DEVELOPMENT OF DESIGN RESPONSE SPECTRA FOR PENANG ISLAND

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DEVELOPMENT OF DESIGN RESPONSE SPECTRA FOR PENANG ISLAND

by

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This thesis is dedicated to my beloved mom, Rehana bt. Jamaludin.

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LIST OF SYMBOLS

M_L	Richter local magnitude
M_s	Surface wave magnitude
m_b	Body wave magnitude
m_{max}	Maximum magnitude of predicted earthquake
m_c	Coda duration magnitude
m_{Lg}	*Lg* waves
M_w	Moment magnitude
$N(m)$	Number of earthquakes with magnitude equal to or greater than magnitude of m
a	Measure of seismic activity
b	Measure of relative abundance of large and small earthquakes
$N(M_{min})$	Number of earthquake with magnitude equal to or greater than M_{min}
λ	Mean seismic activity rate
M_{max}	Maximum possible earthquake
M_{min}	Minimum of the given sample
$\overline{M}$	Average magnitude in the sample
n	Number of seismic events
R_{hypo}	Hypocentral distance
H	Focal depth
Y	Mean of peak ground acceleration
N-spt	Standard penetration test
γ	Unit weight
v_{si}	Shear wave velocity
V_s	Shear wave velocity
γ_b	Bulk density
w	Moisture content

d_i	The thickness of any layer between 0 and 30 m from surface
S	Site classification
S_A	Hard Rock
S_B	Rock
S_C	Very Dense Soil/Soft Rock
S_D	Stiff soil
S_E	Soft Soil
σ	Standard deviation
∑	Sum
M	Individual data
n	Sample size
C_a	Ground motion coefficients at T_o
C_v	Ground motion coefficients at T_s
T_o	Short period
T_s	Longer period
Z	Effective peak ground acceleration
F_a	Amplification factor for short period spectral response acceleration
F_v	Amplification factor for mid period spectral response acceleration
$PS_{A1.0sec}$	Design response spectra at 1 second period
T	Fundamental period of the structure second
$S_e(T)$	Elastic response spectrum
a_g	Design ground acceleration on Type A ground
T_B	Lower limit of the period of the constant spectral acceleration branch
T_C	Upper limit of the period of the constant spectral acceleration branch
T_D	Value defining the beginning of the constant displacement response range of the spectrum

η	Damping correction factor with a reference value of $\eta=1$ for 5% viscous damping
$T(m)$	Recurrence interval
r_{rup}	Closest distance to fault rupture

LIST OF ABBREVIATION

AF	Amplification Factor
DSHA	Deterministic Seismic Hazard Analysis
EN 1998	Eurocode 8
GIS	Geotechnical Information System
IRIS	Incorporated Research Institutions for Seismology
ISC	International Seismological Centre
JMA	Japanese Meteorological Agency Scale
MMI	Modified Mercalli Scale
MMS	Malaysia Meteorological Services
MSK	Medvedev-Spoonheuer-Karnik Scale
NEHRP 2000	National Earthquake Hazard Reduction Program
NERA	Nonlinear Earthquake site Response Analysis
PEER	Pacific Earthquake Engineering Research
PGA	Peak Ground Acceleration
PSHA	Probabilistic Seismic Hazard Analysis
RF	Rossi-Forel Scale
RSA	Response Spectrum Acceleration
SFZ	Sumatra Fault Zone
SSZ	Sumatra Subduction Zone
UBC 97	Uniform Building Code 1997
USGS-NEIC	United States Geological Survey-National Earthquake Information Center (USGS-NEIC)

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LIST OF PUBLICATIONS & SEMINARS

1. **M.N Fadzli**. T.A. Majid and S.S Zaini (2007) "Design Response Spectra for Penang Soil based on UBC 97'', Persidangan Kebangsaan Kejuruteraan Awam (AWAM07), Hotel Helang, Langkawi 29-31 May 2007.

2. S.S Zaini**,** T.A. Majid, T.L. Lau and **M.N Fadzli** (2007) "Study on Irregularities of Building Structures in Penang Under the Effect on Long Distance Sumatran Earthquakes'', Persidangan Kebangsaan Kejuruteraan Awam (AWAM07), Hotel Helang, Langkawi 29-31 May 2007.

3. Ahmad. F**,** T.A. Majid, and **M.N Fadzli** (2007) "Data Management of Seismic Parameters for Penang Soil'', Persidangan Kebangsaan Kejuruteraan Awam (AWAM07), Hotel Helang, Langkawi 29-31 May 2007.

4. Ismaili. G., **,** T.A. Majid, **M.N Fadzli** and M.R. Arshad (2007) "Establishment a Empirical Relationship Equation of Magnitude Conversion Specific for Malaysia'', Persidangan Kebangsaan Kejuruteraan Awam (AWAM07), Hotel Helang, Langkawi 29-31 May 2007.

5. Ahmad, F., Majid, T.A., and **Fadzli M.N.** (2007) "Seismic Hazard Analysis for Penang Soil'', ATC10 Workshop: Geotechnical Information System in Vietnam: Construction, Maintenance & Application, Water Resources University, 26 March 2007.

6. **M.N Fadzli** and T.A. Majid, (2006) "Peak Ground Acceleration (PGA) for Georgetown Due to Sumatran Subduction and Fault Zones'', National Seminar on Civil Engineering Research (SEPKA), Universiti Teknologi Malaysia, 19-20 December 2006.

7. **M.N Fadzli** and T.A. Majid, (2006) "Peak Ground Acceleration (PGA) for Georgetown & Alor Setar Due to Sumatran Subduction and Fault Zones'', 1st Civil Engineering Colloqium, School of Civil Engineering, Universiti Sains Malysia, 24 -25th May 2006.

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10. T.A. Majid, K.K. Choong, T.L. Lau, S. Zaini, **F.M. Nazri** and M.R. Arshad, (2005) "Structural Damage for Irregular Building under Earthquake Loading", Seminar and Dialog on The Treat of Earthquake and Tsunami Disasters and Development of Strategic Planning in Malaysia, 12-13 July 2005, Kuala Lumpur Convention Centre.

PEMBANGUNAN SPEKTRA SAMBUTAN REKABENTUK UNTUK PULAU PINANG

ABSTRAK

Semenanjung Malaysia terletak di dalam kawasan yang kejadian gempa buminya kurang aktif yang dipanggil 'para Sunda yang stabil' dan dianggap sebagai kawasan yang bebas dari kejadian gempa bumi. Walaupun demikian, tiada kerosakan yang berlaku tetapi berdasarkan fakta, Semenanjung Malaysia terletak di kawasan yang dekat dengan kejadian gempa bumi yang memperuntukkan tambahan terhadap kod rekabentuk yang sedia ada dalam merekabentuk bangunan teruatamanya di Pulau Pinang. Dalam penyelidikan ini, jangkaan magnitud yang maksimum, m_{max} bagi zon gelinciran di Sumatra (SFZ) dan zon *subduction* di Sumatra (SSZ) adalah 7.8 dan 9.2 yang berkemungkinan menyebabkan gempa bumi di Semenanjung Malaysia. Hubungan perlemahan dipilih berdasarkan penyelidikan yang lepas bagi setiap zon dan menentukan pemecutan bumi puncak (PGA) bagi kawasan Pulau Pinang adalah 0.041 g bg SSZ dan 0.063 g untuk SFZ. Dari penyelidikan ini juga didapati kebanyakan tanah di Pulau Pinang adalah kategori S_D (tanah kukuh) iaitu 50 lubang jara, S_E (tanah lembut) 7 lubang jara and S_C (tanah tumpat) dengan 38 lubang jara daripada 95. Batu Feringghi adalah dalam keadaan kritikal dimana faktor penguatan (AF) adalah 4.76 dan tempat yang paling selamat adalah di kawasan Bukit Jambul iaitu AF 0.32. Bagi spektra sambutan rekabantuk juga dikaji berdasarkan pelbagai jenis kod (UBC 97, NEHRP 2000 and EN 1998) bagi keseluruhan jangka masa dalam penggunaan rekabentuk struktur berdasarkan keputusan spektrum sambutan pemecutan (RSA). Dalam spektra sambutan rekabentuk, nilai maksimum bagi RSA untuk S_C bagi ketiga-tiga kod adalah 0.7 g dalam jangka masa 0.02 hingga 0.3 saat berbanding S_D dan S_E, 0.6 g dalam jangka masa yang lebih panjang (0.15 hingga 0.7 saat). Kesemua nilai ini adalah penting dalam analisis rekabentuk struktur bangunan dalam jangka masa tertentu.

DEVELOPMENT OF DESIGN RESPONSE SPECTRUM FOR PENANG ISLAND

ABSTRACT

The Peninsular Malaysia is located in a low–seismicity region, the so called 'stable Sunda Shelf', thus, it is assumed to be an earthquake free zone. Fortunately, no significant damage was reported but the fact that the Peninsular Malaysia is situated close to the earthquake tremors may demand an additional guideline on the existing design code for designing structures, especially for Penang Island, being one of the most highly developed regions in Malaysia. In this study, the prediction of maximum magnitude, m_{max} for the Sumatra fault zone (SFZ) and the Sumatra subduction zone (SSZ) are 7.8 and 9.2 respectively of the causative earthquakes for Peninsular Malaysia. The attenuation relation was selected from previous studies, which is for each zones and determine the peak ground acceleration (PGA) for the Penang area is 0.041 g for the SSZ and 0.063 g for the SFZ. This study also found that most of Penang soil falls into S_D (stiff soil) with 50 boreholes and S_E (soft soil) only 7 boreholes and S_C (very dense soil) is 38 out of 95 boreholes. Batu Feringghi location was found to be in critical condition with amplification factor (AF) of 4.76 and the safest place is Bukit Jambul area with AF of 0.32. The design response spectra were carried out based on various codes (UBC 97, NEHRP 2000 and EN 1998) for the period of 40 s on modification results of response spectrum acceleration (RSA). In the development or design response spectra, the maximum values of RSA for all three codes are 0.7 g (S_C) with a range of periods is 0.02 to 0.3 second compared to S_D and S_E, 0.6 g at long range of period (0.15 to 0.7 seconds). All these values are important in structural design analysis of building that has a period of vibration at this range of period.

CHAPTER 1
INTRODUCTION

1.0 General

Earthquakes are considered to be the most powerful natural disaster. Seismic hazards include ground shaking, structural failures, liquefaction, land slides, and lifelines damages. Most earthquakes can be explained by the two theories of plate tectonics and elastic rebound.

The crust of Earth is broken into many pieces called plates. These plate boundaries include spreading ridge, subduction zone, and transform fault boundaries. Plates separated by spreading ridge boundaries move away from one another without building up any significant stress. At subduction zone boundaries, one plate subducts or dives beneath the other, whereas transform fault boundaries exist where plates move past one another.

Plate tectonics is that the earth's surface consists of a number of large, intact blocks called plates, and that these plates move with respect to each other. Currently, there are seven large plates; that are Pacific plate, Australian plate, the North American plate, the Eurasian plate, the Antarctic plate, the South American plate and the African plate.

The elastic rebound theory suggests that elastic strain energy is stored in the materials near the subduction zone and transform fault boundaries as shear stress increases on the fault planes that separate the plates. As the shear stress approaches the shear strength of the rock material along the fault, the rock material begins to fail and releases the stored energy. If the rock material is strong and brittle, the level of the stored energy can be very high. In addition, rupture along the plain of the fault will be rapid and the energy release will be violent.

Peninsular Malaysia is located relatively faraway from seismic source zone of Sumatra but is situated close to the most seismically active plate boundary which is interplate boundary between the Indo-Australia and Eurasian plates on the west which is marked by a concave subduction zone known as Sumatra Trench. Also interplate boundary between the Eurasian and Philippines Sea plates on the east.

Actually, Malaysia is situated on the so call ‘stable Sunda Shelf’, thus it is assumed to be an earthquake free zone. In fact, this shelf is divided to three directions an earthquake free zone. Whereas, for the east part, the Indian plate is currently pushing in the north-easterly direction at the rate of 6-8 mm/yr. Whereas, the Australian plate have undergoing a north direction compression for the Sunda Shelf for creating the Java Trench as a southern part. In the other direction, which is the western part, Philippine plate (pacific plate) is compressed the Sunda Shelf.

However, major earthquake originating from those plate boundaries which is the ‘ground shaking’ have been felt in Malaysia, even though Malaysia is situated on the stable shelf (Sunda Shelf). The effect still can be felt whenever a moderately to high earthquake happened at Sumatra Island due to the close proximity to subduction zone, Sumatra Trench.

Malaysia Meteorological Services (MMS) reports that Peninsular Malaysia tremors felt along the west coast is originating from large earthquake in the centre seismic areas of Sumatra and Andaman Sea. East Malaysia has experienced earthquake of local origin and also affected by tremors originating from large earthquake located over Southern Philippines and Northern Sulawesi. Beside that, the

Great Sumatra Strike-Slips Fault which slicing through Sumatra Island also posing a potential treat to Malaysia (MMS, 2005).

On 26 December 2004, Malaysia was affected by the Indian Ocean earthquake that caused panic around the region. Despite its proximity to the epicenter of the earthquake (approximately 500 km), Malaysia is fortunate to escape from major damage.

Therefore, the possibility of a large earthquake in Sumatra should not be ignored, and some preparedness and mitigation place should be in place.

1.1 Problem Statement

Penang Island is located on the north-east coast of Peninsular Malaysia. which is an island of 293 square kilometers located in the Straits of Malacca bounded by latitudes, 5°15'N to 5°30'N and longitudes 100°10'E to 100°20'E and one of the most highly developed regions in Malaysia. In the past few decades, there were a lot of high rise and commercial buildings built around Penang Island of which some of these buildings were built on soft soil areas or reclaimed lands.

Large earthquakes from Sumatra may pose threats to these buildings as Penang is only 350 km away from the Sumatra fault and 500 km away from the subduction zones.

Malaysian Meteorological Services (MMS) reported that Penang is the second most frequent earthquake felt area after Kuala Lumpur for the earthquake events occurred over the last 20 years.

For these reasons, Penang Island has been chosen as a case study area and this seismic hazard analysis is important in order to help some preparedness and mitigation plan in future.

1.2 Objectives

This study is based on the proximity of Sumatra earthquake and its analytical effect on the Penang Island. The main objectives of this study are as follows:

i. To predict the maximum magnitude, m_{max} for Peninsular Malaysia. This include of determination of the expected frequency and recurrence interval for Peninsular Malaysia
ii. To determine the Peak Ground Acceleration (PGA) for Penang island
iii. To develop the design response spectrum based on various codes of practice. This cover the site classification for Penang Island, the response spectrum acceleration (RSA) and the amplification factor (AF).

1.3 Scope of Works

The following scopes of works are needed to be carried out in order to achieve all the objectives in this study:

i. Earthquake catalogue study area from years1900-2005.
ii. Study area of 90°E to 110°E longitude and 10°S to 10°N latitude, cover Peninsular Malaysia and Sumatra earthquake zone.
iii. Two attenuation relationships in determining peak ground acceleration (PGA) are Adnan *et al.* (2005) for Sumatra subduction and Campbell (2002) for fault zones.
iv. Due to availability soil data of Penang Island, only east coast area will be studied.

v. Two strong-motion data in establishing response spectra acceleration (RSA) are El Centro and Mexico Earthquake.

vi. Non-linear Earthquake site Response Analysis (NERA) software will be used for performing RSA.

vii. Design response spectra will be established based on three different codes, which are UBC 97, NEHRP 2000 and EN 1998.

1.4 Research Methodology

This study has been conducted in three main phases:

i. Phase 1: Prediction of maximum magnitude, m_{max}

This phase is important because the input from this phase will correlate with other phases. In this phase, it involves a collection of earthquake data from the International Seismological Centre (ISC), United States Geological Survey-National Earthquake Information Center (USGS-NEIC) and Incorporated Research Institutions for Seismology (IRIS). The earthquake data was complied from year 1900 until 2005. In order to complete the first phase, it is important to differentiate the earthquake data which occurred along the fault and subduction zone.

ii. Phase 2: Peak Ground Acceleration (PGA)

This phase is divided into two sub phases namely subduction and fault zones. The relationship between parameters in each zones are determined separately to obtain the PGA before selecting the maximum PGA as the final value. The highest PGA value (selected as final value) will be used in phase 3.

iii. Phase 3: Design Response Spectra

The main objective in this phase is to develop the design response spectra. The design response spectrum is based on the analysis of response spectrum acceleration (RSA), amplification factor and also the site classification. To analyze these factors, a lot of data which collected from the private sectors in Penang Island is required. The strong motion data which based on El Centro and Mexico earthquake are used as input for the Nonlinear Earthquake site Response Analyses (NERA) software was used to generate RSA. Other tool such as ArcView was also used in order to manage the database of each location of site investigation (S.I) reports in the GIS format.

1.5 Organization of Thesis

The thesis is arranged so that each chapter can be read individually. In addition, the chapters were organized in a manner that presented information in a logical order. Some of the data tables, graphs, and other materials were reproduced more than once for convenience when it was appropriate.

This thesis is divided into five chapters. Chapter 1 introduces the general background of this study, the objectives and the research methodology. Chapter 2 describes the studies from previous researchers, which are related to the topic.

Chapter 3 covers the methodology, which is about the theoretical background and the equation used in this study. Results and discussions for each phase will be presented in Chapter 4. Chapter 5 presents the conclusions and future recommendations of this study.

CHAPTER 2
LITERATURE REVIEW

2.0 Introduction

Seismology engineering covers a very wide scope, whereby it involves plate tectonics, types of faults, elastic rebound theory, deterministic and probabilistic method of analysis. This chapter will focus and highlight on specific topic which is relevant on this research. This literature review is divided into 4 main divisions:-

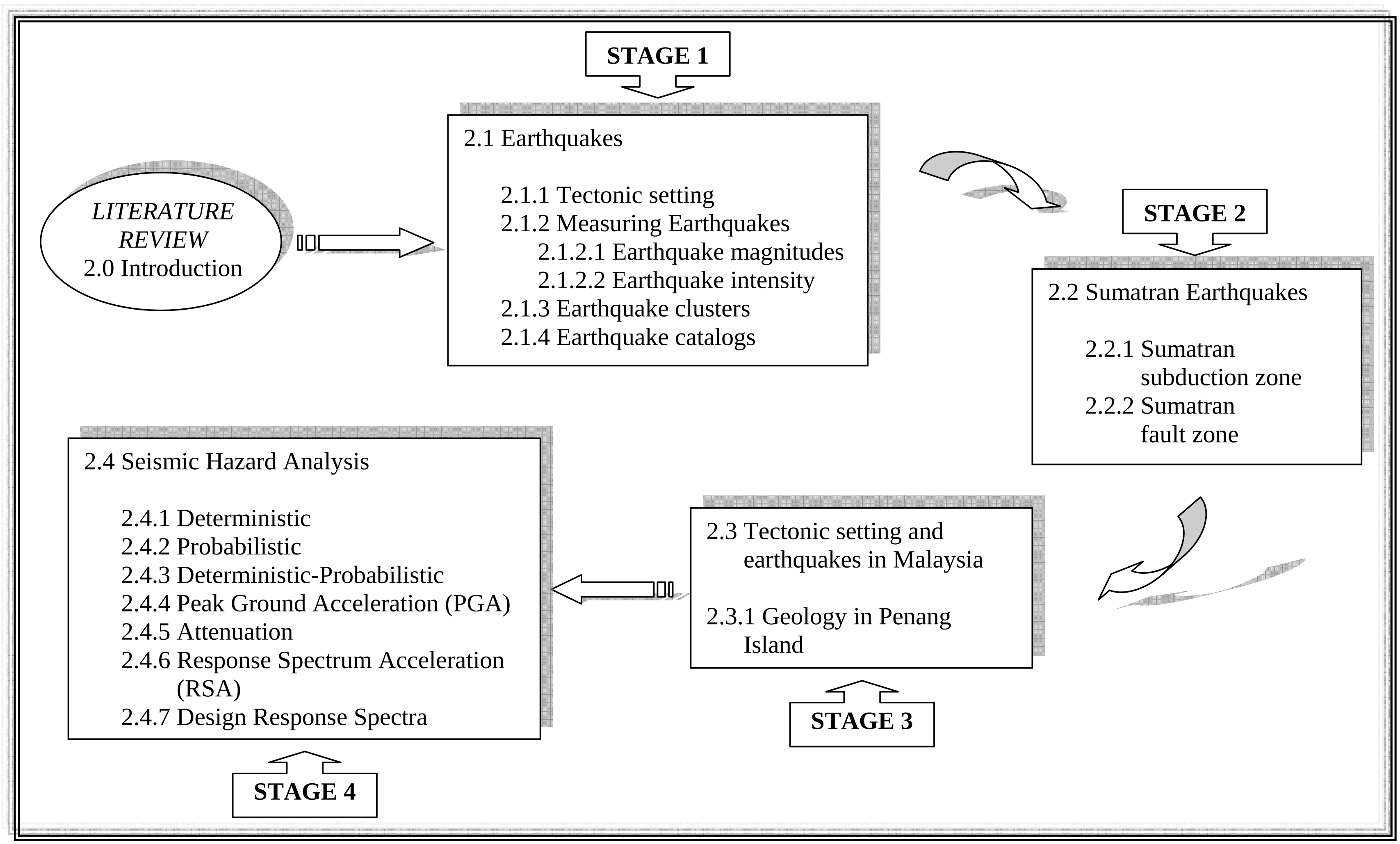
i. Stage 1: Earthquakes
ii. Stage 2: Sumatran Earthquake
iii. Stage 3: Tectonic setting and earthquake in Malaysia
iv. Stage 4: Seismic Hazard Analysis

The first stage discusses in general about the phenomenal of the earthquake, the formation of the quake, the tectonic setting that joint world's plate as well as earthquake measurement from magnitude and intensity. Flow chart in Figure 2.1 shows the details of each stage.

Earthquake clusters will also be discussed in detail of the phenomenal when the earthquakes happen. The data for this research is from the established earthquake catalogues.

The second stage will discuss about the Sumatra earthquake which occurs on the subduction and fault zone. This is due to the fact that most of the earthquake occurs at these zones and it eventually affects Malaysia too, as what happened during the major tsunami occurred in 2004.

Figure 2.1: Flow of literature review



The third stage explains about tectonic and earthquakes which were recorded in Malaysia. Geology condition of Penang Island will also be discussed as it is covering the study area for this research.

Lastly, the fourth stage, which is seismic hazard analysis, was the main objective in this study. It covers both deterministic and probabilistic hazard analysis to estimate the nature and intensity of possible ground motion at particular site due to future earthquakes known as response spectrum acceleration (RSA) and hence development of design response spectra. This phase also reviews about the attenuation formula in relation to the importance of magnitude, source to site distance and also local site condition.

2.1 Earthquakes

An earthquake is a phenomenon that results from the release of stored energy that radiates seismic waves away from the source and travels rapidly through the earth's crust (Shedlock and Pakiser, 1997; Kramer, 1996). This based on the elastic rebound theory that elastic strain energy is stored in the material near the subduction zone and transforms fault boundaries as shear stress increases on the fault planes that separate the plates.

Based on shear stress approaching the shear strength of the rock material along the fault, the rock material begins to fail and releases the stored energy. The level of the energy depends on how strong and brittle the rock material is (i.e. more strong and brittle, the stored energy can be high).

The location within a fault where the rupture takes place is called the hypocenter and the point on the earth's surface directly above the hypocenter is called the epicenter, as shown in Figure 2.2 (Kramer, 1996).

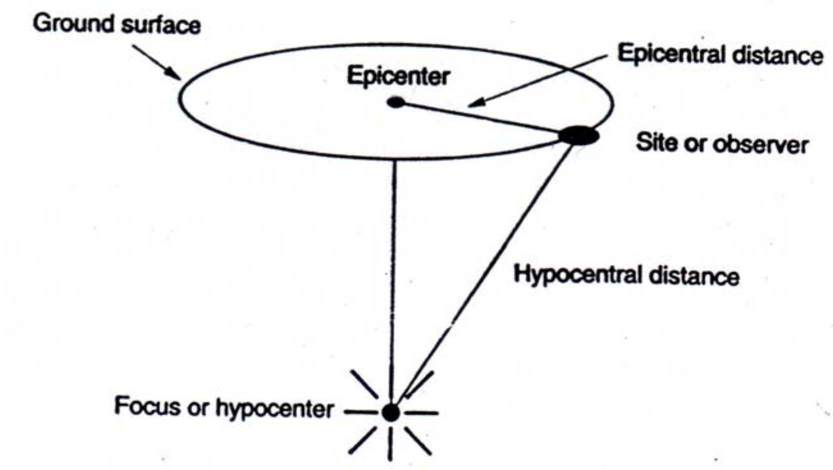


Figure 2.2: Schematic diagram of notation for description of earthquake location (Kramer, 1996).

The released energy is transmitted through the earth in the form of many types of seismic waves. These waves fall into two main categories, namely, body waves and surface waves, as shown in Figures 2.3 and 2.4. Body waves include primary and secondary waves (p-waves and s-waves, respectively). The surface wave includes Rayleigh waves and Love waves. The most destructive component of seismic waves are Rayleigh waves, since they carry about two third of the energy of an earthquake.

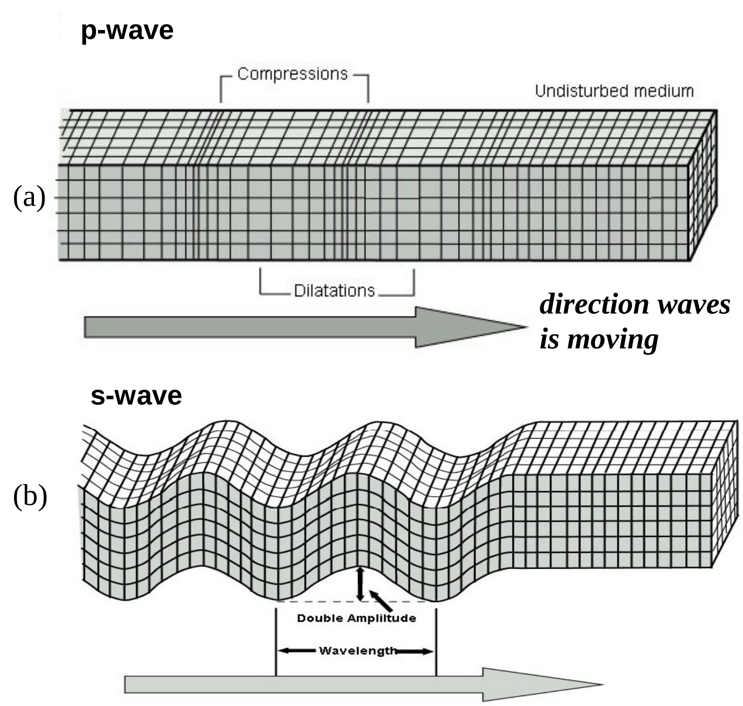


Figure 2.3: Main type of body waves; (a) p-wave, (b) s-wave (Penington, 2006)

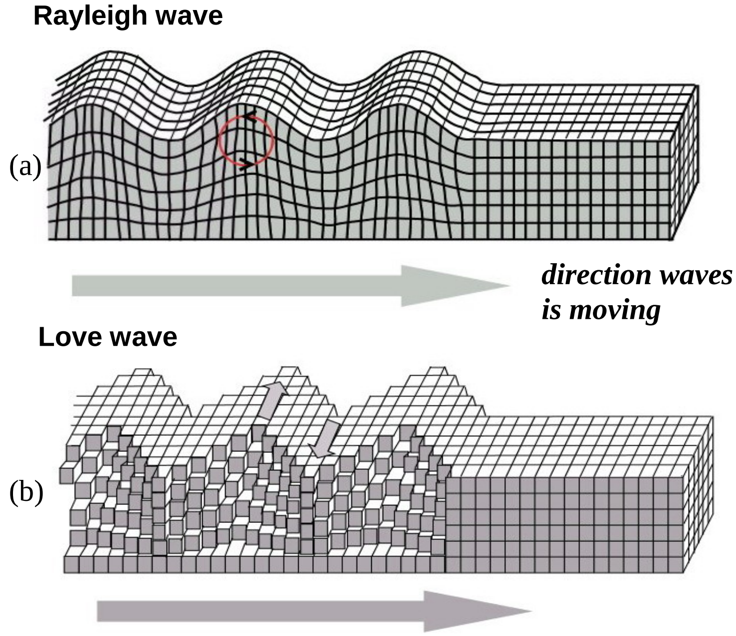


Figure 2.4: Main types of surface waves; (a) Rayleigh wave, (b) Love wave (Penington, 2006)

The passage of these waves causes vibrations of the ground surface that can be damaging to the built environment (Bommer, 2005). The strength and duration of shaking at a particular site depends on the size and location of the earthquake and on characteristics of the site (Kramer, 1996). The term earthquake is used to describe any seismic event, whether a natural phenomenon or an event caused by humans which can generate seismic waves, such as the nuclear weapons test by the North Koreans that can cause an earthquake (Agensi, 2006). United State geological survey (USGS) reported that, they recorded an earthquake with a magnitude of 4.2 on the Richter scale at Hwaderi, east coast of North Korea.

Earthquake effects can cover hundreds of thousands of square kilometers, which can cause damage to structures or infrastructures facilities, result in loss of life and injury to hundreds of thousands of people, and disrupt the social and economic functioning of the affected area (Adnan and Hendriyawan, 2005). This is an important factor to consider for preserving and safeguarding the built environment, which must be seriously addressed by government officials, administrators, planners, and engineers worldwide (Taly, 2005).

Table 2.1 shows the top ten largest earthquakes in the world since 1900. Off the West Coast of Northern Sumatra as a reference in this study is the third largest with magnitude 9.1 (PDE, 2006), where the earthquake was located at longitude of 95.854°E and latitude 3.316°N and the depth of the earthquake was 30 km (USGS, 2004). It is the greatest earthquake in 40 years, when it generated a disastrous tsunami that caused destruction in 11 countries bordering the Indian Ocean (Pararas-Carayannis, 2005).

This earthquake has also been called as the largest disaster in the modern years, created a tsunami that killed 283,100 people from surrounding countries, including Malaysia with 68 people dead (Adnan and Hendriyawan, 2005). This shows that Malaysian also confront such disasters which not only originate from our country but also from countries near by.

Table 2.1: 10 largest earthquakes in the world since 1900 (USGS, 2007)

No.	**Location**	**Date**	**Magnitude**	**Coordinates**		**Reference**
1	Chile	22/5/1960	9.5	-38.24	-73.05	Kanamori, 1977
2	Prince William Sound, Alaska	28/3/1964	9.2	61.02	-147.65	Kanamori, 1977
3	Off the West Coast of Northern Sumatra	26/12/2004	9.1	3.3	95.78	PDE, 2006
4	Kamchatka	4/11/1952	9.0	52.76	160.06	Kanamori, 1977
5	Off the Coast of Ecuador	31/1/1906	8.8	1.0	-81.5	Kanamori, 1977
6	Rat Islands, Alaska	4/2/1965	8.7	51.21	178.5	Kanamori, 1977

7	Northern Sumatra, Indonesia	28/3/2005	8.6	2.08	97.01	PDE, 2006
8	Andrean of Island, Alaska	9/3/1957	8.6	51.56	-175.39	Johnson, 1994
9	Assam, Tibet	15/8/1950	8.6	28.5	96.5	Kanamori, 1977
10	Kuril Islands	13/10/1963	8.5	44.9	149.6	Kanamori, 1977

2.1.1 Tectonic Setting

Plate tectonics, is the theory that the outer shell of the earth is made up of thin, rigid plates that move relative to each other. Scientists have successfully used it to explain many geological events, such as earthquakes and volcanic eruptions as well as mountain building and the formation of the oceans and continents (Coney, 2006).

Figure 2.5 shows the illustrated of the internal structure of the earth. The descriptions of each part are:

i. Crust - the rigid, rocky outer surface of the Earth composed mostly of basalt and granite. The crust is thinner under the oceans.
ii. Inner core - the solid iron-nickel center of the Earth that is very hot and under great pressure.
iii. Mantle - a rocky layer located under the crust - it is composed of silicon, oxygen, magnesium, iron, aluminum, and calcium. Convection (heat) currents carry heat from the hot inner mantle to the cooler outer mantle.
iv. Outer core - the molten iron-nickel layer that surrounds the inner core.

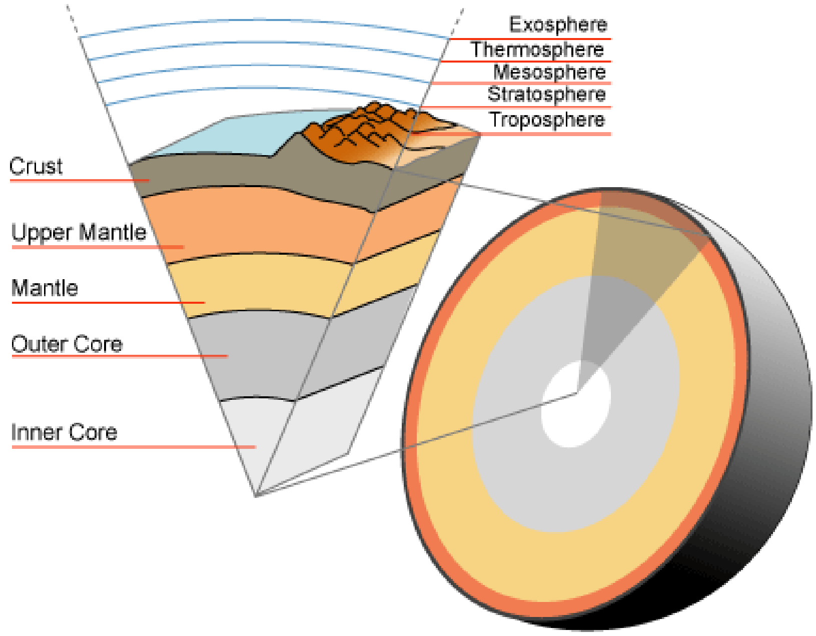


Figure 2.5: Internal structure of the earth
(http://library.thinkquest.org, 2007)

The tectonic plates are made up of Earth's crust and the upper part of the mantle layer underneath. Together the crust and upper mantle are called the lithosphere (solid part of the earth) and they extend about 80 km deep. The lithosphere is broken into giant plates that fit around the globe like puzzle pieces. These puzzle pieces move a little bit each year as they slide on top of a somewhat fluid part of the mantle called the asthenosphere (ductile part of the earth) is about 180 km thick and is relatively soft.

The basic hypothesis of plate tectonics is that the earth's surface consists of a number of large, intact blocks called plates, and that these plates move with respect to each other (Kramer, 1996). Currently, there are seven large and several small plates. The largest plates include the Pacific plate, Australian plate, the North American plate, the Eurasian plate, the Antarctic plate, the South American plate and the African plate. Smaller plates include the Cocos plate, the Nazca plate, the Caribbean plate, and the Gorda plate (Figure 2.6). Plate sizes vary a great deal. The Cocos plate is 2000 km

(1400 mi) wide, while the Pacific plate is the largest plate at nearly 14,000 km (nearly 9000 mi) wide (Coney, 2006).

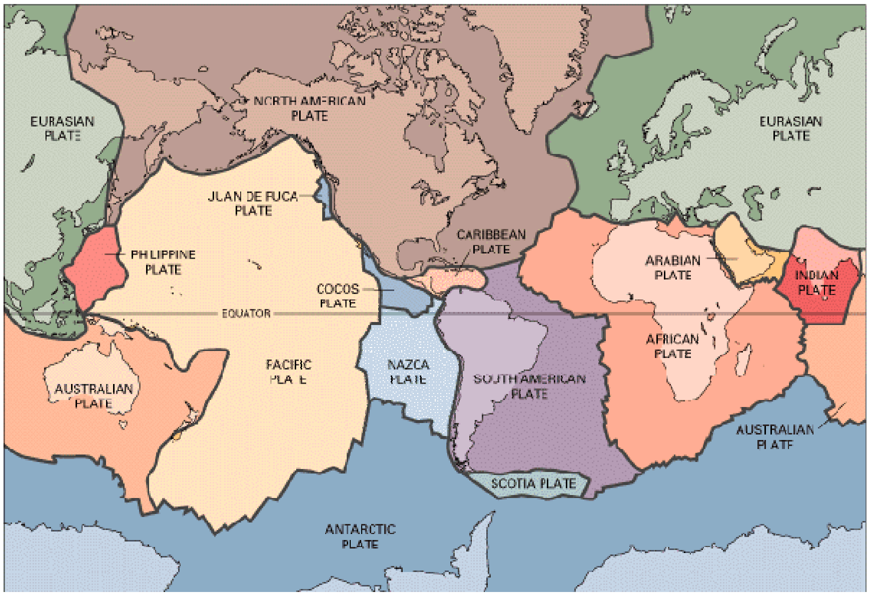


Figure 2.6: Tectonic plates on the earth's surface
(http://geology.er.usgs.gov/eastern/plates.html, 2007)

Tectonic plates move relative to a fixed spot in the earth's mantle and they move relative to each other. The first type of motion is called absolute motion, and it can lead to strings of volcanoes. The second kind of motion, called relative motion, leads to different types of boundaries between plates: plates moving apart from one another form a divergent boundary, plates moving toward one another form a convergent boundary, and plates that slide along one another form a transform plate boundary. In rare instances, three plates may meet in one place, forming a triple junction. Current plate movement is making the Pacific Ocean smaller, the Atlantic Ocean larger, and the Himalayan mountains taller.

2.1.2 Measuring Earthquakes

2.1.2.1 Earthquake Magnitudes

An earthquake's magnitude is an objective, quantitative measurement of the earthquake's size. Most measurements of an earthquake's magnitude are based on some measured characteristic of ground shaking (Kramer, 1996). The Richter Local Magnitude, M_L is the best-known magnitude scale. Is it defined as the logarithm (base 10) of the maximum trace amplitude (in micrometers) recorded on a Wood-Anderson seismograph located 100 km from the epicenter of the earthquake (Giovinazzi, 2005).

Other magnitude scales that base the magnitude on the amplitude of a particular wave have been introduced. The surface wave magnitude M_s is based on the amplitude of Rayleigh waves with a period of about 20 sec (approximately 18 to 20 sec.), therefore M_s only recorded seismic wave released energy at this period (Wells and Coppersmith, 1994). The value of M_s will describe the depth (less than 70 km focal depth) and distance (further than 1000 km) of earthquake from moderate to large earthquake (Kramer, 1996; Giovinazzi, 2005).

The body wave magnitude, m_b is a worldwide magnitude scale based on the amplitude of the first few cycle of p-waves (usually about one second). m_b commonly used to describe for deep-focus earthquakes (more than 70 km focal depth) (Kramer, 1996; Wells and Coppersmith, 1994).

These magnitude measurements (M_s and m_b), however cannot be used to specify the size of any earthquake within the whole range of sizes of earthquakes, which is considered a more reliable measure of the energy released during an earthquake (Wells and Coppersmith, 1994). Aware of this limitation, a new magnitude specification that can be used to measure earthquakes of any size have been proposed, which is called moment magnitude (M_w), which is defined in terms of the strain energy drop during faulting (Pacheko and Sykes, 1992).

2.1.2.2 Earthquake Intensity

The intensity is a qualitative description of the effects of the earthquake at a particular point, as evidenced by observed damage on the natural and built environment and human reactions at that location (Kramer, 1996) and was used before the actual instrumental measurements of strong ground motion became available.

The earthquake intensity is the oldest measure of the earthquake size and it remains, nowadays, a universal recognized parameter to provide, immediately after an earthquake event, an indicator of the overall earthquake damages. The MMI scale was originally developed by the Italian seismologist Mercalli and modified in 1931 to better represent conditions in California.

Intensity scales include the Modified Mercalli (MMI), Rossi-Forel (RF), the Japanese Meteorological Agency (JMA), and the Medvedev-Spoonheuer-Karnik (MSK) scale, which is based on seismometer measurements.

MMI is one of the many scales used to classify the intensity of an earthquake by examining its effect on the earth's surface, humans, objects of nature and man-made structures.

The Rossi-Forel (RF) scale of intensity, describing intensities with values ranging from I to X, was developed in the 1880s and used for many years. The JMA intensity scale is a measure used in Japan and Taiwan to indicate the strength of earthquakes. Unlike the Richter scale, JMA scale describes the degree of shaking point on the Earth's surface.

The MSK scale is a microseismic intensity scale used to evaluate the severity of ground shaking on the basis of observed effects in an area of the earthquake occurrence. A comparison of the MMI, RF, JMA and MSK scales is shown in Figure 2.7, according to Ricther, Murphy and O'Brien as quoted by Kramer (1996) and Giovinazzi (2005).

<table>
<tr><th>MMI</th><th>JMA</th><th>MSK</th><th>EMS</th></tr>
<tr><td rowspan="2">I</td><td>0</td><td rowspan="2">I</td><td rowspan="2">I</td></tr>
<tr><td rowspan="3">I</td></tr>
<tr><td>II</td><td>II</td><td>II</td></tr>
<tr><td>III</td><td>III</td><td>III</td></tr>
<tr><td>IV</td><td>II</td><td>IV</td><td>IV</td></tr>
<tr><td>V</td><td>III</td><td>V</td><td>V</td></tr>
<tr><td rowspan="2">VI</td><td>IV</td><td rowspan="2">VI</td><td rowspan="2">VI</td></tr>
<tr><td rowspan="3">V</td></tr>
<tr><td>VII</td><td>VII</td><td>VII</td></tr>
<tr><td>VIII</td><td>VIII</td><td>VIII</td></tr>
<tr><td>IX</td><td rowspan="2">VI</td><td>IX</td><td>IX</td></tr>
<tr><td>X</td><td>X</td><td>X</td></tr>
<tr><td>XI</td><td rowspan="2">VII</td><td>XI</td><td>XI</td></tr>
<tr><td>XII</td><td>XII</td><td>XII</td></tr>
</table>

Figure 2.7: Comparison of intensity values from Modified Mercalli (MMI), Rossi-Forel (RF), Japanese Meteorological Agency (JMA) and Medvedev-Spoonheuer-Karnik (MSK) scales (Kramer, 1996; Giovinazzi, 2005).

Earthquake intensities are usually obtained from interviews of observers after the events. In some seismically active areas, permanent observers are organized and trained to produce rational and unemotional accounts of ground shaking. Table 2.2 shows the MMI scale, where the qualitative nature of the MMI scale is apparent from the descriptions of each intensity level. Table 2.2 shows a rough guide to the degree of the Modified Mercalli Scale, the lower degrees of the MMI scale generally deals with the manner in which the earthquake is felt by people and the highest numbers of the scale are based on observed structural damage.

Table 2.2: Modified Mercalli Intensity Scale (1956 version) (GeoNet, 2004)

Intensity value	Description
I	*Instrumental* No felt except by a very few under especially favorable conditions
II	*Feeble* Felt only by a few persons at rest, especially on upper floors of buildings. Delicately suspended objects may swing.
III	*Slight* Felt quite noticeably by persons indoors, especially on the upper floors of building. Many do not recognize is as an earthquake. Standing motor cars may rock slightly. Vibration similar to the passing of a truck. Duration estimated.
IV	*Moderate* Felt indoors by many, outdoors by few during the day. At night, some awakened. Dishes, windows, door disturbed; walls make cracking sound. Sensation like heavy truck striking building. Standing motor cars rocked noticeably. Dishes and windows rattle.
V	*Rather strong* Felt by nearly everyone; many awakened. Some dishes and windows broken. Unstable objects overturned. Clocks may stop.
VI	*Strong* Felt by all; many frightened and run outdoors, walk unsteadily. Windows, dishes, glassware broken; books off shelves; some heavy furniture moved or overturned; a few instances of fallen plaster. Damage slight.
VII	*Very strong* Difficult to stand; furniture broken; damage negligible in building of good design and construction; slight to moderate in well-built ordinary structures; considerable damage in poorly built or badly designed structures; some chimneys broken. Noticed by persons driving motor cars.
VIII	*Destructive* Damage slight in specially designed structures; considerable in ordinary substantial buildings with partial collapse. Damage great in poorly built structures. Fall of chimneys, factory stacks, columns, monuments, walls. Heavy furniture moved.
IX	*Ruinous* General panic; damage considerable in specially designed structures, well designed frame structures thrown out of plumb. Damage great in substantial buildings, with partial collapse. Buildings shifted off foundations.
X	*Disastrous* Some well built wooden structures destroyed; most masonry and frame structures destroyed with foundation. Rails bent.
XI	*Very disastrous* Few, if any masonry structures remain standing. Bridges destroyed. Rails bent greatly.
XII	*Catastrophic* Total damage - Almost everything is destroyed. Lines of sight and level distorted. Objects thrown into the air. The ground moves in waves or ripples. Large amounts of rock may move.

2.1.3 Earthquake clusters

As mentioned by Reasenberg and John (2005) in their reports of seismologists, earthquakes occur in clusters. Means that, when one earthquake strikes, other earthquakes will occur at nearby locations. Uhrhammer (1986) stated that, only events lying in a zone approximately parallel to the fault rupture or surrounding the main events are considered as a potential foreshock or aftershock.

For example, the Indian Ocean earthquakes (26 December 2004), reported that, magnitude with 9.1 on the Richter scale have been recorded which made it necessary for Malaysians to remain alert (Emmanual and Fatt, 2004), and presumed that the 8.7 magnitude that struck the off northern coast of Indonesia's Sumatra Island on Monday, March 28, 2005 to be an aftershock. The aftershocks can occur within a few hours to a few days after the mainshock (Wells and Coppersmith, 1994).

In this phenomenon, there are three terms namely foreshock, main shock, and aftershock. The one with the largest magnitude is called the main shock and the earthquakes that occur before the main shock are called foreshock, while those that occur after the main shock are called aftershock. Usually, all these clusters of earthquakes occur near the location of the main shock. A main shock will be redefined as a fore shock if a subsequent earthquake in the cluster has a larger magnitude. The fault will produce most of the aftershocks when the stress on the main shock fault changes drastically during the main shock.

As a rule of thumb, earthquakes can be considered to be aftershocks if they are located within a characteristic distance from the main shock. The distance is usually taken to be one or two times the length of the fault rupture associated with the main shock (Reasenberg and John, 2005).

Gardener and Knopoff (1974) notified that any complete earthquake catalogue is clearly non-Poissonian, which is means that not entirely all earthquake events are time-independent because any substantial earthquake is usually followed by a cluster of aftershocks whose occurrence is dependent on the appearance of the main shock. Thus, a basic assumption of seismic methodology is that earthquake sources are independent. Therefore, for estimating seismic future activity catalogs that are prepared must be free of dependent events such as foreshocks and aftershocks. In probabilistic analyses of seismic hazard, assumes that seismicity follow a Poisson process, with generally considered essential to remove any non-Poissonian behaviors from earthquake catalogues.

2.1.4 Earthquake catalogues

Earthquakes catalogues from past earthquakes are used as a rate for future seismic activity estimation. In the case of estimation of these rates, the seismograph will detect the felt even it is a small earthquake. From frequency-magnitude distribution of past earthquakes, frequency of future larger shocks that control the hazard can be computed (Petersen *et al.,* 2004).

In this hazard assessment, worldwide earthquake catalogues have been used by all the scientific and engineering communities. Usually geophysicists use these catalogues for seismicity studies, long-term earthquake prediction and forecasting, and detailed studies of plate tectonics.

Earthquakes are classified by their size using either a magnitude or intensity scale (oldest measure of an earthquake's size), which is evidenced by observed damage and human reactions at that location after earthquake occur at a particular location (Kramer, 1996). Seismicity is generally catalogued by a felt intensity scale

(Modified Mercalli Intensity), part of the pre-instrumentally period (Pacheko and Sykes, 1992).

2.2 Sumatran Earthquakes

Sumatra is part of the Indonesia island arc, has always experienced volcanoes, earthquakes and fires and well known-known 1,350 km long Sumatra fault system (Pan and Lee, 2002), which is located adjacent to the Sunda Trench (Figure 2.8), where the India-Australia plate subducts below the Eurasian plate along this arc at a rate of about 6 cm/yr (Sun and Pan, 1995a; 1995b; Pan and Megawati, 2002).

The most active seismic source in Indonesia is the Sunda Arc, which extends approximately 5600 km between the Andaman Islands, in the northwest and Banda Arc to the east (Newcomd and McCann, 1987). The island is a result from convergence and subduction of the Indo-Australia, Pacific and Eurasian Plate (Kertapati, 1999).

The Sumatra tectonics generates a very high annual rate of earthquakes in and near the island of Sumatra (Peterson *et al.,* 2004). These make Sumatra one of the most active seismic zones on earth (Sieh and Natawidjaja, 2001).

Usually, earthquakes at Sumatra occur at the two most active zones, which is the fault and subduction zones. Numerous earthquakes ranging from magnitude 5 to 9 have occurred historically in both zones (Figure 2.8). These include the 1994 Liwa (Mw 6.9), 1995 Kerinci (Mw 7.0), and 2006 Yogyakarta (6.2). Sometimes, these earthquakes that occurred at both the zones were felt in many distant, especially Malaysia.

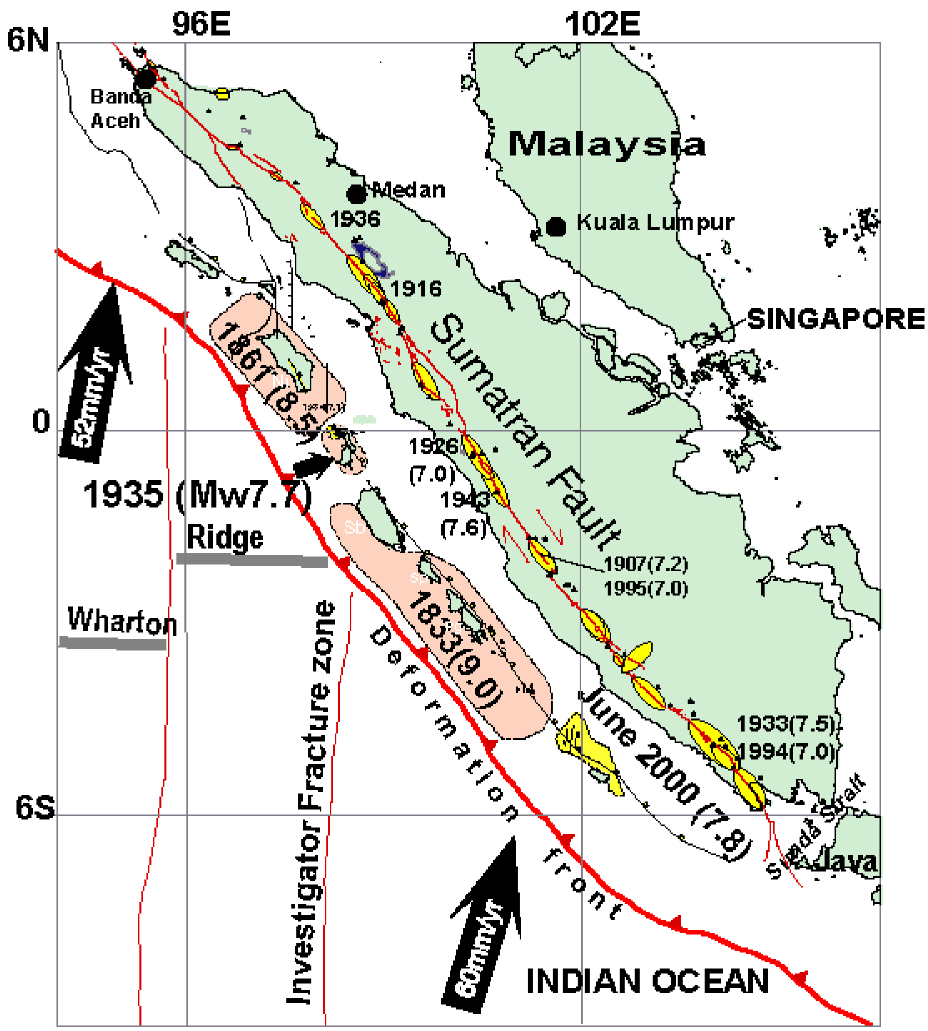


Figure 2.8: Active tectonic and seismologic summary, part of the Sumatra. (www.gps.caltech.edu)

2.2.1 Sumatran Subduction Zone

The Sumatra subduction zones define one of the most active plate tectonic margins in the world (Figure 2.9), accommodating about 49 mm/year of oblique north-westward convergence between the Eurasian and India-Australia plates (Peterson, 2004).

Subduction zones are found where one plate overrides, or subducts, another, pushing it downward into the mantle where it melts (Shedlock and Pakiser, 1997). This zones vary dramatically in their ability to store elastic strain energy such variation has been explained by different in convergence rates and subducting plate ages and others (Prawirodirdjo, 1997). This energy whether is small or strong earthquakes, is of great significance for human society and for engineering design and corresponding codes as well (Jeng *et al.,* 2002)

In fact, the 10 largest earthquakes since 1900 have occurred at subduction zones (www.rpi.edu). Those entire earthquakes occurred near convergent boundaries where Indo-Australian plates are subducting beneath under Eurasian plate (Figure 2.9) (Zachariasen *et al.,* 1999), whereby the Indian plate is sliding approximately northward beneath Sumatra and Java, with the direction of convergence is N20°E and the overall rate convergence is 7 cm/yr (Adnan *et al.,* 2005).