PROBABILISTIC SEISMIC HAZARD ASSESSMENT OF EAST MALAYSIA USING PROPOSED EMPIRICAL GMPE FOR SHALLOW CRUSTAL EARTHQUAKE

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To my beloved husband, children and family members

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ABSTRACT

East Malaysia has witnessed an increase in low to moderate seismic activities due to a few active fault lines. While damaging earthquakes are fortunately rare, from historical records ranging between 1874 and 2014, the region already experienced devastating earthquake with a magnitude M_W 5.2 in Sarawak, M_W 5.8 in Lahad Datu and just recently with a magnitude M_W 6.0 in Ranau. Over the years, a total of 159 with magnitudes ranging from 2.9 to 6.0 are known to have occurred. The effects of the earthquakes should be anticipated in order to mitigate the catastrophic failure of structures. In the seismic design of structures, the most critical part is the development of seismic design ground motion. In order to develop this ground motion, seismic hazard analysis such as probabilistic seismic hazard analysis (PSHA) is required. This study presents technical research into seismic hazard assessment for East Malaysia based on three objectives. The first objective is to determine the fault characteristics mechanism and layouts for the region. Next, to produce spectral ground motion prediction equation (GMPE) for the region due to scarcity and incompatible equation of GMPE from other region. Then, to determine the peak ground acceleration (PGA) throughout the region to be plot inside hazard map in terms of 10% and 2% probability of exceedance (PE) in design time period of 50 years with respect to 475 and 2,475 years return period. Since there is limited information regarding the fault sources in East Malaysia, the relevant source zones are divided into three different possible earthquake source (far-field and near-field due to background seismicity and local fault). In general, the plot of the new generated GMPE accurately represents an earthquake condition in East Malaysia. The hazard map shows the PGA values for 10% probability of exceedance is in the range of 0 to 250 cm/s^2 and 2% probability of exceedance in the range of 20 to 400 cm/s^2. In conclusion, the main contributor to hazard is dominated by local fault sources with Sabah has the highest seismic hazard level than Sarawak.

ABSTRAK

Kawasan Malaysia Timur mempunyai garisan sesar yang mampu menghasilkan gempa bumi bermagnitud rendah dan sederhana. Sementara gempa yang memusnahkan adalah jarang berlaku, rekod sejarah diantara tahun 1874 hingga 2014 menunjukkan kawasan ini pernah mengalami kejadian gempa bermagnitud M_W 5.2 di Sarawak, M_W 5.8 di Lahad Datu dan baru-baru ini M_W 6.0 di Ranau. Sepanjang tahun tersebut, sebanyak 159 jumlah gempa bumi bermagnitud 2.9 hingga 6.0 telah direkodkan. Kesan akibat gempa bumi hendaklah diambil kira bagi mengelakkan kegagalan dalam struktur. Reka bentuk yang sedia ada perlu dipertingkatkan dengan memasukkan elemen-elemen penilaian bahaya sismik menggunakan pendekatan kebarangkalian atau PSHA. Di dalam kajian ini, terdapat tiga objektif yang perlu dicapai pada akhir kajian. Objektif pertama adalah untuk menentukan ciri-ciri mekanisma dan susun atur sesar di kawasan Malaysia Timur. Objektif kedua adalah untuk menghasilkan spektrum persamaan ramalan gerak tanah (GMPE) bagi rantau ini kerana persamaan GMPE dari rantau lain adalah kurang serasi. Akhir sekali adalah penentuan nilai pecutan tanah maksimum (PGA) untuk rantau ini diplotkan di dalam peta sismik pada 10% dan 2% kebarangkalian dilangkaui dalam reka bentuk tempoh 50 tahun, masing-masing 475 dan 2,475 tahun tempoh ulangan. Oleh kerana terdapat sedikit informasi berkaitan sesar di rantau ini, garisan sesar dibahagikan kepada tiga kemungkinan (sesar jarak jauh dan jarak dekat yang terdiri daripada taburan sismik serta garisan sesar tempatan). Merujuk kepada peta sismik untuk kebarangkalian dilangkaui pada 10%, nilai PGA adalah antara 0 hingga 250 cm/s^2 dan kebarangkalian dilangkaui pada 2% pula, adalah antara 20 hingga 400 cm/s^2. Kesimpulannya, punca kebarangkalian adalah tinggi disebabkan oleh garisan sesar tempatan di mana Sabah mempunyai nilai tertinggi berbanding Sarawak.

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LIST OF ABBREVIATIONS

ACR	-	Active Continental Region
ANSS	-	Advanced National Seismic System
CMT	-	Harvard Centroid Moment Tensor
GMPE	-	Ground motion prediction equation
GPS	-	Global Positioning System
GSHAP	-	Global Seismic Hazard Assessment Program
ISC	-	International Seismological Centre
MMD	-	Malaysian Meteorological Department
MMI	-	Modified Mercalli Intensity
PGA	-	Peak ground acceleration
PSHA	-	Probabilistic Seismic Hazard Analysis
NEIC	-	National Earthquake Information Centre
NGDC	-	National Geophysical Data Centre
RSA	-	Response spectral acceleration
SCR	-	Stable Continental Region
UHRS	-	Uniform hazard response spectrum
USGS	-	United States Geological Survey

LIST OF SYMBOLS

M_b	-	Short period P-wave magnitude
M_L	-	Local magnitude
M_{max}	-	Maximum magnitude
M_{min}	-	Minimum magnitude
M_S	-	Surface-wave magnitude
M_W	-	Moment magnitude
R_{hypo}	-	Distance in hypocenter
σ	-	Standard deviation
λ	-	Recurrence rate

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CHAPTER 1

INTRODUCTION

1.1 General

An earthquake is an event where two pieces of the earth's crust shift against each other and create a series of vibrations. An earthquake can occur anywhere, and thousands happen every day around the world, creating events such as faulting, tsunamis, volcanos, landslides and liquefaction. This seismic vibration will cause the ground to shake in a way that might affect densely urbanized regions and can cause damage and loss of life to human beings. An earthquake itself might not kill people, but the structure collapsing due to it will. The buildings or structures must be able to sustain the seismic load so the loss of life can be prevented. Seismic activity refers to earthquakes experienced over a period of time. Most parts of the world experience at least occasional shallow earthquakes from low to high intensity.

A region where the number of seismic activities is low is known as a stable continental region (SCR) and active seismicity for active continental region (ACR). Seismic hazard analysis in SCR and ACR is different in terms of the definition of seismic sources and ground-motion prediction equation (GMPE). The faults are often not known in SCR and there are more uncertainties in the characteristics of seismic sources in comparison to ACR. It should be noted, however, that the geographic distribution of smaller earthquakes is less completely determined than more severe quakes, partly because the availability of relevant data is dependent on the distribution of observatories.

In the first chapter, the nature and the causes of earthquakes will be explained. The types of plate boundaries that create earthquakes are described. Based on this general view about earthquakes, the situation of earthquakes in East Malaysia is evaluated. Previously, damaging earthquakes were fortunately rare in East Malaysia; however, the increment in the number of small earthquakes each day and a sudden magnitude 6.0 earthquake that occurred recently has proven that the region has already experienced devastating earthquakes. There will be three objectives to cover throughout the whole study in performing seismic hazard analysis for East Malaysia, including six scopes and limitations. The research of methodology throughout the study is being summarized in this chapter. The significance of this research in potentially estimating future earthquakes is also explained. The organization of the thesis is described in the final section.

1.2 Seismology and Earthquake Genesis

From a seismological view, movements underground are governed by the earth's crust. The earth's crust can be categorized into six continental tectonic plates around the world, namely African, American, Antarctic, Australia-Indian, Eurasian and Pacific, with a few others subcontinents in smaller plates. It is known that plates are moving and are part of an active, fragile and not rigid crust. Plate boundaries are prone to earthquakes because the motion of tectonic plates creates tension that can cause significant shaking when the stress gets released. The frequency of earthquakes is much greater in areas around the plate boundaries (Kramer, 1996). South-East Asia is considered to be one of the most seismically active and tectonically complex regions (Yin, 2010). It is well known that the deformation of South East Asia was a combined result of continental collision and oceanic subduction (Gero *et al.*, 2000, 2001). As an example, the northward moving Indo-Australian plate is colliding with the Eurasian plate (rate of spreading 6.0 cm/year) (Hall, 2011) and the west/northwestern part of the Philippine Sea plate is subducting beneath the continental Eurasian plate (rate of spreading 11.0 cm/year) (Cardwell *et al.*, 1980, Metcalfe, 2011, Smoczyk *et al.*, 2013), as shown in Figure 1.1. The rate of spreading means it can store up to a few centimeters at average per year to be released in infrequent earthquakes. At the South East of the Eurasian plate, the location of Sundaland comprises the Malay Peninsula, Sumatra, Java, Borneo and Palawan. The Sundaland block moves eastward at a velocity of 6.0 to 10.0 mm/year from south to north respectively (Simons *et al.*, 2007).

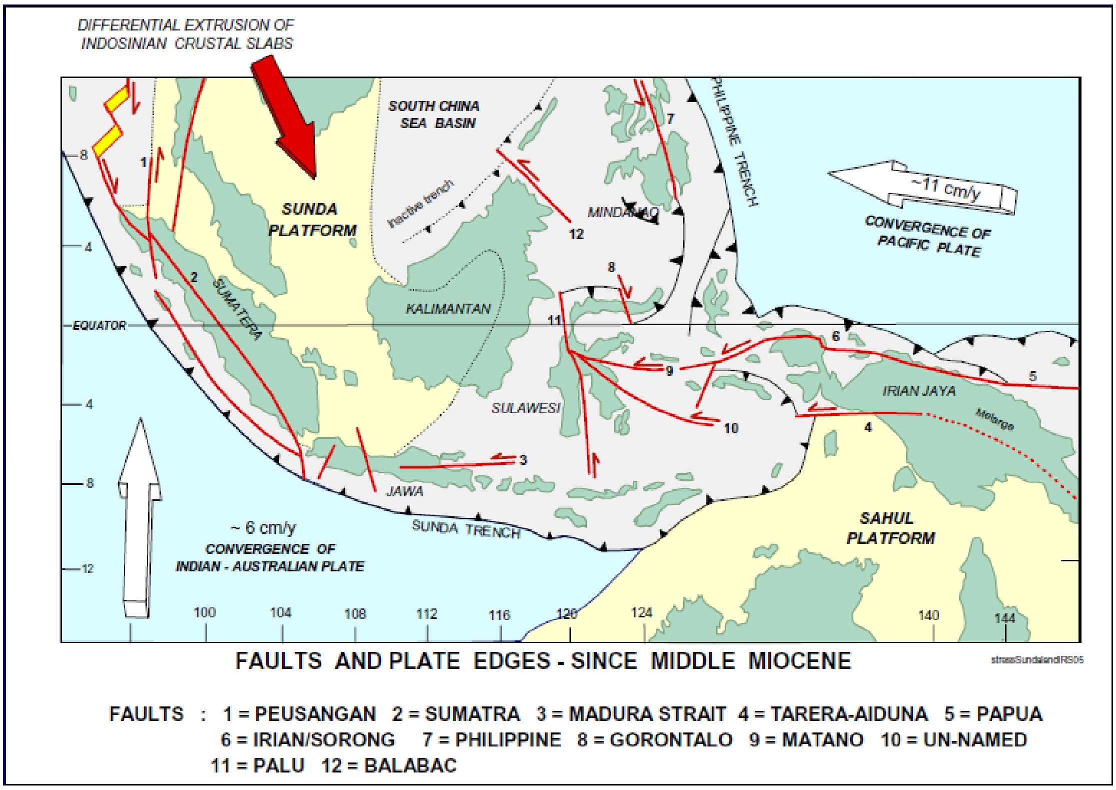

Figure 1.1: Plate Tectonic Setting of Southeast Asia (Alexander *et al.*, 2006)

In terms of plate boundaries, they can be divided into three main categories, namely convergent, divergent and transform boundaries, as illustrated in Figure 1.2. Convergent boundaries occur when two plates collide, crushing and diving under one another with the oceanic or continental crust. These phenomena are known as the subduction zone. The deeper-focus earthquakes commonly occur in patterns called Benioff zones that dip into the Earth, indicating the presence of a subducting slab. Dip angles of these slabs average about 45°, with some shallower and others nearly vertical. Usually, Benioff zones coincide with tectonically active island arcs such as the Sumatran subduction zone. A dense plate is plunges steeply through the earth's crust that can be as much as 300 km deep. Divergent boundaries are when two plates are pulling apart from each other. Land masses separate and oceans are born between them where it grows wider over time. Transform boundaries occur when two plates are sliding horizontally past one another. These are also known more commonly as faults. During an earthquake the rocks usually move several centimeters, or even as much as a few meters. This movement releases the energy that was stored in the rocks, which creates an earthquake. The stresses on both sides of a fault cause the rocks to deform plastically. The description of how earthquakes occur is called the elastic rebound theory.

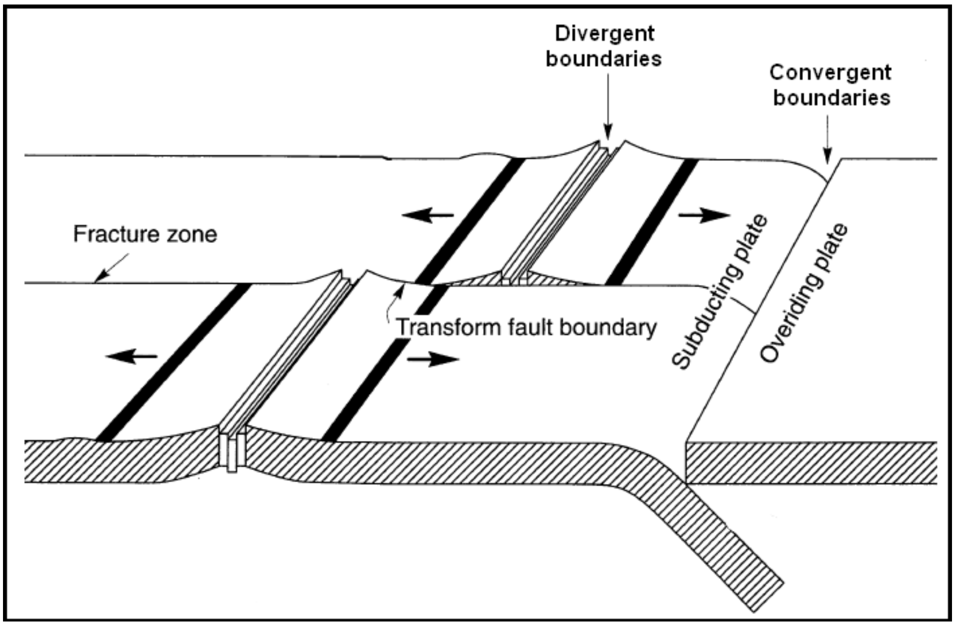

Figure 1.2 Primary types of tectonic plate boundaries (modified from Kramer, 1996)

Usually, a major or even moderate earthquake of shallow focus is followed by many other earthquakes. Seismic source zones are the representation of uniform seismicity characteristics such as focal depth, seismicity rate and maximum magnitude. The characterizations rely on geological, seismological, geophysical and geotechnical investigations. Each piece of earthquake data is chosen within an enclosed area that are likely to occur within a source zone of equally related seismicity and tectonism. In those active tectonic regions, localization of faults that cause earthquakes are often very accurate due to the high rate of occurrence of events and the fact that a relatively large amount of research is performed. However, in seismic hazard analysis, the small amount of earthquake data is not the factor in predicting future earthquakes. The results of De Vos *et al.* (2010) shows that an important factor of hazard estimate is source zonation. It has been agreed by

Ornthammarath *et al.* (2011) on the importance of characterizing the earthquake source especially for low-rate seismicity region that could produce a better seismic hazard assessment.

1.3 Background

East Malaysia consists of the Malaysian states of Sabah and Sarawak, and the Federal Territory of Labuan bordered internationally with Brunei Darussalam and Kalimantan, Indonesia located on the island of Borneo. East Malaysia is considered as a stable continental shield region at the triple junction zone of convergence between the Philippine, Indian-Australian and Eurasian Plates (Simons *et al.,* 2007) with moderate seismicity (Alexander *et al.,* 2006, 2008). According to the historical records; there has been a low amount of moderate earthquake activity across the East Malaysia region that has caused casualties, damage to properties and created narrow fissures in the ground (Tjia, 2007, Leyu, 2009, Chai *et al.,* 2009, Azhari, 2012, Mohd Hazreek *et al.,* 2012). In recent years, East Malaysia has witnessed an increase in low to moderate seismic activities due to a few active fault lines since it was first monitored years ago by Leyu *et al.* (1985).

In accordance with Tjia (2007), Sabah experienced moderate seismicity in the active Mensaban, and Lobou-Lobou fault zones (Figure 1.3) located in Kundasang, Ranau, which have brought earthquakes that caused light damage to infrastructures. The major faults around Sabah include the Belait Fault, Crocker Fault, Jerudong Fault, Mensaban Fault, Mulu Fault and the Pegasus Tectonic Line, and they can be illustrated in Figure 1.4.

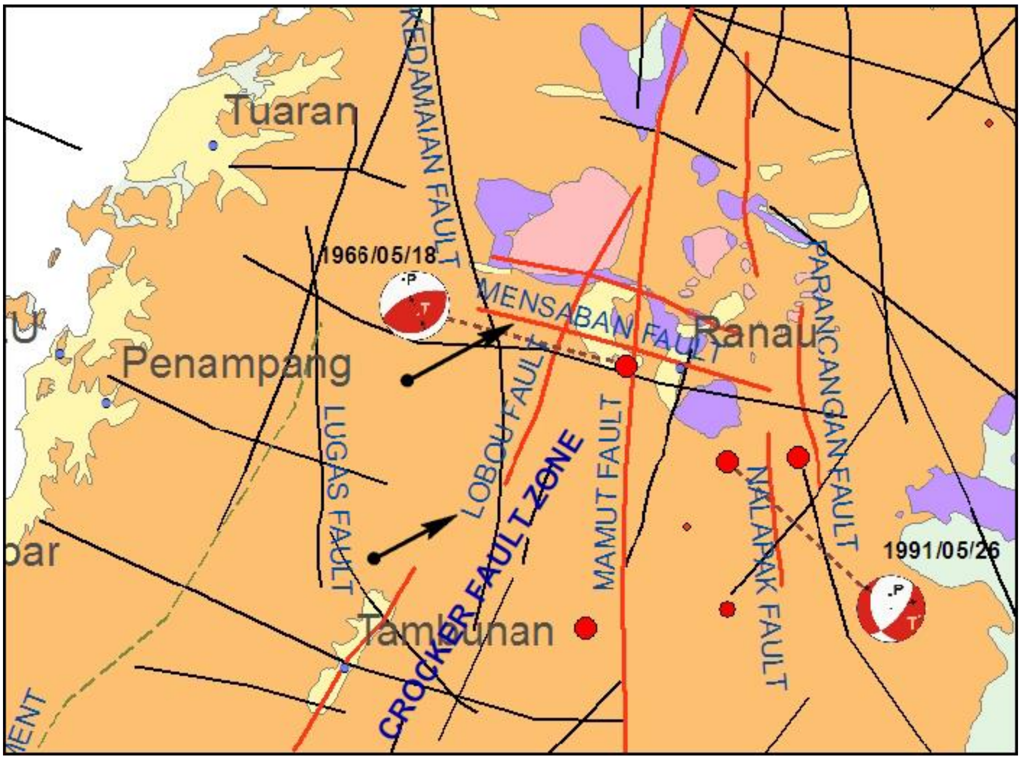

Figure 1.3 Active Mensaban and Lobou-Lobou faults within Crocker fault zone (Tjia, 2007, Leyu, 2009)

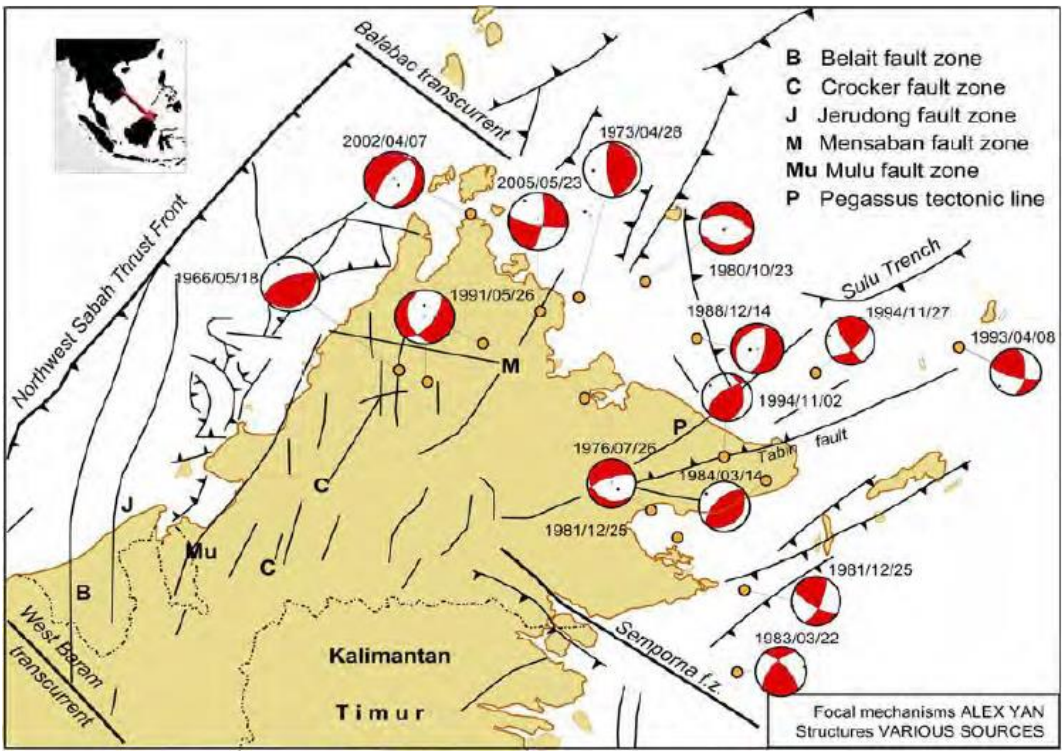

Figure 1.4 Seismic geometry of local earthquake around Sabah (Alexander *et al.*, 2006)

There are quite a few seismic activities that have been recorded around Sarawak in comparison to Sabah. Therefore, the major faults known as Kalawit, Mersing, Tubau and Tinjar Fault as illustrated in Figure 1.5 are starting to produce damaging earthquakes (Alexander *et al.*, 2006). As an example, two major earthquakes occurred within its local fault, including M_W 5.2 on 12th February 1994 within the Mersing fault and M_W 5.2 on 1st May 2004 along the Tubau fault. From historical records ranging between 1874 and 2014, we can see a total of 35 earthquakes with magnitudes ranging from M_W 3.5 to 5.3 were recorded. Sarawak has experienced tremors of the Maximum Mercalli Intensity scale equivalent to VI (Alexander *et al.*, 2006).

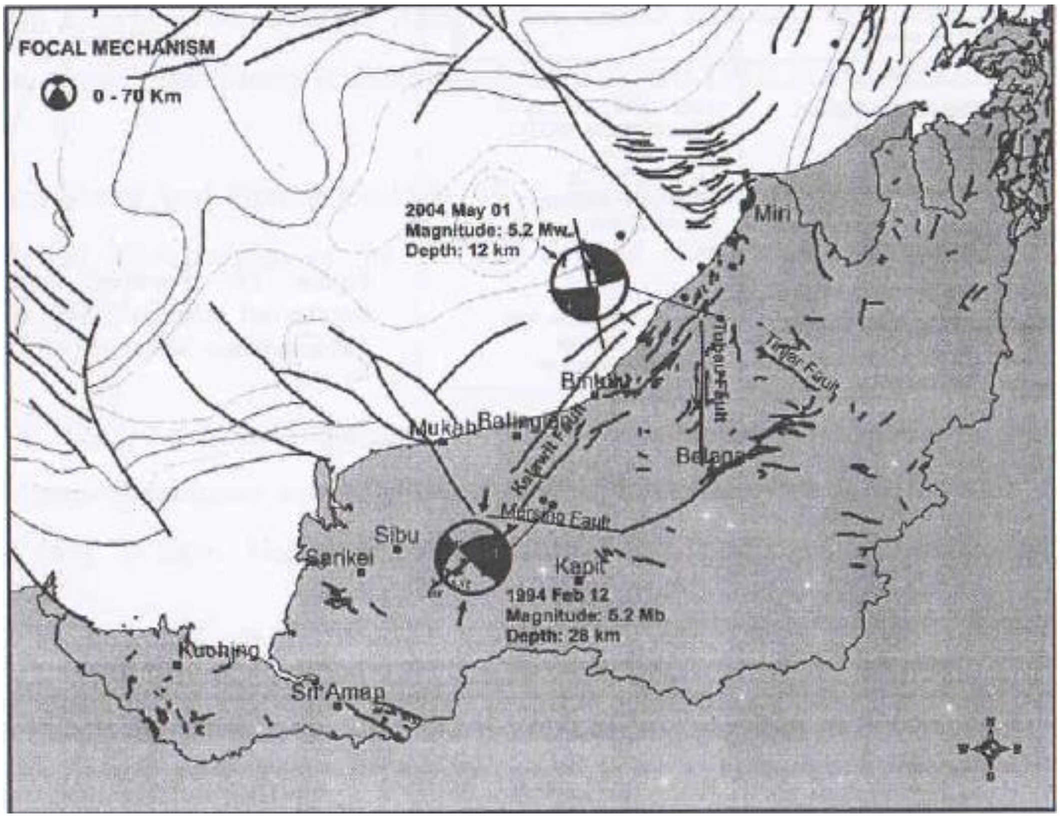

Figure 1.5 Seismic geometry of local fault and earthquakes around Sarawak (Alexander *et al.*, 2006)

The intensity-based mapping of East Malaysia was early presented in a 1985 report prepared by Leyu *et al.* (1985). The report recorded all the information of felt areas across the region from 1884 to 1984. Since the data has a lack of accurateness in terms of local time, coordinates and magnitudes, the Modified Mercalli Intensity (MMI) scale is used and Leyu *et al.* (1985) found out that an earthquake with an intensity of III to VII occurring across the East Malaysia region. The recent MMI scale can be seen in Majid *et al.* (2007) statement and Leyu (2009), where the MMI scale seems to increase from VII to VIII (Table 1.1). The severe damage of buildings due to fault movement has created enough concern to understand the seismically potential zones of the region (Mohd Hazreek *et al.*, 2012).

Table 1.1: Published MMI scale in East Malaysia region

Reference	**MMI scale**
Leyu *et al.* (1985)	III - VII
Majid *et al.* (2007)	V – VII
Leyu (2009)	V – VIII

The historical earthquake records in East Malaysia have only been compiled and interpreted over a few years, so they will not give a true indication of the seismic potential within an area (Emad, 2005). The statistics for an updated earthquake recorded from 1874 through 2014 represented by magnitude indicates a large increment of earthquake events for the last 140 years (Figure 1.6). The whole catalog shows that for the period 1874 to 1976, the data’s poor quality may be due to a lack of observations. However, it can be observed that a moment magnitude greater than 4.7 was reported in this period. In the records from 1976 – 2014 better data can be observed.

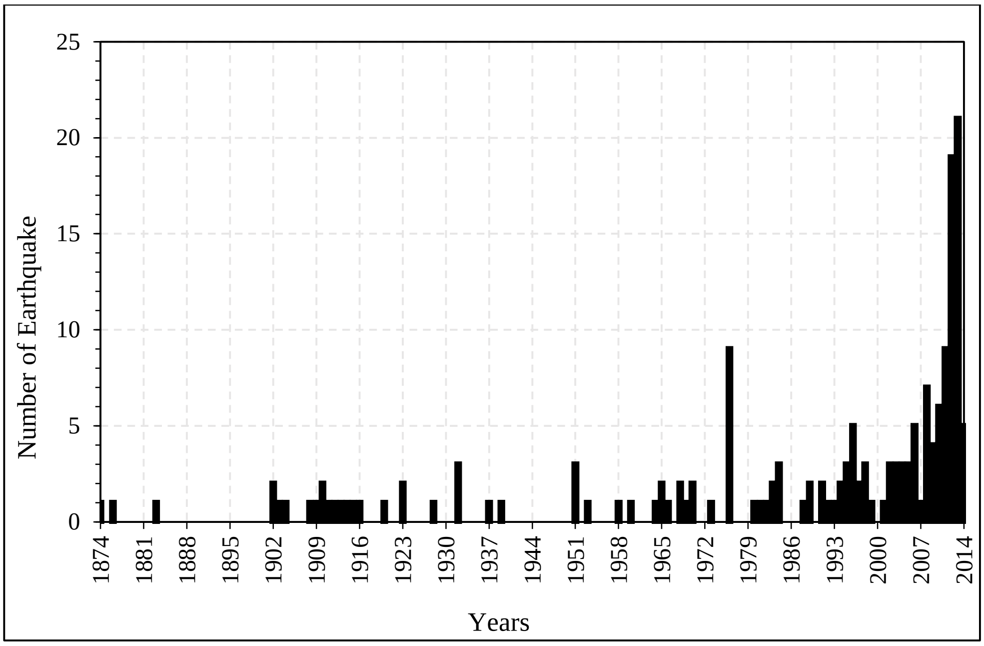

Figure 1.6 Number of local earthquakes with a magnitude greater than 2.0 reported in each decade (1874-2014) around East Malaysia

In accordance with previous historical earthquake record and studies in seismic monitoring in Malaysia by previous researchers (Alexander *et al.*, 2006; Tjia, 2007; Alexander *et al.*, 2008; Leyu, 2009; Chai *et al.*, 2009; Azhari, 2012; Mohd Hazreek *et al.*, 2012), the seismicity of East Malaysia is classified as a low to moderate earthquake. Figure 1.7 shows the distribution of local earthquake data in the study area representing moment magnitude ranging between 2.0 and 7.9.

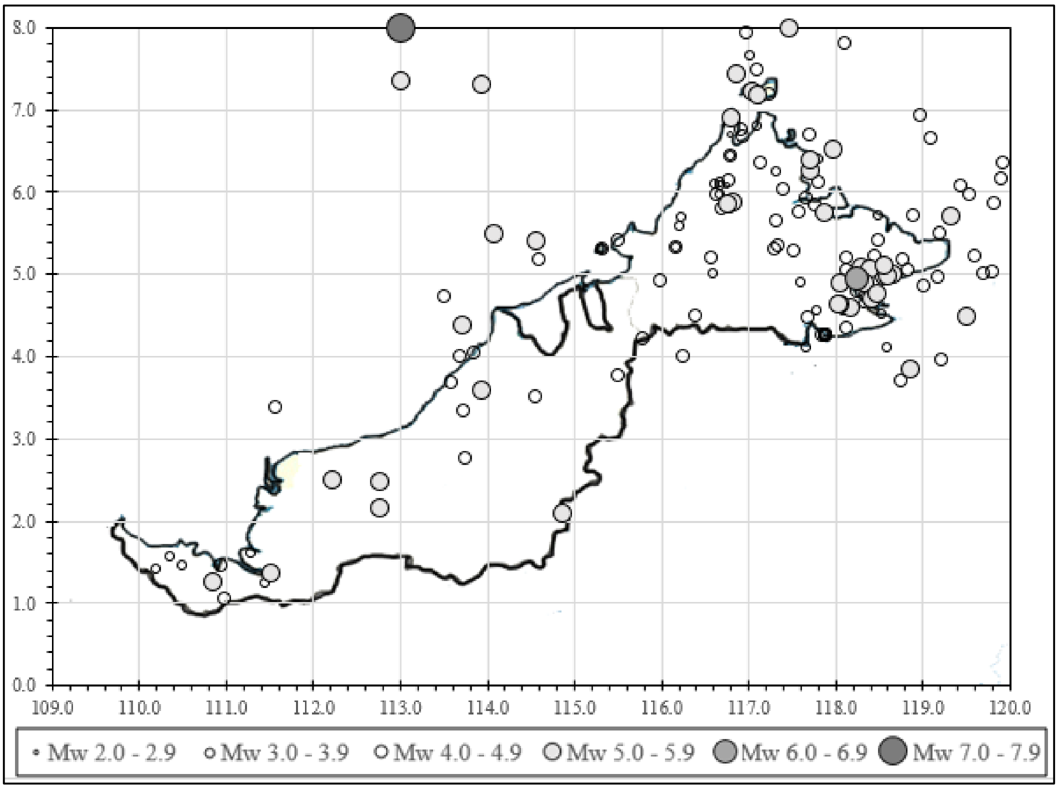

Figure 1.7 Earthquake events distribution map in the study area from year 1874 to 2014

In the seismic design of structures, the most critical part is the development of seismic design ground motion. In order to develop this ground motion, seismic hazard analysis such as probabilistic seismic hazard analysis (PSHA) is required. PSHA requires a strong ground motion prediction equation (GMPE) to estimate earthquake ground motion parameters characterizing the earthquake source, propagation path and geological conditon. Seismic hazard analysis is different in terms of definition of seismic sources and GMPE. Unfortunately, there is no GMPE that was derived previously for the condition in the East Malaysia region (Adnan, 2008). The GMPE that is available may not be suitable for handling accurately the low-to-moderate earthquake condition in East Malaysia as applied to other models, which might provide different estimates at a large distance (Chintanapakdee *et al.*, 2008; Chandler *et al.*, 2004, 2006). In the recent past, sufficient ground motion records from low-to-moderate magnitudes have become available to help derive equations, since there are various lists of currently available GMPE, as seen in Douglas (2004, 2011) and Douglas *et al.* (2010). The GMPEs that are available make it possible to be investigated and tested their sensitivity with the ground motion records (Cotton *et al.*, 2006). A large number of GMPE databases are necessary to illustrate the situation that may occur, especially for a region with no GMPE (Sabetta *et al.*, 2005).

1.4 Problem Statement

While damaging earthquakes are fortunately rare in East Malaysia when compared to seismically active regions, in the history of earthquakes, the region already experienced devastating earthquake with a magnitude of M_W 5.8 on 26th July 1976 centered in Lahad Datu, and just recently a M_W 6.0 on 05 June 2015 in Ranau. All signs indicate that it will continue to have the same problem in the future. The highest intensity of these earthquakes reached VIII degrees, and they will cause serious economic loss and social unrest. Over the past 114 years, a total of 124 with magnitudes ranging from 2.9 to 6.0 are known to have occurred.

According to a national Annex for the Eurocode 8, it is necessary to give priority to public safety by designing buildings or structures that are earthquake proof. In understanding earthquake behavior, characteristics and distribution, coupled with appropriate mitigation measures, it is possible to reduce their adverse impact and degree of damages. Although numerous conducted studies have explained the effect of seismic loading on buildings in Malaysia, it has not always been adequately considered in the Malaysian construction code. The occurrence of ground shaking in the past, mainly due to active fault zones able to cause casualties and damage to properties and unfortunately the majority of existing buildings were built consequently without seismic consideration. Earthquakes are acts of nature, and therefore their occurrence cannot be avoided. A number of local earthquakes of low-to-moderate magnitude (more than magnitude 2.0) have occurred in the past. The earthquake events have increased by about 30% since reported by the Malaysian Meteorological Department (MMD) in 2007. As a result of increasing seismic activities around the region, East Malaysia is experiencing more tremors and there is a need to design for seismic loadings. Even though the seismicity of this area is much lower than other moderate seismicity regions, the seismic risk cannot be regarded as negligible.

Since engineering structures respond differently to different frequencies, there should be information about the dominant frequencies that are present in seismic waves that occur in particular areas. In areas where the limiting value of ground acceleration is expected to be exceeded for a return period of 475 years, engineers have to design their structures in such a way that they are resistant to the accelerations and frequencies that could be expected.

1.5 Objectives

This study presents technical research into seismic hazard assessment for East Malaysia. The selection of seismic parameters, methods of analysis and the final evaluation for the seismic hazard analysis are based on three objectives.

i) To determine the fault characteristics mechanism and layouts for the East Malaysia region. This consideration is taking care because the region is being affected by shallow crustal faults and a subduction zone in the surrounding region, as well as local faults that have recently been considered as active in generating earthquakes.

ii) To produce a local ground motion prediction equation (GMPE) suitable for the region due to the scarcity and incompatible equation of GMPE from other regions.

iii) To determine the peak ground acceleration (PGA) and response spectral acceleration (RSA) to be a plot in map. The probabilistic seismic hazard assessment (PSHA) is performed for 2% and 10% probability of exceedance in a design time period of 50 years or the corresponding to return period of approximately 475 and 2,475 years respectively.

1.6 Scope and Limitation

The following tasks are performed for this study:

1. Review and research literature on available regional geological and tectonic environments to identify the regional earthquake activity and prepare a seismic sources zone map for use in seismic hazard analysis. The procedure will consider the faults, lineaments and shear zones which are associated with earthquakes of magnitudes of more than M_W 2.9.
2. Evaluate regional historical seismic data to provide seismic parameters for the source zone models influencing the East Malaysia region.
3. Selection of appropriate ground motion prediction equation (GMPE) for the types of faults present in the region to be used in the assessment of ground motion hazard. It is considered one of the critical factors in seismic hazard analysis. There has been a number of attenuation relations derived in the last two decades since the records of ground motions became more available. In general, they are categorized according to tectonic environment (i.e. subduction zone and shallow crustal earthquakes) and site condition.
4. Determine seismic hazard parameters such as, a-b value and magnitude maximum, which will be used in probabilistic seismic hazard analysis (PSHA).
5. Calculate a rock level peak ground acceleration (PGA) and response spectrum acceleration corresponding to 10% and 2% probability of exceedance in 50 years.
6. Develop a uniform hazard response spectrum (UHRS) at rock level for 5% damping and 10% and 2% probability of exceedance in 50 years.

1.7 Research Methodology

In general, the methodology throughout the study is divided into three steps (Figure 1.8). The first step is the determination of the fault characteristics mechanism and layouts for the East Malaysia region. The assessment includes an earthquake events database to analyze seismic hazard parameters. Secondly, a new ground motion prediction equation is developed in terms of peak ground acceleration and response spectrum acceleration. Last but not least is the calculation of seismic hazard in terms of probabilistic for 10%, 2% probability of exceedance and the development of a uniform hazard response spectrum. The description of each methodology can be summarized in the flow chart below, and the details are explained in the next section.

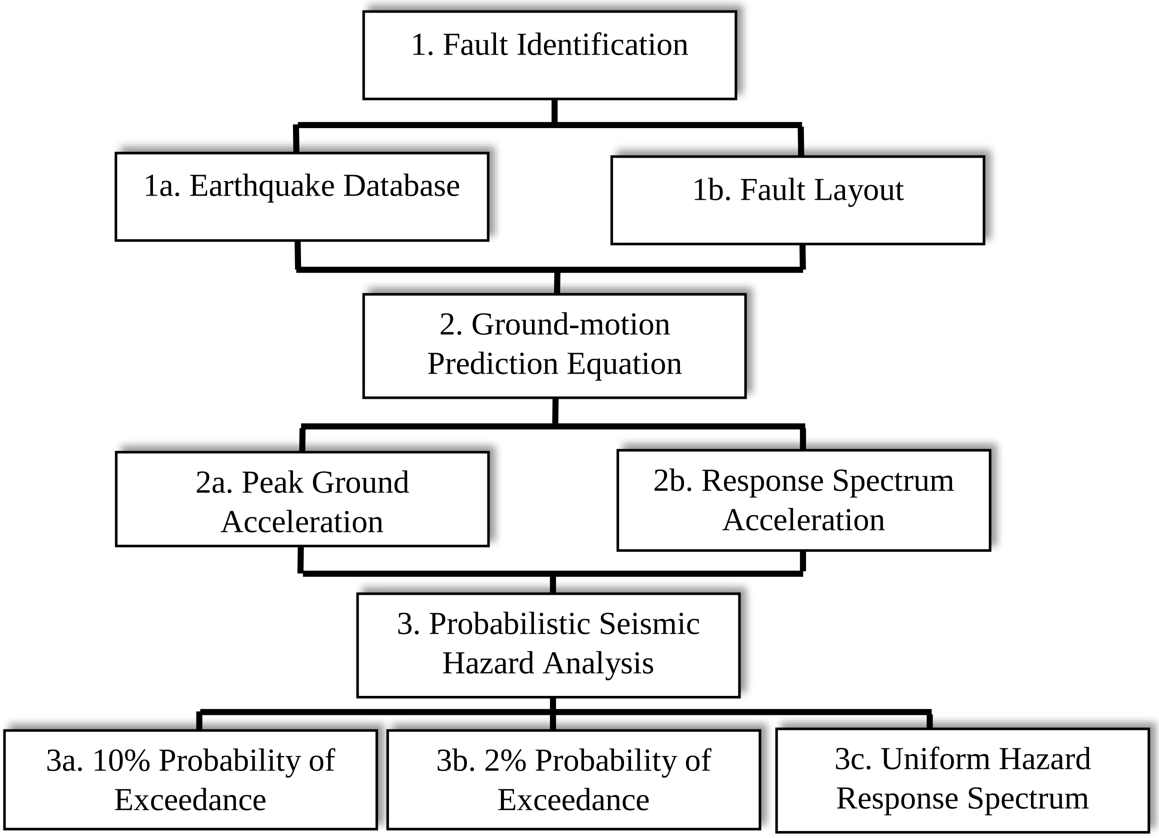

Figure 1.8: Flow Chart of Research Methodology

1.7.1 Fault Identification

This study presents a comprehensive description of the various tectonic features and the association of seismicity with them in order to define the probable seismic sources in East Malaysia and adjacent areas. A large dataset dating back to 1900 was provided by various national and international agencies are collected. This study has broadened the study area, extending it up to 1000 km encompassing by latitudes 5^0S to 10^0N and longitudes 105^0E to 125^0E. An attempt has been made to delineate seismic source zones in the study area based on the seismicity parameters. Seismicity parameters and the maximum probable earthquake for these source zones were evaluated and used in the hazard evaluation.

The link between the database and any calculational model for deriving hazard levels is a regional seismotectonic model, which should be based on a coherent merging of the regional databases. In the construction of a model, all existing interpretations of the seismotectonics of the region that may be found in the available literature will be taken into account. The procedure will integrate the elements of the seismological, geophysical and geological databases in order to construct a coherent seismotectonic model (or alternative models) consisting of a discrete set of seismogenic structures.

1.7.2 Ground Motion Prediction Equation

Since there is no new development of ground motion prediction equation (GMPE) for East Malaysia until recently, the GMPE for rock sites in the East Malaysia region is developed for peak ground acceleration (PGA) and response spectral acceleration (RSA). There has been a number of attenuation relations derived in the last two decades since the records of ground motions have become more available. In general, they are categorized according to tectonic environment (i.e. subduction zone and shallow crustal earthquakes) and site condition. The GMPE that is available may not be suitable for handling accurately the low-to-moderate earthquake conditions in East Malaysia. In order to perform seismic hazard analysis for a site region, it is fundamental to determine the GMPE using available ground motion records from the region. The modelling of seismic hazard analysis should capture the uncertainties about earthquake input parameters such as magnitude and distance of the earthquake. It is considered one of the critical factors in seismic hazard analysis.

1.7.3 Probabilistic Seismic Hazard Analysis

Probabilistic seismic hazard analysis or PSHA is the process of evaluating the design parameters of earthquake ground motion at a particular site quantitatively. The ground motion parameters that become considered in this assessment are peak ground acceleration and response spectral acceleration. PSHA will be performed using the below approaches.

There are four steps that should be conducted in PSHA:
1. Earthquake data collection
2. Characterize seismic source in terms of magnitude and distance.
3. Identifying earthquake ground motion parameter
4. Calculate seismic hazards on selected locations.

Two hazard levels were produced in PSHA, such as 10% and 2% probability of exceedance in 50 years ground motions or corresponding to 475 and 2,475 years return periods of earthquakes, respectively. The hazard also is being calculated separately for a range of frequencies into one uniform hazard response spectrum or UHRS by using the same source zone model spectral prediction model. From this we can build up a spectrum that reflects the real levels of hazard at the site at all frequencies.

1.8 Significance of Research

The most effective way to reduce disasters caused by earthquakes is to estimate the seismic hazard and to disseminate this information for use in improved building design and construction. The seismic activity in and around East Malaysia emphasizes the importance of defining the seismic zoning of the country and the need for the assessment of seismic hazard based on the available geophysical, geological, and seismological database. The seismic hazard analysis has become more important in Malaysia for the safety requirements of engineering structures and public interest.

In order to predict the size of future earthquakes, analysis of seismic activity for the past few decades needs to be further studied. A step by step process such as seismic hazard analysis is required to achieve the results. SHA can be performed by doing a Probabilistic Seismic Hazard Analysis (PSHA) step. It is mathematical procedure involving probabilistic study to assess the answer for uncertainties about seismic location, earthquake size and shaking intensity that might happen in the future. In the probabilistic study, two main parameters are important: the limitation of magnitude and distance. Several attenuation functions that are suitable for situations in East Malaysia are considered.

Seismic hazard analysis is often studied for a place with high earthquake potential or near to the epicenter. Malaysia is known as a stable continent free from earthquakes. However, it has been recently recognized that this region, even at rather remote distances, is at significant seismic risk from two main active earthquake sources i.e. Indonesia and Philippines. East Malaysia has a dense population and is going through a development boom. Due to the fact that it is free from earthquakes, many buildings were designed without considering seismic loading.

The increasing number of earthquakes around the East Malaysia region with the evidence from historical documents and reports and paleoseismic studies makes it strongly recommended for hazard map production. The production of the map is important, especially when it comes to seismic evaluation of existing structures or building a new one, particularly for nonlinear response history analysis. The current available earthquake database makes it possible to develop a new GMPE to predict future earthquakes.

1.9 Organization of Thesis

This thesis was developed into 5 chapters. The first chapter described nature and the causes of earthquakes around the world. In Chapter 2 the historical record of earthquakes from low-to-moderate magnitude dating back to 1900, typically in East Malaysia, were investigated. There are already previous seismic hazard maps done for this region however, it may be different in terms of the applied GMPE and source zonation used. The available literatures was reviewed and discussed on the topics of GMPE and then compared with available data recorded.

In Chapter 3 the analysis on compiled earthquake database collected from various sources and prepared a complete catalog of East Malaysia and the adjoining area was analyzed. This chapter also provided a procedure in deriving a new ground motion prediction equation (GMPE) in terms of response spectral acceleration and the development of seismic hazard maps at 2% and 10% probability of exceedance for use in the seismic design of building structures.

Chapter 4 comprised the results of the hazard calculations in terms of hazard curves and hazard spectra for the selected sites. This chapter also explained the results of the hazard assessment in the form of hazard maps. All the input parameters that were mentioned in Chapter 3 are used and comparisons among the respective maps are carried out. Finally, the most important conclusions that were drawn from the studies are discussed and summarized in Chapter 5.

zonation model. This will be helpful in reducing the uncertainty due to variation of seismicity parameters.

The PGA and RSA values at ground surface may vary significantly from the values at bedrock level. These variations, either amplification or de-amplification, will depend upon the site conditions. The seismic waves will travel differently through the overlying soil, which tends to increase the peak ground acceleration (PGA) values. Thus, the site characterization has to be done by considering four different site classes, including site class A to D.

Although the new GMPE here is important to predict the seismicity pattern across the region, more work is needed to refine the analysis. The curve-fitting of the new GMPE seems to not accurately match the earthquake records for magnitude between M_W 3.3 to 5.7 at a distance less than 100 km. Therefore, this study recommended to make a separate GMPE equation for this range of magnitude. More observations, especially for small earthquake ground-motion are needed with further seismo-tectonic research is recommended by incorporating epistemic variability. This study also recommended to refine some parameters used in the development of GMPE by including hanging wall effects, dividing faulting mechanism to three main categories such as reverse, strike-slip and normal faulting) and nonlinear soil response in the analysis.

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