Geological hazard zoning in the seismically active Liwa area, West Lampung, Sumatera, Indonesia

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ABSTRACT

This thesis is concerned with geological hazard zoning in Indonesian Regency of West Lampung, Sumatera. The area covered is that of the capital city of Liwa and surroundings. This area is associated with present-day earthquake-generated faults, and is also the epicentral area for the two devastating earthquakes which occurred in the last century. It is also susceptible to landslides. In this study, the distribution and severity of damage caused by earthquakes and/or landslides was surveyed and studied.

Understanding the geological conditions is basic for the identification, evaluation and qualification of hazards in order to delineate hazard zones. To facilitate this zonation, remote sensing data comprising Landsat Thematic Mapper prints and aerial photographs were used to identify the hazards. GIS ARC/INFO was also used for evaluation, especially slope instability evaluation, and for presentation of maps.

Correlation between the geological conditions and the earthquake effects, permitted division of the study area into moderate and high damage areas including areas subjected to both liquefaction and landslides. Correlations between landslide distribution, lithological units and slope gradients were used to divide the study area into four categories that describe the potential degree of landslide hazard. These categories range from highly unstable to generally stable slope areas. Combining the degree of past damage, caused by earthquakes and landslides, and the relative slope instability categories permitted the division of the study area into four zones which show the probability of earthquakes and landslides occurring again in the Liwa area and potential severity of the damage caused by these.

Zone One (Zone A) designates landslide deposits, areas subjected to liquefaction, severe earthquake damage potential which is underlain by the Pumiceous
Volcanic Rock unit, and area along the fault lineaments which is subject to ground displacement and surface rupture.

Zone Two (Zone B) designates areas of moderately unstable slopes and moderate earthquake hazard potential.

Zone Three (Zone C) designates areas of moderate stable slope and moderate earthquake hazard potential.

Zone Four (Zone D) designates areas of generally stable slope but moderate earthquake hazard potential.

This study, especially the zonation of the Liwa area will provide an important data base for future planning of the development of this region as the population grows.
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CHAPTER 1
INTRODUCTION

1.1 Background

Geological hazards are recognised as phenomena associated with geological processes that can produce a disaster when a critical threshold is exceeded. Accordingly, hazards may result in a significant loss of life or property (Coates, 1981). Zonation of potential hazard areas means dividing a particular region into areas according to the known hazard levels so that some judgement as to the potential for future hazards can be made. In a susceptible geological disaster area, therefore, the zonation map drawn as a result of this division is useful data for land use planning in order to reduce the effects of future hazards because the hazard-producing processes tend to be intermittent and vary considerably in their frequency and magnitude.

For the Indonesian city of Liwa and areas nearby, such zonation becomes most important for two reasons. Firstly, the area has experienced geological disasters. Secondly, Liwa has been ratified by Act no. 6, 1991, to be the capital city of the new regency in Lampung Province, Sumatera. Development of infrastructure, housing and industry in Liwa and surrounding areas will increase accordingly. As a result, any future geological hazards or disasters are likely to have a greater effect as the population, facilities and infrastructure grows.

Zonation of geological hazards in the seismically-active zone of Liwa and adjacent areas is achieved by understanding, identifying, evaluating and qualifying the influence of geological factors contributing to the hazards. Lessons should have been learned, and probably have, from the previous effects of the disasters in this area. The results have been noted and plans made for the future. A map showing hazard zones will make a significant contribution to future planning of Liwa and its surrounding area.
1.2 Location of the Study Area

The study area is situated in Lampung, one of twenty seven provinces in Indonesia. The province is located in the southern part of Sumatera Island that is adjacent to the most densely populated island of Jawa (Fig. 1.1). The 1990 population census showed the Indonesian population to be 179.3 million people. Of that, 107.5 million lived in Jawa, an island that only constitutes 6.9% of the Indonesian landmass. Sumatera, which is three and half times the size of Jawa was occupied only by 36.5 million people. This large difference in the density of the population of Jawa compared to that of Sumatera has forced the Indonesian government to conduct a formal transmigration program in order to resettle people to the less densely populated areas across the country, including Sumatera, so as to increase development and prosperity in those underdeveloped areas and relieve the population pressure in Jawa.

There has been spasmodic migration of Javanese people to Sumatera since the Dutch colonial era. In the era of Indonesian independence, the government has resettled some 2.25 million people during the fourth Five-Year Development Plan dating from the fiscal year 1984/1985 through to the fiscal year 1988/1989. Of this 2.25 million, 60% was resettled somewhere in Sumatera (Central Bureau of Statistics of Indonesia, 1990; Department of Information, Republic of Indonesia, 1993).

Jawa is still a densely populated island and a target for development. Accordingly, Lampung Province situated on the southern edge of Sumatera and adjacent to Jawa, is a target for transmigration, and expansion of agricultural and industrial activities. To cope with this increasing development, Lampung Province, with Bandar Lampung as the capital city of the province, has been restructured and expanded administratively from three to four regencies. The new regency is West Lampung, with Liwa as its capital city. Approximately 371,000 people live in the West Lampung
Regency and of these, approximately 15,000 live in the city of Liwa. The study area is geographically situated between 4°55' and 5°12'SL, and between 103°55' and 104°15'E, with a total population of approximately 100,000 people including the people of Liwa.

During the twentieth century, the regency has experienced two fatal earthquakes with the epicentres of the earthquakes a few kilometres outside Liwa. Landslides have also occurred within the study area. The dynamic geological conditions, together with the push by the Indonesian government to continue, and probably increase the development program for the area, makes conducting a geological investigation essential for providing geological hazard zoning for regional land-use planning in the West Lampung Regency.

This study provides the first basic hazard zonation which will not only serve as a blueprint for future hazard studies but will permit better planning for future monitoring of hazards and planning for the reduction of the impact of disasters that are likely to occur in the future.

1.3 Aim of this Study

A comprehensive evaluation and zoning of geological hazards in Liwa and nearby areas is the prime objective of this study. The hazards discussed here are limited to seismic hazards and slope instability to which the area is prone. To achieve the objectives, the thesis has the following specific aims:

1. To study the hazards in relation to geological conditions, using remote sensing images and field investigations.

2. To prepare a geological hazard zonation map by combining the distribution of previous damage that has been reported with geological factors contributing to the hazards. These processes will be facilitated by the ARC/INFO Geographical Information System (GIS).
3. To develop a qualitative method for evaluating geological hazards in a specific area.

In order to achieve these aims, the methodology given below will be followed.

1.4 Methodology

This study will consist of the following activities:

1. Preparation of a base map using the 1:50,000 topographic map and identification of geological features from aerial photographs and field work, and then transferring these to the base map. The geological features include the known stratigraphy, the interpreted landslides and faults. Topography will also be identified for guidance in preparing a slope class map that will be derived manually from the topographic map. The aerial photographs are 1:25,000 in scale, taken on March 9th, 1993, almost a year before the February 1994 earthquake which caused 201 fatalities.

2. False-colour satellite images of Landsat TM will be used to identify geological conditions related to faults and lithology. The identified image is a hard copy, printed from digital images taken on May 31st, 1994, a few weeks after the last fatal earthquake in February 1994. Information provided by the image is quite good because the resolution of the image is 30 metres.

3. Fieldwork will be conducted to check the interpreted features and make direct investigations to obtain more information.

1.5 Previous Work

The study area has been under investigation since the Dutch colonial era. Van Bemmelen (1934), who studied the general geology of Sumatera, suggested there are three longitudinal block Faults in South Sumatera. One of these, which cuts through the study area, is called the Semangko Fault system.
Berlage (1934) observed the widespread damage caused by the 1933 earthquake that caused 550 fatalities. He reported the greatest damage was confined to a rather narrow but extremely long zone, coinciding with the NW-SE trending Semangko Fault System. Nearer to the epicentre, in the Liwa and surrounding areas, the severest shocks were horizontal and homes were shifted in a NW-SE direction.

Recently, the study area, together with the areas nearby, has been subjected to closer geological investigation. A year before the last devastating earthquake in 1994, Natawidjaja et al. (1993) studied the characteristics of landslide and active faults in the subprovince of Western Lampung. They pointed out that the condition of rocks and soils may have caused many landslides of various types and mechanisms. The sandy tuff and its residual soils in Liwa have been studied for their engineering characteristics (Anwar et al. 1994). These characteristics should be considered when siting buildings. In 1994, the Geological Research and Development Centre published the geological maps of Kotaagung and Baturaja quadrangles that cover the study area. Kumoro (1994) reported the characteristics of the Liwa fault segments in order to understand the mechanisms and the age of faulting that has occurred in the area. Sudarsono et al. (1994) conducted a geological engineering investigation comprising engineering mapping, shallow drilling and soil penetration tests. Other engineering investigations comprising cone penetration tests and hand-augering also have been carried out for hospital site planning (Local Government Agency for Planning of Lampung Province, 1996). In relation to roadwork on roads connecting Liwa and Krui, Djakamiharja and Soebowo (1996) studied the stability of rock masses in slope excavations.

1.6 Geological Hazards in the Study Area

Around Liwa and surrounding areas, two types of geological hazards have occurred - earthquakes and landslides. Historically, the three interrelated features of
earthquakes that lead to loss of life and damage to property are: ground shaking, ground faulting and ground failure. Experience from the 1994 Liwa earthquake indicated some difference in the intensity of damage within relatively close areas that are composed of different geological units. This suggests that the shaking was influenced by local geological conditions and this needs to be considered in future plans.

Hazards related to ground faulting are displacement of the ground and surface rupture along the fault lineaments. In relation to ground failure hazards in the Liwa area, some scarps of earthquake-induced landslides tend to have southeast-northwest directions. Some of these scarps are associated with earthquake-generated faults. Other landslides that commonly occur elsewhere in the study area are likely to be related to unstable slopes and rainfall. It has been suggested that some human activities, especially road works and excavations, have triggered landslides.

Considering the characteristics of geological hazards and zoning of such hazards in the study area, requires an understanding of the environmental aspects of geological conditions. Important conditions are lithological and structural characteristics. Any particular hazard and damage related to that hazard have to be identified for the purposes of evaluation and qualification.
CHAPTER 2
IMPORANT ASPECTS OF THE STUDY AREA

2.1 Regional Geological Setting

From a tectonic viewpoint, Sumatera is situated on the western margin of Sundaland, the south-east Asian continental extension of the Eurasian Plate, which forms part of the Sunda Arc. The oceanic crust of the Indian-Australia Plate is presently being obliquely subducted along the Sunda Trench off the west coast of Sumatera (Hamilton, 1979). The subduction which occurred from Early Tertiary to Recent, has given rise to the extensive magmatic arc of the Barisan Mountains which form the 1650 kilometres long backbone of Sumatera (Amin et al., 1994). Relative to this magmatic arc, Sumatera and the west coast areas can be subdivided into four tectonic provinces. They are, from west to east, the accretionary or Mentawai Zone, the fore-arc or Bengkulu Zone, the magmatic arc or Barisan Zone and the back-arc or Jambi-Palembang Zone. Within this tectonic setting, the study area lies in the magmatic arc or Barisan Zone except the south-west part which is in the fore-arc or Bengkulu Zone (Fig. 2.1).

During the Early Tertiary, magmatic activity in South Sumatera was relatively insignificant. Widespread volcanic activity began in the Late Oligocene and produced andesitic to basaltic rocks. This activity decreased in the Early Miocene and was marked by predominantly acid extrusions and intrusions. Volcanic activity was prominent again during the Middle Miocene and extended into the Early Quaternary. During this period, the composition of volcanic rocks of the Barisan Zone became more diverse, ranging from andesitic-basaltic to rhyolitic. Later in the Early Quaternary, the magmatic activity was characterised by basic to intermediate rocks (van Bemmelen, 1949; Amin et al., 1994 and Gafoer et al., 1994).
The fore-arc basin is located west of, and parallel to, the magmatic arc and both are considered to have existed since the Early Tertiary. The basin has been broken into multiple sub-basins by transverse structural highs (Hamilton, 1979). Amin et al. (1994) gave the name Bengkulu Basin to the fore-arc basin located in the western part of South Sumatera; the basin was established in the Early Oligocene and at the same time as the back-arc basins of south and central Sumatera. Near the magmatic arc, the Benbkulu Basin has been partially exposed above sea level and currently constitutes the main landmass of the western part of Sumatera.

The development of the Barisan Zone started with a progressive subsidence of the fore-arc basin which occurred from the Late Oligocene onwards and resulted in a marine transgression that reached its maximum by Middle Miocene. Once the Barisan Zone had risen and widespread volcanic rocks had been produced, uplift of the adjacent Bengkulu Basin started. As a result, sedimentation took place under regressive conditions during the Middle to Late Miocene. Until the Middle Miocene, the depositional environment changed from shallow marine to brackish water. Further uplift of the basin produced terrestrial sediments of Plio-Pleistocene age. The thickness of these sediments varies from 1000 m to 1700 m (Amin et al., 1994; Gafoer et al., 1994).

In the southwest part of study area, a series of marine sediments in the Krui section located in the Gunungkemala area, has an aggregate thickness of 800 metres. The sedimentary rocks are tuffaceous in origin and contain molluscan fauna. Since 50 % of the mollusca are recent species, the species are believed to have been derived from Upper Pliocene deposition (van Bemmelen, 1949).

2.2 Regional Structural Geology

Sumatera developed its structural entity as a response to the tectonic activity of the region. The subduction of the Indian-Australia Plate under the Eurasian Plate, is
believed responsible for the formation of the fore-arc and back-arc basins and movement of magma along the magmatic arc, which in turn, has given rise to the sedimentary basins and produced folding and faults (Hamilton, 1979). The uplift period of the Middle-Miocene is marked by a local unconformity within the fore-arc basin of the Bengkulu Zone (Amin et al., 1994). In the back-arc region, a major Plio-Pleistocene orogeny produced regional upright folds with northwest-southeast trending axes (de Coster, 1974). Within the magmatic arc, which coincided with the axis of Sumatera Island, a 1650 kilometre long fault-zone stretches from Aceh in the northwest to Semangko Bay in the southeastern part of the island (Katili and Hehuwat, 1967 and Hamilton, 1979).

Of these structural features, a fault zone within the magmatic arc, called the Sumatera Fault System, is the most significant structure because it crosses the study area. The fault system was earlier considered to consist of graben-like structures (van Bemmelen, 1949; Westerveld, 1953). In a later publication, Katili and Hehuwat (1967) mentioned the presence of important large-scale horizontal displacements, mainly dextral, along the fault zone. This regional fault zone is interpreted as consisting of a series of independent subparallel faults of different ages rather than a single zone of approximately coeval faults. Some vertical movement resulting in graben-like structures, were also found along the entire length of the Barisan Mountains. These vertical movements had already started in the pre-Tertiary and continued during the Tertiary. However, horizontal movements of a dextral nature, affecting the pre-existing faults, originated later during the Lower Pleistocene and are still continuing today. The evidence for present right-lateral movements are based on the displacements involving the Quaternary rocks. Earthquakes such as the Padangpanjang and Tes earthquakes, which occurred in 1926 and 1952 respectively, proved that the fault system is active with dextral displacements.
After studying the Sumatera Fault System, Tjia (1977) proposed that the system consisted of at least eighteen segments, the majority of which are arranged in a dextral \textit{en echelon} pattern. During the main period of dextral slip faulting along this fault zone, in the Plio-Pleistocene, normal faulting occurred at these \textit{en echelon} junctions, resulting in mini-graben structures or volcanic centres.

Part of the fault system in the study area consists of three sub-parallel dextral faults which are joined together in the southeastern part of the study area. According to Berlage (1934), the fault line crossing the area west of Sukarame village, within the study area, was activated during the 1933 Liwa earthquake. About 1 kilometre of surface fracture was identified after the shock. More recently, during the 1994 Liwa earthquake, two of the faults in the study area were activated. A 20 cm right-hand lateral displacement has been reported to the southeast of the Liwa (DGSM, 1994). By referring to the Fitch (1972) concept, these earthquakes can be considered as the events which release stress build-up as a result of the present oblique subduction off the west coast of Sumatera. Another weak zone of stress release, forming a long linear structure parallel to the Sumatera Fault System, has been discovered on the western flank of the present fore-arc basin located west of Sumatera. The structure which is located below sea level, has been interpreted as a strike-slip fault zone and is called the Mentawai Fault Zone (Diament \textit{et al.}, 1992).

\subsection*{2.3 Geomorphology of the Study Area}

The study area which is located in the magmatic arc of the Barisan Mountains and the Bengkulu fore-arc Basin, can be broadly divided into five geomorphological
units, each of which reflects the local geology. The geomorphic units are volcanic cones, mountainous areas, rolling hills, plateaus and coastal plains (Fig. 2.2).

The volcanic cones are those of Mount Pesagi and Mount Seminung which are located on the northeastern and northwestern side of the study area respectively. The cone shape can be identified on aerial photographs and satellite imagery. Geologically, they are composed of the younger Quaternary volcanic rocks. Mount Pesagi, 2,137 m high, has a very steep section where the gradient of the slopes near the peak is more than 70 % (35°). In this steep area, the streams deeply incise the land, forming V-shaped valleys. A landslide in this steep area, during the period of the 1933 Liwa earthquake, allowed the Warkuk River to quickly transport the debris, burying some areas including Bahway village. Unlike Mount Pesagi, Mount Seminung with its peak of 1,891 m is located outside the study area and neither it, nor surrounding areas, have experienced any devastation so far.

The mountainous area which occupies the central and southeastern part of the study area, exhibits very steep slopes ranging from 5 % to 80 %. In the central part of the study area this geomorphological unit shows a series of southeast-northwest elongated mountains. The prominent peaks are Bukit Sipulang (1,315 m), Pegunungan Limaukunci (1,063 m) and Liu (1,265 m), all of which are situated between two strike-slip faults. The northwestern part of the elongated zone is a crater-like structure that is interpreted as the former central volcanic eruption which ejected the older Quaternary volcanic rocks which are associated with this geomorphological unit. In the southeastern part of the study area, the mountainous geomorphic unit contains the Penetoh Mountains, a range that has three peaks having heights of 1,120 m, 1,166 m and 1,220 m above sea level and which are composed of the younger Quaternary volcanic rocks.

Rolling hills are widespread in the study area and are underlain by many types of rocks but no alluvial deposits. The drainage patterns within the unit are sub-parallel and
sub-dendritic. In some areas, streams show fault-controlled patterns. The elevation of
this geomorphological unit varies from 40 m near the coastal plain up to 1,500 m to the
southeast of Lombok village. Slope gradients range from 5 % to 70 %. On the southern
and western sides, valleys are V-shaped with very steep slope gradients. The tops of
hills have gentle slope gradients.

The central and the northwestern parts of the study area are composed of
plateaus. The Liwa Plateau is located in the central area and is mostly underlain by a
pumiceous volcanic rocks. The plateau is transected by two sub-parallel strike-slip faults
causing offset of some streams. Landslides are very common along the streams that
mostly flow in a NW-SE direction. River banks are the steepest part of this
geomorphological unit.

The elevation of the Liwa Plateau ranges from 775 to 950 m above sea level. Other plateaus are the Lombok Plateau and the Buaynyerupa Plateau which are located in the northwestern part of study area. All plateaus are transected by strike-slip faults. The Lombok Plateau is located adjacent to Ranau Lake and is underlain by the younger Quaternary volcanic rocks; it has elevations of 575 to 700 m above sea level. The Buaynyerupa Plateau developed on alluvial deposits and the pumiceous volcanic rocks. The plateau has elevations of 600 to 750 m above sea level.

The fifth geomorphological unit is the coastal plain. It is situated in the
southwestern part of the study area and includes the city of Krui and adjacent areas. The
plain is composed of alluvial deposits with elevations from 0 to 40 m above sea level
and slope gradients of less than 5 %.

2.4 Climate

In common with the rest of South Sumatera, the study area is located within the
Indo-Australian climatic zone which is characterised by variable but high temperatures,
humidity and rainfall. In the study area, the rainfall data for the period of 1986 to 1996, showed annual precipitation ranging from 2,249 mm in the highlands of the Liwa area to 3,027 mm in the coastal area of Krui. The monthly average rainfall within this period shows that the two months of November-December is the period of heaviest precipitation (Fig. 2.3). The period of lowest precipitation occurs from May through August and corresponds with the driest season of the monsoon. The Liwa climatological station recorded no rain falling within the months of June to September, 1994, when a long dry season was experienced by the region. Although there are no data correlating the time of high rainfall and landslides which commonly occur in the area, the highest precipitation was reported to trigger or cause landslides in the unstable slopes (Office of West Lampung Regency, 1996, oral communication).

Within the study area, the lowest night temperature varies from 16° C to 21° C. The highest daytime temperature varies from 26° C to 30° C and the humidity ranges from 70% to 90%.

2.5 Geology of the Study Area

The active zone of the Great Sumatera Fault System and surrounding areas have received considerable attention from geologists. Van Bemmelen (1949) produced the first comprehensive record of the geology of the Indonesian region including the Lampung Province. South Sumatera was stated to be composed of metamorphic, volcanic and sedimentary rocks ranging in age from presumably pre-Mesozoic to Recent. Structurally, Lampung Province was described as an area sliced by a fault zone that can be identified along the length of Sumatera. Berlage (1934) identified long horizontal surface fractures near Liwa after the 1933 Liwa earthquake shook the area. Because of the existence of the fault zone along Sumatera, which is associated with
lakes and volcanoes, Westerveld (1953) related the phenomena to the acid pumice tuff eruptions which occurred in the Early Quaternary.

More recently, a comprehensive description of the geology has been published by the Department of Mines and Energy, Republic of Indonesia (Amin et al., 1994 and Gafoer et al., 1994). The geological maps presented in the publications are of 1:250,000 scale.

Map 1 shows the geology of the study area. It is based on previously published data with some refinements, particularly those related to geological hazards.

2.5.1 Stratigraphy

In the Liwa area, outcrop is sparse unless it is exposed along some river beds and unless uncovered by construction works such as roads. Although stratigraphic units such as formations have been recognised, many formal units contain similar lithologies and behave in a like manner when experiencing earthquakes. In addition, many of the stratigraphic units were defined from drill core and in the Liwa area, outcrop is generally not as abundant as elsewhere where some of the units have been defined. Thus in the following text, informal names such as the older Quaternary volcanic rocks and younger Quaternary volcanic rocks are generally used.

2.5.1.1 Tertiary Clastic Sedimentary Rocks

The Seblat Formation, the Lemau Formation and the Simpangaur Formation (Amin et al., 1994 and Gafoer et al., 1994) are the main Tertiary sedimentary units (Fig. 2.4; Map 1). All are composed of claystone and sandstone. The upper part of this section is characterised by conglomerate which were deposited in the fore-arc Bengkulu Basin during the Late Oligocene to Pliocene.
The Seblat Formation is the oldest unit exposed in the study area, ranging in age from Late Oligocene to Middle Miocene. The formation consists predominantly of alternating claystone, tuffaceous sandstone, shale and siltstone. It has a maximum thickness of 500 m. Outcrop of the formation is found in an excavated road, approximately 1.5 km from Liwa to Krui. The outcrop shows an unconformity between the formation and the younger older Quaternary volcanic rocks (Plate 2.1) and also shows significant differences in the weathering patterns of the claystone (weathers easily) and the siltstone (weathers less easily than the claystone). Another lithological contact between these two rocks is also found on the road between Liwa and Krui (11 km from Liwa).

The Lemau Formation was deposited during Middle to Late Miocene. The formation consists of sandstone and calcareous claystone, and is approximately 200 m thick.

The youngest unit is the Simpangaur Formation which was deposited during the Late Miocene to Pliocene. The formation is found in the southwestern part of the study area and comprises tuffaceous sandstone, siltstone, polymictic conglomerate and tuff. It has a thickness of 700 m. Some outcrops of the formation are found on the Liwa to Krui road near Gunungkemala village. At this locality, 17.5 km from Liwa, the outcrop comprises intercalations of polymictic conglomerate, sandstone and siltstone (Plate 2.2; the rocks are not greatly weathered in this photograph). The conglomerate is brownish-yellow to yellow in colour with rounded to sub-rounded clasts, mostly of volcanic origin, up to 10 cm in diameter in a matrix of coarse-grained tuffaceous sandstone. The sandstone and siltstone layers are characterised by cross-bedded and parallel laminations respectively. In Gunungkemala village, the conglomerate has clasts of up to 20 cm in diameter. Twenty kilometres from Liwa, along the Liwa to Krui road, the formation
contains tuff layers that are brownish-white in colour. The maximum thickness of any tuff layer is 50 cm.

2.5.1.2 Tertiary Volcanic Rocks

The Tertiary volcanic rocks comprise volcanic breccia, tuff and andesitic rocks. The breccia is grey in colour, hard and compact with poorly-sorted, angular to subangular fragments of andesitic rocks, intercalated with grey tuff. Throughout the study area (Map 1), the Tertiary volcanic rocks occupy three separate sites, to the south-west of Kubuprahu village (Plate 2.3), to the south-west of Buaynyerupa village and to the south of Bakhu village. The volcanic rocks are responsible for the higher topographic areas to the south of Bakhu. Along the road between Bakhu and Batukebayan villages, in the eastern part of study area, the highly weathered Tertiary volcanic rocks are subject to sliding. Formation of the volcanic rock in south Sumatera commenced during the Late Oligocene and finished in the Middle Miocene with dacitic rather than andesitic composition during the latter stages. The volcanic rocks are divided into the older rocks of the Hulusimpang Formation and the younger rocks of the Bal Formation (Amin et al., 1994). The Hulusimpang Formation can be correlated with the 'Old Andesitic Rocks' which were interpreted by Van Bemmelen (1949) to be of the Early Miocene age.

2.5.1.3 Pumiceous Volcanic Rocks

The pumiceous volcanic rocks are found between volcanoes and mountainous areas covering Buaynyerupa Plateau and extend to the southeastern part of the study area. The rocks consist of pumiceous tuff, pumiceous breccia and welded tuff. The pumiceous tuff is pale-grey to brown in colour, medium- to coarse-grained and mainly composed of pumice, rock fragments and glass. The pumiceous breccia is yellow to pale
grey in colour with poorly-sorted cobble- to pebble-sized fragments, mostly tuff, pumice and andesite in a matrix of coarse-grained sandy tuff (Plate 2.4). The pumiceous tuff and pumiceous breccia are locally intercalated with the yellowish-grey welded tuff. Plate 2.4 shows a large amount of pumiceous scree at the base of the cutting. Some of this is due to the excavation but some of it is also due to rapid weathering of the pumiceous rocks.

The pumiceous rocks have been interpreted as the products of the great Ranau eruption during the Early Quaternary (van Bemmelen, 1949; Westerveld, 1953). Amin et al. (1994) interpreted the pumiceous rocks as associated with a major Plio-Pleistocene orogeny that produced wrench faulting. This generated local tensional pull-apart structures that probably acted as volcanic conduits.

2.5.1.4 Older Quaternary Volcanic Rocks

The older volcanic rocks consist of andesite, volcanic breccia and tuff (Map 1). The andesite unit is grey to blackish-grey in colour with columnar jointing. The outcrops of breccia are black to brownish-grey in colour with poorly-sorted angular to subrounded clasts of andesitic to basaltic composition (up to boulder size) tuff and volcanic glass in a sandy tuff matrix as shown in Plate 2.5. (It is also noticeable in this photograph that the slope has little vegetation. Where slopes have little vegetation, the slopes are more easily eroded leading to increased instability) The tuff layers are brownish-grey in colour with both crystalline and lithic variants made up of andesitic to basaltic rocks, glass and oxidised materials. The andesitic unit is grey to blackish-grey in colour with columnar jointing. The rocks are responsible for the presence of mountains that are characterised by a crater-like structure to the west of Liwa. The former crater has been interpreted as the central eruptional point.

Van Bemmelen (1949) and Westerveld (1953) interpreted the older Volcanic rock unit to be part of the last eruption phase which was commenced in the Quaternary.
Amin et al. (1994) stated the eruption was of Pleistocene to Holocene age. The thickness of the unit is approximately 300 m.

2.5.1.5 Younger Quaternary Volcanic Rocks

In comparison to the older Quaternary volcanic rocks, outcrops of the younger Quaternary volcanic rocks are characterised by volcanic cones which are composed of volcanic breccia, tuff and andesitic rocks (Plates 2.6 and 2.7). However, a closer examination of the rocks show some differentiation. In the younger volcanic rocks, the breccia is blackish-grey in colour with poorly-sorted angular fragments of andesite up to 155 cm diameter. The breccia is intercalated with yellowish- to brownish-grey tuff which is coarse-grained and comprises poorly-sorted, angular to subangular pebbles of volcanic rock, iron oxide and glass in a tuffaceous matrix (Plates 2.6 and 2.7). The volcanic rock is blackish-grey in colour and is of andesitic to basaltic composition. Plates 2.6 and 2.7 also show that in this unit some rocks weather more rapidly than others. The sandy tuff in Plate 2.7 weathers more rapidly that the breccia in Plate 2.6. Important differences in the weathering patterns of different lithologies, such as shown in Plates 2.6 and 2.7 in the same stratigraphic unit need to be documented and taken into account where possible in hazard planning.

According to Amin et al. (1994) and Gafoer et al. (1994), the younger Quaternary volcanic rocks formed as a result of volcanic activity which has been attributed to Mount Seminung, Mount Pesagi and Mount Penetoh, which all erupted during the Holocene. The unit is 750 m thick.

2.5.1.6 Alluvial Deposits

The coastal area has flat topographical features in the city of Krui and is composed of alluvial deposits. The sediments are derived either from Tertiary
sedimentary rocks or from Quaternary volcanic rocks with fragments of coarse-grained sand up to boulder size, set in clayey or sandy matrix.

2.5.2 Structural Geology of the Liwa Area

The structural geology of Sumatera, where the study area is located, has been studied and discussed by Berlage (1934), van Bemmelen (1934; 1949), Westerveld (1953), Katili and Hehuwat (1967), Fitch (1972), Tjia (1977), Hamilton (1979), Katili et al. (1987), Natawidjaja et al. (1993), Amin et al. (1994) and Gafoer et al. (1994) In general, the authors have agreed that the development of the structural geology in the region is directly related to tectonic developments in the region. The main displacements of the Sumatera Fault System are of a horizontal right-hand nature with some vertical movement. The fault system can be traced along the 1,650 km backbone of the island.

The study area, situated along part of the backbone of the island, has three sub-parallel strike-slip faults trending in a NW-SE direction. These are called the Sukarame Fault, Liwa Fault and Kubuprahu Fault. The three faults can be identified on aerial photographs and Landsat TM images as lineament features.

2.5.2.1 Sukarame Dextral Strike-Slip Fault

The Sukarame Fault cuts across, from southeast to northwest, the Semangka River and its tributaries near Selipas and Sukabumi, the Robok River in Sukarame and the Rebo River, the Menjadi River and the Warkuk River near Buaynyerupa. The direction of the lineament is N325°E, N305°E and N335°E near the Semangka River, Sukarame and Buaynyerupa villages respectively. On the surface, the fault forms NW-SE scarps along the river banks as shown in Plate 2.8. In this photograph the scarp is easily recognised
and show the very steep gradients which tend to characterise such scarps. A similar scarp can be seen in Plate 2.9.

The rocks that have been subjected to movement by the fault are less consolidated and therefore easily slide, and are easily weathered and eroded. The direction of the fault can be interpreted from the offset of streams such as the Robok River, Rebo River and Menjadi River. The fault is still currently active and information from the recent earthquakes associated with the fault may establish a better understanding of the fault displacement. Earlier information comes from the aftershock investigation of the 1933 tremor. The 1933 Liwa earthquake left horizontal displacements along the fault that are of a right-handed nature (Berlage, 1934). The right hand offsets can be identified in the Robok River, Rebo River and Menjadi River in the northern part of Liwa.

2.5.2.2 Liwa Dextral Strike-Slip Fault

Similarly to the Sukarame Fault, the Liwa Fault also has a SE-NW lineament and is characterised by right hand displacements. The trends of lineaments observed on Landsat TM images along the Melbuilunik, Kububihan and Robok Rivers are N330°E, N310°E and N320°E respectively. The lineament represents the fault scarps found on the ground during field observations (Plate 2.9). To the southeast, the Liwa Fault may extend and join with the Sukarame Fault outside the study area whereas to the northwest it probably terminates in the western part of Tanjungkemala village. The direction of the movement of the fault can be interpreted from the offsets of the Robok River. A report on the 1994 Liwa earthquakes (DGSM, 1994) mentioned some ground displacements
between Liwa and Sebarus village with N320°E to N330°E horizontal right hand displacement of approximately 20 cm length.

2.5.2.3 Kubuprahu Dextral Strike-Slip Fault

Another strike-slip fault with a right-handed nature is the Kubuprahu Fault. The lineament of the fault can be traced from Lake Ranau in the northwestern part of study area to the southeastern part of study area through Kubuprahu village (Plate 2.10). The right-handed nature may be determined by the offsets of some rivers such as the Tenumbang River and Kububihan River. The fault is unlikely to have been activated for a long time since there is no report of it moving during the recent earthquakes. From the rocks that have been affected by the fault, it can be interpreted that the main faulting episode occurred between the eruption of the older younger Quaternary volcanic rocks and the younger Quaternary volcanic rocks. Away from the Penetoh Mountains, in the area covered by the older volcanic rocks, the lineament of the fault extends outside of the study area where the fault is joined with the Sukarame and Liwa Faults.

2.6 Summary

Sumatera is one of the heavily populated islands of Indonesia, a country that comprises many islands in a tectonically active zone at the boundary between two plates. The study area is transected by three faults, two of which have been associated with earthquakes for a long period of time; these are the Liwa Fault and the Sukarame Fault. The township of Liwa, which is located in the study area has suffered extensively from two large earthquakes which occurred in 1933 and 1994. Both caused significant damage to buildings and death and injury to people. The Liwa area is likely to experience earthquakes of the same magnitude and ferocity in the future. It is with this background that this study was initiated.
CHAPTER 3
GEOLOGICAL HAZARDS IDENTIFICATION

3.1 Introduction

The identification of geological hazards is the identification of phenomena related to geological processes that can produce disasters. In order to minimise the risk of hazards, past hazards have to be evaluated and then an assessment of the likelihood of the hazard occurring in the future so that hazard zones can be delineated. The evaluation and zonation of hazards in the Liwa area will be discussed in detail in the next chapters. For later discussions, it is necessary to understand the distinction between hazard and risk.

According to Varnes (1984), hazard refers to the probability of the occurrence of an event in an area within a specified period of time. In relation to earthquakes, Stevens (1988), stated that hazard expresses the probability of an earthquake occurring whereas risk expresses the probability of damage or disaster when earthquakes occur. The statements of Varnes and Stevens are mathematical expressions because the probability of a hazard can be expressed using mathematical probability methods.

Another simple explanation was given by Blair et al. (1979) for the case of earthquakes. In their explanation, seismic hazard is the effect of an earthquake such as surface faulting, ground shaking, tsunami, liquefaction, landslide and other forms of ground failure. Seismic risk is the degree of exposure of individuals and structures to potential injury or damage from seismic hazards. It is this sense that the terms hazard, risk and damage, whether earthquake derived or otherwise, are used in this thesis. For example, the presence of an active fault is clearly a hazard; however, the degree of risk depends on the location, type of construction of the dwelling and infrastructure, and occupancy of buildings with respect to the fault.
3.2 Methodology

As well as identifying geological hazards and recognising features related to the hazards is very important that the spatial distribution of hazards be determined and these data transformed into an inventory map of hazards. For the purpose of recognition, remote sensing data have been used in this study. The interpretation of hazards on remote sensing print outs was followed by field checking.

Collecting other data and information relating to hazards is also part of the hazard identification. Important data are characteristics of hazards and spatial distribution of hazards. The most prominent hazards in the region are earthquakes and landslides (which may or may not be induced by earthquakes). Parameters of earthquakes such as intensity, epicentre, displacement on the surface and geometry of faults that cause the earthquakes, are the means for obtaining information in post-earthquake studies. Information about spatial damage distribution can be correlated with the characteristics of geological units that, together with fault lineaments and landslide-related features, can be recognised on the remote sensing images.

In this study, features of recognised hazards were plotted on a base map prepared from the topographic map of 1:50,000 scale provided by the Topographic Division of the Indonesian Military Army (Jawatan Topografi TNI-AD Indonesia, 1977). In order to make the maps more effective, the inventory maps were digitised using the GIS ARC/INFO systems. Details will be discussed in the next chapter.

3.3 Remote Sensing

The term remote sensing, according to Lillesand and Kiefer (1994), is the science and art of obtaining information, from a distance, of the objects under
consideration by the use of sensing devices. The products of remote sensing used in this study are Landsat Thematic Mapper (TM) output and aerial photographs. The Thematic Mapper is equipped with sensors that can detect seven spectral bands emitted by the Earth’s surface. Important bands for this study are bands 3, 4, 5 and 7 because of the following characteristics (Avery and Berlin, 1992):

(i) Band 3 detects a strong chlorophyll reflectance and a strong reflectance region for most soils; it can thus discriminate between vegetation and soil;
(ii) Band 4 distinguishes between dry and moist soil; the latter has a high absorption of water;
(iii) Band 5 and 7 are valuable for lithological mapping because of sensitivity to ferric iron/haematite and hydrous minerals, respectively.

The Landsat TM provides a two dimensional image with 30 m ground resolution. Resolution is the minimum distance between two points or the size of an object that can be recognised. For the Liwa region, the TM image was taken on 31 May, 1994 (almost 4 months after the last earthquake). Hard copies of composite colour band images that were used for the interpretation of geological hazards, were printed from the digital TM images provided by the Indonesian Institute of Sciences (Lembaga Ilmu Pengetahuan Indonesia/LIPI).

The aerial photographs used for interpretation are black-and-white prints at a scale of 1:25,000 or 0.25 m ground resolution. These were provided by the Coordination Agency for National Survey and Mapping (Badan Koordinasi Survei dan Pemetaan Nasional/BAKOSURTANAL), Indonesia. The aerial photographs were taken on 9 March, 1993 (before the last earthquake). Unlike Landsat TM images, the aerial photographs provide a three dimensional overview of the terrain and thus it is easier to
recognise landslide-related features on these than on Landsat TM images. The high resolution of aerial photographs also allows identification of small landslides that cannot be recognised on Landsat TM images. However, the composite colour band allows the TM images to accentuate lithological units. Because the areas of damage caused by earthquakes are associated with the specific lithologies, the accentuation can delineate damaged areas. The studies of Mantovani et al. (1996) provided a useful insight into how remote sensing can be useful in examining landslides.

3.4 Earthquake Hazards

The most threatening geological hazards in the region, in terms of loss of life and property, are earthquakes. Berlage (1934) reported 550 people killed and 927 houses destroyed as a result of the earthquake that occurred on 24 June, 1933. For that earthquake, the epicentre co-ordinates were 104°9’ E longitude and 5°2’ S latitude (within the study area). According to Indonesian Bureau of Meteorology and Geophysics, the surface-wave magnitude (Ms) was 7.5.

Another earthquake struck the region on 16 February 1994 local time, with its epicentre located at 104°12’0” E longitude and 5°0’0”S latitude. The surface-wave magnitude reached 7.2 and the intensity was 6.5 on the Richter scale. Two hundred and one people were killed, 1,871 houses completely destroyed, 4,915 heavily damaged, 3,596 others slightly damaged and 223 government buildings damaged (DGSM, 1994; and Tim SATLAK-PBA Kabupaten Lampung Barat, 1994). During the field work for this study (August, 1996), two government officers were still on leave as a result of injuries related to earthquakes (Plate 3.1). One of the important reasons for producing plans to mitigate the effects of geological hazards of the future is to reduce their influence on both humans and infrastructure. Many of the provincial capitals of Indonesia lack both the infrastructure and funds to quickly repair buildings, such as
shown in Plate 3.1, that are damaged by natural disasters and many buildings are used inefficiently for long periods simply because of the inability of provincial agencies to repair them quickly.

Most of the above damage and injury was caused by the primary earthquake effect of ground shaking with intensity related to the local geological conditions. Thus, areas susceptible to becoming hazards can be identified on the remote sensing images. Other targets to be considered for identification are active faults with potential to generate earthquakes, landslides and zones susceptible to liquefaction, whether or not they have been induced by earthquakes.

3.4.1 Ground Shaking

The shaking or motion of the ground during earthquakes occurs as seismic waves pass through the earth’s surface layers. The factors governing the characteristics of ground motion maybe categorised into three:

* source of energy release;
* wave passage towards the surface; and
* surface of the ground.

At the source of the energy release, the initial character of ground motion is determined of several parameters, including fault type, fault dimension, magnitude, stress drop and propagation pattern. Towards the surface, geological discontinuities and the distance the body wave has to travel can alter the resulting ground motion. At the surface, ground motion may be further altered by local geological and topographical conditions (Lajoie and Helley, 1975; Berlin, 1980; Aki, 1993). A hazard is produced when the ground motion interacts with man-made structures and this can lead to various degrees of damage or complete failure.
A report available in the local government office of West Lampung Regency (Tim SATLAK-PBA Kabupaten Lampung Barat, 1994) indicated that the percentage of damage to houses of almost similar construction (mostly wooden and a very few of brick) differs in different locations. Combining these data with the geological conditions (Table 3.1) shows the highest intensity of damage is distributed in those areas close to the faults that caused the earthquake and those located on the pumiceous volcanic rocks and alluvium deposits. Another report (DGSM, 1994), noted that the destruction of land, in terms of landslides related to earthquakes (elaborated in the next section) mostly occur in areas located on the pumiceous volcanic rocks and is less severe in adjacent areas situated on the older Quaternary volcanic rocks. Geomorphologically, the pumiceous volcanic rocks are characterised by an almost flat area of plateau which is surrounded by hilly areas consisting of different geological units.

The distinctive geomorphology of the pumiceous rocks area, which is suspected to be extensively damaged in the event of an earthquake, can be identified using the aerial photographs. The different geomorphological and geological characteristics of the pumiceous volcanic rocks, in contrast with the surrounding areas, causes different electromagnetic-wave emission and transmission and it is thus possible to identify the pumiceous rocks and their distribution using the colour-composite TM image (Plate 3.2).

3.4.2 Ground Faulting

Faults may be considered as “planes or surfaces in the earth materials along which failure has occurred and materials of opposite sides have moved relative to one another in response to the accumulation of stress” (Nichols and Buchanan-Banks, 1974). During quite large earthquakes, fault slippage often extends to the Earth’s surface
where sudden and abrupt ground displacement occurs. The displacement or slip along
the fault plane may be primarily horizontal or vertical. When the fault extends to the
surface of the Earth’s crust, the movement often produces a line or a narrow zone of
visible features such as scarps and surface ruptures. The displacement, in turn, causes
damage to structures located astride the fault. For the purpose of mitigating earthquake
damage in the future, recognising and mapping faults are important factors that should
be considered.

A hard copy of Landsat TM indicates three lineaments that are manually
interpreted as fault patterns in the study area (Plate 3.2). Similar features are also
identified in aerial photographs. The lineaments control drainage patterns and in terms
of stream changes and offsets, this translates into dextral movements. The three faults
are: the Sukarame Fault, the Liwa Fault and the Kubuprahu Fault (section 2.5.2).

Of the three faults, only the Kubuprahu fault has no history of earthquakes in the
Liwa and surrounding areas. During the 1933 Liwa earthquake, surface ruptures in a
zone approximately 1 km long and 1 m wide, were identified in nearby Negeri Ratu
village. The orientation of ruptures were parallel to the Sumatera Fault System (Berlage,
1934). In this thesis, such ruptures are interpreted as corresponding to the Sukarame
strike-slip fault and are seen as a lineament feature on the Landsat TM image and on
aerial photographs. The lineament passes near Negeri Ratu village in a NW-SE direction
(Plate 3.3).

Another report (DGSM, 1994) mentioned the occurrence of some surface
ruptures in the villages of Selipas, Sukarame and Hanakau, after the 1994 earthquake.
These villages are located along the Sukarame Fault lineament (Plate 3.4).

The occurrence of another surface rupture zone of approximately 2.5 km length
was also reported (DGSM, 1994). The ruptures crossed and damaged the road between
Liwa and Sebarus in the Sebarus Valley. Along the ruptures, houses collapsed and
agricultural land within the valley was damaged. Some 21 *en echelon* displacements occurred in the valley. These were oriented approximately 320° to 330° (NW-SE). Some displacements within the rupture zone showed horizontal right hand movements. The displacements reached 20 cm in length. In this thesis, the 2.5 km rupture zone is interpreted as the Liwa Fault because the fault lineament which is identified on Landsat TM passes through the Sebarus Valley and Liwa.

Road damage, associated with the Sukarame Fault, was still under rehabilitation during the field visit for this thesis (Plate 3.5), some years after the event that caused them. Again, as with the slowness to repair the building shown in Plate 3.1, this demonstrates the need for better planning to mitigate natural hazards and disasters. Fault scarps were found along both the Sukarame and Liwa Fault traces (previous section, Plates 2.8 and 2.9). As a result, both the Sukarame and Liwa Faults were clearly activated during the 1994 earthquake.

After-shock detection devices were used after the main shock of 1994 earthquake. This was achieved by locating 12 seismographs in the Liwa-Krui-Sekincau-Suwoh region. These instruments recorded some 140 epicentres within 33 days (Harjono *et al.*, 1994). The distribution of after-shocks was limited geometrically to an area roughly 30 km long, 15 km wide, and less than 20 km deep. The effective rupture zone was 20 km long, 10 km wide and less than 20 km deep. A very important zone of surface rupture was clustered between Liwa and Sukarame faults. Thus it appears a highly ruptured area was located between the Liwa and Sukarame Faults, and therefore on the Liwa Block. Consequently, it was suggested that the main shock was located in this block, most likely along the Liwa Fault.

3.4.3. Liquefaction
The term "liquefaction" refers to the process of changing a saturated granular material from a solid state into a liquid state as a result of increased pore-water pressure during earthquakes (Youd et al., 1975). An initially stable granular material can be transformed quickly by vibration where the solid particles are in suspension, similar to quicksand, and all frictional resistance is lost.

During the 1994 earthquake, such phenomenon occurred on the river floodplain of the Sebarus Valley (within the study area), causing some plants to be uprooted. Approximately 25 cm of subsidence was noted in some areas (DGSM, 1994). In the Suwoh Sub-District (southeast of the study area), pore-water was forced towards the surface and water jets reportedly reached heights of 30 to 40 cm. These water jets contained some sand and muddy sand.

The Sebarus Valley is located along the Kububihan tributary and is situated in the downstream foothills of Mount Selabut and Mount Sipulang. The landscape is flat and geologically, is composed by alluvial deposits with grain sizes ranging from clay to coarse sand. The water table is approximately 0.5 m below the surface and reaches to more than 10 m depth in the surrounding areas underlain by the pumiceous volcanic rocks and older Quaternary volcanic rocks. The differences in geomorphology and geology allow the liquefaction prone area to be identified on the aerial photographs (Plate 3.6). On Landsat TM image, the liquefaction zones show an identical colour-composite image to the man-made cultures, so it is difficult to distinguish between them.

3.5 Landslide Hazards

The term "landslide" is used here as a general term to describe the mass movement of soil and rock downslope under gravitational influence. Landslides result
from natural slope instability and other factors such as material properties, earthquakes and precipitation.

In terms of loss of life and damage, landslides must be included as one of the prominent hazards in the study area. Oversteepened valleys of the Warkuk River on Mount Pesagi collapsed following the 1993 Liwa earthquake. A mass of debris flowed downwards rapidly and swept away part of Bahway village, causing 53 deaths (Natawidjaja et al., 1993). Destruction of land, in term of landslides, was also reported during the 1994 earthquake (DGSM, 1994).

Landslides are also likely to occur during periods of heavy rainfall. In the wet month of February 1995, a landslide closed the road between Liwa and Krui. Two vehicles were pushed off the road and plunged into the Kububihan River. One person died as a result (Rusbani, 1995).

During field investigations (August, 1996), other roads subjected to landslides were found around the villages of Selipas, Kubuprahu and Tanjungkemala and along roads between Bakhu and Batukebayan, Pasar Liwa and Waymengaku, and Tanjungkemala and Buaynyerupa. Some river banks also were found to be susceptible to landslides. A field investigation was carried out following the interpretation of such hazards on the images and these were confirmed (Tables 3.2 to 3.5). Map 2 shows the distribution of known present landslides in the Liwa area.

3.5.1 Landslide Distribution

Land use in the study area consists of populated areas, arable land and rain forest where road access is limited. Considering these limitations, recognition of features on aerial photographs, related to the traces of mass movement, is an effective method, in terms of cost and time, for preparing landslide hazard maps. The interpreted landslides in the affected area were plotted onto a topographic map of 1:50,000 scale. To make the landslide hazard map, the preliminary map was then randomly checked on the ground.
The aerial photograph interpretation is referred to a pattern analysis approach that is based on the premise that the landforms have distinct patterns on aerial photographs (Rib and Liang, 1978). Landforms developed by the same geological processes will have similar patterns but those developed by different processes will show different patterns. Accordingly, the traces of the mass movement will show up as a different image to that of the surrounding areas on the aerial photograph.

Significant features that are interpreted as landslide traces are spoon-shaped troughs, sharp lines of break at scarps and hummocky surfaces of sliding masses below the scarps (Plate 3.3). The shapes of troughs and scarps can be identified because of the three-dimensional view from aerial photographs when seen under a stereoscope. The differences in radiation caused by the shadow aspect, are also helpful for identifying some scarps. The interpreted features from the distribution of the 97 landslides are related to oversteepened morphology, mostly within river valleys and to fault-traces and road cuttings. In some areas, such as along the Kububihan and Tenumbang Rivers and areas between Liwa and Krui, the aerial photographs show the traces of mass movement are concentrated within zones of slightly different tone which look slightly darker than the surrounding areas. The darker tones may correspond to clayey soils and wetter areas (water seepage). These soils and wetter areas were still identifiable on the ground during the field investigation.

Other small landslides that are not recognised on aerial photographs were also found on the ground within the delineated darker tone zones. As a result, the darker tones are interpreted as landslide-susceptible terrains. Besides observing landslides that are not identified on aerial photographs, random ground observations provided checks of the interpretation of landslides and allowed for the verification of the types of landslides interpreted from aerial photographs and Landsat TM images. The numbers
and occurrences of landslides ascertained from data gathered during the field observations are summarised in Tables 3.2 to 3.5.

Landsat TM hard copy images were not used for detailed landslide mapping because the images only give a two dimensional view and have less resolution than aerial photographs. Consequently, only large landslide traces can be recognised on Landsat TM such as along the Robok River and in Penetoh Mountain areas. These appear as arcuate features and have shadow effects (Plate 3.4).

3.5.2 Types of Landslides

The types of mass movements used here are based on the classification of Varnes (1978). By using this classification, materials involved in the movements are described, while the processes that occurred can be interpreted. The classification recognises six principle types of mass movements: falls, topples, slides, spreads, flows and complex types (Fig. 3.1).

Ground observations of areas of mass movements in the study area permitted interpretation of two types of mass movements: slides and falls. Considering the materials involved in the movements, they can be categorised into debris slides and debris slump rock fall, debris fall, and earth fall.

In the various types of falls, materials that are detached move downward, mostly through the air, or along the surface with little or no shear displacement taking place. For slides, the materials move downslope along the surface with shear displacement. The movements may be rotation or translation. The most common rotational movement is slump that may leave spoon-shaped underlying surface ruptures and exposed scarps. Translational sliding occurs along planar or gently undulatory surfaces where the mass has little of the rotary movement or backward tilting characteristic of slumps.
3.5.2.1 Slides

Debris slides and rock masses occur in every rock unit. The landslides are commonly controlled by surface weaknesses such as faults and by discontinuities near or at the soil-bedrock interface. Another controlling factor that can be taken into account in slide mass movement is the discontinuity between two different rocks. The most common trigger factors for every kind of mass movement are earthquakes and precipitation.

A composite of slide and fall, oriented in NW-SE direction, forms scarps along river banks such as along the Semangko River, Kububihan River, Robok River, Rebo River and Menjadi River. These areas are underlain by the pumiceous volcanic rocks. Such scarps are identified in association with the Sukarame Fault and the Liwa Fault (Plates 2.8 and 2.9). On aerial photographs and Landsat TM images, the traces of such mass movements along the river banks often show a shadowy effect (Plates 3.3 and 3.4). Because the faults are currently active due to their relationship with present earthquakes, it is suggested that abundant mass movement has occurred in the area during the earthquakes. In addition, landslides may also occur without being triggered by earthquakes due to the weakness of the areas and the looseness of pumiceous soils situated on the very steep river banks.

The sliding of debris in other parts of study area are more likely to occur along the discontinuities near or at the soil-rock interface and along the discontinuities between two rocks. Abundant debris slides along the road between Bakhu and Batukebayan, near Bukit Tungkutiga, are associated with the highly weathered Tertiary volcanic rocks (Plate 3.7). The intercalation of tuff, in a highly weathered condition, may act as a discontinuity interface that becomes lubricated during the rainy season. The landslides are initiated when the regolith becomes saturated and overloaded with water that increases the pore water pressure. On areas associated with pumiceous rocks that
have little cohesive quality, surface masses commonly slide on such discontinuity planes near soil-rock interfaces. Such landslides occur between Liwa and Waymengaku, and near Selipas village, causing road damage to approximately 250 m and 600 m of the road respectively (Plates 3.8 and 3.9). Similar discontinuities near soil and rock interfaces also cause numerous debris slides along the roadside to Krui from Liwa. This area is situated on the older Quaternary volcanic rocks. Along this line, debris slides also occur along the unconformable contact where claystone of Tertiary sediments are overlain by the older Quaternary volcanic rocks (Plate 3.10). The coincidental direction of slope and claystone dip can be taken as a contributing factor for the sliding of overburden weathered rock, particularly during the rainy season.

Plates 3.7 to 3.9 show various stages of revegetation of the slopes after the debris slides. Almost all steep slopes, whether road cuttings or fault scarps, are slow to revegetate because of the very high precipitation which occurs regularly. Although growth of plants is promoted by the rainfall and high temperatures, the steep slopes and heavy rainfall combine to promote severe erosion on the faces of the slopes, thus removing many plants before they can be properly established. Plate 3.10 is also interesting in that it shows that boundaries between two different lithologies, whether this be for two unit boundaries as in this situation, or different lithologies in the same unit, act as planes of weakness across which debris flows can easily move. Such boundaries probably act as frictionless surfaces.

Beside translational mass movements of debris slides and rock slides, rotational slides of debris slumps also occur. In Tanjungkemala village, debris slumps were identified by the backward tilting of plants near the headwall scarp. These rotational movements were located in highly weathered pumiceous rock. The headwall scarp heights range from 3 m to 10 m. The face of one prominent fracture surface trends
approximately N 60 - 70 E (Plate 3.11). Information given by local people suggested that the landslides occurred during the 1994 earthquake and blocked the road.

3.5.2.2 Falls

Rock falls and debris falls are the most common types of falls in the study area and occur where almost vertical slices of pumiceous rocks break away from the upper part of river-banks on the Liwa Plateau (Plate 3.12). In very steep excavated areas, the less consolidated pumiceous rocks and the loose pumiceous soils are subject to falls. Such excavations were found along the road to Buaynyerupa, between 11 km and 14 km from Liwa (Plate 3.13). Movements after failure commonly include some bouncing or rolling.

On other rocks, rock falls are rare. Approximately 1 km from Liwa to Krui, a highly weathered outcrop of the Old Quaternary Rocks unit, together with its top soil, fell to the road and along the road between Jagaraga and Lombok, some boulders of the younger Quaternary volcanic rock unit have disintegrated and fallen to the road. The scarps have an irregular, more or less concave outward surface.
CHAPTER 4

EARTHQUAKE HAZARD EVALUATION

4.1 Introduction

The study area is categorised as a seismically active zone because it is transected by active faults that are segments of the Sumatera Fault System and historically, earthquakes often occurred in areas along and close to the fault system as well as in offshore areas. The experience gained from the 1994 Liwa earthquake showed that there were different degrees of damage for different geological units. The highest percentage of the damage and the most severe damage and destruction of land, occurred in areas underlain by the pumiceous rock unit and alluvial deposit, close to the fault. On the other hand, liquefaction occurred in the Sebarus Valley that consists of alluvial deposits.

Because of the past damage in the study area, it is essential to evaluate hazards with respects to local geological characteristics for future action to predict likely hazards and consequent damage in theses areas. In this chapter, the recurrence time of earthquakes is estimated by faults and their role in previous earthquake activity. Regional seismicity also has to be examined because earthquakes can affect areas large distances from their epicentres. Landslides will be evaluated in Chapter 5 because their occurrence may also be related to factors not associated with earthquakes.

4.2 Seismicity

The number of earthquakes in the study area, and surrounding areas, is relatively high in number. In a region between 2°SL to 7°SL and 100°E to 107°E, fourteen epicentres with magnitudes equal to and greater than 5 on the Richter Scale were recorded in 1994, the year when the study area was struck by a very destructive earthquake, Fig. 4.1.
Most of the earthquakes had epicentres in the Indian Ocean that corresponds to the present subduction and accretionary zones of the two colliding plates. Deep focus earthquakes were more abundant than shallow focus earthquakes. It is of interest that both earthquakes with magnitudes of ≥ 5 on the Richter Scale caused fatalities. This is partly a function of the population density and it augments the need to provide contingency plans that will reduce the number of fatalities in the future when earthquakes of magnitude ≥ 5 occur. The data also suggest that the chance of an earthquake causing fatalities when the magnitude is ≥ 5 is high.

Regionally, the recorded earthquake history of Sumatera and surrounding areas began in 1661 when a seaquake was observed near western Sumatera. Then a huge catastrophic earthquake was reported in 1883 and the islands located west of Sumatera were destroyed (Newcomb and McCann, 1987). The epicentres of these earthquakes were probably coincident with the Mentawai Fault System, a major strike-slip fault that is parallel to the Sumatera Fault System (Diament et al., 1992). On Sumatera itself, the earliest recorded earthquake was the destructive earthquake in 1892. It was located at Tapanuli, North Sumatera. The epicentre of the earthquake was located along the trace of the Sumatera Fault System. Numerous other destructive earthquakes occurred afterwards and were also located along this fault (Katili and Hehuwat, 1967; Natawidjaja and Sieh, 1994). Examples are the Kerinci earthquake of 1909, the Liwa earthquakes of 1933 and 1994, and the Sungai Penuh earthquake of 1994 (Fig. 4.2; earthquakes post 1892 only are shown as the epicentres for earlier earthquakes is uncertain).

Besides the relationship between earthquakes and faults, another interesting phenomenon is that of the tendency for hazardous events to re-occur. An example of this tendency is the Kerinci Earthquake in 1909 and the Sungai Penuh earthquake in 1994 where the destruction took place in almost the same areas.
The earthquake recurrence interval in Sumatera has been analysed by the linear regression method, using the earthquake data within the period of 1967 to 1994 (Sun and Pan, 1995). The analysis found that very large earthquakes of a magnitude 8.5 have a recurrence interval of 430 years, 283 years, and 204 years if the maximum magnitude of possible earthquakes in Sumatera are assumed to be 8.75, 9.0 and 10, respectively.

4.3 Faults

Fault evaluation, based on an understanding resulting from studies of the behaviour of a known fault, can be used to interpret the potential of that fault to contribute to future earthquakes and the consequent hazards associated with earthquakes. The three faults in the study area have experienced movement within the Quaternary period. Sudden movements in the present century have generated earthquakes and damage. The occurrence of earthquake epicentres and the relationship between faults and geological units is presented in Figure 4.3 and Table 4.1. (it should be noted that Figures 4.2 and 4.3 show that the association of faults and earthquakes occurs on a regional scale as well as a local scale, with both associations being a function of the tectonic activity of Sumatera and Indonesia as a whole, suggesting that this study may have relevance to other parts of Indonesia.) The epicentre data covers the period from early 1931 to late 1995. This may appear to be a very short period from which to estimate recurrence interval. However, the data covers the dates of two large destructive earthquakes that had almost similar surface wave magnitude (the destructive earthquakes in 1933 and 1994). Their epicentres were also in almost the same location. These earthquakes were also caused by the sudden slipping of the same faults, the Sukarame Fault and the Liwa Fault.
Plotting the epicentre locations on a geological map also shows that for earthquakes within the period of 1931 to 1995, the epicentres are concentrated near the Sukarame Fault and the Liwa Fault. Extrapolating these data suggests many, if not most, future earthquakes will occur in the same area in the immediate and possibly medium-term future. The only epicentre close to the third major fault in the area, the Kubuprahu Fault, was the earthquake of medium focal depth that occurred on October 4, 1969. There is no report on any other related earthquake damage or movement along the Kubuprahu Fault. To reinforce this, no damage was found along the Kubuprahu Fault during the destructive Liwa earthquakes in 1933 and 1994.

Identifying the relationship between Kubuprahu Fault lineament and geological units suggests the fault has been inactive since the eruption of the younger Quaternary volcanic rock unit. K-Ar dating (Amin et al., 1994) gave 0.1 million years age for rocks of this unit in south-east of study area.

A study of the Sumatera Fault System, from the north-west edge to the south-east edge, using SPOT images indicates the evolution of the fault system (Bellier and Seberier, 1994). Figure 4.4 provides a summary of the study. The study considered the present pattern in the southern part of the Sumatera Fault System as pertaining to two major NW-SE trending fault segments, the Ranau Suwoh Fault segment and Semangka Fault segment. Both are connected by a releasing stepover fault zone (Figure 4.5). The Sukarame Fault, accordingly, represents the main fault that is regionally called the Ranau Suwoh Fault, whereas the Liwa Fault can be considered to be a branch of the Ranau Suwoh Fault. An important stage in the evolution of the fault system was the generation of a new fault segment that substitutes for an extinct segment along the Sumatera Fault System. In the study area, the extinct segment is represented by the Kubuprahu Fault. Since the evolution has been accompanied by volcanic activity, and whereas the Kubuprahu Fault does not offset the younger Quaternary volcanic rocks, the
age of the new strike-slip fault segment is estimated to be as old as the younger Quaternary volcanic rock unit. This age is used in the estimation of the earthquakes recurrence time for the study area.

4.4 Earthquake Recurrence Time

Estimation of the earthquake recurrence interval in the study area is based on the Wallace Theory (Wallace, 1970) which uses slip rate data and the length of ground displacement during an earthquake event. The theory considers that slips along an active fault are accumulations of intermittent sudden slips associated with earthquake and fault creep. The relationship can be formulated as follows:

\[ R = \frac{D}{S - C} \]  

where

- \( R \) = average earthquake recurrence time
- \( D \) = average displacement per-earthquake event
- \( S \) = slip rate, from offset of geological unit
- \( C \) = fault creep rate

Fault creep is the slow gradual movement along a fault and is not accompanied by an earthquake. The creep allows the strain in the crustal rocks to be relieved. As a result, the magnitude of the earthquake becomes less because part of the stored energy has been released. Alternatively, the elapsed time of the earthquake becomes longer because there is a need for a longer period of time to store the accumulated energy to reach the maximum elasticity of the rocks.

The creep effect may be seen as the offset of some structures when a fault cuts across a settled area. In the study area, there are no data or reports on the structural damage related to offsets caused by creep along the Sukarame and Liwa Faults, the
faults that caused the 1933 and 1994 earthquakes. This is possibly because the creep is very small, or did not occur. The accumulated energy is mostly, or only, released by sudden displacements resulting in frequent earthquake events. In these circumstances, the role of fault creep on the offset of a geological unit can be neglected in comparison with the role of sudden slip during the earthquakes. Consequently, equation (4.1) can be simplified as follows:

\[ R = \frac{D}{S} \]  

(4.2)

### 4.4.1 Displacement during Earthquakes

Ground displacement during an earthquake provides useful data for estimating earthquake recurrence time. The displacement can be directly measured in the field once the earthquake has occurred. Alternatively, it can be calculated using intensity data from the earthquake. Mark and Bonilla (1977) formulated a relationship between the intensity of an earthquake and the displacement along the strike-slip fault as follows:

\[ I = 6.974 + 0.804 \log D \]  

(4.3)

where

- \( I \) = intensity of earthquake, in Richter scale
- \( D \) = displacement during earthquake, in metres.

Intensity data for both the 1933 and 1994 Liwa earthquakes are available. For the 1933 Liwa earthquake, there are many interpretations of Richter scale intensity values which range from 6.5 to 7.5, with an average of 7.0 (GSDM, 1994). Using a value of 7.0, equation (4.3) gives a ground displacement of 1.077 m. For the 1994 earthquake, where the average intensity was 6.5 on the Richter scale, equation (4.3)
provides 0.257 m of ground displacement. Taking into account both the field data and the calculated values, the average ground displacements are 1.04 m and 0.29 m for the Sukarame Fault and the Liwa Fault, respectively.

4.4.2 Slip Rates

The slip rate of the faults that caused the Liwa earthquakes can be calculated from the offset of streams, from the age of the fault or the age of the geological unit related to the generation of fault. The offset of the Robok River near Sukarame village is related to the Sukarame Fault, whereas the offset of the Robok River near Waymengaku is related to the Liwa Fault. These offsets can be identified both on Landsat Thematic Mapper images (Plates 3.2 and 3.4) and on the topographic map of scale 1:50,000. Measurement of the offsets on the topographical map gives a distance of approximately 700 m and 350 m for the Sukarame Fault and the Liwa Fault, respectively. The fault related to the offsets are part of the Sumatera Fault System that, according to Katili and Hehuwat (1967) has been active since the Lower Pleistocene. All activity along the fault commonly displays prominent horizontal movements. Based on this, the offsets of the Robok River can be considered to be an accumulation of displacements that are associated with all the earthquakes that have occurred, with perhaps a very small contribution from fault creep. Assuming this, the slip-rate can be calculated by dividing the length of geological offset by the age of the fault of a related geological unit. Thus:

\[
S = \frac{L}{t}
\]  

where \( S \) = slip rate  
\( L \) = length of the offset  
\( t \) = age of fault
As given in Section 4.3, the age of the fault is as old as the younger Quaternary volcanic rock unit which have been dated by K-Ar method, to be 100,000 years.

4.4.3 Calculations

The 1933 Liwa earthquake was related to the Sukarame Fault because most destruction of the land surface was along surface ruptures (Berlage, 1934) which coincided with the Sukarame Fault. During the 1994 Liwa earthquake, the Sukarame Fault was also activated, but the main destruction was ground faulting with some displacements (GSDM, 1994) along the Liwa Fault. The highest concentration of after-shock epicentres (Harjono et al., 1994) also took place along the trace of the Liwa Fault. From these phenomena, it is concluded that the 1994 earthquake was more likely to be related to the Liwa Fault rather than to the Sukarame Fault and for the 1933 earthquake vice versa. Accordingly, the recurrence interval for the 1933 earthquake is calculated with respect to the 700 m stream offset near Sukarame whereas for the 1994 Liwa earthquake the recurrence interval is calculated with respect to the 350 m stream offset near Waymengaku, Liwa. Since the absolute age of the younger Quaternary volcanic rocks is known and the average displacement related to each earthquake in 1933 and 1994 can be obtained, equation 4.4 provides recurrence intervals for the earthquakes. These are 148 years and 65 years for the Sukarame Fault and the Liwa Fault, respectively. It should be noted that the ages are statistical probabilities and therefore represent an expected time rather than an absolute time.

Based on statistical probability, potentially destructive earthquakes, with epicentres in the study area, will occur once on every 65 years. Other destructive earthquakes with epicentres outside the study area could occur earlier. The effects of these unpredicatable earthquakes may cause damage, perhaps as much as the
earthquakes associated with the Sukarame and Liwa Faults in specific parts of the study area. Experience from the 1994 Liwa earthquake indicates the propensity of a susceptible area to damage (besides the area along the lineament of active faults) was related to geological characteristics and these need to be evaluated.

4.5 Ground Shaking

The discussion in Sections 3.3.1 and 3.3.2 established the most intensive destruction during earthquake is likely to be located in areas close to both or either the Sukarame and Liwa Faults, especially if those areas are coincidentally located on the pumiceous volcanic rocks. The evidence suggests spatial variation effects are likely to be related to the distance from the focus of earthquakes, the source of energy release and the local geological conditions.

4.5.1 Variation in Damage with Distance

The effect of ground shaking on man-made structures tends to diminish with increasing distance from the source of the energy. The Krui Sub-District was the most distant part of the study area from the epicentres of both the 1933 and 1994 earthquake and from the faults which caused the earthquakes. In Krui, 20 km from the 1994 epicentre, no buildings collapsed. In contrast, other areas that were located 8 km or less from the epicentre or the faults, had a large number of buildings collapse. This phenomenon can be explained by the decreasing earthquake energy with increasing distance from the source of the energy. Doyle (1995) stated that the energy of the seismic waves is absorbed during their propagation. The forces on buildings are commonly expressed by peak horizontal acceleration of the waves. A study based on California’s earthquakes (Page et al., 1975) showed that peak acceleration is inversely proportional to the distance from the source of the energy. By referring to available
earthquake data, Seed and Idriss (1982) also showed that acceleration decreases with increasing distance from the source of the energy. Abraseys and Zatopek (1968), in studies of the Varto Ustukran earthquake in Anatolia, gave useful information on the energy associated with that earthquake.

The epicentre or source of energy for the 1994 Liwa earthquake is located below a valley between Liwa and Sebarus. The areas along the faults also experienced strong vibrations due to slip that occurred on the faults. The large number of buildings that collapsed and the damage in Buaynyerupa, a village that is located approximately 14 km away from the epicentre, is interpreted as being related to the Sukarame Fault that transects the village. Another factor that may have contributed to the large number of collapsed buildings and damage in Buaynyerupa, is the lithology underlying the village which will be discussed below.

4.5.2 Effects of Geology

For areas that are located close to the earthquake epicentre and faults that caused the earthquakes, ground shaking is sufficient to cause significant damage to ordinary structures such as houses, and cause significant damage to the surface of land. The interest in ground shaking effects in the study area is because the greatest damage and destruction is more likely to occur in areas underlain by pumiceous volcanic rocks rather than adjacent areas underlain by the older Quaternary volcanic rocks. Physically, these two lithological units have different characteristics and it is these differences that are assumed to be the factors responsible for the different responses to ground shaking which, in turn, causes differences in the degree of damage and destruction.
Studies around the world indicate that the intensity of ground shaking during earthquakes, and associated damage to buildings, is influenced by local geological and soils conditions. Evidence shows that the greatest damage occurs in areas underlain by soft soils or young sediments. Examples are the San Francisco earthquake of 1906 (Borcherdt et al., 1975) and the Northridge earthquake of 1994 (Stewart et al., 1994). According to Doyle (1995), the amplitudes of seismic waves at given distances from an epicentre vary a great deal depending on the geological conditions. Ground vibrations are amplified by soft soils and younger sediments because the low rigidity of soft soils and younger sediments cause low shear wave velocity. Consequently, vibrations of the ground are amplified. Such soils and sediments will be in resonance with the incoming seismic wave.

The different intensity of damage in the pumiceous volcanic rocks and the adjacent older Quaternary volcanic rocks is hypothesised to be related to the effect of soft soil as well as the effect of being near epicentral factor. The pumiceous volcanic rocks is predominantly composed of less consolidated sandy tuff. Soils formed on this rock comprise loose sand more than 5 m thick. The loose nature of the soils is the cause of the landslides (earthfall type) in roadside excavations. On the other hand, the old Quaternary volcanic rocks have clayey soils which are relatively firm. A study of the physical characteristics of the soil in the Liwa area was undertaken by Sudarsono et al. (1994). The methods that were applied included shallow drilling combined with the dynamic standard penetration test (DSPT). The results show that soils above the pumiceous volcanic rock unit are loose to very loose sandy soils. The thickness of the soils is more than 10 m. For the old Quaternary volcanic rocks, the soils are clayey with thicknesses less than 10 m; some soft clayey soils are less than 2.5 m thick.

The thickness of soils is thought to be a factor that is important in amplifying seismic waves. The thicker the soil, the greater the amplification of the seismic waves.
and, in turn, causes a higher degree of damage in the areas developed on the pumiceous volcanic rocks than in adjacent areas above the older Quaternary volcanic rock unit. Besides the amplification factor, the looseness of the sandy soils is assumed to be another factor responsible for the widespread landslides. The high number of collapsed buildings in Buaynyerupa village is also probably caused by the amplification in the young deposits of alluvium.

4.6 Liquefaction

The part of the study area that has experienced liquefaction is the floodplain located in Sebarus Valley. The plain is crossed by the Kububihan River and is composed by unconsolidated alluvial sand deposits. During the field study, a well on the plain indicated that the water table is approximately 0.5 m below the surface, and the alluvial is more than 5 m thick. These values are probably good estimates for each of the water table depth and the alluvium thickness. From these data it can be determined that the unconsolidated sediments extend from the surface to below the water table and are in a water-saturated condition.

According to Berlin (1980), Seed and Idriss (1982) and the Committee on Earthquake Engineering (1985), an unconsolidated deposit of saturated sand tends to compact and decrease in volume when it is subjected to shaking. If drainage is stopped, the decreasing volume increases pore water pressure. In a state where the pressure is equal to the overburden pressure, the effective stress becomes zero and the sand loses its strength completely and is in state of liquefaction.

During the 1994 earthquake, the alluvial sand showed approximately 25 cm of subsidence and some plants were uprooted (Chapter 3). From these phenomena, it is interpreted that the earthquake caused the grains of the sand to move closer together,
resulting in settling. This also caused the sediments to become buoyant due to the
increasing pressure thus resulting in some plants being uprooted.

Adjacent areas, where the liquefaction did not occur, are underlain by the
pumiceous volcanic rocks of Plio-Pleistocene age. The water table in the pumiceous
rock is deep, at approximately 10 m. These conditions are different to those in the
alluvium which was subjected to liquefaction. It is concluded that the pumiceous rocks
are not subject to liquefaction.

4.7 Summary

In this Chapter, it has been shown that the major earthquakes that have occurred
on the Indonesian Island of Sumatera have been associated with the faults and that this
applies to the study area as well. From this association it can be postulated, that many if
not most earthquakes that will occur in the future will also be associated with faults.

The recurrence time for earthquakes of the magnitude of the 1933 and 1994
Liwa earthquakes is of the order of 65 to approximately 150 years. For earthquakes of
this order of magnitude, offsets of almost 1 kilometer can be expected and average
ground displacements will be of the order of 0.3 to 1 m.
CHAPTER 5
LANDSLIDE HAZARD EVALUATION

5.1 Methodology

Evaluation of landslide hazards in the study area focuses on the spatial variability by considering the possibility of landslide occurrence in relation to the factors causing them. These factors, according to Ward and Simons (1979) can be divided into two large categories, the internal causes or controlling factors and the external causes or triggering events. Controlling factors may be broadly divided into the properties of the media that in turn are related to geological conditions and terrain conditions. The triggering events include earthquakes, precipitation and human interaction.

Considering both the geological conditions and the terrain conditions, identification of landslide zones shows that factors that contribute to the occurrence of landslides in the study area are geological conditions and slope gradients. Evaluation based on these inherent factors gives clues as to those areas likely to suffer future landslides when triggering factors are imposed. To reach the evaluation targets, two attribute maps, one a slope class map (Map 3) and the second a geological map (Map 1), are provided as well as a landslide inventory map (Map 2). The attribute maps covering the study area and the landslide inventory map were digitised using the software of the Geographic Information System (GIS) ARC/INFO 3.4D+. Analysis was facilitated by overlaying the three maps.

5.2 Geological Map

The geology of the study area is presented in map form (Map 1). This map is a combination of the existing geological map, provided by the Indonesian Geological
Research and Development Centre (Amin et al., 1994) with general field data that not only provided a check on those data obtained from the digital images but also provided additional data. The map shows the spatial distribution of general rock types and structural geology. Both of these factors influence \textit{in situ} rock unit strength and loss of strength through physical and chemical weathering (Terzaghi et al., 1996) which, in turn, influences landslide potential of the rocks. Therefore, overlaying a landslide map with a geological map may indicate the areas for each rock unit where future landslide events are likely to occur.

5.3 Slope Class Map

A slope angle map is not a precise measure of slope stability. However, it provides data that are adequate for the study and as a rule of thumb, slope contributes to instability and angles cannot be neglected. This is described in Figure 5.1 where increased slope promotes instability or even failure of the slope. Considering the relationship between slope angle and slope instability, overlaying a slope class map with landslide distribution map may indicate areas for each slope class unit where landslides are more likely to occur.

The slope class map for the study area (Map 3) is derived from a topographical map of scale 1: 50,000 with 25 m contour intervals. A simple mathematical method is applied to calculate and group the slope steepness into a range of slope percentages. This range is taken from Ward and Simons (1979). The suggested ranges of slope steepness are:

- $<5\%$
- $5\%$ - $15\%$
- $15\%$ - $30\%$
- $30\%$ - $70\%$
and $>70\%$.

In summary, a slope class map generally reflects the topography of the area that it depicts. Such a map is needed in later evaluation of the hazards because there is a good correlation between hazards, such as landslides, and the slope of the landscape. In this study, the gradient of the slopes was found to be a significant factor influencing and in some cases controlling the intensity of some hazards.

### 5.4 Data Analysis and Limitation of GIS

Overlaying layers of a geological map and a slope class map with a landslide map is the basic methodology for spatial landslide evaluation (Maps 4 and 5, respectively). Utilising GIS ARC/INFO to overlay the maps, provides quantitative data which shows each component (rock unit, slope class unit) that contributes to the landslides. Therefore the data can be used to define the zone or zones that show potential for future landslide activity. Features of the map provided by the ARC component are described by the INFO component in numeric form. Such numerical data, resulting from overlaying a geological map and a landslide map are the area or width of the geological unit occupied by landslides and the area or width of the unit without landslide. Analysis and manipulation of the data provides a risk factor map. The data are developed by using an arithmetic operation such as multiplication and division. The rating of each unit on a risk factor map (rock unit and slope class unit) for risk of future landslides is expressed as the landslide weighting value for each unit. The landslide weighting value for each unit (each given geological unit, each given slope class unit and each given geological unit for each given slope class) is defined as the percentage of landslides that occurs in a given unit, divided by the percentage area or width of the given unit:
\[ W_{xi} = [%LS_{xi} : [%X_i] \right) \] (5.1)

where \( W_{xi} \) = landslide weighting value of variable \( i \)
\( %LS_{xi} \) = percentage area of landslide in variable \( i \)
\( %X_i \) = percentage area of variable \( i \)

The percentage area of landslide in variable \( i \) and the percentage area of variable \( i \) is defined as follow:

\[ %LS_{xi} = [LS_{xi} : [LS \cdot [100\%]] \right) \] (5.2)

\[ %X_i = [X_i : [X \cdot [100\%]] \right) \] (5.3)

where \( LS_{xi} \) = total area of landslide in variable \( i \)
\( LS \) = total area of landslides on the map
\( X_i \) = total area of variable \( i \) on the map
\( X \) = total area of the map (minus ocean and minus lake)

The landslide weighting value for each variable (each geological unit, each slope class unit and each given geological unit for each slope class) is presented in Tables 5.1 to 5.3. In each table, the total area of landslide is obtained by summing the landslide areas in all given units whereas the total area of the map is obtained by summing areas with landslides and areas without landslides in all given units. There are differences in the calculated total landslide area and for the total area of the map in each table. These differences are related to the difference in spatial forms between geological units and slope class units. With GIS, an area is represented by the number of polygons (pixel or picture elements) that cover the area. Since the spatial patterns of geological units are
different to the spatial patterns of slope class units, the total number of polygons resulted by summing the polygons which cover each geological unit may be different to those obtained by summing the number of polygons which cover each slope class unit. This difference represents the limitation of using GIS to sum areas on a map to obtain the total area of the map.

In this study, the total landslide areas in Tables 5.1, 5.2 and 5.3 are 29,596,871 m², 29,598,671 m² and 29,596,873 m² respectively; whereas the total areas of the map are 1,144,098,391 m², 1,144,100,211 m² and 1,144,098,456 m² respectively. This means that the maximum deviation from the average value is:

i) 0.004% for calculation of the total landslide area
ii) 0.0001% for calculation of total area of the map

5.5 Influence of Geological Conditions on Landslides

The landslide weightings for the risk of landslides in each rock unit is described quantitatively in Table 5.1. The highest and the lowest landslide weighting is in the pumiceous volcanic rocks (QTr) and alluvium deposits (Qa), respectively. Most landslides in the pumiceous volcanic rocks occur along river banks which trend NW-SE. Several landslides commonly combine to form a long landslide scarp. The weakness of weathered the pumiceous volcanic rocks often causes mass creeping along the surface of scarps. This phenomenon suggests physical weakness is a factor that contributes to the density of landslides.

Another factor that can be taken into account is earthquake-triggering events. Some streams, where landslides are associated, are controlled by the faults that caused earthquakes. Since higher vibrations occur along the faults due to the sudden slip when an earthquakes occurs, the earthquake-induced landslides are expected to be greater in number in the pumiceous rocks than other rocks which are not transected by the faults.
An earthquake is also a triggering factor for landslide in alluvium deposits. Alluvial deposits have the lowest landslide weighting in Table 5.1. Landslides in the alluvium deposits were found along the river bank controlled by Sukarame Fault in the north-west part of the study area.

In the young Quaternary volcanic rocks (Qhv), the landslide weighting is also low. Significant landslides in this rock unit occur in the Mount Pesagi and Mount Penetoh areas, in the northern and southeastern parts of the study area, respectively. In these mountainous areas, landslides are associated with steep slopes and streams. The similar topographic expressions for the two areas suggest that landslides in the Mount Pesagi and Mount Penetoh area were caused by a similar triggering event. This suggestion is made after considering the number of earthquakes around the world where local conditions were affected by the topography during the earthquake (Aki, 1993). A simulation model also suggests vibrations are amplified by steep slopes (Ashford et al. 1997). It has already been mentioned above in Section 3.4 that the triggering mechanism for the Mount Pesagi landslides was the 1933 earthquake. The indigenous people who were questioned during the field study suggested that this was the cause of the landslides in Mount Pesagi area. These people live in the downstream part of Mount Pesagi. They provided anecdotal evidence of the timing of the landslides which was coincident with the earthquake activity.

Landslides in other lithological units are related to streams that transect areas with steep slope. The different weightings given to these, reflect the difference in physical properties of related rocks. An example of this are landslides in the slope class 50%-70% along the Simpangkkanan River, located west of the Liwa to Krui road. In this area, landslides are likely to occur in the Tertiary volcanic rock unit rather than in the Tertiary Sedimentary Rocks unit (Map 4 and Map 5). The landslide weighting for the
risk in this slope class is 9.466 and 5.326 for the Tertiary volcanic rock unit and the Tertiary Sedimentary Rocks unit, respectively (Table 5.3).

5.6 Influence of Slope on Landslides

Calculated landslide variations in each slope class unit are presented in Table 5.2 and these are transcribed spatially on Map 5. The table shows that the highest weighting for any landslide is for the slope class that ranges from 50% to 70%. Significant landslides in this class unit occur along very steep river banks. Landslides are also common where steep slopes are disturbed by human activities such as excavations. In relation to the river banks, the occurrence of landslides may be triggered by the high soil moisture; whereas on the excavation areas, the landslides are triggered by the dramatic increase in slope steepness.

The second highest landslide weighting is in the slope class of >70%. This class covers the Mount Pesagi area and a crater-like area (Section 2.3) near Limaukunci village, west of Liwa. In this class, landslides have only occurred in the Mount Pesagi area. These have been discussed in the previous section (Section 5.5). The absence of landslides in the former crater near Limaukunci will be discussed in the next section (Section 5.7).

An interesting point on weighting values is shown in Table 5.2 where the landslide weighting for the slope class of 0% to 5% is higher than in the slope class 5% to 50%. The higher weighting in the slope class 0% - 5% is related to the almost vertical banks in the upper parts of the Robok River which are associated with the Liwa Fault which caused 1994 Liwa earthquake. Thus, it appears here that it is not the slope of the topographic surface that is important, it is the river bank that is the critical factor. However, one must be careful when taking this interpretation too far as very steep
slopes on narrow river banks cannot be represented on a 1:50,000 scale map and would be classed as 0-5% slope because of this.

5.7 Factors Controlling Landslides

An evaluation of factors controlling the occurrence of landslides in the study area is limited to geological and slope gradient factors. The overlaying of a landslide inventory map, a geological map and a slope class map, provides the data presented in Table 5.3. These data indicate that the weighting values, which reflects the potential degree of landslide risk, tends to increase with increasing slope gradients in each lithological unit. Deviation from this trend can be explained using the rule of triggering factors, particularly earthquake, where the study area is prone to the hazard. The deviations are as follows:

1. In the older Quaternary volcanic rocks (Qv), the landslide weighting is higher in the slope class 5% to 15% than in slope class 15% to 30%. The overlay of slope class and landslide distribution (Map 5), shows numerous landslides within the slope class 5% to 15%. These occur in an area located southeast of Liwa where the landslides are associated with the Kububihan River. This area is located along the Liwa Fault (Map 4) where sudden slip along the fault caused the 1994 Liwa earthquake. The epicentre of this earthquake was located southeast of Liwa (Section 3.3) near Sebarus village. It caused severe ground shaking in nearby areas. The earthquake, accordingly, triggered the landslides that occurred along the bank of Kububihan River to the southeast of Liwa.

Another deviation is related the older Quaternary volcanic rocks where the slope class of >70% has no landslides. The area is an arcuate zone around a former volcanic crater (Section 2.3) located near Limaukunci village, west of Liwa (Map 5).
The magnitude of the gravitational force (Fig. 5.1) in this area with a high slope gradient may explain the absence of landslides, since the increasing force does not allow any material that accumulates to form a sufficient or efficient landslide supply. Erosion on this slope class is quite high.

2. In the pumiceous volcanic rocks (Qtr), slopes with a gradient in the range from 5% to 15% have a larger landslide weighting than in the range of 15% to 30%. This rock unit is spatially distributed under the Liwa Plateau and streams in this area commonly trend in a NW-SE direction. On the geological map, the trend is likely to be controlled by active faults, in this case the Liwa Fault and the Sukarame Fault. Numerous landslides occur along the stream banks and they mostly trend in a NW-SE direction.

On the overlay map (Map 5), streams which have a NW-SE trend and that are controlled by faults are more abundant in the slope class 5% to 15% than in the slope class 15% to 30%. Accordingly, the landslide weighting for the slope class 5% to 15% is higher than the weighting for the slope class 15% to 30%.

3. For the Tertiary volcanic rocks (Tv), the landslide weighting in the slope class 15% to 30% is lower than that of the slope class 50% to 70% and there are no landslides in the slope class 30% to 50%. The triggering factors may explain this phenomenon.

Areas that have a slope class of 15% to 30% are located in the eastern part of the study area, between Bakhu and Batukebayan villages. In this area, landslides are found along the roads. A similar association is also found along the road from Liwa to Krui that is underlain by the Tertiary volcanic rocks and falls within the 50% to 70% slope class. In these areas with high slope gradients, landslides are also related to streams. Seepage of groundwater may also trigger landslides. On the other hand,
areas of the Tertiary volcanic rocks with the slope class of 30% to 50%, have no landslides. However, roads or streams are few. These factors may explain the absence of landslide within this slope gradient range. Areas with such conditions are located west of Batukebayan village.
6.1 Introduction

Effects of geological hazards in an area can be reduced if the use of land is planned with respect to the previous hazard information. Maps that show the hazard risk zones (such as slope stability Map 6 of this thesis) can be particularly effective in reducing future damage from these hazards. The hazard zoning in Liwa and surrounding areas provides information regarding the relative degree of seismic and landslide hazards. Plate 3.1 clearly shows the degree of damage that can occur to buildings when earthquakes of magnitudes 6 to 7 are located close by. This can be used as a general guide for planning in the area, but it cannot substituted for site-specific geologic investigations.

Seismic hazards in the study area are divided into two categories - hazards along the fault traces which cause the hazard (ground displacement and surface rupture) and hazards related to ground shaking which can be shown as the relative intensity of damage and liquefaction they cause. Hazards from seismically induced slope failure will be assessed in the slope stability analysis because post-earthquake studies cannot differentiate between earthquake-induced landslides and landslides caused by other factors.

It has been shown that most damage in the Liwa area is caused by earthquakes associated with faults and slip/debris flows. In both cases, the gradients of the slopes have a strong influence on the degree of damage that occurs. Thus any geological hazard zonation must delineate the areas of earthquake activity (Map 7), the areas where land slip is likely to occur and then take cognisance of the slopes and the geology.
6.2 Hazards along Faults

Faults (Figs 2.8 and 2.9) represent zones of crustal weakness and various seismic events always have been, are, and will continue to be related to these. Related hazards during earthquakes are ground displacement and surface rupture. The extent of the rupture can be clearly seen in Plates 2.8 and 2.9. In Figure 2.8, using the house as a scale, the throw of the fault is of the order of at least 30 m at this locality. Fault creep, that is a very gradual movement, also may occur along faults within the elapsed time of earthquake events.

The width of the affected area along the faults causing the historic catastrophic Liwa earthquakes has never been reported. However, comparative data may be gained from North America earthquakes caused by strike-slip faults. An assumption is that the effects of the North American earthquakes are similar to those of Indonesian earthquakes, giving similar earthquake magnitudes and similar influences by geological factors irrespective of the underlying lithologies. Whilst this assumption may not be absolutely accurate, using it probably gives ‘ball-park’ comparisons which are not likely to be orders of magnitude out. Where earthquake magnitudes range from 5.5 to 8.5 on the Richter scale, the maximum width was 92 m from the central line of the main fault to the edge of affected area (Wesson et al., 1975). Since the magnitude of the Liwa earthquakes range from 6.5 to 7.5 on the Richter scale, the width area affected along the faults is probably less than 92 m.

It has been deduced that Sukarame Fault and Liwa Fault caused the earthquakes in the study area. Therefore areas along these faults have a high risk for future seismic events. Kubuprahu Fault is the only fault in study area that is categorised as an inactive fault. But it is naive to conclude that no future earthquake will be related to this fault. Nature is not that simple. Individual segments of the Dixie Valley Fault in Nevada produce large earthquakes once every few thousands or even tens of thousands of years...
In the event of an earthquake, the land adjacent to the Kubuprahu Fault could develop into a significant hazard zone if the fault causes an earthquake in the future.

6.3 Ground Shaking and Related Hazard

Inversions of the body wave from the 1994 Liwa earthquake suggest the dip of Liwa Fault is 87° (Hidayat and Widiwijayanti, 1995). This means that epicentres of any earthquake caused by sudden slip along the fault are very close to the fault lineament (Fig. 4.3). Studies after the main shocks described the epicentres of both the 1933 and 1994 Liwa earthquakes as located on or very close to Sukarame Fault and Liwa Fault, respectively, and as stated before these were in the study area. Considering the magnitude of the earthquakes (7.5 and 6.5 Richter scale), all parts of study area are within the damage radius which according to the Krinitzsky and Chang (1988) method is in the near field or epicentral area. Within this radius, reflection and refraction of seismic waves are very complicated and are usually associated with resonance effects. As a result, all parts of the study area could be subjected to strong ground shaking if a seismic event comparable to 1933 and 1994 Liwa earthquakes were to occur again. Damages would vary according to the variation in lithological characteristics and the topographical variation.

Lessons from the previous earthquakes lead to conclusion that the pumiceous volcanic rocks unit is susceptible to large scale damage and this is caused by the weakness and the looseness of the weathered rock. Parts of the Buaynyerupa and Sebarus areas are underlain by alluvium deposits and these are also weak and loose. These characteristics of alluvium are considered to be factors that promote the high level of damage in Buaynyerupa. In spite of these factors, water table depth and the thickness of alluvium in Sebarus may cause such deposits to be subject to liquefaction.
Damage in other parts of the study area is relatively lower, and accordingly, they are categorised as moderate earthquake hazard zones except along the fault traces that have been discussed.

These categories of damage, related to ground shaking and fault lineaments, were overlain on the geological map (Map 1) and then the GIS used to create an earthquake hazard risk map (Map 7) from this information.

6.4 Relative Slope Stability

It was shown in the previous chapter that evaluation of landslide distribution provides a method for classifying the land surface in terms of relative slope stability, or the relative susceptibility of the land surface to landslides. The calculated landslide weighting for each rock unit in each slope class (Table 5.3) is converted to a chart (Figure 6.1). For each lithological unit, the charts show the following trends:

(a). In general, landslides are unlikely to occur within the slope class 0% to 5% in each rock unit except where the pumiceous volcanic rocks (QTr) and alluvial deposits are present. Exceptions are narrow areas along the banks of the Robok River, north of Waymengaku, where abundant landslides occur on pumiceous rock, and along the Warkuk River, near Buaynyerupa in the northwestern part of the study area, where alluvium deposits are subject to failure. These landslides are related to the Liwa Fault and Sukarame Fault.

(b). In the higher domain slope class of 5% to 30%, the landslide weighting is still relatively low. A deviation from this trend is for the pumiceous volcanic rocks (QTr) which has a high landslide weighting in slope class 5%-15%. This deviation
is related to the intensive faulting in the pumiceous volcanic rocks with slope class 5%-15% and also related to the weakness of the rock unit.

(c) A dramatic change in landslide weighting occurs:

i) from slope class 30%-50% to slope class 50%-70% in the lithological units of the younger and older Quaternary volcanic rocks (QHv and Qv) and the Tertiary sedimentary rock unit (TSc); and

ii) from slope class 15%-30% to slope class 30%-50% in the pumiceous volcanic rocks (QTr); a similar condition in the Tertiary volcanic rocks (Tv) is predicted to occur if the rock unit does not absence in the slope class 30%-50%. This prediction is because of the tendency for the landslide weighting to increase slightly from slope class 5%-15% to slope class 15%-30% and increase dramatically from slope class 15%-30% to slope class 50%-70%.

By overlaying the landslide weighting patterns over the slope class of each geological unit, slope stability in the study area is divided into four categories ranging from unstable areas, where landslides are very likely to occur, to stable areas where landslides are unlikely to occur. The categories are:

**Category 1 or Highly Unstable Slopes**

There is only one subcategory for this category:

*Areas underlain by landslide deposits

**Category 2 or Moderately Unstable Slopes**

Subcategories for this category are:
Category 2 or Moderately Unstable Slopes

Subcategories for this category are:

* Areas which are not underlain by landslide deposits
* Areas with slope gradients >30% in QHv, Qv, and TSc
* Areas with slope gradients >15% in QTr and Tv

Category 3 or Moderately Stable Slopes

Subcategories for this category are:

* Areas which are not underlain by landslide deposits
* Areas with slope gradients >5% excluding gradients in Category 2

Category 4 or Generally Stable Slopes:

Subcategories for this category are:

* Areas which are not underlain by landslide deposits
* Areas in slope class 0%-5%.

Putting each category on a map (Map 5), which was created by overlaying the landslide map and the slope class map, produced a new slope stability map (Map 6). The map shows four slope stability risk zones. They are highly unstable slopes, moderately unstable slopes, moderately stable slopes and generally stable slopes.

6.4.1 Category 1 - Highly Unstable Slopes

Areas that have experienced previous landslide hazards are categorised as highly unstable slopes. These areas include the mappable areas affected by intensive small individual landslides where the distances between landslides are unmappable but excludes small individual landslides which are unmappable given the scale of the maps.
used. Areas in this category have gradients ranging from 0% to 90% and can be underlain by any rock unit in study area. However, they are underlain most commonly by the pumiceous volcanic rocks, the Tertiary volcanic rocks, the older Quaternary volcanic rocks and the younger Quaternary volcanic rocks. This category comprises a wide variety of topographic situations, with areas steeper than 5% adjacent to river banks and roadside excavated batters included in this category. Areas in Category 1 have experienced landslides in the past and are generally very susceptible to future landslides, especially during annual heavy rain periods and when earthquakes occur.

6.4.2 Category 2 - Moderately Unstable Slopes

This category consists of:

i) areas which are not underlain by mappable landslide deposits, but are commonly underlain by small individual landslide deposits which are unmappable.

ii) areas of greater than 30% slope gradients for all lithological units except the pumiceous volcanic rocks and the Tertiary volcanic rocks where the cut-off is greater than 15% slope.

This category comprises rolling hills, volcanic cones and mountainous areas that are commonly underlain by volcanic rocks. These areas have a relatively high potential for landslides. Landslides may occur in steeper slopes saturated by ground water seepage or when areas are cut or excavated. Such significant landslide hazards have been found by the author in an area near Limaukunci, between Bakhu and Batukebayan, where landslide scarps of approximately one kilometre long occur on high steep slopes of the pumiceous volcanic rocks and on the Tertiary volcanic rock unit located. Landslides are more likely to occur in excavated areas when the areas are associated
with clayey soils, areas with low permeable claystone which are underlain by weak
weathered rocks or underlain by thick soils. Such areas are along the road to Krui,
approximately 1.5 and 12 km from Liwa. Another significant landslide hazard is
excavated areas associated with weak pumiceous rock on the road to Buaynyerupa,
approximately 12 to 15 km from Liwa.

6.4.3 Category 3 - Moderately Stable Slopes

Areas with greater than 5% slopes that are not underlain by landslide deposits,
and that are not covered by moderately unstable areas, are categorised as Category 3 or
the moderately stable slope category. These areas may be underlain by rocks that are
susceptible to slope failure on steeper slopes. Small unmappable landslides commonly
occur in association with streams or human activity such as excavations along roadsides.
Most susceptible areas for future landslides in this category are likely to be located
adjacent to existing landslide deposits.

6.4.4 Category 4 - Generally Stable Slopes

This category consists of areas of 0% to 5% slope gradients that are not
underlain by landslide deposits. The areas within this category are generally underlain
by the pumiceous volcanic rocks on the Liwa Plateau and alluvium deposits. Exceptions
may include some flat areas at the crest of high mountainous areas. The areas are
generally relatively stable at these low slope gradients. However, this category may
include some small areas of steeper slopes adjacent to rivers and roads. Considering the
weakness of the pumiceous volcanic rocks, these steeper parts may be subject to failure,
especially during heavy rain periods or when earthquakes occur.
6.5 Geological Hazard Zones

Overlaying the earthquake hazard map (Map 7) with the slope stability map (Map 6) permitted a geological hazard risk map (Map 8) to be constructed with the following zones:

Zone A: This zone has the highest potential for geological hazards due to the previously occurring hazards. The zone comprises:

- areas of landslide deposits
- areas subject to liquefaction (alluvial deposits in the Sebarus Valley)
- areas subject to high earthquake damage (areas underlain by the pumiceous volcanic rocks and alluvium deposits in the Buaynyerupa area)
- fault traces with areas subject to ground displacement, fault creep and surface rupture.

Zone B: This zone contains those areas of moderate earthquake damage and with moderately unstable slope, but excluding those areas underlain by the pumiceous volcanic rocks.

Zone C: This zone contains those areas of moderate earthquake damage and moderately stable slope, but excluding those areas underlain by the pumiceous volcanic rocks.

Zone D: This zone contains those areas of least or no earthquake damage and generally stable slopes, but excluding those areas underlain by the pumiceous volcanic rocks.
6.6 General Planning for Hazards

In recent years, many parts of Indonesia have come under increasing scrutiny as to the best way to utilise maximum productivity and conservation from land use patterns. In a growing population region, such as Liwa and the surrounding district are likely to become in the future, it is vitally important to maximise land use. In other parts of the world, land use planning is developing into almost a science and several texts and publications have been useful guides as to how to maximise land use. For this study, the studies of Griggs and Gilchrist (1977) and Robison and Lowe (1993) provided interesting contrasts in land use planning. Whilst this study addresses some of the data that are needed for future planning in the Liwa region, other studies of the scope and nature that are also included in the above publications should be done as they cover aspects of land use planning that are beyond the scope of this thesis. This thesis is a geology-based thesis that relies heavily on an understanding of the geology of the region.

For this study, several key issues have to be considered in land use planning. Although the population of the Liwa region is relatively small compared those in other parts of Indonesia, the government policy based on the Five-Year Development plans will result in an increasing population. Also, consideration of the existing land use patterns with regard to the conservation policies of the Rain Forest National Park, the need for additional land to cope with future development and the likely geological hazards and risk factors, have to be taken into account. A guide for general land use planning is as follows:

In zone A:

i. settlements and building construction should be avoided on:

a. areas underlain by landslide debris deposits;
b. zones within at least 100 m of faults;
c. alluvium deposits subject to liquefaction in the Sebaru Valley.

ii. restricted non-irrigated agriculture is permissible in landslide areas.

iii. with respect to the existing land use and infrastructure which are mostly located in this zone, settlement expansion is allowed on areas with low slope gradients (<15%) but excluding river banks.

In Zone B:
expansion of any settlement area, building construction and agriculture area should be allowed in any part of this zone.

In Zone C:
As for Zone B but agriculture is more likely because slope gradients are less than in Zone B.

In Zone D:
the land surface is:

i. generally suitable for settlement except in isolated elevated areas or areas traversed by faults;

ii. agriculture is permissible

For each zone:
i. any construction of concrete buildings is likely to need specific site investigations before building commences;

ii. steeper slopes along rivers should be conserved for open space because these areas are prone to landslides;

iii. any future use of land should respect and avoid areas of the Rain Forest National Park.

The above three activities should become automatic valuations in any future assessment of land use planning.
CHAPTER 7

CONCLUSIONS

A comprehensive evaluation and zoning of geological hazards in Liwa and nearby areas was undertaken to define the seismic hazards and slope instability to which the area is prone. To achieve the objectives, the thesis had the following specific aims:

1. To study the hazards in relation to geological conditions, using remote sensing images and field investigations.
2. To prepare a geological hazard zonation map by combining the distribution of previous damage that has been reported with geological factors contributing to the hazards. These processes will be facilitated by the ARC/INFO Geographical Information System (GIS).
3. To develop a qualitative method for evaluating geological hazards in a specific area.

To achieve these aims, a base map showing the geological features taken from aerial photographs and field work was made. The geological features included the known stratigraphy, the interpreted landslides and faults. Topography will also be identified for guidance in preparing a slope class map that will be derived manually from the topography map. The aerial photographs are 1:25,000 in scale, taken on March 9th, 1993, almost a year before the February 1994 earthquake which caused 201 fatalities. False-colour satellite images of Landsat TM was used to identify geological conditions related to faults and lithology. The Landsat TM image was printed from digital images taken on May, 31st. 1994, a few weeks after the last fatal earthquake in February 1994. Information provided by the image is quite good because the resolution of the image is 30 metres.
In this research, the use of remote sensing data was found useful in studying geological conditions related to geological hazards. The black-and-white aerial photographs of scale 1:25,000 gave a three dimensional image which permits identification of individual landslides, fault lineaments, topography, geomorphological units and drainage patterns. Specific young sediments, such as alluvium deposits, can be identified as can former damage on the alluvium.

The Landsat TM false colour image hard-copy provided information on fault lineaments, general lithological units, drainage patterns and limited landslides features. In this study, the aerial photographs used were taken before the 1994 earthquake and the Landsat TM images used were taken a relatively short time after the 1994 earthquake. The TM images, therefore, permits interpretation and delineation of areas subjected to significant damage caused by earthquake ground shaking. These areas are underlain by the pumiceous volcanic rocks. Both the aerial photographs and the Landsat TM images show fault lineaments and these can be used as guide for tracing ground displacement and surface rupture during earthquakes.

Plotting the spatial distribution of hazards on the base map was followed by random checking of the damage during the field work. A geological hazard map of the study area was then produced. The maps were digitised and this was been done using Geographical Information System (GIS) ARC/INFO method.

Potential landslide hazards are described in terms of the geology and relative slope stability. Input data composed of a landslide distribution map, slope class map and geological map. Field knowledge was used to evaluate and analyse the hazards. Areas likely to be subjected to ground shaking in the future were determined by selecting the known epicentral areas of past earthquakes and assuming these are likely to be the areas where earthquakes are most likely to occur in the future. Lithological characteristics and water table conditions were used to identify areas subject to liquefaction.
Zoning of geological hazards has been done by combining a relative slope stability map with an earthquake hazard map showing intensity of damage, and liquefaction and fault traces which indicate areas of ground displacement and surface ruptures.

The lack of data related to ground shaking, liquefaction and surface rupture, limits the scope of this study to a semi-quantitative evaluation.

Future work, particularly soil studies and seismic investigations may provide quantitative data that can contribute to microzoning and establishing earthquake resistant designs in this seismically active zone of Sumatera. Irrespective of any future work, this study provides the detailed plan which will benefit the new Regency of Lampung Province which has Liwa as its capital when it makes decisions on the placement of infrastructure and housing.

If fewer casualties and less damage occur when future earthquakes strike the Liwa area, this study will have achieved its major objective.
REFERENCES


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Proceedings Indonesian Institute of Science, Geotechnology LIPI, Bandung, 110-122.


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FIGURES
Figure 1.1 Location of the study area
Fig. 2.1 Geological province of south Sumatra

Legend:
- Sedimentary rocks of the back arc basin
- Volcanic rocks of the magmatic arc
- Sedimentary rocks of the fore arc basin
Figure 2.3 Monthly average rainfall, 1986-1996
Fig. 2.4 Simplified stratigraphy of the study area

<table>
<thead>
<tr>
<th>Surficial Deposits</th>
<th>Qa</th>
<th>Alluvium</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volcanic Rocks</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Younger Quaternary Volcanic Rocks</td>
<td>Qhv</td>
<td>andesite breccia and sandy tuff (angular)</td>
</tr>
<tr>
<td>Older Quaternary Volcanic Rocks</td>
<td>Qv</td>
<td>andesite breccia and sandy tuff (angular to subrounded)</td>
</tr>
<tr>
<td>Pumiceous Volcanic Rocks</td>
<td>QTv</td>
<td>tuff, breccia</td>
</tr>
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<td>Tertiary Volcanic Rocks</td>
<td>Tv</td>
<td>breccia and tuff</td>
</tr>
<tr>
<td>Sedimentary Rocks</td>
<td></td>
<td></td>
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<tr>
<td>Tertiary Clastic Sedimentary Rocks</td>
<td>Tsc</td>
<td>claystone, sandstone, conglomerate</td>
</tr>
<tr>
<td>TYPE OF MOVEMENT</td>
<td>TYPE OF MATERIAL</td>
<td>MATERIAL</td>
</tr>
<tr>
<td>------------------</td>
<td>-----------------</td>
<td>---------</td>
</tr>
<tr>
<td></td>
<td>Bedrock</td>
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</tr>
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<td></td>
<td>Predominantly Coarse</td>
<td>Soil</td>
</tr>
<tr>
<td></td>
<td>Predominantly Fine</td>
<td></td>
</tr>
<tr>
<td>FALLS</td>
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</tr>
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<td></td>
<td>Earth fall</td>
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</tr>
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<td></td>
</tr>
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<td>Earth block slide</td>
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<td>Rock slide</td>
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<tr>
<td>MANY UNIT</td>
<td>Earth slide</td>
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<td>Debris spread</td>
</tr>
<tr>
<td></td>
<td>Earth spread</td>
<td></td>
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<tr>
<td>FLOWS</td>
<td>Rock flow</td>
<td>Debris flow</td>
</tr>
<tr>
<td></td>
<td>Earth flow</td>
<td></td>
</tr>
<tr>
<td>COMPLEX</td>
<td>combination two</td>
<td>or more types of movement</td>
</tr>
<tr>
<td></td>
<td>movement</td>
<td></td>
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</table>

Figure 3.1 Classification of slope movement

(source: Varnes, 1978)
Figure 4.1 The distribution of earthquake epicentres with magnitude $\geq 5$ on the Richter Scale (source: Indonesian Agency of Meteorology and Geophysics)
Figure 4.2 Catastrophic earthquakes in Sumatera (after Katili and Hehuwat, 1967; Natawidjaja and Sieh, 1994)
Fig. 4.3 Epicentre related to structural geology of the study area

LEGEND

- Aluvial deposits (Holocene)
- Younger Quaternary volcanic rocks (Holocene)
- Older Quaternary volcanic rocks (Holocene)
- Pumiceous volcanic rocks (Plio-Pleistocene)
- Tertiary clastic sedimentary rocks (Late Oligocene to Pliocene)
- Tertiary volcanic rocks (Late Oligocene to Middle Miocene)
- Fault
- River
- Road

1 number of epicentre related to Table 4.1.
Figure 4.4 Processes related to the formation of the Ranau-Suwoh Fault and to the de-activation of the Kubuprahu Fault (adopted from Bellier et al. 1994):

A. Formation of Ranau Pull-Apart Basin marks the Ranau Stepover stage.
B. Formation of Ranau Caldera due to the increasing volcanic activity (Kubuprahu Fault was still active).
C. Formation of a new strike-slip fault marks the extinction of the Ranau Stepover; formation of a new Pull-Apart in Suwoh; Kubuprahu Fault was inactive.
D. Suwoh Pull-Apart grows to be a complex with depression.
Figure 4.5 Structural pattern in the southern part of Sumatra and its relationship with structural geology of the study area. The active Sukarame and Liwa Faults correspond to the Ranau-Suwoh Fault, and the Kubuprahau Fault corresponds to the inactive fault segment.

Legend:
1. Major active fault of the Sumatra Fault Zone
2. Inactive fault
3. Minor active fault
4. Normal active fault
5. Caldera rims
6. Quaternary alluvial and volcano-sedimentary deposits
7. Volcano
Fig. 5.1 Vector diagram showing the increase in resultant gravitational force \((G)\) with increasing slope \((\beta)\).

For the given two similar materials with different slope steepness, the higher gravitational resultant \((G')\) corresponds to the higher angle \((\beta')\); resistive forces \((R)\) are similar due to the similarities in their properties. The failure or sliding will occur when \(G'\) is higher than \(R\).
<table>
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<tr>
<th>Slope class</th>
<th>0% - 5%</th>
<th>5% - 15%</th>
<th>15% - 30%</th>
<th>30% - 50%</th>
<th>50% - 70%</th>
<th>&gt; 70%</th>
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</thead>
<tbody>
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<td>Rock</td>
<td>W</td>
<td>E</td>
<td>I</td>
<td>G</td>
<td>H</td>
<td>T</td>
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<td>0.419</td>
<td>0.447</td>
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<td>0.448</td>
<td>0.355</td>
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<tr>
<td>Qv</td>
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<td>3.372</td>
<td>1.461</td>
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<td>QTr</td>
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<td>0</td>
<td>0.231</td>
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</table>

Figure 6.1 Landslide weightings for each geological unit in given slope class unit
TABLES
Table 3.1  Relationship between the distribution of structural damage, caused by the 1994 Liwa earthquake, and the geological conditions source: SATLAK-PBA, West Lampung Regency Office.

<table>
<thead>
<tr>
<th>Location</th>
<th>Destroyed (%)</th>
<th>High Damaged (%)</th>
<th>Minor Damaged (%)</th>
<th>Lithology</th>
<th>Distance to Liwa Fault (km)</th>
<th>Distance to Sukarame Fault (km)</th>
</tr>
</thead>
<tbody>
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<td>Bakhu</td>
<td>3</td>
<td>10</td>
<td>10</td>
<td>QHv</td>
<td>13</td>
<td>8</td>
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<td>Kenali</td>
<td>10</td>
<td>30</td>
<td>50</td>
<td>QTr</td>
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<td>6</td>
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<tr>
<td>Kotabesi</td>
<td>10</td>
<td>50</td>
<td>40</td>
<td>QTr</td>
<td>8</td>
<td>2.5</td>
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<tr>
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<td>50</td>
<td>40</td>
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<td>25</td>
<td>QTr</td>
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<td>50</td>
<td>30</td>
<td>QTr</td>
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<tr>
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<td>65</td>
<td>5</td>
<td>QTr</td>
<td>5</td>
<td>0</td>
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<td>30</td>
<td>QTr</td>
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<td>65</td>
<td>5</td>
<td>QTr+Qv</td>
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<td>4</td>
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<td>65</td>
<td>5</td>
<td>QTr</td>
<td>0</td>
<td>4</td>
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<tr>
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<td>65</td>
<td>5</td>
<td>QTr</td>
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<td>T.Kemala</td>
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<td>45</td>
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<td>Buaynyerupa</td>
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<td>25</td>
<td>35</td>
<td>QTr+Qa</td>
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<td>15</td>
<td>20</td>
<td>QHv</td>
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<td>3</td>
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<tr>
<td>Lombok</td>
<td>-</td>
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<td>20</td>
<td>QHv</td>
<td>13</td>
<td>10</td>
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<td>Krui</td>
<td>-</td>
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<td>10</td>
<td>Qa</td>
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Table 3.2 Field observations of landslides; Liwa - Krui line

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<th>Location</th>
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<th>Lithology</th>
<th>Slope (%)</th>
<th>Land-Use</th>
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<td>Km 1.5</td>
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<td>Qv, Tsc</td>
<td>50</td>
<td>forest</td>
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<td>Km 3</td>
<td>debris slide</td>
<td>Qv</td>
<td>55</td>
<td>forest</td>
</tr>
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<td>Km 6</td>
<td>debris slide</td>
<td>Qv</td>
<td>60</td>
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<td>debris slide</td>
<td>Qv</td>
<td>55</td>
<td>wet arable-land</td>
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<td>Km 10</td>
<td>earth and debris slide</td>
<td>Qv</td>
<td>60</td>
<td>dry arable-land</td>
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<td>Km 10.5</td>
<td>earth and debris slide</td>
<td>Qv</td>
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<td>forest</td>
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<td>65</td>
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<td>Type</td>
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<td>Slope (%)</td>
<td>Land-use</td>
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Table 3.4  Field observations of landslides; Liwa-Batukebayan line

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<th>Lithology</th>
<th>Slope (%)</th>
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</tr>
<tr>
<td>Sukarame</td>
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<td>QTr</td>
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<td>Kotabesi T</td>
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<td>Bakhu 2</td>
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</tr>
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<td>forest</td>
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<td>Tv</td>
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Table 3.5 Field observations of landslides; Liwa-Hantatai line

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<td>Sukabumi</td>
<td>debris slide and fall</td>
<td>QTr</td>
<td>25</td>
<td>dry arable-land</td>
</tr>
<tr>
<td>Selipas 1</td>
<td>debris slide</td>
<td>QTr</td>
<td>20</td>
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<tr>
<td>Selipas 2</td>
<td>debris slide</td>
<td>QTr</td>
<td>25</td>
<td>dry arable-land</td>
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<td>QTr</td>
<td>30</td>
<td>dry arable-land</td>
</tr>
<tr>
<td>Selipas 4</td>
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<td>QTr</td>
<td>20</td>
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</tr>
<tr>
<td>P.Salimun 1</td>
<td>debris slide</td>
<td>QTr</td>
<td>30</td>
<td>dry arable-land</td>
</tr>
<tr>
<td>P.Salimun 2</td>
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<td>QTr</td>
<td>40</td>
<td>forest</td>
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<tr>
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<td>debris slide</td>
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<tr>
<td>Bunguyan 1</td>
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Table 4.1 Seismicity in the study area from 1933 to 1995 (sources: Berlage, 1934; DGSM, 1994; Indonesian Bureau for Meteorology and Geophysics (1996, unpublished data)).

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<th>East Longitude</th>
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<th>Magnitude (Rs)</th>
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Table 5.1 Landslide weighting for each geological unit

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<th>AREA (m²)</th>
<th>AREA (%)</th>
<th>LANDSLIDE (%)</th>
<th>WEIGHTING</th>
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Table 5.2 Landslide weighting for each slope class

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<th>LANDSLIDE (%)</th>
<th>WEIGHTING</th>
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Total Landslide (m²) 29,598,671

Total Area (m²) 1,144,100,2
### Table 5.3 Landslide weighting for each slope class in each geological unit

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<th>ROCK (%)</th>
<th>SLOPE (%)</th>
<th>LANDSLIDE</th>
<th>AREA (m$^2$)</th>
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**Total Area**: 1,144,098,456 m$^2$

**Total Land-Slide**: 29,596,873 m$^2$
PLATES
Plate 2.1 A contact between Tertiary Clastic Sedimentary Rocks (Tsc) and the Older Quaternary Volcanic Rock (Qv).

The intercalation between claystone and siltstone is characteristic of the Seblat Formation.

Location: 1.5 km from Liwa, Liwa to Krui road.
Plate 2.2  An intercalation of polymictic conglomerate with siltstone, typical of the upper part of the Tertiary Clastic Sedimentary Rocks (Simpangaur Formation).

Location: 17.5 km from Liwa, Liwa to Krui.
Plate 2.3 An excavated Tertiary Volcanic Rock unit (compact, angular to subangular breccia).
Location: 13 km from Liwa, Liwa to Krui road.

Plate 2.4 The excavated Pumiceous Tuff (text explanation in section 2.5.1.3).
Location: 14 km from Liwa, Liwa to Buay-nyerupa road.
Plate 2.5 An outcrop of Older Quaternary Volcanic Rock
(breccia, less of consolidation, poorly-sorted, angular to subrounded).
Location: 2 km from Liwa, Liwa to Krui road.

Plate 2.6 An outcrop of Younger Quaternary Volcanic Rock
(breccia lacking consolidation, poorly sorted, angular to subangular).
Location: 2 km from Jagaraga, Jagaraga to Lombok road.
Plate 2.7 An outcrop of sandy tuff, Younger Quaternary Volcanic Rock unit.

Location: Jagaraga village.
Plate 2.8  The Sukarame Fault scarp, along the Robok River, south of Sukarame.

Plate 2.9  The Liwa Fault scarp, along the Kububihan River, east of Liwa.
Plate 2.10 Colour composite Landsat TM image showing part of the Kubuprahu Fault lineament (F-F') and the former crater of Older Quaternary volcano (C).
Plate 3.1 A photograph of a government building damaged by the 1994 Liwa earthquake. The office has not been rehabilitated up to the time of the field work. It is located in Waymengaku, approximately 6 km from the epicentre of the earthquake and sits on the Pumiceous Volcanic Rock.
Plate 3.2 A Landsat TM composite colour bands 5,4,7 image which shows differences in reflectance and morphology for different lithological units. The Pumiceous rock (QTr), which contributed to the high structural damage during the 1994 earthquake, shows:

* relatively medium brightness between those of Tertiary Volcanic Rocks (Tv) and Quaternary Volcanic Rocks (Qv and Qhv)
* relatively flat morphology with smooth texture.

Part of three faults are also shown:

- $F_S - F'_S$ : Sukarame Fault
- $F_L - F'_L$ : Liwa Fault
- $F_K - F'_K$ : Kubuprah Fault
Plate 3.3 Aerial photograph showing the Sukarame Fault lineament (F - F') and landslide areas near Negeriratu and Sukabumi villages. The shadow effects along the fault are related to the fault scarps and landslides as well.

S : spoon-shape trough

H : hummocky surface
Plate 3.4 Landsat TM composite colour bands 4,3,2 image showing fault lineaments and large landslides:

- $F_S - F'_S$ : Sukarame Fault
- $F_L - F'_L$ : Liwa Fault
- $A$ : Arcuate shapes of landslide (proved on the ground; also see plate 2.8).

Composite landslides often form large landslides along the bank.

- $H$ : Hummocky shape of landslide deposit
Plate 3.5 A photograph of a damaged road under rehabilitation. The road is situated within the Sukarame Fault Zone, south of Sukarame village.
Plate 3.6  Aerial photograph showing alluvium deposits ($L_0$), in Sebarus Valley which experienced liquefaction during the 1994 earthquake. The photograph was taken before the earthquake that activated the Liwa fault. Unlike in Plate 3.2 which is a Landsat TM image which was taken after the earthquake, the fault lineament in this aerial photograph ($F_L$-$F'_L$) is obscured.
Plate 3.7 Debris slide of highly weathered Tertiary Volcanic Rock, along the roadside between Bakhu and Batu-kebayan villages.

Plate 3.8 Debris slide of highly weathered Pumiceous Volcanic Rock, along the road between Liwa and Waymengaku. The top soils (T) moved downward over the discontinuity near the rock-soil interface (D).
Plate 3.9 Debris slide along the road near Selipas. The slide occurred on a relatively gentle slope composed by Pumiceous Volcanic Rock.
Plate 3.10 Debris slide of Older Quaternary Volcanic Rock (Qv). The slide occurred on the unconformable-contact with claystone of the Tertiary Sediment (Tsc).
Plate 3.11 A rotational slide of earth and debris slump, in Tanjungkemala, indicated by tilting backward (T) at the headwall scarp (H)

Plate 3.12 Debris fall of pumiceous rock along the Kububihan River, between Liwa and Sebarus and associated with the Liwa Fault Zone.
Plate 3.13 Earth-fall type on the very loose soils derived from the Pumiceous Volcanic Rock.

Location: 12 km from Liwa to Buaynyerupa.