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DERIVATION OF ATTENUATION EQUATIONS FOR DISTANT EARTHQUAKE SUITABLE FOR MALAYSIA

(PENERBITAN PERSAMAAN ATTENUASI UNTUK GEMPABUMI JAUH YANG BERSESUAIAN UNTUK MALAYSIA)

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TAJUK PROJEK : **DERIVATION OF ATTENUATION EQUATIONS FOR DISTANT EARTHQUAKE SUITABLE FOR MALAYSIA**

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ABSTRACT

One of the critical factors in seismic analysis is selecting appropriate attenuation equations. This formula, also known as ground motion relation, is a simple mathematical model that relates a ground motion parameter (i.e. spectral acceleration, velocity and displacement) to earthquake source parameter (i.e. magnitude, source to site distance, mechanism) and local site condition (Campbell, 2002). It is considered one of the critical factors in seismic hazard analysis. It may lead the design load for building either become too conservative or under design.

There has been a number of attenuation equations derived in the last two decades since the record of ground motions becomes more available. In general, they are categorized according to tectonic environment (i.e. subduction zone and shallow crustal earthquakes) and site condition. There are several attenuation relationships derived for subduction zone earthquake, which are commonly used such as Crouse (1991), Youngs (1997), Atkinson and Boore (1997), Petersen (2004). Whereas attenuation relationships, which are developed by Abrahamson and Silva (1997), Campbell (1997, 2002), Sadigh et al. (1997), Toro (1997), are frequently used to estimate ground motion for shallow crustal earthquake.

The shortcomings of this method are by the limitation of the attenuation relationship itself. Usually attenuation relationship is derived for near source earthquake. Therefore, most of the attenuation relationships have a distance limitation. Except attenuation developed by Toro (1997), and Campbell (2002), all of the attenuations are only valid to be applied for distances between 80 km and 400 km. Since there is no attenuation relationship has been derived directly for Malaysia region, which is affected by long distance earthquake, therefore selection or development of appropriate attenuation relationship for Malaysia is needed. This

research is collaborating with related institutions such as Malaysian Meteorological Department (MMD), Jabatan Mineral dan Geosciences Malaysia (JMG) and United States Geological Survey (USGS).

There are 481 recordings from 40 mainshocks and aftershocks which magnitude greater than 5.0 in the full data set. Recordings with unknown or poor estimates of the magnitude, mechanism, distance, or site condition were excluded from the data set used in the regression analysis. This reduced the data set used in the analysis to 91 recordings from 14 earthquakes.

ABSTRAK

Salah satu faktor kritikal dalam analisis seismik adalah pemilihan persamaan attenuasi yang tepat. Formula ini, yang dikenali sebagai hubungan pergerakan permukaan tanah, juga merupakan model matematik mudah yang menghubungkan parameter pergerakan permukaan tanah (seperti percepatan spektra, kelajuan dan perpindahan) ke parameter sumber gempabumi (seperti magnitud, sumber ke jarak tempat, mekanisme) dan kondisi tempat lokal (Campbell, 2002). Persamaan attenuasi diambilkira sebagai salah satu faktor kritikal dalam analisis bencana seismik. Persamaan attenuasi ini akan menyebabkan beban rekabentuk bangunan baik menjadi terlalu berlebihan atau berada di bawah tahap yang sepatutnya.

Sejak dua dekad yang lalu, beberapa persamaan attenuasi telah dapat dihasilkan melalui ketersediaan rakaman pergerakan tanah. Secara umumnya, persamaan attenuasi dikategorikan mengikut keadaan tektonik (seperti zon gempa subduksi dan zon gempa cetek) dan keadaa setempat.Terdapat beberapa persamaan attenuasi yang dihasilkan untuk gempa zon subduksi, yang mana ianya seringkali digunakan seperti Crouse (1991), Youngs (1997), Atkinson and Boore (1997), Petersen (2004). Manakala persamaan attenuasi yang dihasilkan oleh Abrahamson and Silva (1997), Campbell (1997, 2002), Sadigh et al. (1997), Toro (1997), kerap digunakan untuk pengiraan pergerakan tanah untuk gempa zon cetek.

Kelemahan kaedah ini ialah wujudnya batasan tertentu daripada persamaan attenuasi itu sendiri. Persamaan attenuasi biasanya dihasilkan daripada sumber gempa jarak dekat. Oleh sebab itu, kebanyakan persamaan attenuasi ini mempunyai batas jarak yang terhad. Kecuali persamaan attenuasi yang dihasilkan oleh Toro (1997), and Campbell (2002), kebanyakan daripada persamaan attenuasi mereka hanya dapat digunakan untuk sumber gempa jarak jauh iaitu jarak di antara 80 km

dan 400 km. Memandangkan persamaan attenuasi yang khusus untuk kawasan Malaysia belum dihasilkan lagi walaupun ianya dipengaruhi oleh sumber gempa jarak jauh. Maka, pemilihan atau pengembangan hubungan persamaan attenuasi yang tepat untuk kawasan Malaysia adalah sangat diperlukan. Penyelidikan ini akan menjalinkan kerjasama beberapa institusi berkaitan seperti Jabatan Meteorologi Malaysia, Jabatan Mineral dan Geosains Malaysia dan United States Geological Survey (USGS).

Terdapat 481 rakaman gempa dari 40 kejadian gempa utama dan gempa sesudah dengan magnitud lebih dari 5.0 pada data yang tersedia. Beberapa rakaman gempa dengan parameter yang tidak lengkap tidak diambilkira untuk data analisis regressi. Hal ini menyebabkan jumlah data yang digunakan untuk analisis berkurang menjadi 91 rakaman daripada 14 kejadian gempabumi.

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LIST OF SYMBOLS/ABBREVIATIONS

r_{seis} seismogenic rupture

Y the mean of peak ground acceleration (PGA) in gal

R_{hypo} the hypocentral distance in km

H the focal depth in km.

g - Gravity = 9.81 m/s^2

gal - cm/sec^2

M_L - Richter local magnitude

M_o - Seismic moment

M_S - Surface wave magnitude

M_W - Moment magnitude

MCE - Maximum credible earthquake

PE - Probability of exceedance

$\overline{N}_{ch}$ - The average standard penetration resistance for cohesionless soil layers

PGA - Peak Ground Acceleration (at Bedrock)

PSA - Peak Surface Acceleration

R_a - Mean annual total frequency of exceedance

r - Coefficient of Correlation

r^2 - Multiple coefficient of determination

r_a^2 - Adjusted multiple coefficient of determination

Sa - Spectral acceleration

Sd - Spectral displacement

SFZ - Sumatra Fault Zone

SHA - Seismic Hazard Assessment

SSZ - Sumatra Subduction Zone

Sv - Spectral Velocity

T_n - Natural period

T_R - Return Period

V_S - Shear wave velocity

$V_{S\text{-}30}$ - The mean shear wave velocity of the top 30 m

Z - Seismic zone factor

β_s - Damping factor

σ - Standard deviation

λ - Rate of earthquake occurrence

ρ - Mass density

ω - Angular frequency = $2\pi f$

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CHAPTER 1

INTRODUCTION

1.1 Introduction

An essential element in both deterministic and probabilistic seismic hazard analyses is the ability to estimate strong ground motion from a specified set of seismological parameters. This estimation is carried out using a ground motion relation. This relation, that is commonly referred to in engineering as an attenuation relation, is a simple mathematical model that relates ground motion parameters (i.e. spectral acceleration, velocity and displacement) to earthquake source parameters (i.e. magnitude, source to site distance, mechanism) and local site conditions (Campbell, 2003).

A large number of attenuation relations have been developed by different investigators since the record of ground motions become more available. In general, they are categorized according to tectonic environment (i.e. subduction and shallow crustal) and site condition (i.e. rock, soft soil, or stiff soil). A state of the art assessment of the attenuation relationships could be found in a special issue of Seismological Research Letters (SSA, 1997). According to the Engineering Seismology and Earthquake Engineering (ESEE) report No. 01-1 that prepared by Douglas (2001), he presented a comprehensive worldwide summary of strong-motion attenuation relationships since 1969 until 2000.

Ground motion attenuation relations can be recognalized into three categories: shallow crustal earthquakes in active tectonic regions (e.g., Western North America), shallow crustal events in stable continental regions (e.g., Central and Eastern North America), and subduction zones (e.g., Pacific Northwest and Alaska). In this study, we develop empirical models for the attenuation of response spectral values for the average horizontal components applicable to subduction zone events in active tectonic regions.

1.2 Statement of Problem

Peninsular Malaysia has been affected seismically by far field earthquakes events from neighbouring countries since years back. At the moment, this natural disaster still has not given any striking effect to Malaysia. However in recent years, this has become an issue in Malaysia. The natural earthquake happen has attracted attention of seismological and earthquake experts. Although, hazard from the earthquake source to Malaysia country is in the unobvious situation, it is essential to analyze the seismic hard within the Asia region so that Malaysia has the emergency plan once Malaysia is seriously affected by the earthquake.

Attenuation is considered as one of the critical factors in seismic hazard analysis. An attenuation relation derived in a certain region may not be necessarily applied in other region although they are tectonically and geologically situated on the same region. In fact, Peninsular Malaysia is affected seismically by far field earthquake events from Sumatera fault or Sumatera subduction fault. The nearest distance of earthquake epicenter from Malaysia is approximately 350 km. Hence, there are problems are raised in this seismic hazard analysis, such as

a) The lack of attenuation function of dip slip earthquakes mechanism derived for distance more than 300 km away from the site

b) A new attenuation function needs to be developed for fulfilling the requirement of seismic hazard analysis in Peninsular Malaysia.

1.3 Purpose and Objective of Study

The main purpose of this study is to compute an attenuation function for Peninsular Malaysia to analyze the seismic hazard distance more than 300 km away from earthquake source. Objectives of this research includes

a) The selecting an appropriate method to formulate the attenuation function.
b) Express ground motion parameters as a function of magnitude, distance, soil classification, and mechanism.

1.4 Scope of Study

The scope of study only includes the seismic hazard analysis by using attenuation function. Furthermore, due to variability in the soil conditions, including soil stratigraphy, ground water level, physical and mechanical properties of soil, only attenuations for rock sites are considered in this research. In addition, this attenuation functions only suitable to estimate the seismic from subduction zone fault.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter will include the development of attenuation relationships. In general, the hybrid empirical method and theoretical method which base on seismological parameters are applied in order to develop the attenuation relationships. Besides, the past development of attenuation function for Peninsular Malaysia is discussed.

One of the critical factors in seismic analysis is selecting appropriate attenuation equations. This formula, also known as ground motion relation, is a simple mathematical model that relates a ground motion parameter (i.e. spectral acceleration, velocity and displacement) to earthquake source parameter (i.e. magnitude, source to site distance, mechanism) and local site condition (Campbell, 2002). It is considered one of the critical factors in seismic hazard analysis. It may lead the design load for building either become too conservative or under design.

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The shortcomings of this method are by the limitation of the attenuation relationship itself. Usually attenuation relationship is derived for near source earthquake. Therefore, most of the attenuation relationships have a distance limitation. Except attenuation developed by Toro (1997), and Campbell (2002), all of the attenuations are only valid to be applied for distances between 80 km and 400 km. Since there is no attenuation relationship has been derived directly for Malaysia region, which is affected by long distance earthquake, therefore selection or development of appropriate attenuation relationship for Malaysia is needed. This research will be collaborating with related institutions such as Malaysian Meteorological Department (MMD), Jabatan Mineral dan Geosciences Malaysia (JMG) and United States Geological Survey (USGS).

2.2 Development of the Attenuation Relationship

Generally, there are two kinds of attenuation relations. The first ones are developed for estimating the peak ground acceleration, which is used to scale a normalized standard spectral shape (Gupta, 2002). However, this approach suffers from several drawbacks and is unable to represent various characteristics of the response spectra in a realistic way (Gupta, 2002). The others are developed for not only estimating peak ground acceleration but also spectral ordinates as well.

The most common method to obtain the relationship is by using an empirical method based on historical earthquake data. This is the oldest method in seismic hazard analysis, dating from 1960s (McGuire, 2004). Several inherent strengths in this method make it the most popular method to obtain the relationship. The first strength is its simplicity because there are many formulas in mathematical statistics that can be used to develop the relationship. The second strength is that it relies on actual earthquake data. Therefore, this method has account aleatory of variability and epistemic variability.

An empirical method can only be developed in a location where the strong motion recordings are abundant such as Western North America and Japan. This method requires lot of data in order to obtain statistically reliable results. Another method to develop an attenuation relationship is by using intensity method (Campbell, 2003). This method has been widely used in regions which lack recorded data. In these latter regions, it has been traditional to predict quantitative ground motion parameters from qualitative measures of ground shaking, such as Modified Mercalli Intensity (MMI) or Medvedev-Spooner-Karnik (MSK) intensity. The disadvantage of this method is that the values of ground motion parameters are relied on subjective measurement of observer. The range of intensity can be affected significantly by many factors including the environment and experience of the observer.

There are other procedures that can be used to obtain attenuation relationship in the location where there are not enough recordings to develop reliable empirical attenuation relationship. These procedures are

1) Utilization of existing attenuation relationship developed for other locations

2) Development of attenuation relationship using theoretical method based on seismological parameters

3) Development of attenuation relationship using hybrid empirical methods.

Utilization of existing attenuation relationship developed for other locations is commonly used to estimate ground motion parameters in location where there are not enough recorded data to develop attenuation relationships. It should be noted that an attenuation relation derived in a certain region may not be necessarily appropriate in other region, although they are tectonically and geologically situated on the same region. For engineering practice, this procedure can be admitted, provided that the selection is conducted based on a similarity of faulting mechanism between site region and that in which attenuation formula was derived.

The shortcomings of this method are by the limitations of the attenuation relationship itself. The fundamental requirements for such an attenuation relationship are that it should represent, at each frequency, the magnitude and distance saturation. Usually attenuation relationship is derived for near source earthquake. Consequently, most of the attenuations are only valid to be applied for short distance (e.g. less than 400 km).

Development of attenuation relationship using theoretical method based on seismological parameters is an alternative method to develop attenuation relationships. In low seismicity area, where the records of ground motions are insufficient to satisfactorily undertake such an empirical study, attenuation relationship is carried out using theoretical methods. One of the critical steps in this method is the selection of an appropriate set of seismological parameters. Therefore, this method requires a good seismological data.

The concept of theoretical method is to derive simple seismological models that can be used to describe the relationship between earthquake source size, site-distance, and ground motion parameters. Generally, there are two main methods to predict ground motion (or to develop an attenuation relationship) based on seismological parameters, i.e. deterministic and stochastic. These methods are admittedly powerful in region where strong motion recordings are limited but have a good seismological data. The shortcoming of these methods is the attenuation relations that have been developed lack many of the important ground motion characteristics that are inherent in empirical attenuation relations. Also in contrast to empirical methods, these methods lack unbiased representation of epistemic variability because of their reliance on a single method (Campbell, 2003). A complete estimate of epistemic variability is an important aspect of the deterministic and probabilistic estimations of design ground motions and should be included in the estimation of ground motions (Budnitz *et al.*, 1997).

Development of attenuation relationship using hybrid empirical method is proposed by Campbell (1981) as an alternative to the intensity method. He used theoretical adjustment factors based on simple seismological models to account for differences in inelastic attenuation and regional magnitude measures between Eastern North America (ENA) and Western North America (WNA). The first formal mathematical framework of this model was published as part of the Yucca Mountain. Project (Abrahamson and Becker 1997) and later in a 1999 Nuclear Energy Agency workshop (Campbell, 2001), which included an example application to ENA.

According to Campbell (2003), the hybrid method has three advantages compared to other methods. The first advantage is that it relies on empirical attenuation relations that are well constrained by strong-motion recordings over the range of magnitudes and distances of greatest engineering interest. As a result, the magnitude- and distance-scaling characteristics predicted by the method, at least in the near-source region, are strongly founded on observations rather than theoretical assumptions. The second strength is its use of relative differences in theoretical estimates of ground motion between the host and target regions to derive the adjustment factors needed to apply empirical attenuation relations to the target region. This avoids the additional and often unmodeled uncertainty that is inherent in calculating absolute values of ground motion using the theoretical method. A third strength of the hybrid empirical method is its ability to provide explicitly in straightforward manner estimates of aleatory variability (randomness) and epistemic variability (lack of scientific knowledge) in the predicted ground motions for the target region.

Both theoretical and empirical method requires reliable seismological parameters to develop the attenuation. Therefore, it might not be possible to apply the method in some regions with lack of reliable seismological data such as Malaysia. Since there is no attenuation function derived for Malaysia, the new attenuation function should be developed that suite the local seismotectonic and site conditions. Alternatively, the assessment of seismic hazard has to use the functions from other countries that consider appropriate according to mechanism that are likely to occur in Malaysia.

There are four parameters that must be clearly defined when using attenuation relationship in SHA: earthquake magnitude, type of faulting, distance and local site conditions. Moment magnitude (M_w) is the preferred magnitude because it has some advantages compare to other magnitude scales. Style of faulting is also considered in developing or using attenuation functions because within 100 km of a site reverse and thrust earthquakes tend to generate larger PGA and high frequency Spectral Acceleration (SA) than strike slip earthquakes, except for $M \geq 8$ (Boore *et al.*, 1994; Campbell and Bozorgnia, 1994).

Different source-to-site distance measures are used by different researchers as shown in Figure 4.1. According to the figure, r_{jb} is the closest horizontal distance to the vertical projection of the rupture (the Joyner-Boore distance); r_{rup} is the closest distance to rupture surface; r_{seis} is the closest distance to the seismogenic rupture surface (assumes that near surface rupture in sediments is non-seismogenic (Marone and Scholz, 1988); and r_{hypo} is the hypocentral distance. A complete summary regarding this topic can be found in Abrahamson and Shedlock (1997).

Another important issue in developing or selecting attenuation functions is the effects of site condition. It has been well recognized that earthquake ground motions are affected by site conditions such as rock properties beneath the site and local soil conditions. Most relations use qualitative measure to represent site conditions, except for Boore *et al.*, (1997), which utilizes average shear velocity over the upper 30 m ($V_{S\text{-}30}$) to represent site condition.

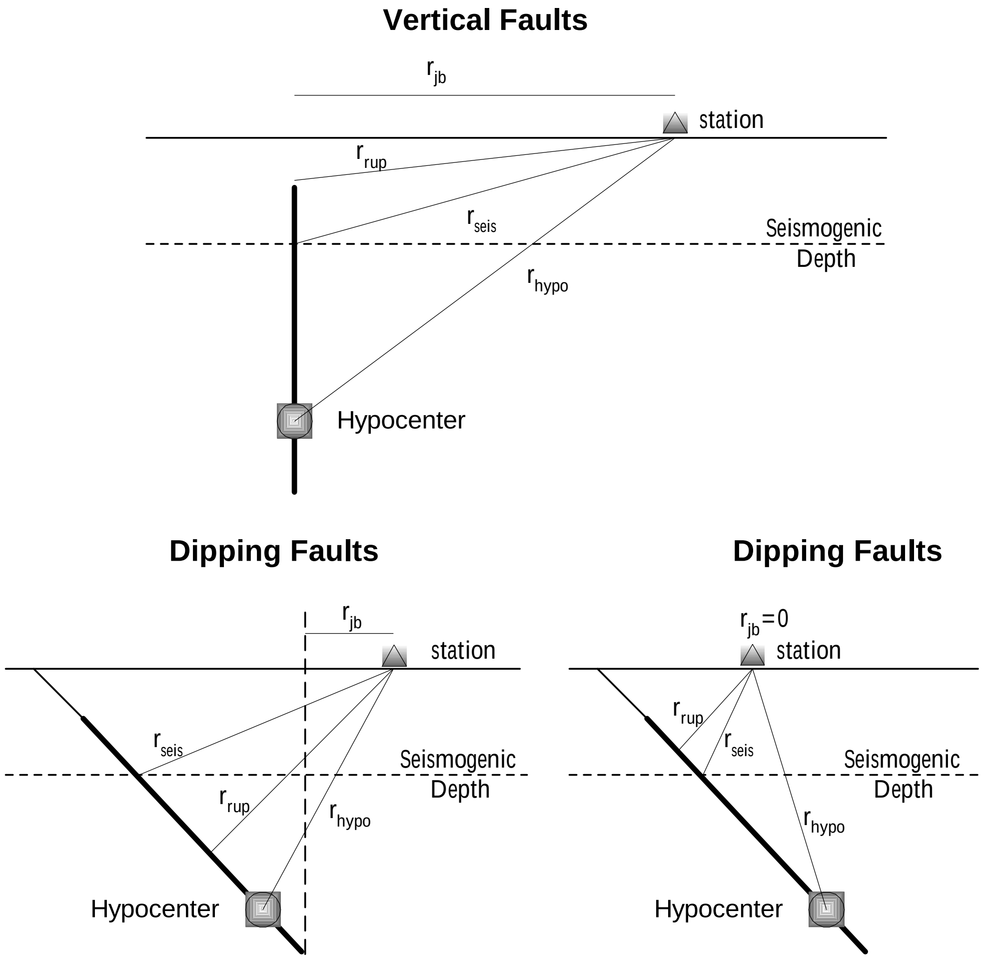


Figure 2.1: Source to site distance measures for attenuation models (Abrahamson and Shedlock, 1997)

2.3 Attenuation Function for Peninsular Malaysia

The attenuation function for Peninsular Malaysia should consider the following situations:

- Peninsular Malaysia is affected seismically by far field earthquakes events from Sumatra Subduction Fault (SSZ) and Sumatran Fault (SFZ).
- The nearest distance of earthquake epicenter from Malaysia is approximately 300-400 km.
- Due to variability in the soil conditions, including soil stratigraphy, ground water level, physical and mechanical properties of soil, only attenuations for rock sites are considered in this research.

Based on the tectonic environment, there are two types of attenuation that should be used in SHA for Peninsular Malaysia. The first is attenuation functions for predicting ground motions due to subduction mechanisms and second is for shallow crustal mechanisms (transform faults).

The new attenuation function for subduction earthquakes was developed using worldwide strong motion earthquake data. The previous attenuation functions for subduction mechanism were also discussed and compared to the new function. Due to the lack of recorded data for shallow crustal earthquakes for distant events, the existing attenuation relations from previous researchers were selected in this research.

2.3.1 Attenuation Relationships for Subduction Mechanisms

Due to the lack of attenuation function of subduction earthquakes mechanism derived for distance more than 300 km away from the site, the new attenuation function has been developed for fulfilling the requirement of seismic hazard analysis in Peninsular Malaysia.

The typical form of attenuation functions are based on the following assumptions (Kramer, 1996; Youngs *et al.*, 1997):

a) Peak value of strong motion parameters are approximately lognormal distributed. As a result, the regression is usually performed on the logarithm of Y rather than on Y itself.
b) Earthquake magnitude is typically defined as the logarithm of some peak motion parameter. Consequently ln Y ~ M.
c) The spreading of stress waves as they travel away from the source of an earthquake causes body wave amplitudes to decrease according to 1/R and surface wave amplitudes to decrease according to $1/\sqrt{R}$.
d) The area over which fault rupture occurs increases with increasing earthquake magnitude. The effective distance is usually greater than R by an amount that increases with increasing magnitude.
e) Peak motions are proportional to the depth of the event.
f) Ground motion parameters may be influenced by source and site characteristics.

A typical attenuation relationship may have the following form (Kramer, 1996 and Youngs *et al.*, 1997):

$$\ln Y = C_1 + C_2 M + C_3 M^{C_4} + C_5 \ln\left(R + C_6 \exp\left(C_7 M\right)\right) + C_8 H + f(P) \quad (2.1a)$$

$$\sigma_{\ln Y} = \sqrt{\frac{\Sigma(\ln y - \ln \hat{y})^2}{n - p}} \quad (2.1b)$$

In Eq. (2.1a), Y is the mean of ground motion parameters, M is the magnitude of the earthquake, R is a measure of the distance from the source to the site being considered, H is the focal depth of earthquake, f(P) is other parameters such as source and site characteristics functions, and C_1 to C_8 are the coefficients of the attenuation function.

In Eq. (2.1b), $\sigma_{\ln Y}$ represents the standard deviation of ln Y at the magnitude and distance of interest. Standard deviation is taken as a measure to quantify variability and to indicate how fit an attenuation model to a set of database. The standard deviation computed this way is called the sample standard deviation. In this equation, y is the actual data points, $\hat{y}$ is the data generated from the equation, n is the number of actual data, and p is the number of degree of freedom. If the data follows a bell shaped Gaussian distribution, then 68% of the values (i.e. observed acceleration) lie within one standard deviation of the mean (on either side) and 95% of the values lie within two standard deviations of the mean.

The data used to develop the attenuation relationships were gathered from several sources; i.e., The National Geophysical Data Center and World Data Center (NGDC), strong motion data compiled by Jibson and Jibson (2003) and by Petersen *et al.* (2004). The data collection consists of 939 strong motion records from more than 30 worldwide earthquake events with magnitudes in the range of $5.0 \leq M_w \leq 8.5$, and the epicenter distances that range from 2.0 km to 1122 km. These earthquakes have unconstrained focal depths that range from 0.0 to 139 km.

The combined data, after the removal of strike slip events or ground motions recorded at soil, contained 776 records from 29 earthquake events and mostly the records were dominated by reverse slip events. The selected strong motion data is summarized in Table 2.1. Some of the moment magnitudes in the table are obtained by using empirical correlation from Eq. (3.7).

In this study, the attenuation function is developed using one-step process nonlinear regression analysis. The source characteristics are constrained only subduction mechanisms whilst site characteristics are restricted only for rock. Therefore, the f(source) and f(site) could be eliminated from the Eq. (2.1a). The analysis is performed using three independent variables, i.e. moment magnitude, M_w, hypocenter distance, R, and focal depth.

The general nonlinear model to be fitted can be represented by:

$$y = y(x, a) \tag{2.2}$$

The goal of nonlinear regression is to determine the best-fit parameters for a model by minimizing a chosen merit function. The merit function is a function for measuring the agreement between the actual data and a regression model with a particular choice of variables. Usually, the process of merit function minimization is an iterative approach. The process is to start with some initial estimates and incorporates algorithms to improve the estimates iteratively. The new estimates then become a starting point for the next iteration. These iterations continue until the merit function effectively stops decreasing.

Table 2.1. Selected strong motion data from worldwide earthquake

No.	Earthquake	Date (mm/dd/yy)	Depth (km)	M_w	Foc. Mech.	No of Recording data	Ref.	Origin Magnitude
1	Kern County 1952	7/21/1952	15.8	7.5	Obl. reverse	6	1	M_w
2	Daly City 1957	3/22/1957	5.0	5.3	Reverse	2	1	M_w
3	San Fernando 1971	2/9/1971	8.5	6.6	Reverse	35	1	M_w
4	Santa Barbara 1978	8/13/1978	12.7	6.0	Obl. reverse	2	1	M_w
5	Tabas, Iran 1978	9/16/1978	42.1	7.4	Reverse	6	1	M_w
6	Mammoth Lakes-1 1980	5/25/1980	9.0	6.3	Obl. reverse	2	1	M_w
7	Mammoth Lakes-2 1980	5/25/1980	6.3	6.0	Obl. reverse	4	1	M_w
8	Coalinga 1983	5/2/1983	10.1	6.4	Obl. reverse	38	1	M_w
9	New Ireland	3/18/1983	89.0	8.2	Reverse faulting	11	2	M_S7.9
10	Michoacan, Mexico City	9/19/1985	16.0	8.5	Reverse faulting	42	2	M_S8.1
11	Michoacan Aftershock	9/21/1985	20.0	7.8	Reverse faulting	6	2	M_S7.6
12	Northwest Canada 1985	10/5/1985	6.0	6.8	Obl. reverse	6	1	M_w
13	N. Palm Springs 1986	7/8/1986	10.4	6.0	Obl. reverse	42	1	M_w
14	Whittier Narrows 1987	10/1/1987	9.5	6.0	Obl. reverse	74	1	M_w
15	Loma Prieta 1989	10/17/1989	17.7	6.9	Obl. reverse	76	1	M_w
16	Cape Mendocino 1992	4/25/1992	10.1	7.1	Reverse	8	1	M_w
17	Hokaido	7/12/1993	34.0	7.8	Subduction	1	3	M_w
18	Northridge 1994	1/17/1994	19.0	6.7	Reverse	172	1	M_w
19	Honshu	12/28/1994	33.0	7.7	Subduction	2	3	M_w
20	Solomon	8/16/1995	30.0	7.7	Subduction	3	3	M_w
21	Kurile	12/3/1995	33.0	7.9	Subduction	5	3	M_w
22	Peru	2/21/1996	10.0	7.5	Subduction	4	3	M_w
23	Aleutians	6/10/1996	33.0	7.9	Subduction	2	3	M_w
24	Santa Cruz	4/21/1997	33.0	7.7	Subduction	2	3	M_w
25	Kamchatca	12/5/1997	33.0	7.8	Subduction	4	3	M_w
26	Sumatera	4/1/1998	56.0	7.0	Subduction	11	3	M_w
27	Chi-Chi, Taiwan 1999	9/20/1999	10.3	7.6	Reverse	150	1	M_w
28	New Britain	11/17/2000	33.0	7.6	Subduction	3	3	M_w
29	Nisqually 2001	2/28/2001	52.4	6.8	Normal	57	1	M_w

Note:

1. Jibson and Jibson (2003)
2. The National Geophysical data Center and World Data Center (NGDC)
3. Petersen *et al.*, (2004)

Generally, the merit function is represented by the following equation:

$$\chi^2(a) = \sum_{i-1}^{N}\left[\frac{y_i - y(x_i;a)}{\sigma_i}\right]^2 \tag{2.3}$$

In Eq. (2.3), χ^2 is the merit function, y_i is the values of original data, and σ_i is the measurement error, or standard deviation of the i^{th} data point.

Based on the analysis, the attenuation relationship for far field earthquake is as follows:

$$\begin{aligned} \ln Y = {} & 21.6187 + 3.3993 M_w + 0.6040 M_w^{1.1034} - 7.7091 \ln(R_{hypo} \\ & + 6.6233 \exp(0.5554 M_w)) + 0.0061 H; \qquad \sigma_{\ln Y} = 0.598 \end{aligned} \tag{2.4}$$

In Eq. (2.4), Y is the mean of peak ground acceleration (PGA) in gal, M_w is the moment magnitude, R_{hypo} is the hypocentral distance in km, and H is the focal depth in km.

In an attempt to know how well the regression model describes the actual data, the level of adjustment between original data and regression model has been measured using multiple coefficient of determination, r^2 and adjusted multiple coefficient of determination, r_a^2.

The validity of the regression model was also tested by plotting the residuals scatter. The residuals should be randomly scattered around zero and show no discernable pattern. Therefore, they should have no relationship to the value of the independent variable. If the residuals increase or decrease as a function of the independent variable, it is probable that another functional approximation exists that would better describe the data.

The plot of residuals against moment magnitudes, epicenters and focal depths are shown in Figure 2.2 to Figure2.4. As can be seen from the figures, the plot of the residuals scatter shows no discernable pattern.

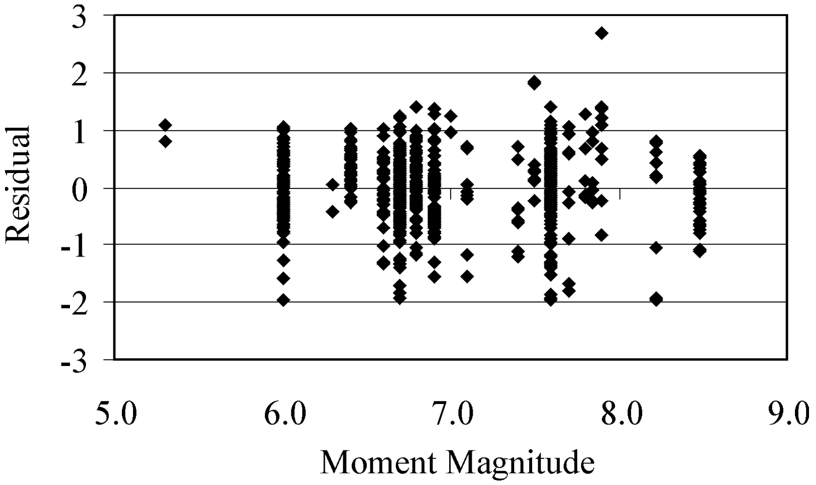


Figure 2.2: Plot of residual error against M_w

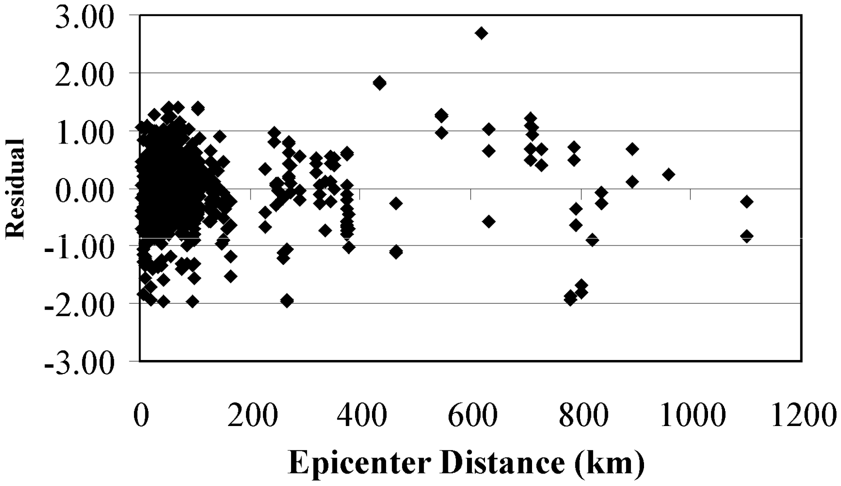


Figure 2.3: Plot of residual error against epicenters

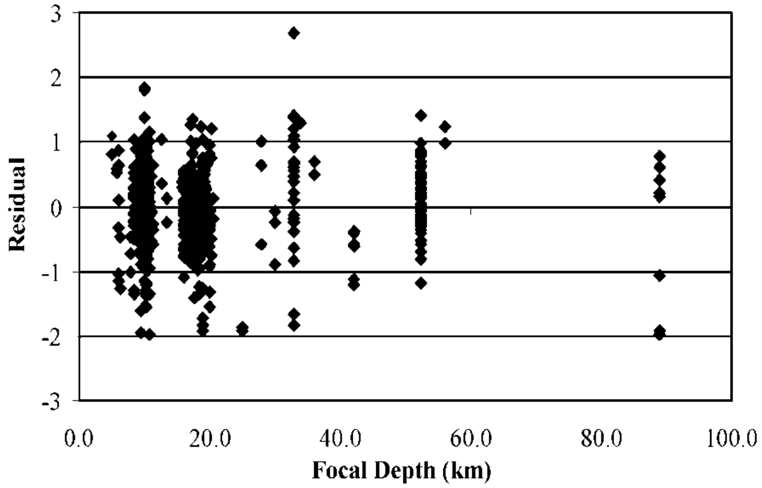


Figure 2.4: Plot of residual error against focal depths

The new relationship is plotted in Figure 2.5 and Figure 2.6. Two existing attenuations for subduction mechanisms were chosen for comparative purposes. The attenuation relationships proposed by Youngs *et al.* (1997) and Petersen (2004) were selected because these two functions were used in previous seismic hazard studies for Indonesia and Malaysia (Petersen, 2004). The results are divided into two ranges of magnitude; i.e., $5.0 \leq M_w < 7.0$ and $M_w \geq 7.0$. The analyses used the average focal depth of 18.5 km.

It can be seen from the figures that for distances less than 100 km, the new attenuation function gives higher value than the others. For further distances (more than 200 km), attenuation from Youngs (1997) tends to attenuate more slowly than the other functions. This attenuation is saturated faster than other functions because the function was derived only for short distance earthquakes (less than 200 km). In contrast, the new and modified attenuations by Petersen (2004) show that the accelerations of the earthquakes decrease significantly at the distance beyond 200 km. For the range of moment magnitude greater than or equal to 7.0 and at the distance beyond 200 km, the new and modified attenuations by Petersen (2004) give relatively close predictions.

The comparison of standard deviations of each model in some intervals of magnitudes is summarized in Table 2.2. Due to insufficient data of earthquakes with M_w less than 6.0, the analysis is carried out for earthquakes with M_w more than or equal to 6.0. It can be seen from the table that there is no particular pattern of standard deviation in relation to magnitude ranges, but in the range of interval $5.0 \leq M_w \leq 8.5$ the standard deviation of the new attenuation is relatively smaller than other attenuations.

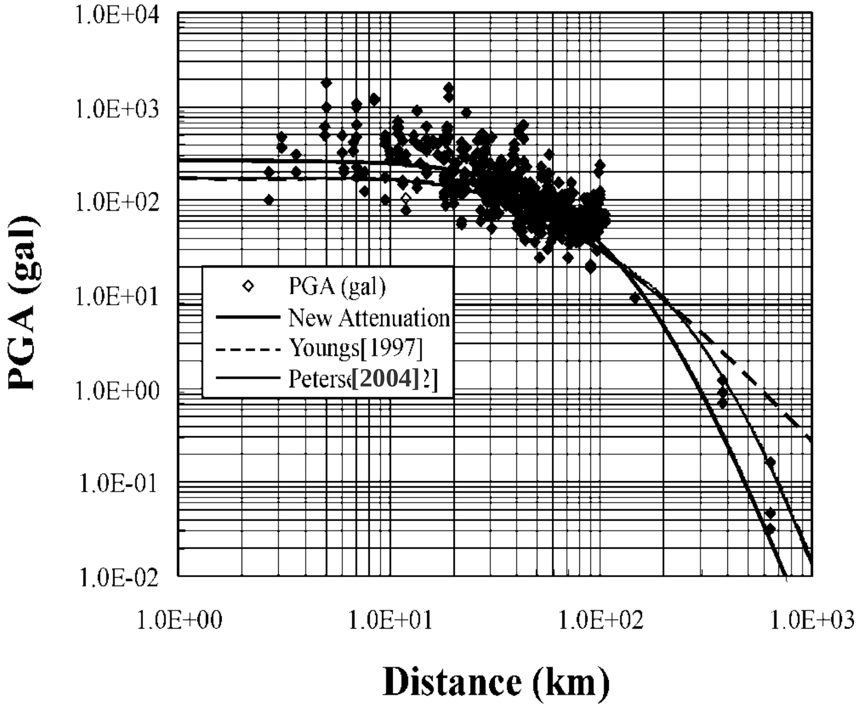


Figure 2.5: The comparison results between the new attenuation relationship and other functions for interval magnitude $5.0 \leq M_w < 7.0$

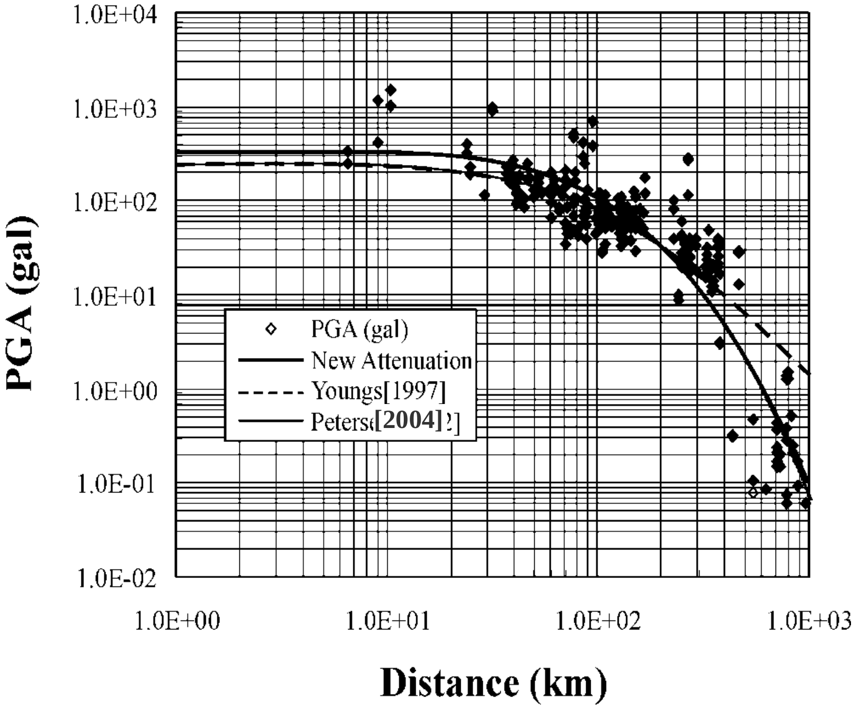


Figure 2.6: The comparison results between the new attenuation relationship and other functions for interval magnitude $M_w \geq 7.0$

Table 2.2. Comparisons of standard deviations ($\sigma_{\ln Y}$) from several attenuation relationships

M_w	**$\sigma_{\ln Y}$**			**No of Data**
	New Attenuation	Youngs *et al.* (1997)	Petersen (2004)	
6.0-6.5	0.53	0.64	0.64	162
6.5-7.0	0.55	0.76	0.71	349
7.0-7.5	1.08	2.12	1.42	18
7.5-8.0	0.72	1.07	0.73	194
8.0-8.5	0.68	0.63	0.91	51
5.0-8.5	0.60	0.84	0.72	776

The earthquake event that occurred on 26 December 2004 at Northern Sumatra was used to check the reliability of the attenuation functions. The strong motion of the earthquake with moment magnitude of 9.3 was successfully recorded by 12 stations of Malaysian Meteorological Department (MMD). The location of the stations can be seen in Table 4.3 and the results are shown in Figure 2.7.

Table 2.3. List of Malaysian Meteorological Department stations

No.	Station	Status	Location	Longitude	Latitude
1	IPM	Open	Ipoh	101.03	4.58
2	FRIM	Reserved	Kepong	101.63	3.23
3	KUM	Open	Kulim/Kedah	101.64	3.10
4	KTM	Reserved	Kuala Trengganu	103.14	5.33
5	KGM	Open	Kluang	103.32	2.02
6	KSM	Open	Kuching	110.31	1.47
7	BTM	Open	Bintulu	113.08	3.20
8	KKM	Open	Kota Kinabalu	116.21	6.04
9	KDM	Open	Kudat	116.83	6.92
10	TSM	Open	Tawau	117.87	4.29
11	SDKM	Open	Sandakan	118.07	5.88

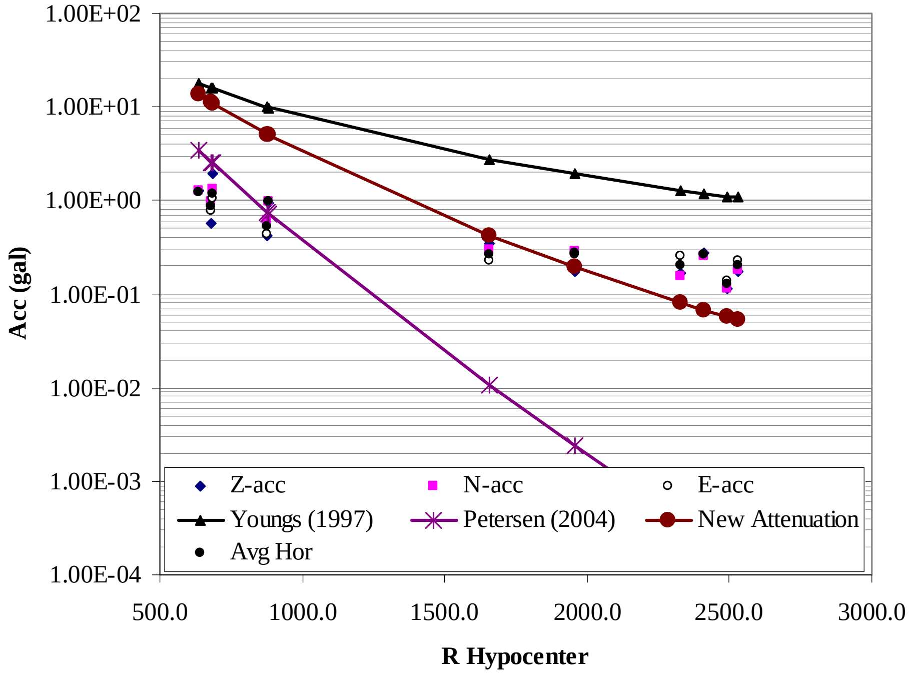


Figure 2.7: Ground motion prediction based on earthquake on 26th December 2004

The results show that the Youngs's attenuation produced overestimate values compared to others. This is because the attenuation was derived for distance less than 200 km. This causes predictions of the average peak horizontal acceleration level at farther distances to be larger than the actual acceleration level at these distances. Petersen's attenuation generated relatively close to values to actual data for a distance less than 1000 km but gave much underestimated results for further distances. The new attenuation produced overestimated values for a distance less than 1000 but generated very close values for further distance. Based on these results, two attenuation functions are used in SHA for predicting ground motions due to subduction mechanism: Petersen (2004) and new function (Eq. (2.4)).

2.3.2 Attenuation Relationships for Shallow Crustal Mechanism

There are several attenuation relationships derived for strike slip zone earthquake such as Fukushima and Tanaka (1992), Boore *et al.* (1997), Sadigh *et al.* (1997) and Campbell (2003). It should be noted that most of the attenuations, except for Campbell (2003), are only valid to be applied for distances less than 300 km. Therefore, attenuation relationship proposed by Campbell (2003) was used in this study. This attenuation relationship was derived using a hybrid method to develop ground motion relations for eastern North America (ENA), for rock sites.

The attenuation relation is given as follows:

$$\begin{aligned}\ln Y = c_1 + c_2 M_W + c_3 (8.5 - M_W)^2 + c_4 \ln\left[f_1(M_W, r_{rup})\right] \\ + f_2(r_{rup}) + (c_9 + c_{10} M_W) r_{rup}\end{aligned} \tag{2.5a}$$

$$f_1(M_W, r_{rup}) = \sqrt{r_{rup}{}^2 + \left[c_5 \exp(c_6 M_W)\right]^2} \tag{2.5b}$$

$$f_2(r_{rup}) = \begin{cases} 0 & r_{rup} \le r_1 \\ c_7(\ln r_{rup} - \ln r_1) & r_1 < r_{rup} < r_2 \\ c_7(\ln r_{rup} - \ln r_1) + c_8(\ln r_{rup} - \ln r_2) & r_{rup} \ge r_2 \end{cases} \tag{2.5c}$$

$$\sigma_{\ln Y} = \begin{cases} c_{11} + c_{12} M_w; & \text{for } M_w < M_1 \\ c_{13}; & \text{for } M_w \ge M_1 \end{cases} \tag{2.5d}$$

Where Y is the geometric mean of the two horizontal components of PGA or PSA in g, M_w is moment magnitude, r_{rup} is closest distance to fault rupture in km, r_1 = 70 km, and r_2 = 130 km, M_1 = 7.16 and C_1 to C_{13} are the coefficients used for Campbell (2003).

In order to evaluate the fitness of Campbell's equation compared to others, four existing attenuations for strike-slip mechanisms were used in this study. Since there is no reliable strong motion data available in Malaysia for testing the attenuations, the intensity data from several historical earthquakes with distances more than 400 km were used in the analysis. The intensity data was obtained from earthquake study by Gibson (2003). The list of earthquake events is shown in Table 2.4. The intensity data from the list was converted to the peak ground acceleration using the formula proposed by Trifunac and Brady (1975). The results are shown in Table 2.5.

The results show that the attenuation proposed by Campbell (2003) gave relatively the smallest standard deviation for long distance earthquakes events. Based on these result, the attenuation proposed by Campbell (2003) is used in SHA for predicting ground motion due to shallow crustal earthquakes.

Table 2.4. The list of earthquakes with distance more than 400 km (Gibson, 2003)

No.	**Date**	**Place**	**Mw**	**Long.**	**Lat.**	**Depth (km)**	**Dist. (km)**	**Int. (MMI)**
1	3/17/1909	Indonesia	7.0	121.0	-2.0	0	937	1
2	2/23/1969	Sulawesi	7.0	118.8	-3.2	62	843	1
3	3/2/1985	Sulawesi	6.7	119.7	-1.9	45	818	1
4	1/8/1984	Sulawesi	6.7	118.7	-2.9	34	810	1
5	5/19/1938	Indonesia	7.5	119.5	-0.4	49	703	2
6	1/1/1996	Minahasa Peninsula	7.7	120.0	0.7	15	702	2
7	5/12/1998	Minahasa Peninsula	6.5	119.6	0.2	20	680	1
8	3/6/1995	Celebes Sea	6.0	118.2	2.7	17	469	1

Table 2.5. Comparison of Attenuation Relations with Observed Data

No.	**PGA (gal) [1]**	**PGA (gal) [2]**	**PGA (gal) [3]**	**PGA (gal) [4]**	**PGA (gal) [5]**	**PGA (gal) [6]**
1	2.20	0.01	2.29	0.352	6.816	0.021
2	2.20	0.02	2.84	0.435	7.400	0.075
3	2.20	0.02	2.03	0.321	6.324	0.054
4	2.20	0.02	2.08	0.328	6.373	0.053
5	4.39	0.11	6.71	1.021	10.846	0.351
6	4.39	0.14	8.48	1.293	12.179	0.344
7	2.20	0.05	2.28	0.363	6.421	0.105
8	2.20	0.24	3.06	0.511	6.866	0.393
	$\sigma_{\ln Y}$	**6.0**	**0.5**	**2.9**	**1.9**	**5.7**

Note:

[1] Trifunac & Brady(1975) as a reference PGA

[2] Fukushima and Tanaka (1992)

[3] Campbell (2003)

[4] Sadigh *et al.* (1997)

[5] Boore *et al.* (1997)

[6] Midorikawa (2000)

CHAPTER 3

METHODOLOGY

3.1 Introduction

This chapter will describe the method used to construct and select the attenuation function in Malaysia. In the current study, several softwares are used. These provide an easy way to develop attenuation relationship for far field earthquakes. An attenuation function will be produced by the end of the study using regression analysis. The activities of the research are as shown in Figure. 3.2.1.

3.2. Flow or Steps Taken to Carry Out the Research

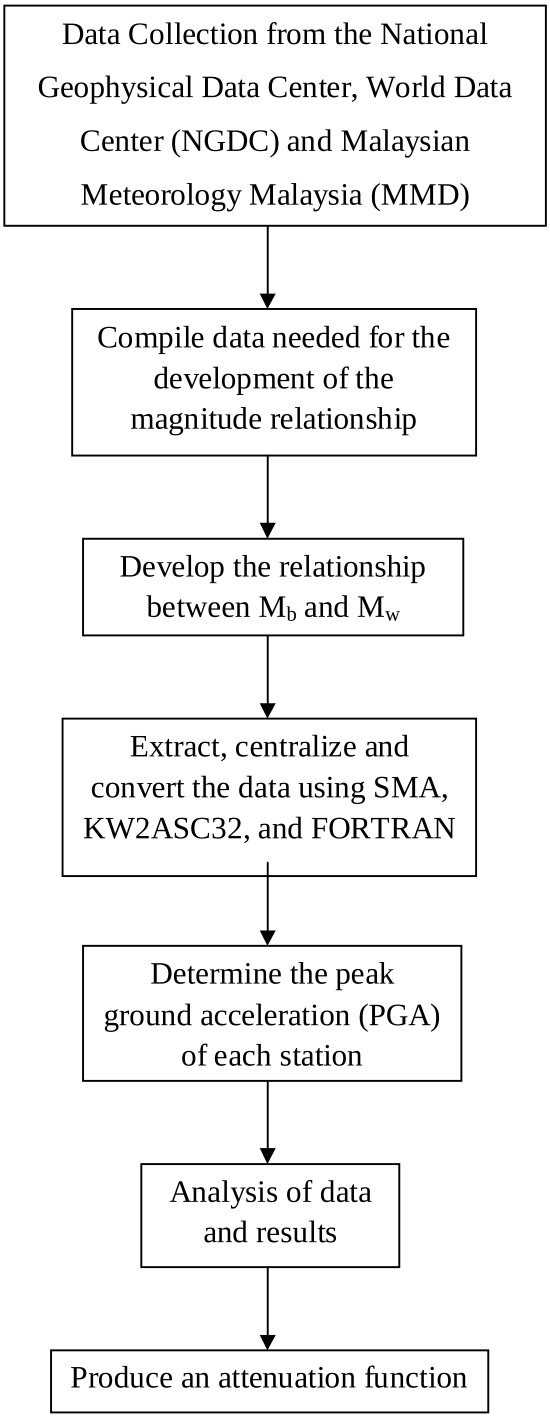


Figure 3.1. Flow chart to carry out the research

Figure 3.2.1 shows the flow of this research. The study begins with collection of data used to develop the far field earthquake attenuation relationships. In the beginning stage, data were gathered from several sources, i.e. The Malaysian Meteorology Malaysia (MMD), National Geophysical Data Center, and World Data Center (NGDC), strong motion data compiled by Randall and Matthew W. Jibson (2003) and by Petersen et al. (2002). The data collection consists of 939 strong motion records from more than 30 worldwide earthquake events with magnitudes in the range of $5.1 \leq M_w \leq 16.6$, and the epicenter distances that range from 352 km to 2434 km. These earthquakes have unconstrained focal depths that range from 4.5 to 32854 km.

Due to the heterogeneity of magnitude type in the data collection, the selection of consistent magnitude is needed. In addition to the consistency of magnitude, Christophersen (1999) has defined a term of the best magnitude. According to Christophersen (1999), the best measurement to quantify size of earthquake is moment magnitude (M_w). However, if this measurement is not available, the biggest measurement from magnitude body, M_b or magnitude surface, M_S could be selected. In order to obtain the single consistent magnitude scale, the relationships to convert other magnitude scales to moment magnitude should be developed. As a part of this research, the relationship between M_b and M_w has been developed empirically using regression analysis.

The development of the magnitude relationships needs the data recorded from the earthquake events. In this research, the data have been compiled from several sources, i.e. U.S. Geological Survey (USGS) of the United State, the International Seismological Center (ISC), the earthquake events catalog published by Pacheco and Sykes (1992), and Malaysian Meteorological Service catalogue.

The relationship between M_b and M_w is derived based on 375 data. Based on regression analysis the relationship between M_b and M_w is:

$$M_w = 0.528 \cdot m_b^2 - 4.685 \cdot m_b + 15.519; \qquad 4 \le Mb \le 7 \tag{3a}$$

$$\sigma_{m_b} = 0.24 \tag{3b}$$

The data is converted into readable data by using several softwares, such as SMA, KW2ASC32, and FORTRAN. Firstly, the time period of maximum amplitude of each station in Malaysia is extracted using SMA. Then, through the application of KW2ASC32, the acceleration of each station is been centralized and convert the accelerograph into digital value which is readable. Due to the previous data conversion, the unit in acceleration has changed to voltage. Therefore, the next step which is the use of FORTRAN to convert the unit from voltage to acceleration must be done. Next, through the converted data from FORTRAN, determine the peak ground acceleration (PGA) of each station.

Attenuation relationships usually express ground motion parameters as a function of magnitude, distance, soil site classification, and mechanism. A typical attenuation relationship may have the following form (Kramer, 1996):

$$\ln Y = C_1 + C_2 M + C_3 M^{C_4} + C_5 \ln\left(R + C_6 \exp\left(C_7 M\right)\right) + C_8 H + f(source) + f(site) \tag{3c}$$

$$\sigma_{\ln Y} = \sqrt{\frac{\Sigma(\ln y - \ln \hat{y})^2}{n - p}} \tag{3d}$$

In equation (3c), Y is the mean of ground motion parameters, M is the magnitude of the earthquake, R is a measure of the distance from the source to the site being considered, H is the focal depth of earthquake, f(source) is the source characteristics function, f(site) is the site characteristics function, and C_1 to C_8 are the coefficients of the attenuation function.

In equation (3d), $\sigma_{\ln Y}$ represents the standard deviation of ln Y at the magnitude and distance interest. Standard deviation is taken as a measure to quantify variability and indicate how fit an attenuation model to a set of database. The standard deviation computed this way is called the sample standard deviation. In this equation, y is the actual data points, $\hat{y}$ is the data generated from the equation, n is the number of actual data, and p is the number of degree of freedom. If the data follows a bell shaped Gaussian distribution, then 68% of the values (i.e. observed acceleration) lie within one standard deviation of the mean (on either side) and 95% of the values lie within two standard deviation of the mean.

In this study, the attenuation function is developed by regression analysis. The source characteristics are constrained only for dip slip mechanism whilst site characteristics are restricted only for rock. Therefore, the f(source) and f(site) could be eliminated from the equation 3(c). The regression analysis is performed using three independent variables, i.e. moment magnitude, M_w, hypocenter distance, R_{hypo} and focal depth, H.

CHAPTER 4

ANALYSIS

4.1 Introduction

This chapter includes the analysis of computation of new attenuation function from subduction zone fault. Total of 93 strong motion earth data for the computation function are collected from the Malaysia Meteorological Department (MMD). The magnitude of earthquake, H is in the range of 6 to 10 and the measure distance from the source to the site being considered, R is more than 400 km. The detail data is shown in the appendices.

4.2 Strong Motion Data Set

The data set used in this study is based on worldwide data which consists of strong ground motions from subduction events in active tectonic regions, excluding shallow crustal events. Events up through the 1994 Northridge earthquake are included. There are 481 recordings from 40 mainshocks and aftershocks which magnitude greater than 5.0 in the full data set. Recordings with unknown or poor estimates of the magnitude, mechanism, distance, or site condition were excluded from the data set used in the regression analysis. This reduced the data set used in the analysis to 91 recordings from 14 earthquakes. The 14 events used in the analysis are listed in Appendix.

Several different distance definitions have been used for developing attenuation relations. In this study, we have used the closest distance to the rupture plane, r_{rup}. This is the same distance as used by Idriss (1991) and Sadigh et al. (1993).

4.3 Development of Attenuation Relations

The Regression analysis is used to analyze the collected data. The Figure 4.1: Residual Error shows that the data are plotted in according to Graph of Residual against Row. However, the result cannot be used due the plotted result are scattered. Thus, it is required to plot in the type of Residual Normal Probability Plot Graph. (Figure 4.2: Residual Normal Probability Plot Graph). The results is shown in the Table 4.1: Regression Variable Results

4.3.1. Regression Method

We use a random effects model for the regression analysis. The random effects model is a maximum likelihood method that accounts for correlations in the data recorded by a single earthquake. For example, if an earthquake has a higher than average stress drop, then the ground motions at all sites from this event are expected to be higher than average. We use the procedure described by Abrahamson and Youngs (1992) to apply the random effect model. In a standard fixed effects regression, the model can be written as

$$Y_k = f\left(M_k, r_k\right) + \varepsilon_k \qquad (4.1)$$

where

Y_k is the ground motion, M_k is the magnitude and r_k is the distance for the kth data point. The ε_k term is assumed to be normally distributed with mean zero. The standard error of the ε_k values gives the standard error of the model.

In contrast, the random effects model can be written as

$$Y_{ij} = f\left(M_i, r_{ij}\right) + \varepsilon_{ij} + \eta_i \qquad (4.2)$$

where

Y_{ij} is the ground motion for the jth recordings from the ith earthquake, M_i is magnitude of the ith earthquake, and r_{ij} is the distance for the jth recordings from the ith earthquake. There are two stochastic terms in the model. Both ε_{ij} and η_i are assumed to be normally distributed with mean zero. The random effects model uses the maximum likelihood method to partition the residual for each recording into the ε_{ij} and η_i terms. There are two parts to the standard error for the model: an inter-event term, which is the standard error of the η_i and intra-event term, σ, which is the standard error of the ε_{ij}. The total standard error of the model is

$$\sqrt{\sigma^2 + \tau^2}\,. \qquad (4.3)$$

The Joyner and Boore (1981) two-step method also accounts for the correlation in the data from a single earthquake by explicitly estimating an event term for each event in the first step. In their model, the random terms, η_i, are replaced by fixed effects terms (coefficients of the model). The random effects model differs from the two step method described by Joyner and Boore (1981) in that for events with only a few recordings, part of the mean event term may be due to random variations of the data (intra-event variations) and poor sampling of the event. As described by Abrahamson and Youngs (1992), for poorly sampled events, the random effects method estimates how much of the event term is likely to be due to random sampling of the intra-event distribution and how much is likely to be due to systematic differences between the event and the average. If all of the events have a large number of recordings, then the two-step method and the random effects method become equivalent.

In developing the functional form of the regression equation, we combined features of the regression equations that have been used in previous studies. The general functional form that we employ is given by:

$$\begin{aligned} \ln Sa(g) = {} & f_1(M, r_{rup}) + Ff_3(M) + \\ & HWf_4(M, r_{rup}) + Sf_5(\widehat{\mathrm{pga}}_{\mathrm{rock}}) \end{aligned} \qquad (4.4)$$

where

Sa (g) is the spectral acceleration in g, M is moment magnitude, rrup is the closest distance to the rupture plane in km, F is the fault type (1 for reverse, 0.5 for reverse/oblique, and 0 otherwise), HW is the dummy variable for hanging wall sites (1 for sites over the hanging wall, 0 for otherwise), and S is a dummy variable for the site class (0 for rock or shallow soil, 1 for deep soil). For the horizontal component, the geometric mean of the two horizontals is used.

The function f1 (M,r_{rup}) is the basic functional form of the attenuation for strike-slip events recorded at rock sites. For f1 (M,r_{rup}), we have used the following form:

$$\begin{aligned}
&\text{for } M \le c_1\\
&f_1(M, r_{rup}) = a_1 + a_2(M - c_1) + a_{12}(8.5 - M)^n\\
&\qquad + \left[a_3 + a_{13}(M - c_1)\right]\ln R\\
&\text{for } M > c_1\\
&f_1(M, r_{rup}) = a_1 + a_4(M - c_1) + a_{12}(8.5 - M)^n\\
&\qquad + \left[a_3 + a_{13}(M - c_1)\right]\ln R
\end{aligned} \qquad (4.5)$$

Where

$$R = \sqrt{r_{rup}^2 + c_4^2} \qquad (4.6)$$

This form is a composite of several previous studies. The slope of the log distance term is magnitude dependent as was used by Idriss (1991). The Idriss model differs from our model in that it uses exponential models for the magnitude dependence of the slope whereas we have used a linear dependence. The saturation of high frequency ground motion at short distances is accommodated by the magnitude dependent slope.

For long periods, a linear magnitude dependence is not adequate. Most recent studies have found that higher order terms are needed. Boore et al. (1993) include a quadratic term; Campbell (1993) includes a hyperbolic arctangent term, Idriss (1991) includes an exponential magnitude term, and Sadigh et al. (1993) includes a higher order polynomial term. These different models give similar models when fit to the same data. We have adopted the functional form used by Sadigh et al. (1993).

For the distance term inside the log, we have used the

$$\sqrt{r_{rup}^2 + c_4^2} \qquad (4.7)$$

Model similar to that used by Boore et al. (1993). In the Boore et al. (1993) model, the c4 term can be interpreted as a fictitious depth. In our model, however, we are using the rupture distance (which can include depth for dipping faults and for fault that do not reach the surface), so the interpretation of c4 as a depth term is not clear. Nevertheless, we have adopted the

$$\sqrt{r_{rup}^2 + c_4^2} \qquad (4.8)$$

model because it yields a marginally better fit to the data at short distances.

4.3.2 Standard Error

Several recent attenuation studies have found that the standard error is dependent on the magnitude of the earthquake (Sadigh, 1993; Idriss, 1991; Campbell, 1993) or is dependent on the level of shaking (Campbell and Bozorgnia, 1994). This issue is discussed at length in Youngs et al (1995).

In this study, both the inter-event (τ) and intra-event (σ) standard errors are allowed to be magnitude dependent and are modeled as follows:

$$\sigma(M) = \begin{cases} b_1 & \text{for } M \le 5.0 \\ b_1 - b_2(M-5) & \text{for } 5.0 < M < 7.0 \\ b_1 - 2b_2 & \text{for } M \ge 7.0 \end{cases} \quad (4.14)$$

and

$$\tau(M) = \begin{cases} b_3 & \text{for } M \le 5.0 \\ b_3 - b_4(M-5) & \text{for } 5.0 < M < 7.0 \\ b_3 - 2b_4 & \text{for } M \ge 7.0 \end{cases} \quad (4.15)$$

The magnitude dependence of the standard error is estimated using the random effects model which avoids underestimating the standard error for large magnitude events due the fewer number of events (as compared to small and moderate magnitude events).

The total standard error is then computed by adding the variance of the two error terms. The total standard error was then smoothed and fit to the form

$$\sigma_{\text{total}}(M) = \begin{cases} b_5 & \text{for } M \leq 5.0 \\ b_5 - b_6(M-5) & \text{for } 5.0 < M < 7.0 \\ b_5' - 2b_6 & \text{for } M \geq 7.0 \end{cases} \tag{4.16}$$

The plot of residuals against moment magnitudes, epicenters and focal depths are shown in Figure 4.1 to Figure 4.4. As can be seen from the figures, the plot of the residuals scatter shows no discernable pattern. Table 4.1 shows the coefficients which is produced from regression analysis.

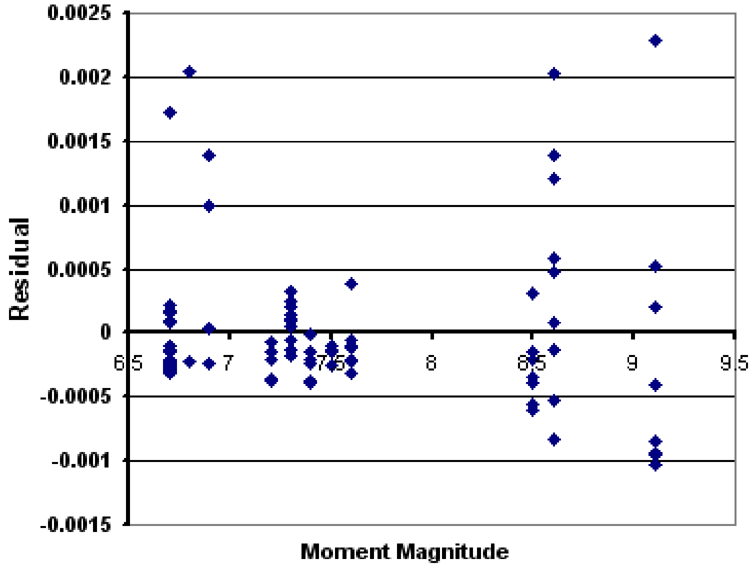


Figure 4.1: Plot of residual error against Mw

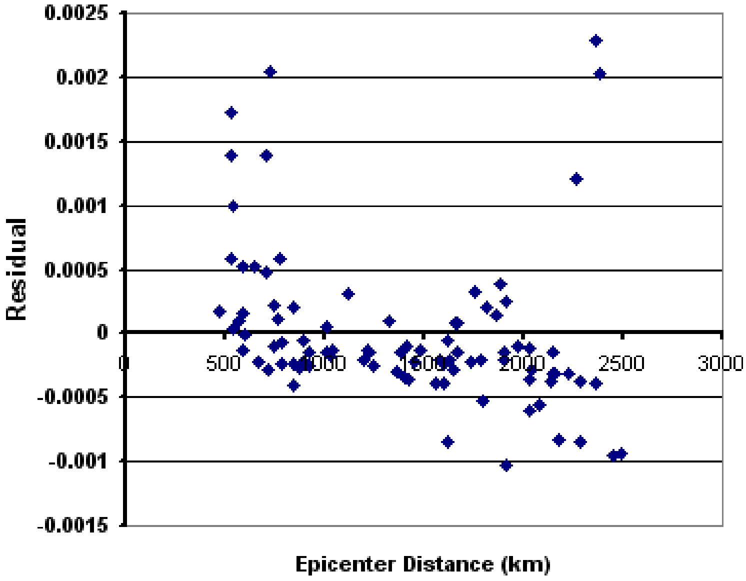


Figure 4.2: Plot of residual error against Epicenter Distance (km)

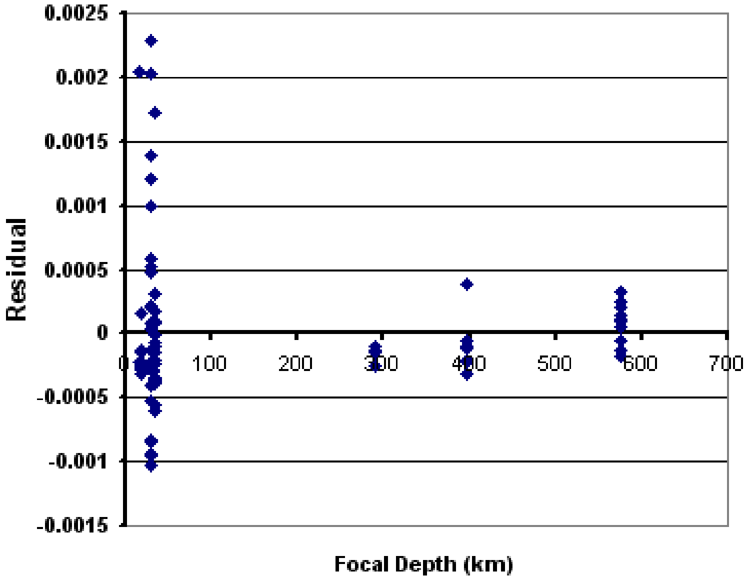
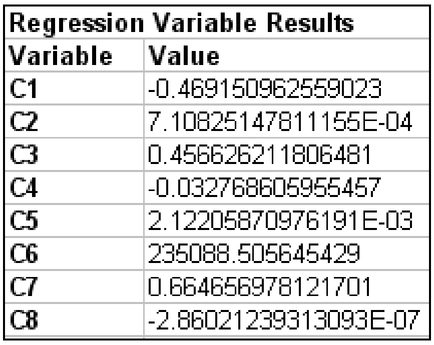


Figure 4.3: Plot of residual error against Focal Depth (km)

Table 4.1: Regression Variable Results



Regression Variable Results	
Variable	**Value**
C1	-0.469150962559023
C2	7.10825147811155E-04
C3	0.456626211806481
C4	-0.032768605955457
C5	2.12205870976191E-03
C6	235088.505645429
C7	0.664656978121701
C8	-2.86021239313093E-07

4.4 Summary

From the obtained result, the new attenuation function is

$$\boxed{\begin{aligned}\ln Y &= -0.469151 + 7.108251\ x10^{-4} M + 0.456626\ M^{-0.032769} \\ &+ 2.122059\ x10^{-3} \ln\left(R + 235088.506 \exp\left(0.664657\ M\right)\right) - 2.860212\ x10^{-7} H\end{aligned}}$$

Where Y = Mean of ground motion (PGA) in gal

M = Magnitude of the earthquake (moment magnitude)

R = Distance from the source to the site being considered (hypocentral distance) in km

H = Focal depth of site characteristics function in km

CHAPTER 5

DISCUSSION

5.1 Introduction

In this chapter, several methods for developing the attenuation functions including its advantages and disadvantages. Figure 5.1 shows the schematic summary of this subject.

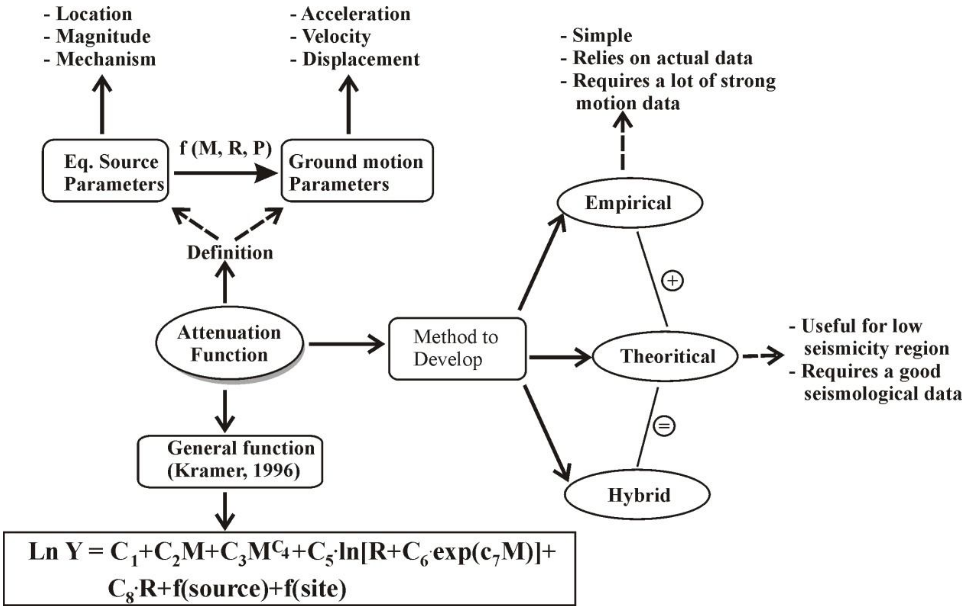


Figure 5.1: The schematic summary for developing attenuation functions

5.2 Discussion

According to Figure 5.1, both of theoretical and hybrid methods require a good seismological data. Therefore, it might not be possible to apply these methods in some regions which lack reliable seismological data such as Malaysia. It requires too many assumptions for using the theoretical method (e.g. crustal parameters, Q factors, geometric factors). Therefore, these methods were not used in this research.

A comparison of the attenuation relationships for many different areas shows that the attenuation characteristics may differ significantly from one region to another due to the differences in geological characteristics and seismic source properties. The selection of attenuation relationship functions can influence the results of SHA to be overestimated or underestimated up to about 50%. Therefore, the selection of appropriate attenuation relationships is very critical in SHA.

For accurate evaluation of seismic hazards, it is essential to have region-dependent attenuation relations based on strong motion accelerograph records for that region only. Until such data become available for a particular site, attenuation relationship from other regions should be used with caution.

In this research, the new attenuation function for subduction earthquakes is developed using South East Asia strong motion earthquake data. The basic regression model followed the typical forms proposed by Kramer (1996) and Youngs (1997). There are many other typical forms for attenuation function (e.g. Sadigh *et al.*, 1997; Boore *et al.*, 1997; Campbell, 2003). That typical form was chosen because of its simplicity and it was derived directly from the basic assumptions of the relation among the peak values of strong motion parameters (e.g. acceleration, velocity, displacement) and its parameters (e.g. magnitude, distance, source and site characteristics).

The statistical analyses show the good correlations between the regression models and the actual data. In order to cover the epistemic uncertainties, attenuation proposed by Petersen (2004) is also used in SHA. This attenuation was chosen because it was derived for distant earthquakes.

Due to the lack of recorded data for shallow crustal earthquakes for distant events, the existing attenuation relations from previous researchers were selected in this research. In this research, Campbell's attenuation (2003) is used in SHA for predicting ground motions for shallow crustal earthquakes events. This attenuation was chosen because this relation was derived for earthquake distances up to 1000 km. The analyses using earthquake events with distances more than 400 km were performed in order to know the reliability of the attenuation. Four existing attenuations were used to compare the attenuation. The results show that the attenuation proposed by Campbell (2003) gave relatively the smallest standard deviation for long distance earthquake events.

CHAPTER 6

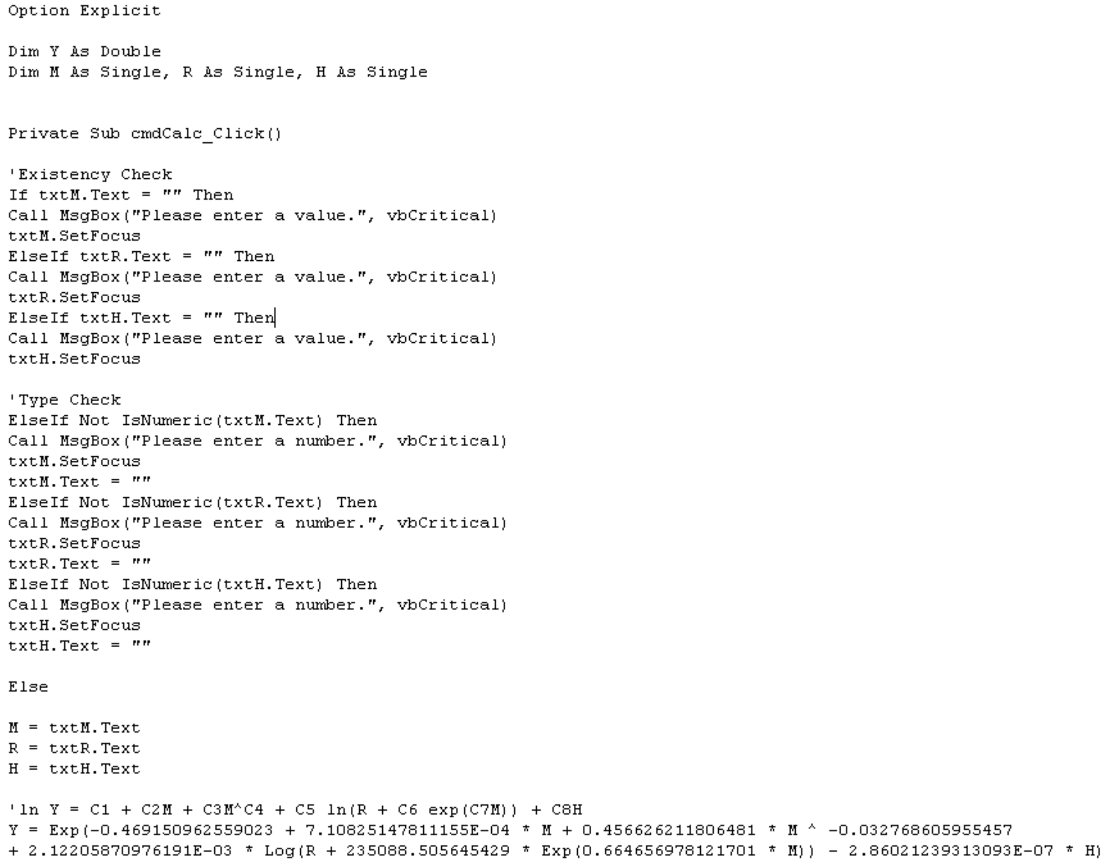
COMPUTER PROGRAM

6.1 Introduction

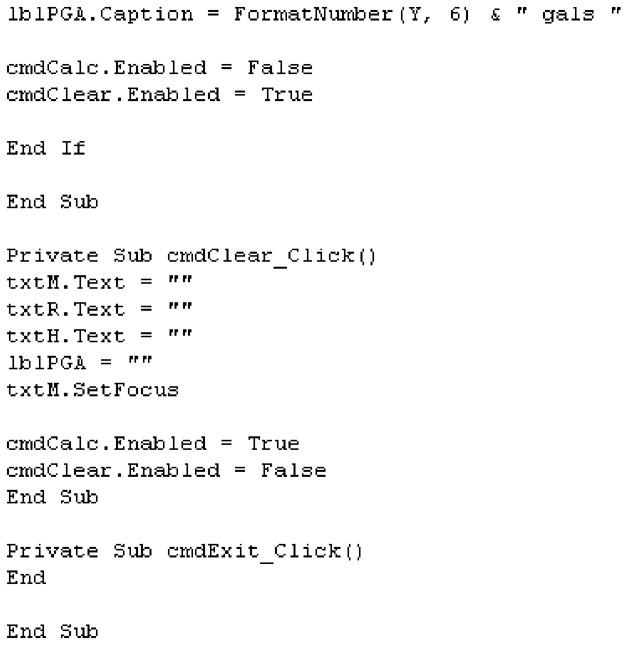
This chapter will describe the program developed at the final stage of this study. In the current study, Visual Basic is used. It provides an easy way to determine the earthquake effect from Sumatera towards Malaysia once the earthquake information is known.

6.2 Instruction to Work on the Application

When an earthquake happens along the subduction zone fault, after obtaining the moment magnitude, M, hypocenter distance, R and focal depth, H from the earthquake source, simply insert the information into the slots in the Visual Basic and click calculate. The peak ground acceleration (PGA) in Malaysia will be computed. Program New attenuation equations Interface can be seen in Figure 6.1.



```
Option Explicit

Dim Y As Double
Dim M As Single, R As Single, H As Single


Private Sub cmdCalc_Click()

'Existency Check
If txtM.Text = "" Then
Call MsgBox("Please enter a value.", vbCritical)
txtM.SetFocus
ElseIf txtR.Text = "" Then
Call MsgBox("Please enter a value.", vbCritical)
txtR.SetFocus
ElseIf txtH.Text = "" Then
Call MsgBox("Please enter a value.", vbCritical)
txtH.SetFocus

'Type Check
ElseIf Not IsNumeric(txtM.Text) Then
Call MsgBox("Please enter a number.", vbCritical)
txtM.SetFocus
txtM.Text = ""
ElseIf Not IsNumeric(txtR.Text) Then
Call MsgBox("Please enter a number.", vbCritical)
txtR.SetFocus
txtR.Text = ""
ElseIf Not IsNumeric(txtH.Text) Then
Call MsgBox("Please enter a number.", vbCritical)
txtH.SetFocus
txtH.Text = ""

Else

M = txtM.Text
R = txtR.Text
H = txtH.Text

'ln Y = C1 + C2M + C3M^C4 + C5 ln(R + C6 exp(C7M)) + C8H
Y = Exp(-0.469150962559023 + 7.10825147811155E-04 * M + 0.456626211806481 * M ^ -0.032768605955457
+ 2.12205870976191E-03 * Log(R + 235088.505645429 * Exp(0.664656978121701 * M)) - 2.86021239313093E-07 * H)
```



```
lblPGA.Caption = FormatNumber(Y, 6) & " gals "

cmdCalc.Enabled = False
cmdClear.Enabled = True

End If

End Sub

Private Sub cmdClear_Click()
txtM.Text = ""
txtR.Text = ""
txtH.Text = ""
lblPGA = ""
txtM.SetFocus

cmdCalc.Enabled = True
cmdClear.Enabled = False
End Sub

Private Sub cmdExit_Click()
End

End Sub
```

Peak Ground Acceleration in Malaysia

Attenuation Function

ln Y = C1 + C2M + C3M^C4 + C5 ln(R + C6 exp(C7M)) + C8H ----- General Equation

For Subduction Zone Fault only

Y = Exp(-0.469151 + 7.108251E-04 * M + 0.456626 * M ^ -0.032769 + 2.122059E-03 * ln(R + 235088.506 * Exp(0.664657 * M)) - 2.860212E-07 * H)

Moment Magnitude, M = 7.6

Hypocenter Distance, R = 478.06 km

Focal Depth, H = 81 km

Peak Ground Acceleration (PGA), Y = 1.000458 gals

Figure 6.1 Program New attenuation equations Interface

CHAPTER 7

CONCLUSION AND RECOMMENDATIONS

7.1 Conclusions

The objective of this paper is to develop the new attenuation relationship for subduction mechanism that could cover the effects of earthquakes from more than 400 km away from the epicenters.

The new attenuation was developed using regression analysis. The advantage of this method is that it relies on actual earthquake data, hence this method has accounted aleatory of variability or the randomness variability due to the unknown or unmodeled characteristics of the underlying physical process. The validity of regression analysis was also tested by plotting the residuals scatter and showed no discernable pattern.

The formulated application is used to estimate the seismic hazard analysis in easier way by key in the input data. However, it only suitable to estimate the seismic hazard that occurs from subduction zone fault.

7.2 Recommendations

In order to improve the results from macrozonation and microzonation in this study, and to enhance earthquake engineering knowledge especially for countries that are affected by distant earthquakes such as Peninsular Malaysia, some suggestions are listed as follows:

1. The attenuation function developed in this study can be improved by using more strong motion data from Malaysian Meteorological Department (MMD).

   The new attenuation function in this study was developed only for estimating the peak ground acceleration. In order to improve the seismic hazard assessment in Malaysia, it is recommended to develop attenuation functions for estimating not only peak ground acceleration but also spectral ordinates as well.

2. The future study for The attenuation Function for shallow crustal zone should be implemented to predict the earthquake ground motion in Malaysia due to Sumatra Fault Zone.

REFERENCES

Abrahamson, N. A. and Silva, W. 1997. Empirical Response Spectral Attenuation Relations for Shallow Crustal Earthquakes. Seismological Research Letters, Vol. 68, No.1.

Atkinson, G.M. and Boore, D.M. 1997. Stochastic Point-Source Modeling of Ground Motions in the Cascadian Region. Seismological Research Letters, Vol. 68.

Boore, D.M., Joyner, W.B., and Fumal, T.E. 1997. Equation for Estimating Horizontal Response Spectra and Peak Acceleration from Western North America Earthquakes: A Summary of Recent Work. Seismological Research Letters, Vol. 68, No. 1, January/February 1997, pp. 128-153.

Campbell, K.W. 1997. Empirical Near Source Attenuation Relationship for Horizontal and Vertical Components of Peak Ground Acceleration, Peak Ground Velocity, and Pseudo Absolute Acceleration Response Spectra. Seismological Research Letters, 68(1), 154-179.

Campbell, K.W. 2002. Prediction of Strong Ground Motion Using the Hybrid Empirical Method: Example Application to ENA. Bulletin of the Seismological Society of America.

Abrahamson N.A. and Silva W.J. 1997. Empirical Response Spectral Attenuation Relations for Shallow Crustal Eartqhaukes. Seismological Research letters, Volume 68, number 1.

EPRI. 1994. The Earthquake of Stable Continental Regions, Vol. I: Assessment of Large Earthquake Potential. Report Prepared for Electric Power Research Institute by Johnson, A.C., Coppersmith, K.J., Kanter, L.R. and Cornel, C.A.

Heaton, T.H., Tajima, F. and Mori, A.W. 1986. Estimating Ground Motion Using Recorded Accelerogram. Surveys in Geophysics, Vol. 8, pp 25-83.

International Seismological Center, On-line Bulletin, http://www.isc.ac.uk/Bull, Internatl. Seis. Cent., Thatcham, United Kingdom, 2001.

Kramer, S. L. 1996. Geotechnical Earthquake Engineering, Prentice Hall, New Jersey.

National Earthquake Information Center United Stated Geological Survey, http://neic.usgs.gov/neis/epic/epic.html.

The National Geophysical Data Center and World Data Center (NGDC), Strong Motion Data Catalog Search. http://www.ngdc.noaa.gov/seg/hazard/smcat.shtml, 2003.

Pacheco, J.F. and Sykes, Lynn R. 1992. Seismic Moment Catalog of Large Shallow Earthquakes, 1900 to 1989. Bulletin of the Seismological Society of America, Vol. 82 No. 3, 1992, pp. 1306-1349.

Petersen, M.D., Dewey, J., Hartzell, S., Mueller, C., Harmsen, S., Frankel, A.D., Rukstakels. 2002. Probabilistic Seismic Hazard Analysis for Sumatra, Indonesia and Across the Malaysian Peninsula, US Geological Survey, (Unpublished Journal).

Randall W. Jibson and Matthew W. Jibson. 2003. Java Programs For Using Newmark's Method And Simplified Decoupled Analysis To Model Slope Performance During Earthquakes. Open-File Report 03-005.

Rong, Yufang. 1998. Evaluation of Earthquake Potential in China. Ph.D. Thesis, Earth and Space Sciences, Department University of California, Los Angeles.

Sadigh, K., Chang, C.Y., Egan, J.A., Makdisi, F. and Youngs, R.R. 1997. Strong Ground Motion Attenuation Relations For Shallow Crustal Earthquakes Based On Californian Strong Motion Data, Seismological Research Letters, 68(1), 190-198.

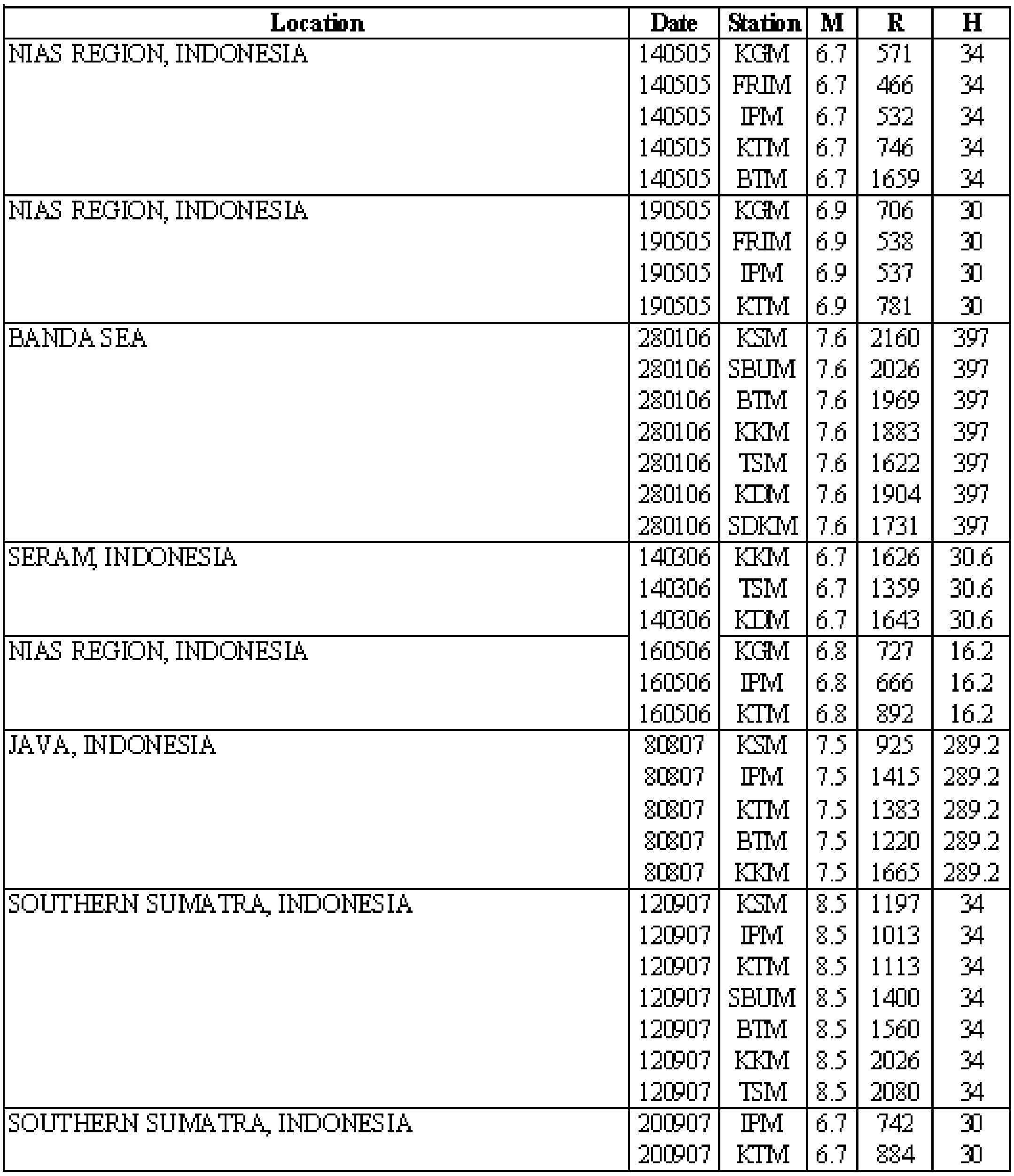
Sadigh, R. K. and Egan, J. A. 1998. Updated Relationships for Horizontal Peak Ground Velocity and Peak Ground Displacement for Shallow Crustal Earthquakes. In: Proceedings of the Sixth U.S. National Conference on Earthquake Engineering.

Toro, G.R., Abrahamson, N.A., and Schneider, J.F. 1997. Model of Strong Ground Motions from Earthquakes in Central and Eastern North America: Best Estimates and Uncertainties. Seismological Research Letters, Vol. 68, No. 1.

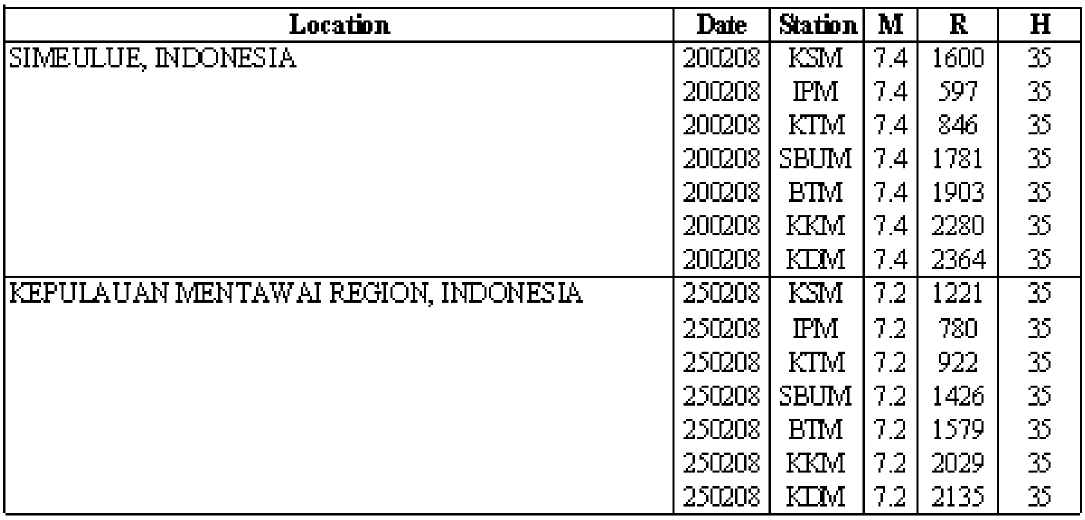
Youngs, R.R., Chiou, S.J., Silva, W.J., Humphrey, J.R. 1997. Strong Ground Motion Attenuation Relationships for Subduction Zone Earthquake. Seismological Research Letters, Vol. 68, No. 1, 1997, pp. 58-74.

APPENDIX

Location	Date	Station	M	R	H
SOUTHERN SUMATRA, INDONESIA	250704	KGM	7.3	764	576
	250704	FRIM	7.3	894	576
	250704	KSM	7.3	1009	576
	250704	IPM	7.3	1025	576
	250704	KTM	7.3	1044	576
	250704	BTM	7.3	1324	576
	250704	KKM	7.3	1754	576
	250704	TSM	7.3	1812	576
	250704	KDM	7.3	1860	576
	250704	SDKM	7.3	1909	576
OFF THE WEST COAST OF NORTHERN SUMATRA	261204	KGM	9.1	843	30
	261204	FRIM	9.1	643	30
	261204	KSM	9.1	1621	30
	261204	IPM	9.1	593	30
	261204	KTM	9.1	841	30
	261204	BTM	9.1	1916	30
	261204	KKM	9.1	2284	30
	261204	TSM	9.1	2451	30
	261204	KDM	9.1	2367	30
	261204	SDKM	9.1	2487	30
NORTHERN SUMATRA, INDONESIA	290305	KGM	8.6	702	30
	290305	FRIM	8.6	531	30
	290305	KSM	8.6	1480	30
	290305	IPM	8.6	527	30
	290305	KTM	8.6	772	30
	290305	SBUM	8.6	1665	30
	290305	BTM	8.6	1792	30
	290305	KKM	8.6	2181	30
	290305	KDM	8.6	2269	30
	290305	SDKM	8.6	2379	30
KEPULAUAN MENTAWAI REGION, INDONESIA	100405	KGM	6.7	587	19
	100405	FRIM	6.7	592	19
	100405	KSM	6.7	1247	19
	100405	IPM	6.7	713	19
	100405	KTM	6.7	874	19
	100405	SBUM	6.7	1450	19
	100405	BTM	6.7	1600	19
	100405	KKM	6.7	2043	19
	100405	TSM	6.7	2143	19
	100405	KDM	6.7	2146	19
	100405	SDKM	6.7	2224	19



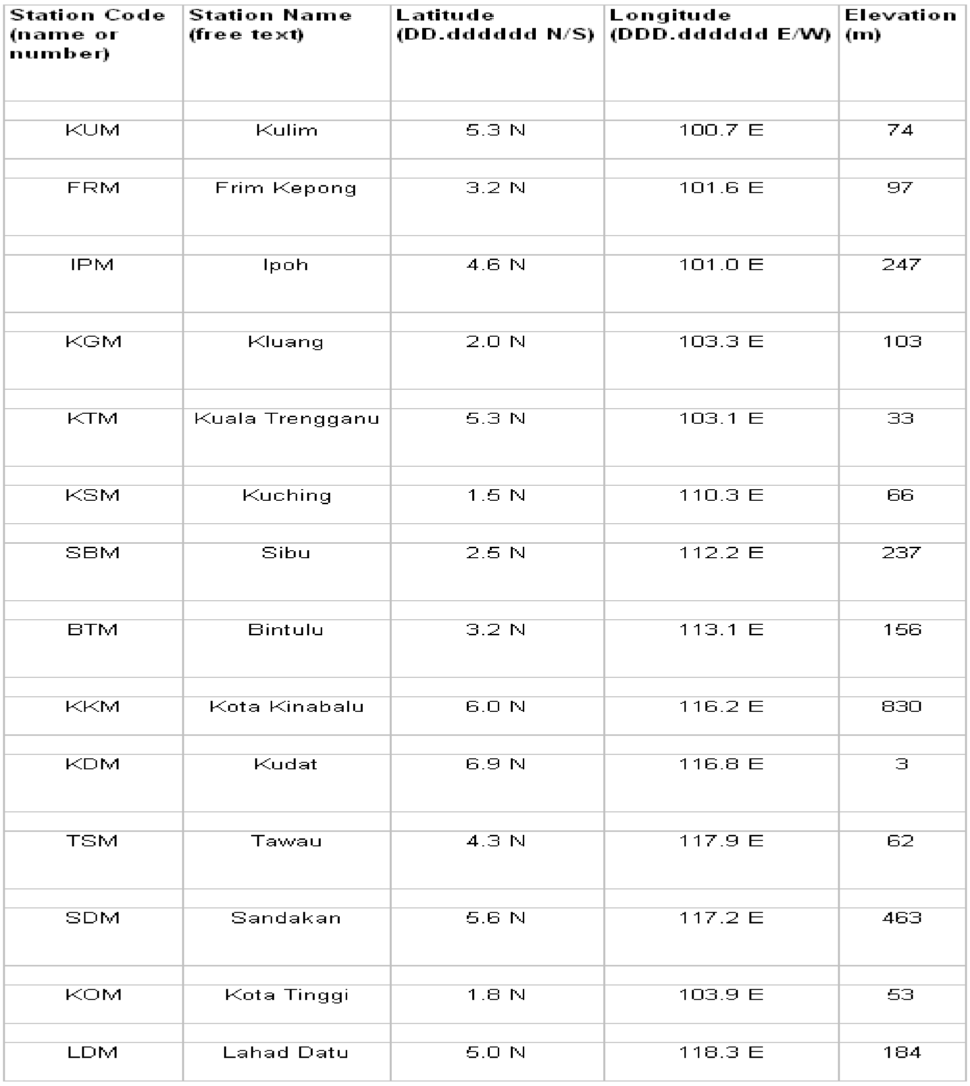
Location	Date	Station	M	R	H
NIAS REGION, INDONESIA	140505	KGM	6.7	571	34
	140505	FRIM	6.7	466	34
	140505	IPM	6.7	532	34
	140505	KTM	6.7	746	34
	140505	BTM	6.7	1659	34
NIAS REGION, INDONESIA	190505	KGM	6.9	706	30
	190505	FRIM	6.9	538	30
	190505	IPM	6.9	537	30
	190505	KTM	6.9	781	30
BANDA SEA	280106	KSM	7.6	2160	397
	280106	SBUM	7.6	2026	397
	280106	BTM	7.6	1969	397
	280106	KKM	7.6	1883	397
	280106	TSM	7.6	1622	397
	280106	KDM	7.6	1904	397
	280106	SDKM	7.6	1731	397
SERAM, INDONESIA	140306	KKM	6.7	1626	30.6
	140306	TSM	6.7	1359	30.6
	140306	KDM	6.7	1643	30.6
NIAS REGION, INDONESIA	160506	KGM	6.8	727	16.2
	160506	IPM	6.8	666	16.2
	160506	KTM	6.8	892	16.2
JAVA, INDONESIA	80807	KSM	7.5	925	289.2
	80807	IPM	7.5	1415	289.2
	80807	KTM	7.5	1383	289.2
	80807	BTM	7.5	1220	289.2
	80807	KKM	7.5	1665	289.2
SOUTHERN SUMATRA, INDONESIA	120907	KSM	8.5	1197	34
	120907	IPM	8.5	1013	34
	120907	KTM	8.5	1113	34
	120907	SBUM	8.5	1400	34
	120907	BTM	8.5	1560	34
	120907	KKM	8.5	2026	34
	120907	TSM	8.5	2080	34
SOUTHERN SUMATRA, INDONESIA	200907	IPM	6.7	742	30
	200907	KTM	6.7	884	30



Location	Date	Station	M	R	H
SIMEULUE, INDONESIA	200208	KSM	7.4	1600	35
	200208	IPM	7.4	597	35
	200208	KTM	7.4	846	35
	200208	SBUM	7.4	1781	35
	200208	BTM	7.4	1903	35
	200208	KKM	7.4	2280	35
	200208	KDM	7.4	2364	35
KEPULAUAN MENTAWAI REGION, INDONESIA	250208	KSM	7.2	1221	35
	250208	IPM	7.2	780	35
	250208	KTM	7.2	922	35
	250208	SBUM	7.2	1426	35
	250208	BTM	7.2	1579	35
	250208	KKM	7.2	2029	35
	250208	KDM	7.2	2135	35

DATA FORMAT AND STATION CODE

Orientation
N, E or Z N : N/S E : E/W Z : vertical



Station Code (name or number)	Station Name (free text)	Latitude (DD.dddddd N/S)	Longitude (DDD.dddddd E/W)	Elevation (m)
KUM	Kulim	5.3 N	100.7 E	74
FRM	Frim Kepong	3.2 N	101.6 E	97
IPM	Ipoh	4.6 N	101.0 E	247
KGM	Kluang	2.0 N	103.3 E	103
KTM	Kuala Trengganu	5.3 N	103.1 E	33
KSM	Kuching	1.5 N	110.3 E	66
SBM	Sibu	2.5 N	112.2 E	237
BTM	Bintulu	3.2 N	113.1 E	156
KKM	Kota Kinabalu	6.0 N	116.2 E	830
KDM	Kudat	6.9 N	116.8 E	3
TSM	Tawau	4.3 N	117.9 E	62
SDM	Sandakan	5.6 N	117.2 E	463
KOM	Kota Tinggi	1.8 N	103.9 E	53
LDM	Lahad Datu	5.0 N	118.3 E	184