of the Sumatra Fault Zone and it has the sense of dextral slip with slight normal component. This result is quite similar to the observation at a quarry in the north of Singkarak lake. The estimated fault length would be 27-28 km using the formula proposed by Aydan (1997, 2007b). In view of the damage around Singkarak Lake, the earthquake fault may involve the entire longitudinal length of the lake. Furthermore, the source areas drawn by Sieh (2007) for 1926 and 1943 events may be overestimations and wrongly placed. If we assume that the seismic gapes are filled in space, the sources areas should be re-located to the south of the epicenter of 2007 by a distance of 20km, at least.

Table 4.1: Main characteristics of Earthquake

Institute	M	Mw	LAT (S)	LON (E)	DEP (km)	NP1 strike/dip/rake	NP2 strike/dip/rake
USGS	6.4	6.3	0.536	100.498	28.0	153/78/-175	62/85/-13
HARVARD		6.4	0.630	100.500	21.3	150/85/-176	60/86/-5

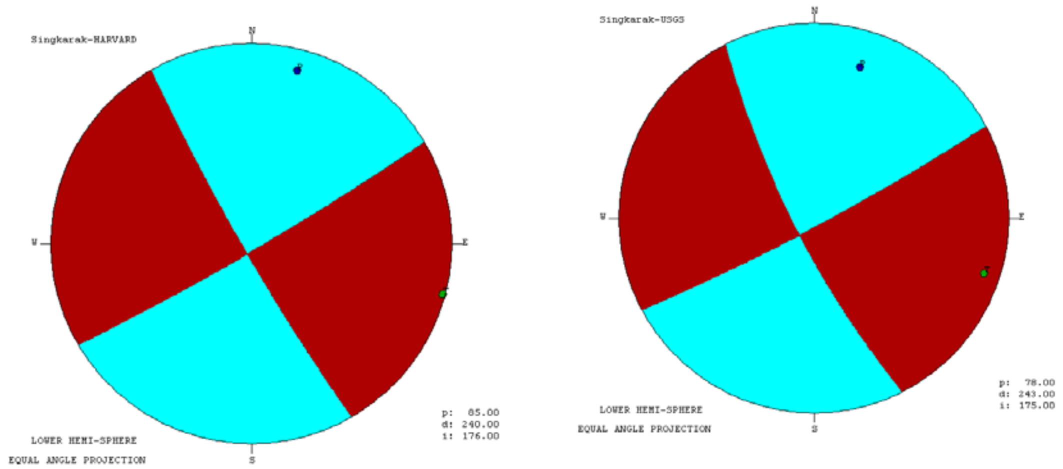


Figure 4.1. Focal plane solutions computed by USGS and HARVARD

4.2 Casualties and Damage

The earthquake caused extensive damage in the disricts of Solok, Tanak Datar, Agam, Paya Kumbuh, Padang Panjang and Bukit Tinggi. Table 4.2 gives the number of casualties and injured people in various cities, town and districts. It is suprising that there are some casualties even in Padang city, which is 50km away from the epicenter. The main causes of heavy damage given in Table 4.3 may be the fragility of buildings against moderate intensity shaking in the epicentral area, which may be a common problem for Indonesia. Some of these problems will be pointed out in the next section.

Table 4.2: Data on Affected People

No.	Location	Died	Injured		IDPs
			Serious	Minor	
1	Solok District	16	223		6,568
2	Tanah Datar District	10	11	31	
3	Padang Pariaman District	3	5		
4	Agam District	14	45	95	
5	Lima Puluh Kota District		4	2	
6	Solok City	6	111		
7	Paya Kumbuh City	2	6	6	
8	Padang Panjang City	10			
9	Bukit Tinggi City	9	100		
10	Padang City	2	1		
	Total	**72**	**506**	**134**	**6,568**

Source: BAKORNAS PB, 8 March, 20:00 hours

Table 4.3: Data on Damages

Location	Damaged Houses			Places of	Schools	Offices	Public
	Severely	Moderate	Slightly	Worship			Facilities
Solok District	594			18	4		
Tanah Datar District	66	147	306	9	5	2	
Padang Pariaman District	555		1,778	4	7	9	9
Agam District	2,472	1,560	1,579	123	114	33	1
Lima Puluh Kota District	5	37	87	11	26	4	
Solok City	307			7	16	6	6
Paya Kumbuh City	76		99	3		24	26
Padang Panjang City							
Bukit Tinggi City	10	39	166				3
Padang City				1		6	
Total	**4085**	**1783**	**4015**	**176**	**172**	**84**	**45**

Source: BAKORNAS PB, 8 March, 20:00 hours

4.3 Pre-Post Seismicity

The past seismic history of the epicentral area is not well known. It is reported that there were earthquakes in 1926 and 1943. Two earthquakes that occurred within three hours of each other on June 28, 1926, which have been assigned magnitudes of 6.5 and 6.8 respectively. 200 people around the epicenter were killed by these events. Besides much damage to buildings and other structures, great parts of the shore of Lake Singkarak inundated, and the depth of subsidence up to 10 meters were found in several places, where the land was dry before. Moreover high waves were formed in the lake. Since Singkarak Lake is a closed water body, the shaking is likely to create sloshing type motions in the lake. The subsidence may also imply liquefaction as well as slumping of ground as observed in Sapanca and Efteni lakes along the North Anadolu Fault during 1999 Kocaeli and Düzce earthquakes (Aydan et al. 2000a, 2000b).

In 1943, two earthquakes having magnitudes of 7.2 and 7.5, respectively, occurred within seven hours of each other on June 8-9, 1943, with epicenters assigned to the section of the fault immediately to the southeast of the epicenters of the 2007 earthquakes. The magnitude 7.5 shock was among the largest earthquakes to have occurred on the Sumatra fault since the late nineteenth century.

Figure 4.2 shows pre-post seismicity of the epicentral area for intraplate earthquakes up to 40km. Data is gathered from international catalogs. The pre-seismicity shocks are since 1982 and aftershock data is scarce since it is difficult to access to the database of Indonesian Seismological Institute. Nevertheless, the aftershocks are distributed over a large area.

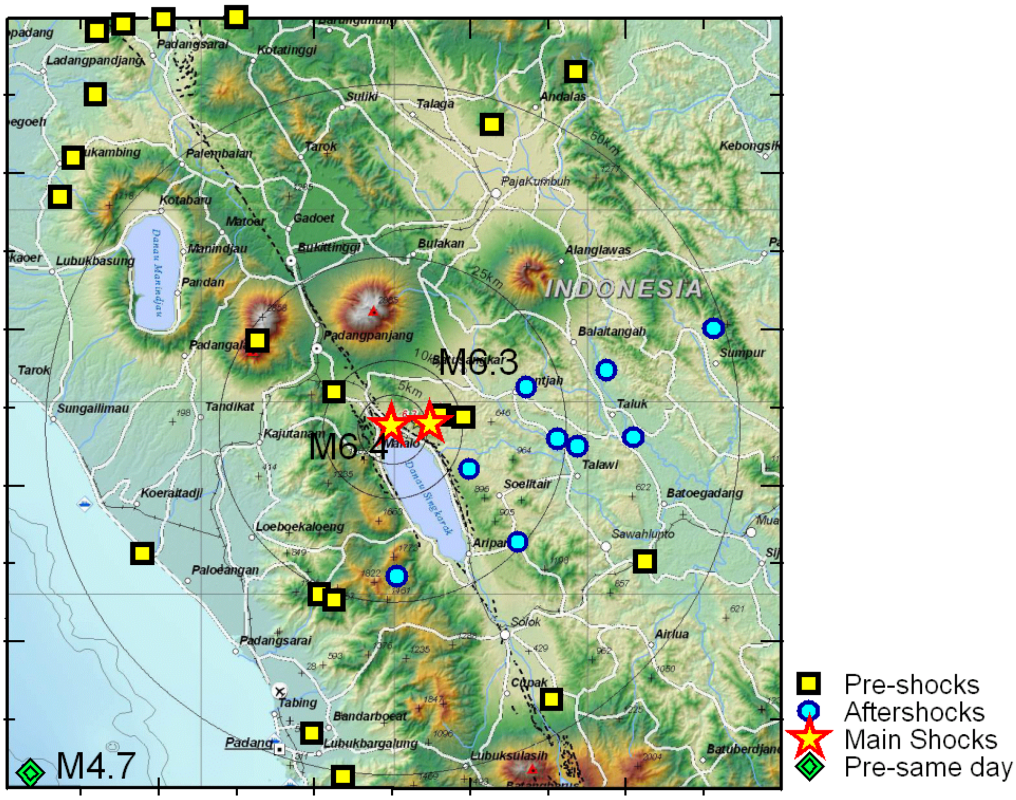


Figure 4.2. Pre-post seismicity of the epicentral area

4.4 Surface Ruptures

The hypocenter depth of the earthquake is about 30km and the projected epicenter is near the north end of Singkarak Lake. The author noticed two surface ruptures to the north of Singkarak Lake at localities called Batipuh and Sumpur. The strike of these surface ruptures were aligned in the direction of N30-50E. The global strike of Sumatra fault is N35W. The acute angle between the strikes of the Sumatra fault and surface ruptures ranges between 65-85. The two locations of surface ruptures are aligned along N40W direction. Therefore, we expect that surface ruptures are associated with the earthquake faulting and the surface ruptures belong to T-fractures of the fracture zones. Particularly, the surface rupture observed in the village of

Sumpur resembles to that observed between Kavaklı and Hisareyn caused by the 1999 Kocaeli earthquake (Aydan et al. 2000a). This fracture was followed by the author for about 500m and the subdidence of the ground up to 30cm were observed.

(a) Rupture of roadway in Batipuh (b) rupture of roadway in Sumpur

Figure 4.3. Surface ruptures

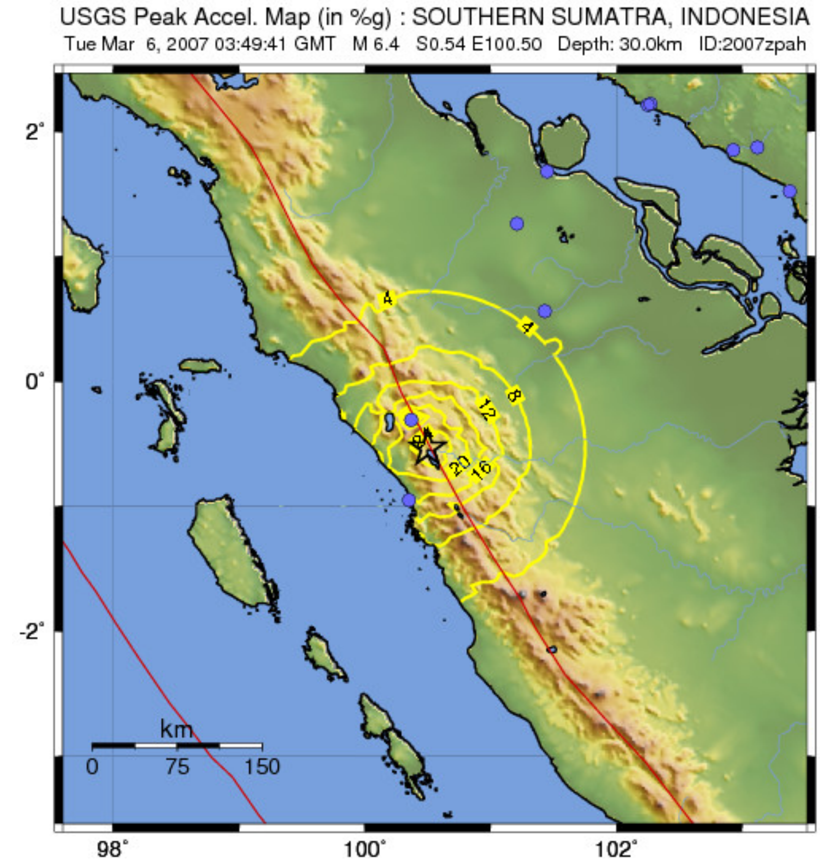
4.5 Strong Motions

As happened in many earthquakes in Indonesia, there is also no strong motion record for this earthquake. Therefore, one has to estimate the likely strong motions using the old conventional procedures based on the collapsed or displaced simple structures. In this earthquake, one can find such simple structures in the epicentral area. Some estimations based on simple structures according to the hypocentral distance are given in Table 4.4.

USGS and the author estimated the areal distribution of the maximum ground acceleration and velocity according to some models based on the past records of the earthquakes and the results are shown in Figure 4.4 and 4.5 The USGS estimated the maximum ground acceleration and velocity to be about 240 gal and 28 kine in the vicinity of the epicenter. The estimations for maximum ground acceleration and velocity at the epicenter for a ground with shear wave velocity of 150m/s by the author according to his models with the consideration of fault orientation and ground conditions are 361 gal and 19 kine, respectively. These results are quite similar to the estimations from collapsed or displaced simple structures as well as to those estimations by the USGS. In spite of well-correlated estimations, it should be noted that the monitoring would always be superior for evaluating the ground motions.

Table 4.4. Estimated maximum ground acceleration and velocity at several locations

Location	Structure	Hypocenter distance (km)	Amax (gal)	Vmax (kine)
Sumpur	Bridge wall	31	286	22
Padang Panjang	Garden wall	32.5	228	18
Bukit Tinggi	Slope failure	41.8	200-300	
Solok	House (RC)	45.0	160-180	
Payakumbuh	House wall	48.0	82	9
Padang	House wall, RC	58.0	82	9



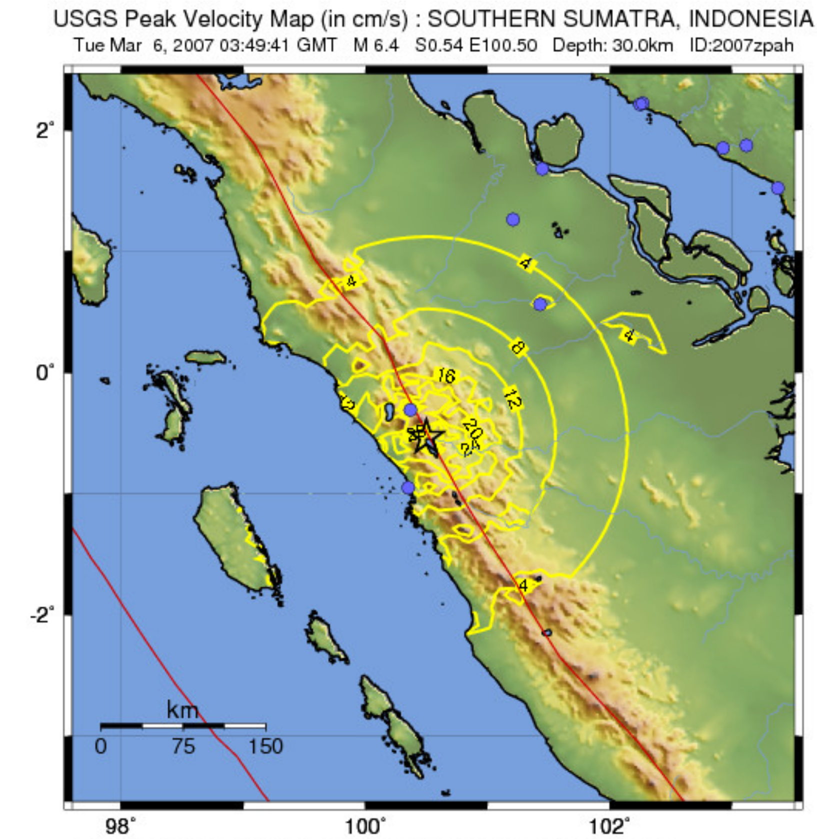
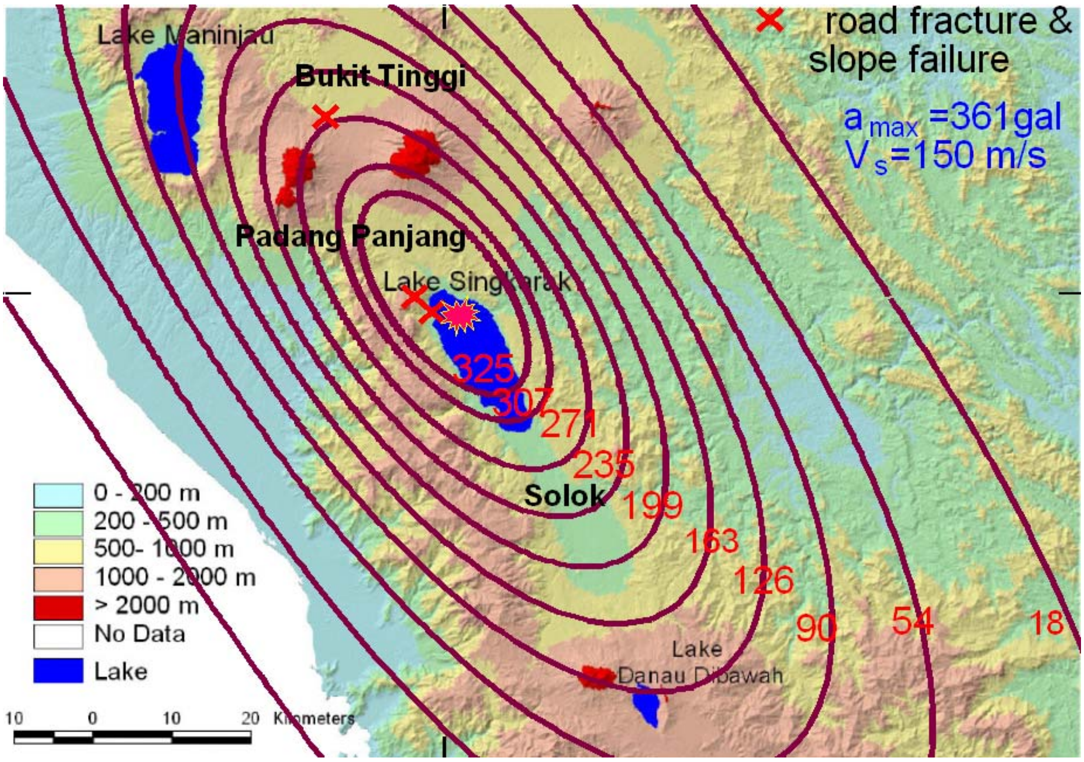
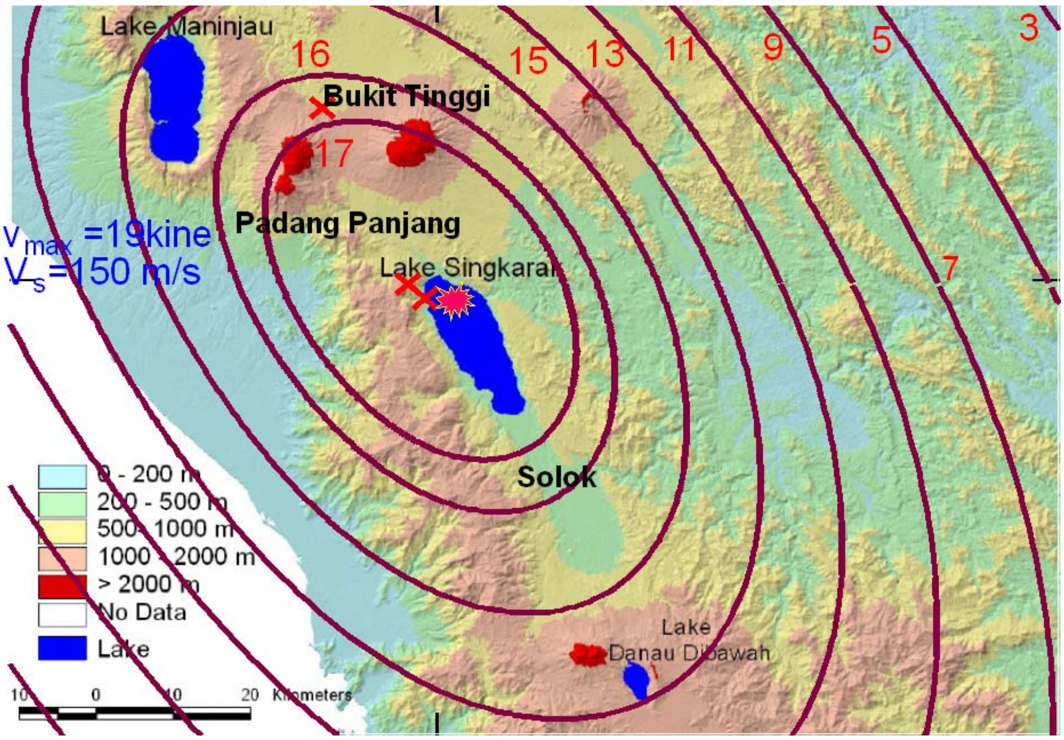


Figure 4.4. Estimated maximum ground acceleration and velocity (from USGS)



(a) Maximum ground acceleration



(b) maximum ground velocity

Figure 4.5 Estimated maximum ground acceleration and velocity (this study)

5 BUILDING DAMAGE

5.1 Mosques

Mosques are semi-reinforced concrete structures. Although reinforced columns and beams are utilized, they are quite small in cross section (15x15 to 20x20cm) and they have 4-6 smooth steel bars with a diameter ranging between 8 and 12mm. The walls are either hollow cement blocks or bricks. The roof of mosques are generally light. The earthquake caused the failure of outer columns and load-bearing walls at corners and subsequent collapse of roofs (Figure 5.1).

(a) Solok (from Reuter) (b) Padang Pajang

Figure 5.1 Damage to mosques

5.2 Masonry Buildings

Masonry buildings are generally constructed with bricks and they are either one story or two story buildings. Old masonry buildings has no reinforced concrete lintels and/or columns. Such collapses were observed even in Payakumbuh and Padang, which are relatively far from the epicenter (Figure 5.2) New constructions utilize reinforced concrete slabs and columns. There is no doubt that when such structural elements are integrated with masonry walls they perform better and they prevent the total collapse of the buildings in-spite of some structural damage. The houses or buildings were slightly damaged even they were just on the surface ruptures (Figure 5.3).

(a) Payakumbuh (from Reuter) Padang (from Reuter)

Figure 5.2 Collapse of walls of masonry buildings due to out-of-plane loading

Figure 5.3. Damage induced by surface ruptures to masonry houses with reinforced slabs and columns in Sumpur

5.3 RC Buildings

RC buildings with two or three stories suffered heavily from the earthquake. The reinforced concrete structures are framed structures with integrated or non-integrated in-fill walls. The reinforcing bars are generally smooth and infill walls are built with red-burned solid clay bricks using mortar. The floor height in the region ranges between 3 to 4m. The inspections of the reinforced concrete buildings indicated that they are mainly failed in the pancake mode. RC buildings are generally found in cities and large towns. The concrete buildings having 2 or more stories were either collapsed or heavily damaged. The causes of damage to RC buildings are similar to those observed in other recent earthquakes in Indonesia and elsewhere (Figures 5.4 and 5.5). They be re-stated for this earthquake as follows:

a. Soil liquefaction and lack of the soil bearing capacity (particularly in Solok)
b. Large ground settlement of embankments nearby river banks
c. Fragile structural walls and lack of lateral stiffness,
d. Poor concrete quality and workmanship,
e. Plastic hinge development at the beam-column joints,
f. Lack of shear reinforcement and confinement,
g. Soft story,
h. Pounding and torsion and
i. Ground motion characteristics (i.e. multiple shocks etc.).

Figure 5.4 Pancake collapse of reinforced building in Padang (from Reuter)

(a) Solok (from Reuter) (b) Padang Panjang Governor Office

(c) Solok (from Reuter and Internews)

(d) Pasar- Padang Panjang (Reuter)

(e) Slightly damaged RC buildings in Padang Panjang

Figure 5.5. Some typical damage to RC buildings

6 TRANSPORTATION FACILITIES

6.1 Railways

There is a railway line which starts from Teluk Bayar port of Padang pass through Anai Valley to Padang Panjang where it joins the line from Lima through Bukit Tinggi and the line from the east coast of Sumatra Island via mining town Sawahlunto and Solok. The construction of the line was associated with the colonial Dutch period, during which Ombilin underground coal field was started to be exploited in 1891. The gradient of a 43km long section of the line between Kayutanam and Batu Tabal is quite steep and it was constructed as rack line. The visual inspection of the railway line near the famous Anai water-fall and Padanglawas near the epicenter revealed that there was no damage to the railway line (Figure 6.1).

Figure 6.1. Views of railway lines in the epicentral area

6.2 Roadways

The roads are open to traffic and accessible to affected areas. Damage to roadways were caused at several places due to surface ruptures and embankment failures along the rivers and Singkarak Lake (Figures 4.3 and 6.2). Some of these roadways were re-asphalted while some of them were re-surfaced with soil. The roadway embankment along the shore of Singkarak lake was damaged and there was a repair to the roadway even 6 months passed after the earthquake (Figure 6.2(b)).

6.3 Bridges

Railway bridges in the epicentral area are truss, arch or simple beam bridges while roadway bridges are of truss or simple beam type. The earthquake shaking did not cause any visible damage to the bridges of railways and roadways even in the nearest location to the epicenter of the earthquake (Figure 6.3). The debris of slope failure in Sianok Valley obstructed a rodway bridge temporarily.

(a) Solok (from Reuter) (b) Shore of Singkarak Lake

Figure 6.2. Damage to roadways due to embankment failures

(a) Truss bridge in Sumpur village (b) Bridge in Sianok Valley

Figure 6.3. Views of roadway bridges

6.4 Airports

The airports in the earthquake affected area are Tabing air-force airport and Minangkabau civil airport (Figure 6.4). Minangkabau airport is newly re-built in 2001 by Shimizu Corporation and PT Adhi Karya through a softloan from Japan International Corporation Bank (JICB) (90%) and APBN (10%). The runway is 2750m long and its elevation is about 5m. The ground condition in the vicinity area is sandy soil. The earthquake did not cause any damage to its runway and terminal building. Furthermore, the airport traffic was not suspended following the earthquake.

(a) Tabing air-force airport

(b) Minangkabau airport

Figure 6.4. Views of airports in earthquake affected area

7 BUKIT-TINGI WORLD WAR II UNDERGROUND SHELTER

The occupation of Indonesia by Holland was ended in 1942 when Japanese Imperial Army invaded Indonesia. Within 3 years, Japanese Imperial Army constructed an undeground shelter along Sianok Valley in Bukit Tinggi, which was hit by the earthquake. Sianok Valley is created by relative dextral movements along the Sumatra Fault Zone (Figure 7.1). The ground consists of pyroclastic flow deposits. Following the immediate thin deposits, there is a pyroclastic flow deposit numbered Layer 1. This layer looks like a pumice and it is whitish. The second pyroclastic flow deposit numbered Layer 2 is slightly welded and it is more resistant. The underground shelter is mainly excavated in Pyroclastic Flow Deposit Layer 2. The access to the underground shelter is a 64m long inclined shaft with 1000 stairs. The layout of the underground shelter and a cross-section is shown in Figure 7.2. The ventilation of the underground shelter is natural and the air pressure difference between the inclined shaft entrance and two adits open to the Sianok valley is 28m and is sufficient to provide enough air circulation. Figure 7.3 shows air pressure, temperature and humidity variations during the investigation of the underground shelter. The humidity varies between 60 to 86% while the temperature 22 to 26^{o}C.

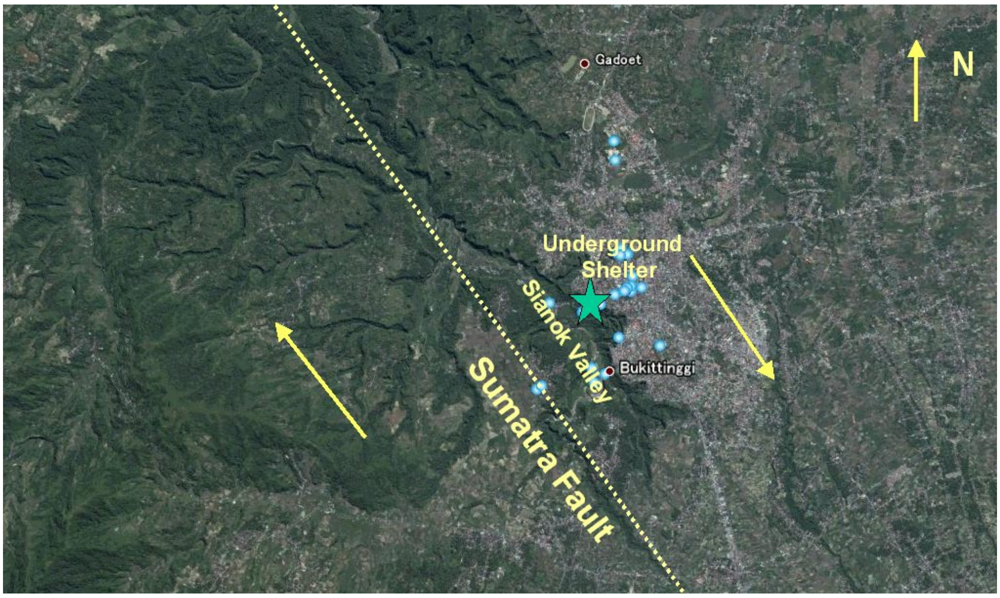
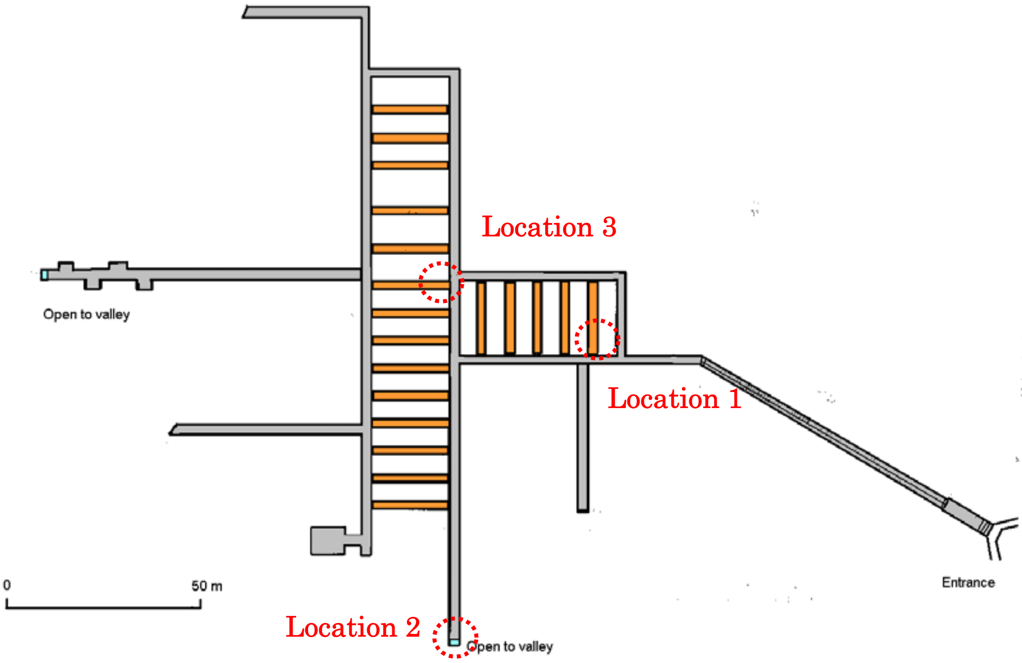


Figure 7.1. A satellite image of Bukit Tinggi underground shelter

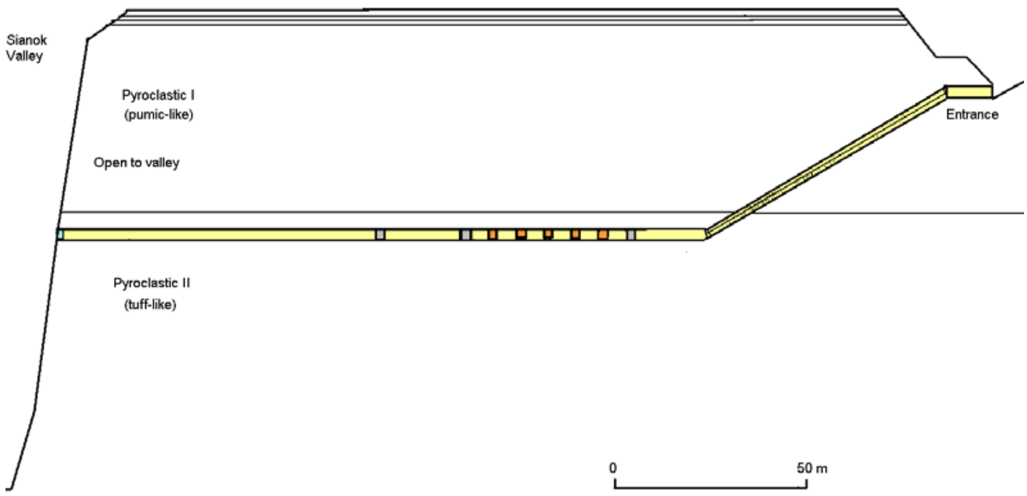
The configuration of adits changes from location to location and their functions. The inclined shaft has arched roof and it is 2.4m high and 3.0m wide (Figure 7.4). The main adits has a trapez shape with a height ranging between 1.8 to 2.1m and its base width ranges 2.4 to 2.6m. The rooms between adits are larger and their width is about 4m with a height of 2m.

The adits were probably supported by wooden supports at the time of the construction. However, the wooden supports got rotten in time and they were taken away at the time of opening of the shelter to touristic visits. Although the inclined shaft and some parts were supported by a recently constructed thin shotcrete layer, the underground shelter is almost non-supported. In other words, it is self-standing for about 65 years since its construction.

The earthquake caused extensive damage to slopes in Sianok Valley, which were facing the epicenter. As discussed in the next section, the maximum ground acceleration to cause the slope failures was estimated to be more than 0.2g. The other estimations yielded similar values (see Sub-section 4.5). Inspite of such high ground motions, the weak rock conditions and extensive slope failures, the undergound shelter was almost intact after the earthquake. The author found three locations where some damaging effects of the earthquake on the undergound shelter were observed (Figure 7.5). The first location was at the first room with a base width of 3.8m near the bottom of the inclined shaft and a 10-20cm thick slab of rock was fallen from the roof for a length of 5m. The rock layer belongs to the pyroclastic flow deposit layer 1. The second location was at the ventilation adit next to slope. A 40-50cm thick rock slab was fallen from the roof for a length of 2m and semi-ruptured roof material could be observed. A 100cm long and 5cm wide spalling occurred at a room with base width of 3.8m was observed. Except these three locations there was no visible damage to the underground shelter.



(a) Plan view



(b) Cross-section

Figure 7.2. Plan and cross sectional views of the underground shelter

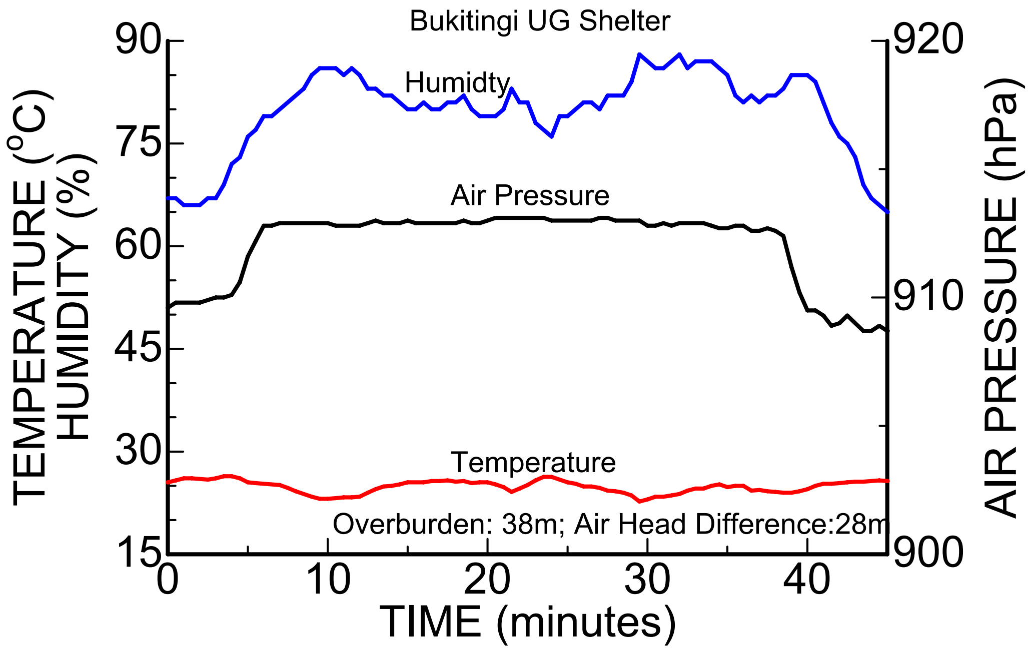


Figure 7.3. Temperature, humidity and air pressure variation in the undergound shelter

(a) Entrance of inclined shaft

(b) View of inclined shaft

(c) Main adit open to the valley at the end

(d) Large rooms

Figure 7.4. Some views of the inclined shaft and adits and rooms in the shelter

(Location 1)

Location 2

(a) Roof falls

(b) Spalling at Location 3

Figure 7.5. Some views of the underground shelter and instability locations

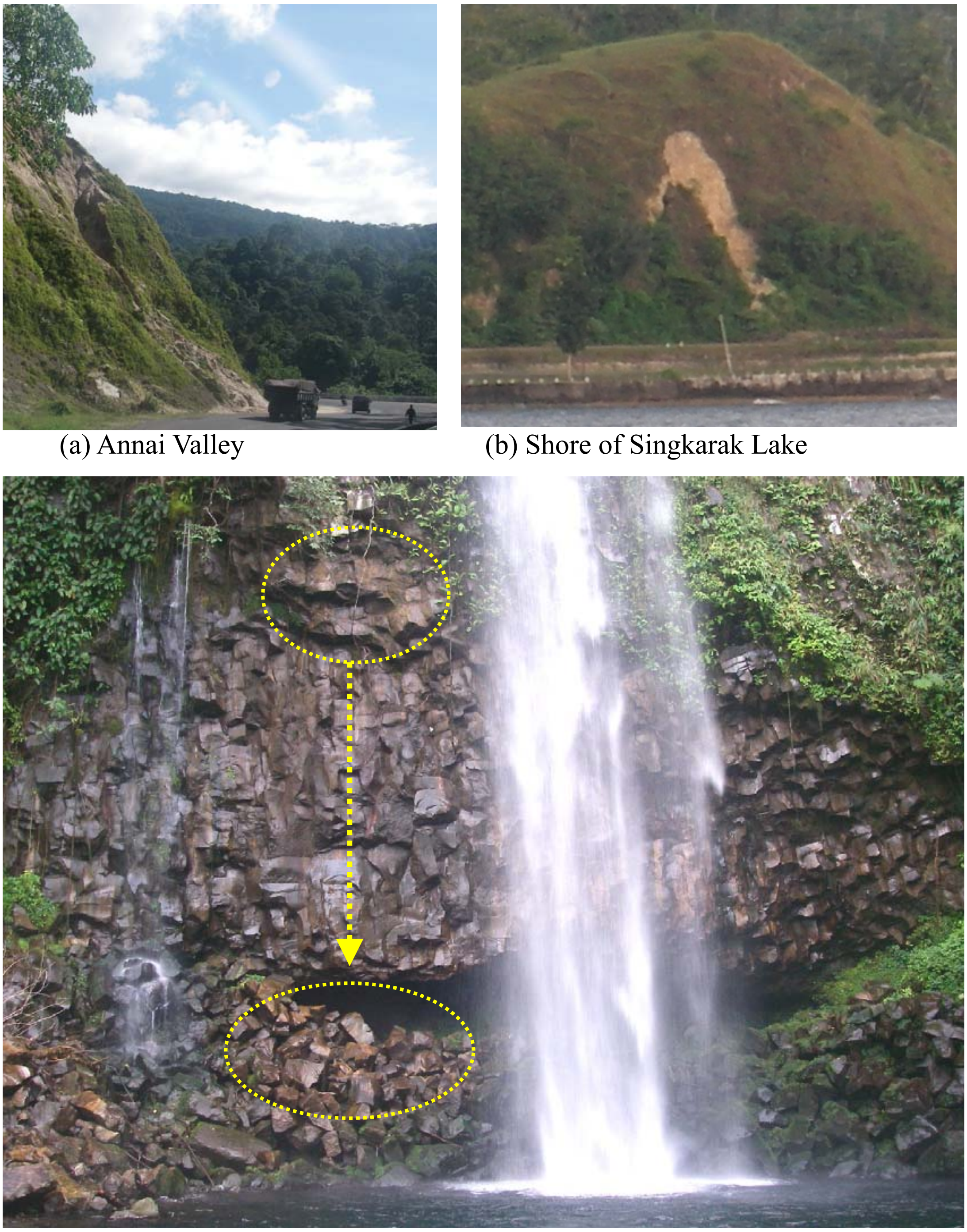
8 SLOPES AND EMBANKMENTS

Extensive slope failures observed in Sianok Valley (Figures 8.1 to 8.3). In additon there were also some slope failures and rockfalls in Annai Valley and shore of Singkarark Lake (Figure 8.4). The depth of Sianok Valley is up to 120m and the valley walls are quite steep and the natural slope angles range between 70-80^{o}. The ground mainly consists of pyroclastic flow deposits from nearby Volcanoes as also presented in the previous section. The inclination of the failure plane is about 60^{o} and it is almost planar. The repose angle of the failed ground is about 30^{o}. The material properties of the rock are not well known and it was not measured.

Figure 8.1. Views of slope failues at Sianok Valley in Bukit Tinggi

Figure 8.2. Images of Sianok Valley before and after the earthquake

Figure 8.3. Images of Sianok Valley before and after the earthquake



(a) Annai Valley (b) Shore of Singkarak Lake

(c) Rockfall at Annai Water-fall

Figure 8.4. Slope failures and rockfalls

Using the seismic coefficient method and assuming that the failure is planar, and the friction angle of the ground is 30^o and pore water coefficient of 0.5, the relation between slope angle and slope height can be obtained as a function of normalised cohesion to the unit weight of rock for a seismic coefficient of 0.2 as shown in Figure 8.5. In view of the self-standing underground shelter discussed in the previous section and the observed slope heights (80-120m), the most likely normalized cohesion by the unit weight is likely to be about 20 . For this value of the normalized cohesion, the value of seismic coefficient varied between 0.2 to 0.3 by an increment of 0.5 (Figure 8.6). From these parametric computations, the expected maximum ground acceleration is likely to be around 0.25g. There is no doubt that it will be desirable to carry out detailed geotechnical investigations for determining the properties of ground around Sianok Valley. Nevertheless, the results from these parametric studies would be quite close to the actual values in view of ground conditions in similar type geological and geotechnical environments.

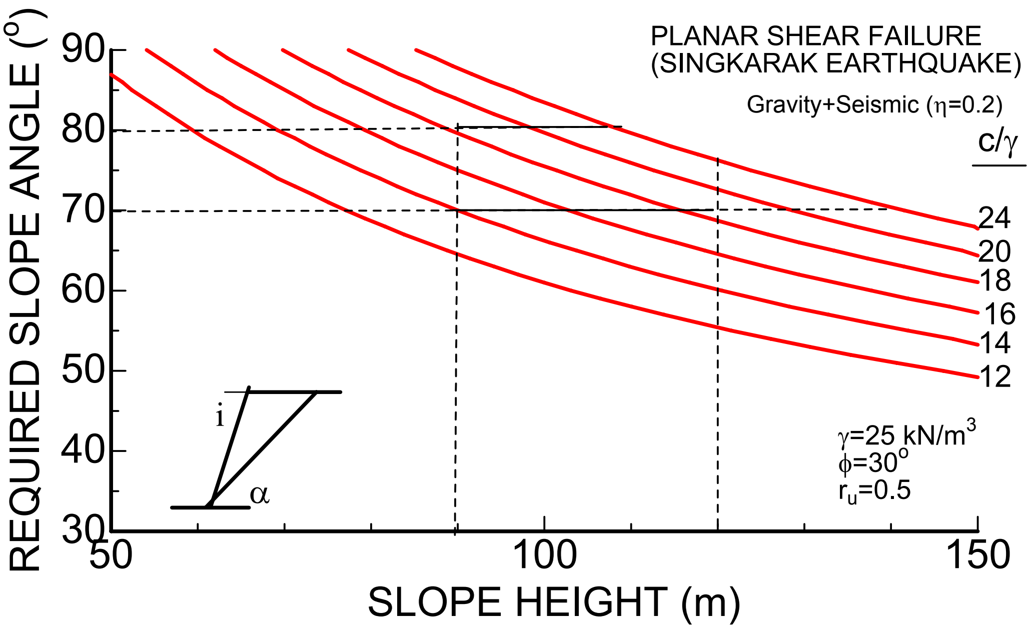


Figure 8.5. The relation between slope angle and slope height as a function of normalized cohesion by unit weight

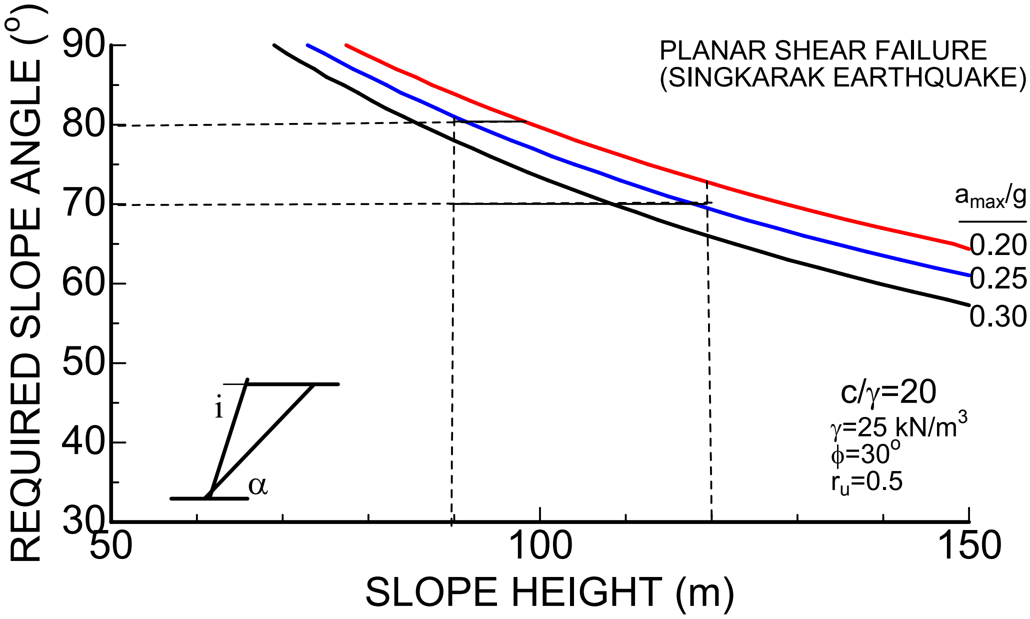


Figure 8.6. The relation between slope angle and slope height as a function of seismic coefficient

Embankment failures of roadways and rivers were also widespread in the epicentral area (Figures 6.2 and 8.7). The main cause of embankment failures were ground shaking, which resulted in either lateral spreading due to ground liquefaction or curved failure.

(a) Embankment failure at Sumpur Village (the nearest site to the epicenter)

(b) Embankment failure along a river in Solok District

Figure 8.7. Some views of embankment failures

9 LIFELINES

Power lines and communication were cut in the affected region following the earthquake. In some areas, electricity has returned to normal.

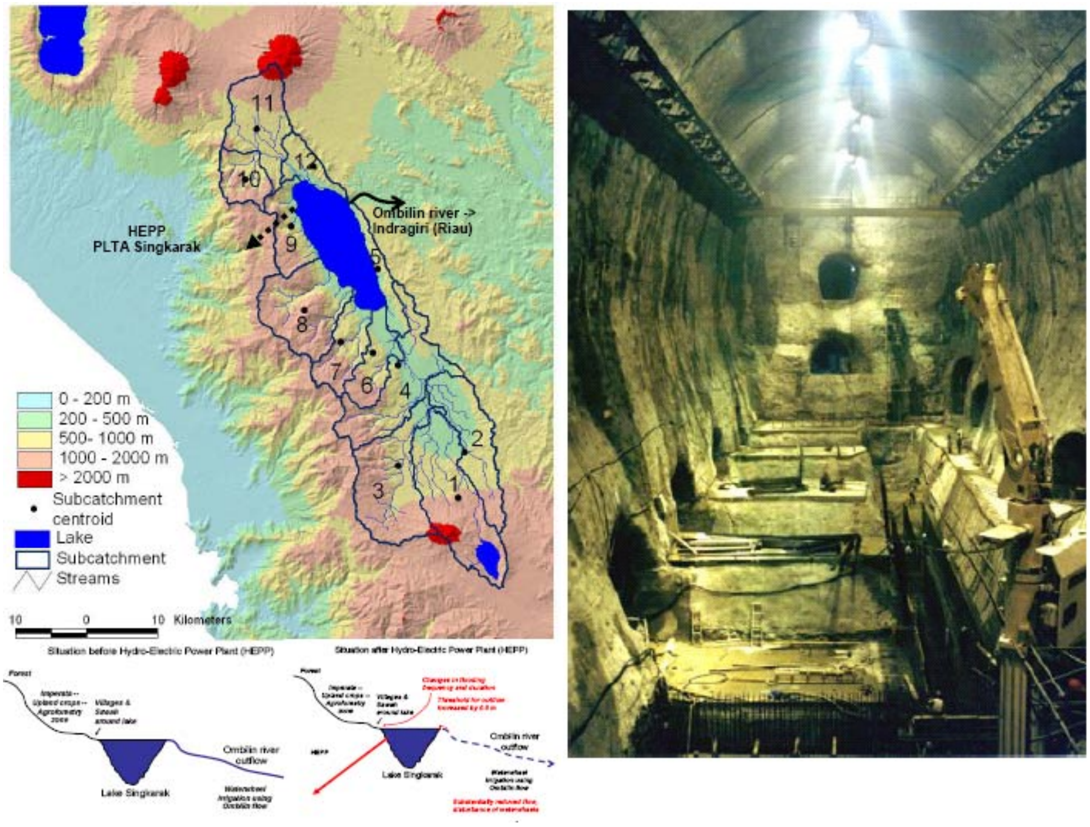
Phone lines were temporarily cut off and jammed but started functioning again in the afternoon. PT Telkom reports that there has been no damage to communication networks caused by the earthquakes.

10 INDUSTRIAL FACILITIES

Major industrial facilities are Singkarak Hydro-electric power plant, Kandi Thermo-electric Power Plant and mines in Ombilin Coal field. In addition there some metallic mines around the epicenter and factories in Padang City.

10.1 Hydro Electric Power Plant of Singkarak

Singkarak hydro-electric power plant was completed in 1998. The hydro-electric power plant has involved an underground power house (station), small dam and 16.5 km long head-race tunnel. The HEPP of Singkarak in Pariaman is at 32 km east of Padang and it was developed to provide electric power of 175 MW. The supply water from Singkarak Lake is flowed through a head-race tunnel as long as 16.5 km with inner diameter of 5.0 m (excavation diameter 6.2 m) (Figure 10.1(a)). The method applied for the development of this tunnel was based on The New Austrian Tunnelling Methods (NATM). During the construction period, Tunnel Boring Machine was used in the first time in Indonesia. In the Singkarak Hydroelectric Project in Indonesia, anchored crane beams have been installed directly against the rock face, which is gneiss of reasonable quality. This installation is shown in the photograph reproduced in Figure 10.1(b), taken during construction of the cavern.



(a) Layout and location of HEPP (b) Underground power house

Figure 8.1. Singkarak hydro-electric power plant

There was no damage to the Singkarak hydro-electric power plant by the earthquake. The electricity production was back after an automatic shut-down of the plant due to ground shaking.

10.2 Ombilin Coal Mine

Ombilin underground coal mine has been operating since Dutch period. The operating underground coal mine is now taking place at the Sawahluhung. This mine adopts longwall and room & pillar methods, by means of double ranging drum shearer and drilling & blasting respectively. In-situ stress measurements conducted at Sawahluhung (about 300 m below surface) indicated that the maximum and minimum in-situ stresses were between 5.6 MPa and 2.0 MPa respectively. Rock strength ranges 20-50 MPa. The mine has been recently abandoned and there was no report of damage to this abandoned coal mine by the earthquake.

Figure 10.3 Kandi lake created by the flooding of the abandoned coal open-pit

10.3 Kandi Thermo-electric Power Plant

Another major power plant in the epicentral area is Kandi Thermo-electric Power Plant near Sawahluhung (Figure 10.4). The coal to this plant was supplied from underground mine at Sawahluhung and it was shut down with the closure of the mine. There was no report of damage to this shut-down thermo-electric power plant by the earthquake.

Figure 10.4. A view of Kandi Thermo-electric Power Plant

11 EARTHQUAKE SOCIAL IMPACTS: TSUNAMIC PANIC IN PADANG

Following the 2005 Great Nias Earthquake, Aydan (2005) pointed out the possibility of earthquake at a seismic gap in Mentawai Island. This issue was seriously taken by UN and donor countries for Aceh earthquake and some early tsunami warning systems are being installed along the west coast of Sumatra Island. So far, three early warning buoys provided by the Indian Ocean Tsunami Early Warning Center are installed. Padang city and the local government are very much concerned and they are trying to do their best to cope with tsunami disaster mitigation and they prepared horizontal evacuation plans and they do some drills (Figure 11.1). Padang City has a very low elevation and the 5m elevation contour line is about 3km away from the shoreline. Depending upon the location of the earthquake, tsunami arrival time may ranges between 20-60 minutes. The tsunami evacuation drills clearly indicated that traffic jam and panic extremely obstruct the evacuation. The organizers of the drills recommend to people not use vehicles. The distance is extremely long for elderly people, small children and pregnant women as well as handicapped people. The best and quickest alternative is the vertical evacuation alternative. Although Japan and USA built some special terraces in such areas, the existing buildings, which are strong against shaking and having terraces on the top with unobstructed stairs, are designated as vertical Tsunami evacuation facilities in Japan. Therefore, the cities such as Padang and alike having potential tsunami risks in Indonesia must undertake actions to utilize such public and private existing or newly constructed buildings with sufficient shaking resistance and terraces for providing refuge to the people.

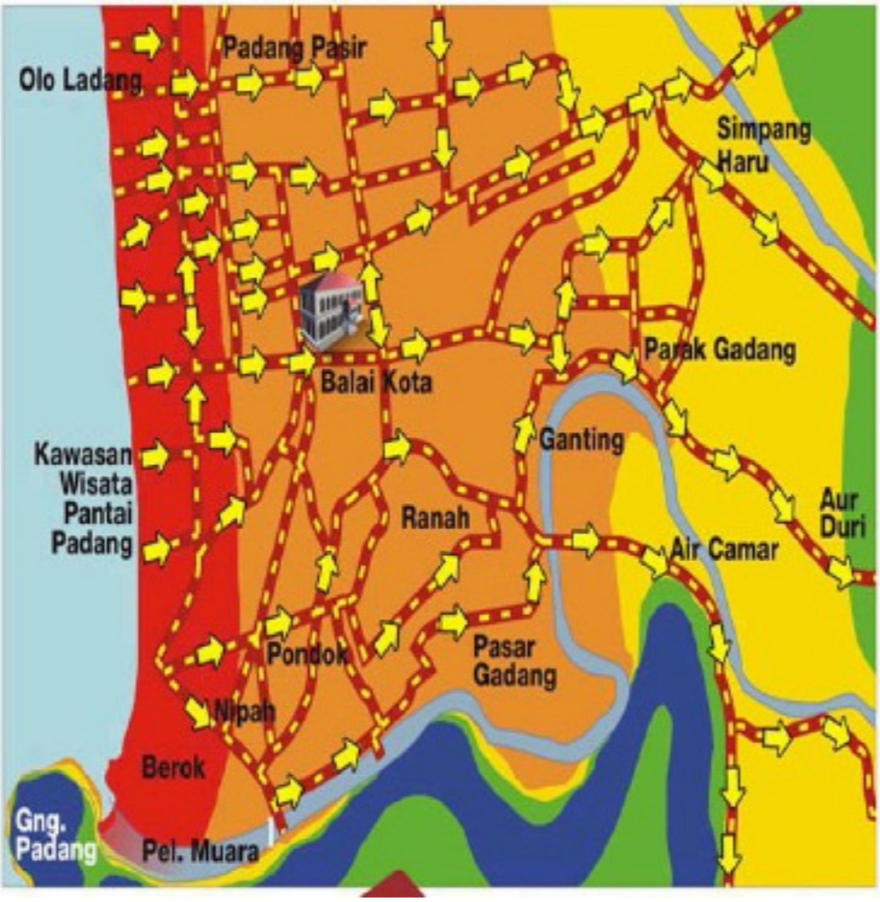


Figure 11.1. Horizontal Tsunami evacuation routes for Padang City

The second important issue is the release of the accurate information to the public as soon as earthquakes occur. Meteorology and Geophysics Agency (BMG) of Indonesia is responsible for releasing such information. However, this agency failed to release such information in most recent earthquakes of 2004 Aceh, 2005 Nias, and 2006 South Java as well as 2007 Singkarak (Solok) earthquake. The information must be provided to public at most in 5 minutes time. The system must be capable of if earthquake has the potential for causing tsunami. If so, it should provide information on expected arrival time and tsunami height. The system used in Japan is probably the most effective one so far in the world. There was a huge panic in Padang city since people did not get information about the location, magnitude and its potential for causing tsunami in due time by Meteorology and Geophysics Agency (BMG) of Indonesia. In-spite of drills, the people tended to use vehicles, motorbikes, bicycles causing traffic jams (Figure 11.2).

Figure 11.2. Panic in Padang city following 2007 Singkarak Lake earthquake

In addition, some terminologies used by earthquake geologists and earth-scientists to describe the inter-seismic and co-seismic crustal deformations are misunderstood by public. For example, the settlement of some parts in Nias Island after the 2005 Great Nias earthquake was interpreted by the people of Nias Island that their island was sinking into the sea. Therefore, an ethical obligation of earth-scientists is required to describe the inter-seismic and co-seismic crustal deformations without causing any misunderstanding by public when they communicate with people directly or indirectly through mass media.

12 CONCLUSIONS

An intraplate earthquake struck West Sumatra Province of Indonesia on March 6, 2007. This earthquake killed people and caused heavy damage in the cities of Solok, Payah Kumbuh, Batusangkar and Simabur. Most affected areas are Padang Pariaman, Bukittinggi, Agam, Batusangkar, Tanah Datar, Padang Panjang, Solok, Limapuluh Kota, Padang, and Payakumbuh .Two large events with a moment magnitude of 6.4 and 6.3 occurred at an interval two hours, which essentially similar pattern to those occurred at 1926 and 1943. This reconnaissance report covers both seismo-tectonics and earthquake engineering aspects of this earthquake with some special emphasis on the seismic activity of Sumatra Fault Zone following the 2004 and 2005 Great Off-Sumatra earthquake. Some of conclusions and recommendations drawn from this earthquake may be summarized as follows:

1) In a very recent study by (Aydan 2007b) on crustal deformation and straining of Sumatra Island using the GPS deformation rates, it is pointed out that there are three high stress rate concentration regions along the Sumatra Fault. These sections are associated with fault segments named by Sieh and Natawidjaja (2000), which are Sianok, Sumpur, Barumun, Angkola, Toru, Dikit, Ketaun Sunda, Semangko and Kumering segments (Figure 2.6). The recent 2007 Singkarak Lake (Solok) earthquake may be a part of this rupture process.
2) The estimated fault length would be 27-28 km using the formula proposed by Aydan (1997, 2007b). In view of the damage around Singkarak Lake, the earthquake fault may involve the entire longitudinal length of the lake. Furthermore, the source areas drawn by Sieh (2007) for 1926 and 1943 events may be overestimations and wrongly placed.
3) As happened in many earthquakes in Indonesia, there is also no strong motion record for this earthquake. Indonesia lacks the strong motion network. It is strongly recommended to establish it as soon as possible. The estimations maximum ground acceleration and velocity at the epicenter for a ground with shear wave velocity of 150m/s by the author according to his models with the consideration of fault orientation and ground conditions are 361 gal and 19 kine respectively. These results are quite similar to the estimations from collapsed or displaced simple structures as well as to those estimations by the USGS.
4) When masonry buildings are constructed with bricks without reinforced concrete slab and columns, they were fragile against ground shaking observed in this earthquake. However, new constructions utilizing reinforced concrete slabs and columns with the integration of masonry walls within the load bearing system performed better and they prevented the total collapse of the buildings in-spite of some structural damage.
5) The causes of damage to RC buildings are similar to those observed in other recent earthquakes in Indonesia and elsewhere. They can be re-stated for this earthquake as follows:
   - ✓ Soil liquefaction and lack of the soil bearing capacity (particularly in Solok)
   - ✓ Large ground settlement of embankments nearby river banks
   - ✓ Fragile structural walls and lack of lateral stiffness,
   - ✓ Poor concrete quality and workmanship,
   - ✓ Plastic hinge development at the beam-column joints,
   - ✓ Lack of shear reinforcement and confinement,
   - ✓ Soft story,
   - ✓ Pounding and torsion and

- ✓ Ground motion characteristics (i.e. multiple shocks etc.).

6) Transportation facilities performed relatively better than other structures. However, there were some obstructions due to slope and embankment failures.
7) Inspite of such ground motions, the underground shelter excavated in 1942 without any support in weak pyroclastic flow deposit rocks was almost intact after the earthquake. However, there were some slight damage to the underground shelter at three localities. This underground shelter deserves more detailed studies for its superior performance during this earthquake.
8) Extensive slope failures observed in Sianok Valley. In additon there were also some slope failures and rockfalls in Annai Valley and shore of Singkarark Lake. From the parametric computations using the seismic coefficient method and planra failure model, the expected maximum ground acceleration at the Sianok valley is likely to be around 0.25g. There is no doubt that it will be desirable to carry out detailed geotechnical investigations for determining the properties of ground around Sianok Valley.
9) Major industrial facilities are Singkarak Hydro-electric power plant, recently shut-down Kandi Thermo-electric Power Plant and abandoned mines in Ombilin Coal field. In addition there some metallic mines around the epicenter and factories in Padang City. These facilities with better engineering were not damaged by this earthquake. However, the performance of abandoned open-pit and underground mines deserve further studies.
10) Padang city is vulnerable to possible tsunamis, which may be caused by offshore inter-plate earthquakes along Mentawai Island. The poor response of Meteorology and Geophysics Agency (BMG) of Indonesia to this earthquake caused a public panic in Padang City. The concerned institutes of Indonesia must respond and act in coordination with each other in order to minimize damage and social impacts on the people prone to such disasters. For people living in lowland areas such as Padang, the horizontal evacuation is not a good alternative. The authorities must re-think about the vertical evacuation as an alternative by constructing new earthquake-resistant buildings of 3-5 stories with terraces on top and rehabilitating the existing ones for such purposes in lowland areas.
11) There is an ethical obligation of earthquake-geologists and earth-scientists to describe the inter-seismic and co-seismic crustal deformations without causing any misunderstanding by public when they communicate with people directly or indirectly through mass media.

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