SEISMIC HAZARD ASSESSMENT OF PENINSULAR MALAYSIA BASED ON NEW GROUND-MOTION PREDICTION EQUATIONS FOR SUBDUCTION EARTHQUAKES

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Sir,

CLASSIFICATION OF THESIS AS RESTRICTED

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BY

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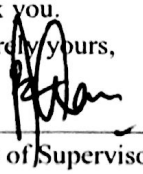
Please be informed that the above mentioned thesis entitled "SEISMIC HAZARD ASSESSMENT OF PENINSULAR MALAYSIA BASED ON NEW GROUND-MOTION PREDICTION EQUATIONS FOR SUBDUCTION EARTHQUAKES" be classified as RESTRICTED for a period of three (3) years from the date of this letter. The reasons for this classification are as follow:

(i) The proposed new empirical Ground-Motion Prediction Equations (GMPEs) have not published yet.

(ii) The products of the thesis as the probabilistic seismic hazard maps as well as the recommended elastic and design acceleration response spectra for the Peninsular Malaysia region may be used for Malaysian National Annex for Eurocode 8.

Thank you.

Sincerely yours,



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DEDICATION

To my beloved father, mother, wife, and

sisters

Thanks for all the love, support, motivation and always being there

whenever I need you

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Praise to God almighty, the compassionate and the merciful, who has created mankind with wisdom and given them knowledge.

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ABSTRACT

On the basis of regional economic growth, most cities in Southeast Asia have seen rapid development over the past forty years. In general, seismic design has not been taken into account in Southeast Asia regions with low to moderate seismicity, as these areas have not experienced disaster caused by earthquakes. Peninsular Malaysia is an example of these regions. Although the main cities of this region are located in a low seismicity area, they may be vulnerable to distant earthquakes generated by active seismic sources located more than 300 km along and off the west coast of Sumatra Island. Since 2007, several earthquakes due to the local faults within the Peninsular Malaysia region with the maximum moment magnitude ($\mathbf{M}_{max}$) of 4.4 have occurred. Even though the local earthquakes were small in size, the epicenters were as close as 20 km to Kuala Lumpur, which could have remarkable effects on seismic hazard of the region. After understanding this fact that Peninsular Malaysia could be affected by either the large magnitude, distant Sumatran earthquakes or the local earthquakes, an appropriate seismic hazard maps and a set of desirable elastic response spectral acceleration for seismic design purposes would be required. Despite the earlier seismic hazard studies for this region, which were proposed based on only the far-field Sumatran earthquakes, this study has presented new maps and elastic response spectra using the combination of the local and Sumatran seismic sources. Ground-Motion Prediction Equations (GMPEs) are the main inputs in any seismic hazard assessment. This study has attempted first to derive new empirical spectral GMPEs for distant subduction earthquakes (the both interface and intraslab events). The proposed GMPEs are for peak ground acceleration (PGA), peak ground velocity, and 5% damped pseudo-acceleration for four site classes (i.e., National Earthquake Hazards Reduction Program (NEHRP) site class B, C, D, and E, corresponding to rock, stiff soil, medium soil, and soft soil site conditions). The response spectra database has been compiled from hundreds of ground-motion recordings from subduction earthquakes of moment magnitude (**M**) 5.0 to 9.1, hypocentral distance (R_{hyp}) of 120 to 1300 km and **M** 5.0 to 7.7, R_{hyp} 120 to 1400 km for interface and intraslab events, respectively. The probabilistic seismic hazard maps for PGA are presented over a 12.5 km grid for 10% and 2% Probabilities of Exceedance (PE) in 50 years corresponding to 475 and 2,475 years return periods, respectively. The proposed new hazard maps give the expected ground motions based on the extended earthquake catalogue, consideration of the both Sumatran and local seismic sources, upgraded seismic source parameters, and more compatible GMPEs. The maximum estimated PGAs on rock site condition across the Peninsular Malaysia region for 10% and 2% PE in 50-year are 11 %g and 20 %g, respectively. In final, the horizontal elastic and design acceleration response spectra following the principles of Eurocode 8, on four soil site conditions with soil factors of 1, 1.45, 2, and 2.35 for rock, stiff soil, medium soil, and soft soil ground types, respectively, have been presented for the Peninsular Malaysia region based on the computed uniform hazard spectra with 475 and 2,475 years return period.

ABSTRAK

Atas dasar pertumbuhan ekonomi serantau, kebanyakan bandar di Asia Tenggara telah pesat membangun sejak empat puluh tahun yang lalu. Secara umumnya, reka bentuk sismik tidak diambil kira di rantau Asia Tenggara yang mempunyai aktiviti sismik berskala rendah dan sederhana, kerana rantau tersebut tidak pernah mengalami bencana yang disebabkan oleh gempa bumi. Rantau Semenanjung Malaysia merupakan salah satu contoh sedemikian. Walaupun kebanyakan bandar utama terletak di kawasan sismik berskala rendah, rantau tersebut mungkin terdedah kepada gempa bumi berjarak jauh yang dijana oleh sumber sismik berskala aktif terletak lebih dari 300 km di sepanjang mahupun di luar pantai barat Pulau Sumatera. Sejak tahun 2007, beberapa gempa bumi yang berpunca daripada sesar tempatan di rantau Semenanjung Malaysia dengan magnitud maksimum ($\mathbf{M}_{max}$) berukuran 4.4 telah berlaku. Walaupun gempa bumi tempatan berskala kecil, jarak pusat gempa adalah hampir 20 km dari Kuala Lumpur dan hal ini menunjukkan bahawa pendedahan kepada bencana sismik membawa kesan yang tinggi. Berikutan pengetahuan ini, Semenanjung Malaysia boleh terjejas disebabkan gempa bumi berskala besar dan berjarak jauh yang berpunca dari Sumatera dan gempa bumi tempatan, oleh itu peta bencana sismik dan tindak balas pecutan spektrum anjal untuk tujuan reka bentuk sismik adalah diperlukan. Disamping kajian bencana sismik sebelum ini, yang telah dibuat berdasarkan gempa bumi berjarak jauh dari Sumatera, kajian ini telah menyediakan peta baru dan spektrum gerak balas elastik dengan menggunakan gabungan sumber sismik tempatan dan Sumatera. Persamaan ramalan gerakan tanah (GMPEs) merupakan intipati utama dalam mana-mana penilaian bencana sismik. Kajian pertama adalah untuk memperolehi empirikal spektrum GMPEs yang baru untuk gempa bumi benam (untuk kedua-dua tujahan permukaan dan dalaman). GMPEs yang dicadangkan adalah untuk tanah pecutan puncak (PGA), halaju tanah puncak, dan 5% teredam pseudo-pecutan pada empat kelas (berdasarkan National Earthquake Hazards Reduction Program (NEHRP) kelas B, C, D, dan E, masing-masing bersamaan dengan batu, tanah keras, tanah keras sederhana, dan keadaan tapak tanah lembut). Pangkalan data spektrum gerak balas telah dikumpulkan daripada ratusan data gelinciran tanah daripada gempa bumi benam dengan magnitud (**M**) 5.0-9.1, jarak pusat tumpuan (R_{hyp}) daripada 120 hingga 1300 km dan **M** 5.0-7.7, R_{hyp} 120 hingga 1400 km, masing-masing pada tujahan permukaan dan dalaman. Kebarangkalian peta bencana sismik untuk PGA yang dibahagikan kepada grid-grid berjarak 12.5 km untuk 10% dan 2% kebarangkalian terlampau (PE) dalam tempoh 50 tahun masing-masing bersamaan dengan 475 dan 2,475 tahun tempoh ulangan. Peta bencana sismik yang baru untuk gelinciran tanah adalah berdasarkan katalog gempa bumi lanjutan dengan mengambil kira kedua-dua gempa bumi dari Sumatera dan sismik tempatan, parameter sumber sismik yang dinaik taraf dan GMPEs yang lebih serasi. Anggaran maksimum PGA pada batuan di seluruh rantau Semenanjung Malaysia untuk 10% dan 2% PE pada 50 tahun masing-masing adalah 11 %g dan 20 %g. Akhir sekali, anjalan mendatar dan tindak balas pecutan spektrum anjal dengan merujuk kepada prinsip-prinsip Eurocode 8 untuk empat jenis tapak tanah dengan faktor 1, 1.45, 2, dan 2.35 masing-masing untuk batu, tanah keras, tanah sederhana, dan lembut jenis tanah tanah telah dibentangkan bagi rantau Semenanjung Malaysia berdasarkan spektrum bencana seragam pada 475 dan 2,475 tahun tempoh ulangan.

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LIST OF ABBREVIATIONS

a_g	-	Design ground acceleration on rock site
a_{gR}	-	Reference peak ground acceleration on rock site
ANSS	-	Advanced National Seismic System
Avg	-	Average
BHRC	-	Building and Housing Research Center (Iran)
c	-	Shallow crustal events
CAM	-	Component Attenuation Model
CMT	-	Harvard Centroid Moment Tensor database
DSHA	-	Deterministic Seismic Hazard Assessment
E	-	East direction
EC8	-	Eurocode 8
f_c low	-	Law-cut frequency filter
g	-	Gravitational acceleration (~ 9.81 m/s^2)
gal	-	Acceleration unit (cm/s^2)
GMPE	-	Ground-Motion Prediction Equation
GSN	-	Global Seismographic Network
ISC	-	International Seismological Center
KiK-net	-	Kiban Kyoshin network (Japan)
KL	-	Kuala Lumpur (Capital of Malaysia)
K-NET	-	Kyoshin network (Japan)
Lat.	-	Latitude (geographic coordinate)
Long.	-	Longitude (geographic coordinate)
M(M_W)	-	Moment magnitude
M_0	-	Seismic moment in dyne-cm
m_b	-	body-wave magnitude
M_L	-	Local magnitude/ Richter magnitude
$\mathbf{M}_{max}$	-	Maximum moment magnitude
MMD	-	Malaysian Meteorological Department (Malaysia)

$\mathbf{M}_{min}$	-	Minimum moment magnitude
M_S	-	Surface-wave magnitude
N	-	North direction
n	-	Subduction intraslab event
NEA	-	National Environment Agency (Singapore)
NEHRP	-	National Earthquake Hazards Reduction Program
NEIC	-	National Earthquake Information Center
NGA	-	Next Generation Attenuation
PDE	-	Preliminary Determination of Epicenters
PE	-	Probability of Exceedance
PEER	-	Pacific Earthquake Engineering Research Center
PGA	-	Peak Ground Acceleration
PGV	-	Peak Ground Velocity
PNG	-	Penang (Malaysian state)
PSA	-	pseudo-acceleration / pseudo-acceleration response spectrum
PSHA	-	Probabilistic Seismic Hazard Assessment
q	-	Structural behavior factor
R	-	Source to site distance
R_{cd}	-	Closest distance to the fault
R_{epi}	-	Epicentral distance
R_{hyp}	-	Hypocentral distance
R_{JB}	-	Closest distance to the surface projection of the ruptured area
RP	-	Return Period
R_{rup}	-	Closest distance to the ruptured area
RSA	-	Response spectral acceleration/acceleration response spectrum
S	-	Soil factor
S	-	South direction
S_d	-	Horizontal design acceleration spectrum
sd/σ	-	Standard deviation
$S_{De}(T)$	-	Elastic horizontal displacement response spectrum
$S_e(T)$	-	Elastic horizontal acceleration response spectrum
SF	-	Sumatran Fault
SHA	-	Seismic Hazard Assessment
SSIF	-	Sumatran Subduction Interface
SSIS	-	Sumatran Subduction Intraslab

T	-	Natural structural period
T_B	-	The lower limit of the period of the constant spectral acceleration
T_C	-	The upper limit of the period of the constant spectral acceleration
T_D	-	The value defining the beginning of the constant displacement response range of the spectrum
t	-	Subduction interface event
T_c low	-	Low-cut period filter
T_{max}	-	Maximum usable period
TSPP	-	Time Series Processing Programs
UHS	-	Uniform Hazard spectrum
USGS	-	U.S. Geological Survey
V_S	-	Shear wave velocity
V_{S30}	-	Average shear wave velocity in the upper 30 m of the soil profile
γ_I	-	Importance factor
λ	-	Mean annual rate of exceedance

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CHAPTER 1

INTRODUCTION

1.1 General

Earthquake is one of the world's most destructive natural hazards. In the last 30 years alone, earthquakes have caused destroyed cities and villages around the world and thousands of people have been injured or lost their lives, with many more left homeless. The unexpected and immediate devastation characteristics of earthquakes produce a unique psychological impact and a fear in modern civilization unsurpassed by any other natural hazards. This devastation, however, is entirely due to the effects of earthquakes on civil engineering structures and the ground that supports the structures. In essence, with the operational application of scientific and engineering principles and construction methods, the impact of catastrophic earthquake could be minimized, if not completely eliminated (Villaverde, 2009).

Usual earthquake damage includes ground shaking, ground failure, and indirect effects. Ground shaking could be considered as the most damaging effect of earthquakes. During an earthquake, as is well known, the ground moves violently in two horizontal and vertical directions. The generated ground-motion makes the structure oscillate back and forth and up and down causing the structure to undergo major stress and deformation. Moreover, since an earthquake is able to shake the ground over extensive areas of the ground surface, the generated ground shaking may simultaneously affect a large number of structures (Figures 1.1 and 1.2). It goes without saying that ground shaking is the main concern of structural engineers in low, moderate, and active seismic regions of the world.

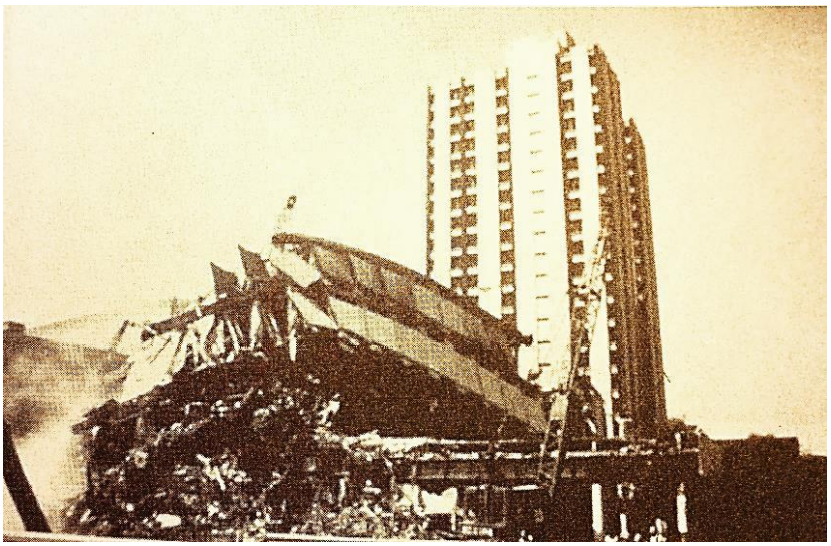

Figure 1.1 Total collapse of a 22-story steel frame building in Pino Suárez Complex during the Michoacán earthquake that affected Mexico City in 1985 (Villaverde, 2009)

Figure 1.2 Collapse of middle rise building during the Chi-Chi earthquake in 1999, Taiwan (Villaverde, 2009)

The possible effects of ground failure are (a) ground cracking, (b) surface faulting, (c) landslides, (d) soil liquefaction, and (e) ground subsidence. Ground cracking occurs when the soil at the surface is transported to a different location, or it sinks as a result of losing its support. When the two sides of an earthquake fault slip relative to one another, surface faulting occurs that may cause severe damage to structures which lie across the fault. Landslides are the failure of marginally stable

slopes before the earthquake, which become unstable due to the shaking induced by the earthquake. Soil liquefaction is phenomenon that involves the temporary change of fine saturated soils from a solid to a liquid state, thus removing from the soil its ability to remain stable or carry loads. Ground subsidence is possible when the ground surface of a site settles due to the compaction generated by earthquake vibrations (Figure 1.3).

Figure 1.3 Settlement of a building in Mexico City due to ground subsidence phenomenon during the 1985 Michoacán earthquake (Villaverde, 2009)

The indirect effects of earthquakes are (a) fires, (b) tsunamis, and (c) seiches. Fire may be considered as the most devastating indirect effect of earthquakes. Fires start when, for instance, an earthquake destroys oil-storage tanks or breaks gas pipes or overturns stoves and heaters. Tsunamis are massive sea waves generated by a sudden vertical dislocation of the ocean floor as a result of the slippage of an earthquake fault under the ocean. Seiches are temporary long-period oscillating waves in enclosed bodies of water such as lakes, reservoirs, bays, and even swimming pools caused by distant earthquakes. When the water body resonates with the earthquake waves, that is, when the natural frequency of the water body matches the frequency of the incoming earthquake waves, the phenomenon of seiches occur (Elnashai and Di Sarno, 2008; Villaverde, 2009).

As mentioned above, in order to minimize the earthquake catastrophes, an effective application of scientific and engineering principles should be followed to control earthquake-induced forces. An elaborate process with participation of architects, seismologist, geologists, geotechnical engineers, foundation engineers, and structural engineers is required to design an earthquake-resistant structure. That this required an elaborate process is due to the unpredictability of earthquake forces, the uncertainty of their occurrence, and their probabilistic devastating effects.

Thus, earthquake engineering which could be considered as one of the civil engineering branches, provides the principles and procedures for the planning, analysis, and design of structures with the capability of resisting the earthquake effects. In the other words, the principles and procedures provided by earthquake engineering are for (a) the selection of an appropriate location for the structures in order to minimize their exposure to earthquake hazards; (b) the estimation of the earthquake forces that may affect the structures in a given time interval; (c) the analysis of structures based on the estimated earthquake forces to determine the maximum stresses and deformations; (d) the detailing of the different components of the structures to make them resist the determined stresses and deformations without any failure or collapse; and (e) confirming the stability of the structures supported on weak soils or slopes with improvement of soils and the stabilization of natural slopes. All the mentioned principles are based on the concepts from seismology, geology, seismic hazard analysis, geotechnical engineering, structural dynamics, and structural engineering (Villaverde, 2009).

As the parameters of future earthquake ground motions (i.e., peak ground acceleration, peak ground velocity, and response spectrum ordinates) are unpredictable and also radically different from one earthquake to another and from one site to another, the selection of such parameters for structural design purposes needs a difficult and elaborate procedure. This procedure involves the use of historical, statistical and geological data, probabilistic models, empirical correlations and engineering judgment. The mentioned elaborated procedure for the purpose of seismic design based on the likely parameters of future earthquake ground motions in a given region is an essential step in the seismic design of the structures and is called

seismic hazard assessment. Seismic hazard analysis as the early stages of seismic design procedure results in the macrozonation maps that present the estimation of the peak ground acceleration, peak ground velocity, or response spectrum ordinates due to the expected earthquakes in the vicinity of a given region within a specific time interval. These maps could be important from the point of view that they give an overview of the seismicity of a given region. They are also valuable for site selection and land-use planning as well as specifying the earthquake intensity that structures should be designed for in different zones of a geographical region.

The first simple approach, in the early days of earthquake engineering, by which such an analysis could be made, was deterministic approach (i.e., called *deterministic seismic hazard assessment* (DSHA)). This method was made without consideration of the uncertainties in the estimation of source to site distances and the magnitudes of future earthquakes. But today, these analysis are being performed through the probabilistic approach (i.e., called *probabilistic seismic hazard assessment* (PSHA)) by considering random characteristic of all variables that are defined in terms of given probability distributions (Kramer, 1996; Villaverde, 2009).

Ground-motion prediction equations (GMPEs) sometimes referred to as *attenuation laws*, *attenuation relationships*, or *ground-motion attenuation relations* are the most critical key factors in any seismic hazard analysis. In the past fifty years many hundreds of GMPEs have been developed in order to relate ground-motion parameters to a set of independent variables such as magnitude, source-to-site distance, focal depth, local site condition, and often focal mechanism (e.g., strike-slip, reverse, and normal mechanism). Where earthquake ground-motion recordings are abundant, these equations are being developed empirically by a regression analysis using data from the recorded ground motions. In contrast, where recordings are limited, the equations are often derived from seismological models based on the simulated earthquake ground motions using stochastic and theoretical methods. However, the calculation of absolute values of the ground motions simulated by seismological models have a large degree of uncertainty in the regions where data are sparse (Campbell, 2003).

1.2 Background and Problem Statement

On the basis of regional economic growth, most cities in Southeast Asia have seen rapid development over the past forty years. In general, seismic design has not been taken into account in Southeast Asia regions with low to moderate seismicity, as these areas have never experienced disaster caused by earthquakes. Peninsular Malaysia is an example of these regions. Although the main cities of this region (such as Kuala Lumpur-capital of Malaysia, Putrajaya, Penang, and Johor Bahru), are located in a low seismicity region, they may be vulnerable to distant earthquakes generated by active seismic sources located more than 300 km along and off the west coast of Sumatra Island. These seismic sources have generated many earthquakes, some of which have shaken medium to high rise buildings in Kuala Lumpur, capital of Malaysia. The number of felt events is being increased due to the rapid construction of medium to high rise buildings in this region (Pan, 1997). Although earthquakes have never caused any severe structural damages in Kuala Lumpur, the effects of even a moderate level of ground-motion can be huge because of the population and many major business activities in the buildings that are not designed for earthquake-induced forces (Megawati *et al*., 2005).

Large-magnitude earthquakes, occurring several hundred kilometers away, are capable of causing substantial damage, especially to medium- and high-rise buildings, due to the long period wave trains generated by the rupture of long fault systems. Experimental evidence of this well-known physical fact has been extensively reported in Bormann (2002) and a remarkable recent example was provided by the 2011 Tohoku earthquake in Japan with moment magnitude (**M** or M_W) 9.1. It was reported that most of the super high-rise buildings in major cities in Japan such as Tokyo and Osaka with epicentral distances of about 385 and 760 km away, respectively, were harshly shaken by long-period ground motions (Takewaki *et al*., 2011).

On the other hand, soil amplification is another factor that could cause serious damage by amplifying the low amplitude, long-period ground motions. The 1985 Michoacán earthquake with a surface-wave magnitude (M_S) of 8.1 could be a

remarkable example. This earthquake caused serious damage in Mexico City, which was 300−450 km from the epicenter, due to the amplification of incoming earthquake waves by the soft soil on the ground surface (Seed *et al*., 1988).

The mentioned concepts have been also seen in Peninsular Malaysia and Singapore. For instance, an earthquake in February 1994 (M_S 7.0) occurred near Liwa in southern Sumatra, 700 km from Singapore. This earthquake affected some buildings in densely populated areas of Singapore (Pan, 1995). Another earthquake occurred in May 1994, when the vibrations of the earthquake with the magnitude of 6.2 on the Richter scale (M_L), near the island of Siberut were felt 570 km from Kuala Lumpur and Singapore (Pan and Sun, 1996). In October 1995, stronger and more extensive ground tremors were felt in Singapore, Kuala Lumpur, and Johor Bahru, the southern state of Peninsular Malaysia. The earthquake with M_S 7.0 took place 450 kilometers away from these areas. Bengkulu earthquake of June 2000 had a moment magnitude of 7.7. Although its epicenter was around 700 km southwest of Singapore, it produced heavy tremors in the city (Pan *et al*., 2001). More recently, the major earthquakes in Aceh, 2004 (**M** 9.0) and Nias Island in 2005 (**M** 8.6) occurred in the Sumatran subduction interface area. Although the movements caused by these earthquakes were offset by distances up to 1000 km, they still resulted in ground-motion that was felt by the occupants of high-rise buildings built on the soft ground in Kuala Lumpur and Singapore (Nabilah and Balendra, 2012). Even though there have never been severe earthquake-induced damages in Peninsular Malaysia, the increasing number of felt tremors shows this fact that the seismic hazard may not be negligible for this region, especially its potential to damage the medium to high rise buildings built on soft sedimentary deposits or reclaimed lands (Megawati and Pan, 2002).

Since 2007, several earthquakes due to local faults with the maximum moment magnitude ($\mathbf{M}_{max}$) of 4.4 have occurred within Peninsular Malaysia. Even though the local earthquakes were small, the epicenters were as close as 20 km to Kuala Lumpur, which could have remarkable effects on seismic hazard of the region. A local earthquake with moment magnitude (**M**) of about 5 to 7 rupturing within 50 km would cause a significant base shear demand on low-rise buildings (Lam *et al*.,

2015). Current design code for building structures in Peninsular Malaysia widely adopts the British Standard (BS) 8110 code (BS 8110-1:1997), which has no provisions for earthquake-induced forces. The fact that the earthquakes have not yet inflicted any serious damage in Peninsular Malaysia historically, should not be taken as an excuse for not considering the effects of earthquakes on the existing and future structures. In the interest of public safety, it is reasonable to comprehensively assess the seismic hazard of the region, where there are main metropolises with high concentrations of high-rise buildings, complex infrastructure systems and large populations.

After understanding the fact that the Peninsular Malaysia region could be affected by either large magnitude, distant Sumatran earthquakes or the earthquakes due to the local faults, an appropriate seismic hazard assessment and a set of desirable elastic acceleration response spectra for seismic design purposes would be required. These basic criteria have been required by the well-known seismic design codes such as international building code (IBC) 2012, Iranian seismic code (standard No. 2800) 2015, and Eurocode 8 (BS EN 1998-1:2004). In order to assess the seismic hazard and construct the design spectra, representative ground-motion prediction equations (GMPEs) as the essential factor in any seismic hazard assessment, compatible with the region are required.

Most of the existing proposed empirical GMPEs for subduction earthquakes (reviewed in Chapter 2) are not tuned to a suitable magnitude-distance range compatible with the Peninsular Malaysia region. In addition, the previous probabilistic seismic hazard assessment studies done for the study region were only based on the far-field Sumatran seismic sources and the seismic effects of the local faults within Peninsular Malaysia were not taken to be considered.

1.3 Objectives of the Study

This research has attempted to achieve the following three (3) primary objectives:

1. To derive new empirical spectral ground-motion prediction equations (GMPEs) for distant subduction earthquakes (the both interface and intraslab events) using the recorded ground motions by the Malaysian Meteorological Department (MMD), Kyoshin network (K-NET) and Kiban Kyoshin network (KiK-net), and Building and Housing Research Center (BHRC) seismic stations located in Peninsular Malaysia, Japan, and Iran, respectively.

2. To improvise the macrozonation maps of Peninsular Malaysia with 10 and 2% probabilities of exceedance in 50 years corresponding to 475 and 2,475 years return period, respectively, through the probabilistic approach of seismic hazard assessment, based on the more appropriate and compatible sets of GMPEs, and due to both the Sumatran seismic sources (i.e., Sumatran subduction and Sumatran fault zones) and the local faults within the Peninsular Malaysia region.

3. To propose new elastic and design acceleration response spectra on four different soil site conditions (i.e., rock, stiff soil, medium soil, and soft soil) for seismic design purposes for the Peninsular Malaysia region following the principles of the Eurocode 8 seismic design code.

Referring to the mentioned objectives, it is sincere hoped that this study could be able to provide the necessary science and engineering principles to guide future seismic hazard studies and provisions for the regions which are subjected to the large-magnitude, distant earthquakes such as Peninsular Malaysia.

1.4 Scope and Limitations

As there are so many parameters that may affect the final results of this study, the following scope and limitations have been considered for analysis:

1. New empirical spectral ground-motion prediction equations (GMPEs):

a) Identifying the subduction earthquakes, including both interface and intraslab events, occurred mainly in Sunda and Japan trenches (i.e., Sumatran and Japan subduction zones) as well as the trench in South-East of Iran, based on their location, focal depth, and faulting mechanisms introduced by Harvard Centroid Moment Tensor catalogue (Ekström *et al*., 2012).
b) Collection of the raw recorded ground-motion data on four different soil site conditions as B, C, D, and E, based on National Earthquake Hazard Reduction Program (NEHRP) site classification, due to the identified subduction interface and intraslab earthquakes.
c) Preparation of an exhaustive response spectra ground-motion database containing the ground-motion parameters as peak ground acceleration (PGA), peak ground velocity (PGV), and 5% damped pseudo-acceleration response spectrum (PSA).
d) Selection an appropriate ground-motion attenuation model and performing regression analysis using least-square method in order to derive the regression coefficients.
e) The GMPEs proposed by this study are considered to be valid for estimating ground motions for subduction earthquakes of moment magnitude (**M**) 5.0−9.1, hypocentral distance (R_{hyp}) of 120−1300 km and **M** 5.0−7.7, R_{hyp} 120−1400 km for interface and intraslab events, respectively.

2. Macrozonation study:

a) Updating the previous earthquake catalogue (i.e., including the earthquake events from 1900 to late 2008) up to 2014, by compiling the reliable earthquake catalogues with minimum moment magnitude ($\mathbf{M}_{min}$) of 5.0.
b) Preparing an earthquake catalogue from the earthquakes induced by the local faults within the Peninsular Malaysia with $\mathbf{M}_{min}$ 2.1.

c) Obtaining the new macrozonation maps of Peninsular Malaysia with 10 and 2% probabilities of exceedance in 50-year corresponding to 475 and 2,475 years return period, respectively.

3. New elastic and design acceleration response spectra:

a) Computing uniform hazard spectra (UHS) of the main regions of Peninsular Malaysia on four different soil site conditions (i.e., rock, stiff soil, medium soil, and soft soil).
b) Proposing new elastic and design acceleration response spectra on four soil site conditions for seismic design purposes for the Peninsular Malaysia region following the principles of the Eurocode 8 seismic design code.

1.5 Significance of the Study

The proposed new sets of spectral ground-motion prediction equations (GMPEs) would be expected to be more compatible with the Peninsular Malaysia region due to the consideration of real ground-motion data recorded in the region. This study will be significant in terms of estimating the seismic hazard of Peninsular Malaysia more accurately and realistically based on the much more compatible ground-motion attenuation relations, consideration of the local intraplate earthquakes, and updated seismic source parameters. The design-basis acceleration maps and the elastic acceleration response spectra presented by this study will be also significant as a future reference for the application of seismic design. Moreover, this study will be helpful in the society of civil engineers in training and informing them in the area of earthquake engineering.

1.6 Research Methodology

The overall methodology in order to achieve the defined objectives has been depicted in two phases in Figure 1.4. The comprehensive descriptions of the phases I and II are presented in Chapters 3 and 4, respectively.

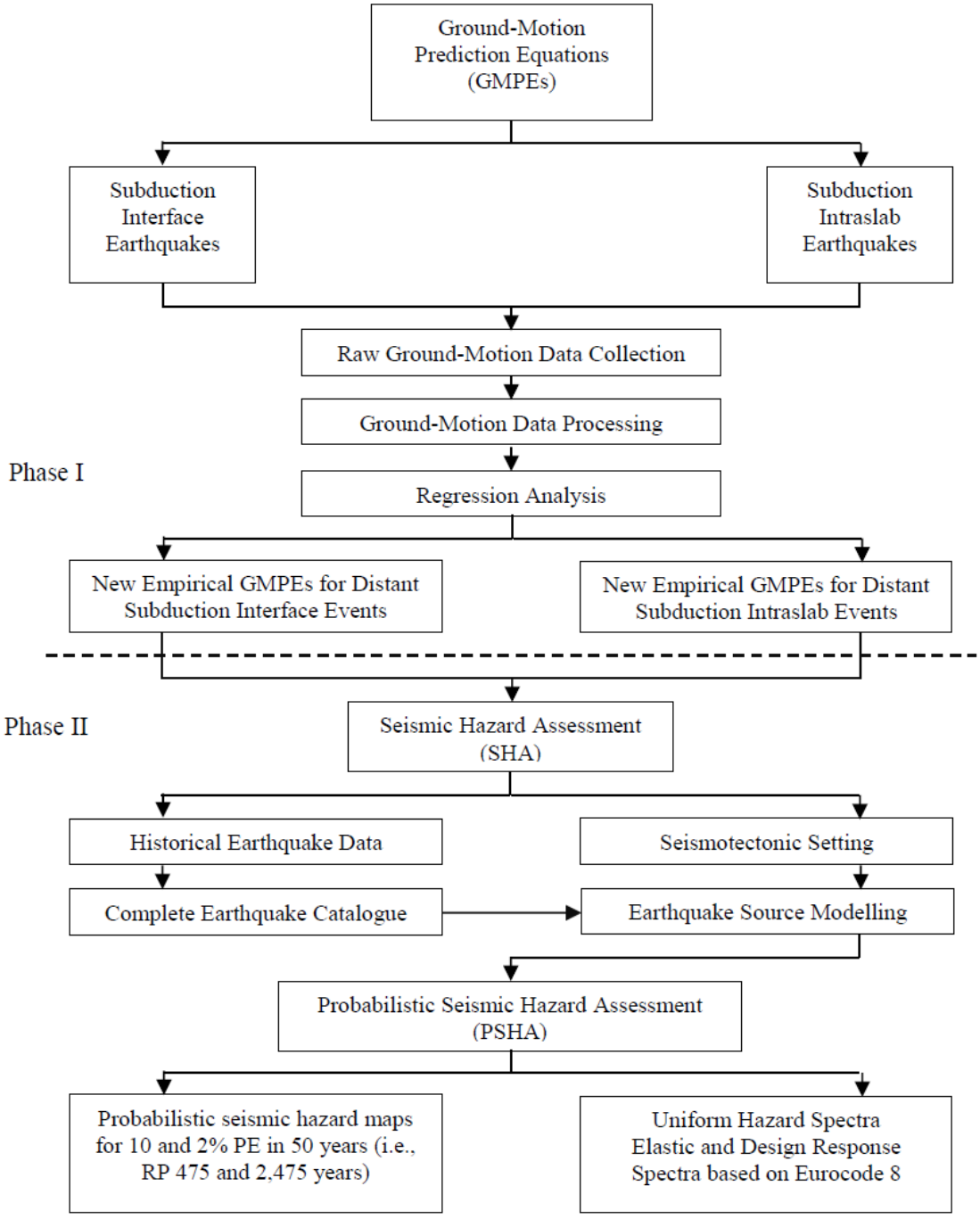

Figure 1.4 The overall schematic methodology of the present study

1.7 Orientation of Thesis

The title and contents of each chapter have been described briefly as follows:

Chapter 1: Introduction This chapter presents a brief description of earthquake-induced direct and indirect effects and importance of earthquake engineering at the first parts. In the next parts, the background and problem statement, objectives, scope and limitations, significance, and the research methodology of the study are described.

Chapter 2: Literature Review This chapter firstly presents a precise explanation about seismology and earthquake genesis in terms of plate tectonics, interplate and intraplate earthquakes, faulting mechanisms, seismic waves, and earthquake size measurements. A review about the previously proposed ground-motion prediction equations for the region of interest as well as other regions of the world is also reported in this chapter. In the next parts, seismotectonic setting of Peninsular Malaysia and a complete review of previously conducted seismic hazard studies of the Peninsular Malaysia region have been presented. Finally, previously presented elastic acceleration response spectra for the study region are also reviewed and presented in this chapter.

Chapter 3: Ground-Motion Prediction Equations (GMPEs) This chapter gives a complete explanation about the considered methodology in order to prepare a response spectra database to derive the new empirical spectral ground-motion prediction equations (GMPEs) for distant subduction interface and intraslab earthquakes. Then, a comprehensive comparison between the proposed GMPEs and the existing ones is discussed and presented at the end of the chapter.

Chapter 4: Seismic Hazard Assessment The first part of this chapter presents the methodology identified to do probabilistic seismic hazard assessment (PSHA) for the Peninsular Malaysia region. Then, the new resulted seismic hazard maps of the region have been proposed. In addition, the uniform hazard spectra using probabilistic approach of seismic hazard assessment have been achieved and

described in this chapter. Referring to the obtained uniform hazard spectra, the elastic and design acceleration response spectra on different soil site conditions for the Peninsular Malaysia region have been presented in this chapter. Finally, the obtained results are evaluated by comparing with the results derived previously by other researchers. As the different input parameters could cause different final results, the influence of various input parameters have been also discussed in this chapter.

Chapter 5: Conclusions and Recommendations This chapter discusses the conclusions of the study and the recommendations for further related researches.

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