APPLICATION OF RISK ASSESSMENT MODELS FOR SEISMIC RISK MAP

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DEDICATION

Above all, thanks to the Almighty Allah s.w.t for giving me a chance to finish my Ph.D. thesis. Allah s.w.t gave me the strength to persevere all the challenges that I met throughout this Thesis journey. Without His guidance, finishing this work would be entirely impossible.

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ABSTRACT

Seismic risk evaluation at a high potential area such as the Ranau district in Sabah is very important. However, the current method of seismic risk analysis through one of its parameters, seismic vulnerability, is mostly focused on assessing the physical damage of structures of the affected area. Thus, this research aimed to develop a simple and novel seismic risk model, specifically for Ranau, by combining two parameters; vulnerability and hazard through Geographic Information Systems (GIS)-based analysis. The model was developed from hybrid models previously used individually for disaster-related analysis. The hybrid models experimented with were the Frequency Ratio-Index of Entropy (FR-IoE), (FR-IoE) with Analytical Hierarchical Process (AHP), (FR-IoE) with Logistic Regression (LR) and (FR-IoE) with Naïve Bayes (NB). The seismic vulnerability results computed from these hybrid models were validated using the areas under the curve (AUC) of the relative operating characteristic (ROC). It was found that the NB model showed the lowest reliability with the AUC values of 0.640 and 0.741 for its success rate and prediction rate, respectively. The AUC values for other models' success rates are 0.853, 0.856, and 0.869 for FR-IoE, (FR-IoE) AHP, and (FR-IoE) LR, respectively, while their prediction rates are 0.863, 0.906, and 0.844 for FR-IoE, (FR-IoE) AHP and (FR-IoE) LR, respectively. A seismic hazard analysis was performed to complete the seismic risk model computation. The determination of seismic hazard was done by evaluating the Peak Ground Acceleration (PGA), which was derived from Ground Motion Prediction Equation (GMPE). From the PGA computation, a non-linear regression model with an accuracy of $R^2 = 0.997$ was obtained from constraint Campbell (1981) fitted GMPE, which was the best-fitted model compared to the other 5 GMPEs tested. Finally, the novel fitted GMPE for Ranau using the Campbell (1981) fitted GMPE were integrated with the seismic vulnerability obtained from the hybrid (FR-IoE) AHP model to derive the seismic risk information for Ranau, Sabah in the form of a seismic risk map. In the long run, the computed seismic risk map obtained from these findings can be implemented for disaster preparedness and mitigation purposes and is useful the future earthquake disaster.

ABSTRAK

Penilaian risiko gempa di kawasan berpotensi tinggi seperti daerah Ranau di Sabah adalah sangat penting. Namun, kaedah analisis risiko seismik semasa melalui salah satu parameternya; kerentanan seismik, kebanyakannya tertumpu pada penilaian kerosakan fizikal struktur di kawasan yang terjejas. Oleh itu, penyelidikan ini bertujuan untuk membangunkan model risiko seismik yang mudah dan baharu, khusus untuk Ranau, dengan menggabungkan dua parameter; kerentanan dan bahaya melalui analisis berasaskan Sistem Maklumat Geografi (GIS). Model ini dibangunkan daripada model hibrid yang sebelum ini digunakan secara individu untuk analisis yang berkaitan dengan bencana. Model hibrid yang diuji ialah Nisbah-Frekuensi-Entropi Indeks (FR-IoE), (FR-IoE) dengan Proses Analisis Hierarki (AHP), (FR-IoE) dengan Regresi Logistik (LR) dan (FR-IoE) dengan *Naïve Bayes* (NB). Hasil kerentanan seismik yang dihitung daripada model hibrid ini telah disahkan menggunakan kawasan di bawah lengkungan (AUC) bagi ciri operasi relatif (ROC). Didapati model NB menunjukkan kebolehpercayaan yang paling rendah dengan nilai AUC masingmasing adalah 0.640 dan 0.741 untuk kadar kejayaan dan kadar ramalannya. Nilai AUC untuk kadar kejayaan model lain masing-masing adalah 0.853, 0.856, dan 0.869 untuk FR-IoE, (FR-IoE) AHP, dan (FR-IoE) LR, manakala kadar ramalan masing-masing adalah 0.863, 0.906, dan 0.844 untuk FR-IoE, (FR-IoE) AHP dan (FR-IoE) LR. Analisis bahaya seismik telah dilakukan untuk melengkapkan pengiraan model risiko seismik. Penentuan bahaya seismik dilakukan dengan menilai Puncak Pergerakan Tanah (PGA), yang diperoleh daripada Persamaan Ramalan Pergerakan Tanah (GMPE). Daripada pengiraan PGA, model regresi tidak linear dengan ketepatan $R^2 = 0.997$ diperoleh daripada model GMPE berpadanan batasan Campbell (1981), yang merupakan model yang paling sesuai dibandingkan dengan 5 GMPE lain yang diuji. Akhirnya, model GMPE berpadanan baharu untuk Ranau menggunakan GMPE Campbell (1981) digabungkan dengan kerentanan seismik yang diperoleh dari model AHP (FR-IoE) hibrid untuk mendapatkan maklumat risiko gempa bumi bagi Ranau, Sabah dalam bentuk peta risiko seismik. Dalam jangka panjang, peta risiko seismik yang diperoleh dari penemuan ini dapat dilaksanakan untuk tujuan kesiapsiagaan dan pengurangan bencana yang berguna untuk bencana gempa bumi pada masa hadapan.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

AHP	-	Analytical Hierarchical Process
AMB96	-	Ambraseys et al. (1996) ground motion prediction equation
ANN	-	Artificial Neural Network
ANP	-	analytical network process
ATC 13	-	Applied Technology Council 1985
AUC	-	area under the curve
BN	-	Bayesian Network
CEN	-	European Committee for Standardization
CI	-	Consistency Index
CNN	-	convolutional neural network
COVID-19	-	Coronavirus Disease 2019
CR	-	Consistency Ratio
csv	-	comma-separated values
CV	-	Consistency Vector
DEM	-	Digital Elevation Model
df	-	degrees of freedom
DPM	-	Damage Probability Matrix
DSHA	-	Deterministic Seismic Hazard Analysis
DT	-	Decision Tree
DYFI	-	Do You Feel It
EC8	-	Eurocode 8
EMS-98	-	European macro-seismic scale 1998
ERA	-	Earthquake Risk Assessment
ERD	-	Earthquake Resistance Design
ESA	-	European Space Agency
ESE	-	East-Southeast
ESRI	-	Environmental Systems Research Institute
FAHP	-	Fuzzy-Analytic Hierarchy Process
FEM	-	finite element modeling

FEMA	-	Federal Emergency Management Agency
FMS	-	Focal Mechanism Solution
FN	-	false negative
FP	-	false positive
FR	-	Frequency Ratio
FR-IoE	-	Frequency Ratio- Index of Entropy
GA	-	Geostatistical analyst
GDP	-	Gross Domestic Product
GIS	-	Geographical Information System
GM	-	gray prediction model
GMPE	-	Ground Motion Prediction Equation
GNSS	-	Global Navigation Satellite System
GRACE	-	Gravity Recovery and Climate Experiment
HAZUS	-	Hazards United States
HCA	-	hierarchical clustering analysis
IBM	-	International Business Machines Corporation
IDW	-	Inverse Distance Weighting
InSAR	-	Interferometric Synthetic Aperture Radar
IoE	-	Index of Entropy
IRIS	-	Incorporated Research Institutions for Seismology
IV	-	Inconsistency Vector
JMA	-	Japan Meteorological Agency
JMG	-	Department of Mineral and Geoscience Malaysia
JUPEM	-	Department of Survey and Mapping Malaysia
KKM	-	Kota Kinabalu seismic station
L	-	linear
LiDAR	-	Light Detection and Ranging
LMT	-	logistic model tree
LR	-	Logistic Regression
LSI	-	Landslide Susceptibility Index
MCDM	-	Multi-criteria Decision Making
MCS	-	Mercalli-Cancani-Sieberg
MetMalaysia	-	Malaysian Meteorological Department

MI	-	macro-seismic intensity
MMI	-	Modified Mercalli Intensity
MSA	-	Multivariate Statistical Analysis
MSK	-	Medvedev-Spoonheuer-Karnit
MSL	-	Mean Sea Level
MVA	-	Multivariate Analysis
NA	-	National Annex
NB	-	Naïve Bayes
NE	-	Northeast
NIBS	-	National Institute of Building Science
NLP	-	Nonlinear Programming
NW	-	Northwest
OWA	-	ordered weight averaging
P	-	polynomial
PE	-	Probability of Exceedance
PGA	-	Peak Ground Acceleration
PGV	-	Peak Ground Velocity
PHA	-	Peak Horizontal Acceleration
PLC	-	pure locational clustering
PRC	-	Precision-recall Curve
PSA	-	pseudo-spectral accelerations
PSHA	-	Probabilistic Seismic Hazard Analysis
RADIUS	-	Risk Assessment Tools for Diagnosis of Urban Areas under Seismic Disasters
RAM	-	Ranau seismic station
RBF	-	radial basis function
RF	-	Random Forest
RI	-	Random Inconsistency Index
ROC	-	receiver operating characteristics
S	-	sigmoid
SAR	-	Synthetic Aperture Radar
SC	-	Silhouette Clustering (SC)
SDOF	-	single-degree-of-freedom

SDSS	-	spatial decision support system
SE	-	Southeast
SOP	-	Standard Operating Procedure
SPSS	-	Statistical Package for the Social Sciences
SQP	-	Sequential Quadratic Programming
SVM	-	Support Vector Machine
SW	-	Southwest
TIN	-	Triangulated Irregular Networks
TN	-	true negative
TP	-	true positive
UNDRO	-	United Nations Disaster Relief Coordinator
UNEP	-	United Nations Environment Programme
USGS	-	United States Geological Survey
Weka	-	Waikato Environment for Knowledge Analysis
WGS84	-	World Geodetic System of 1984
WNW	-	West-Northwest
WSV	-	Weighted Sum Vector

LIST OF SYMBOLS

δ - standard deviation
ε - error term
λ_{max} - principal eigenvector
μ - mean
(Pij) - the probability density
h or d - depth
H_j - the entropy values
I/I_{mm} - instrumental intensity
I_j - the information coefficient
M - magnitude
M_b - body-wave magnitude
M_L - local magnitude/ Richter magnitude
M_O - seismic moment
M_S - surface-wave magnitude
M_W - Moment Magnitude Scale
P_{ij} - Frequency ratio
P_r - Probability
R^2 - coefficient of determination
R_{epi} - epicentral distance
R_{hypo} - hypocentral distance
S_a - spectral acceleration
S_d - spectral displacement
S_j - the number of classes
S_v - spectral velocity
W_j - entropy values/weight value for the parameter as a whole/weightage
W_k - the final weightage of each class of a conditional factor

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Background of the Study

The past seismo-tectonic studies of South-East Asia showed that Malaysia does face a certain level of risk from magnitude >5.0 (VI or higher Modified Mercalli Intensity (MMI)) earthquakes originating from the surrounding regions as well as from local seismic tremors (USGS, 2015a; USGS, 2017a; Wong and Said, 2020). Malaysia is considered to lie in a low seismic region; though located less than 300 km from the tectonically active Pacific Ring of Fire (Bakar et al., 2016). In addition, it is located near 2 inter-plate boundaries; between the Indo-Australian and Eurasian Plates on the west and between the Eurasian and Philippines Sea Plates on the east. Both are known as the most seismically active plate boundaries (MetMalaysia, 2017). Figure 1.1 (Petersen et al., 2007) shows the earthquake epicenter data for the period 1964–2005 in the South-East Asian region.

Although being considered seismically stable with no current history of major seismic and volcanic activity, the East Malaysia region, particularly Sabah, is at risk of experiencing moderate magnitude earthquakes due to the fact of its proximity to an active tectonic zone; the Ring of Fire, with the earliest record earthquake in the country occurring in the state in 1976 in Lahad Datu at 5.3 Magnitude (Cheng, 2016; USGS, 2015b). A recent earthquake in Sabah occurred with 18 casualties; all victims being the climbers of Mount Kinabalu. On June 5th, 2015, a 6.0-moment magnitude scale (M_W) and VII MMI (categorized as very strong) earthquake in Ranau, Sabah give rise to many issues, primarily the requirements for seismic hazard risk assessment for Malaysia (Cheng, 2016; Khalil et al., 2018). The 6.0 M_W earthquake also progressively developed into prolonged after-shocks in the form of ground shaking; posing a bigger threat to the community living within the seismic activity zone; triggering geological hazards such as mud-flood.

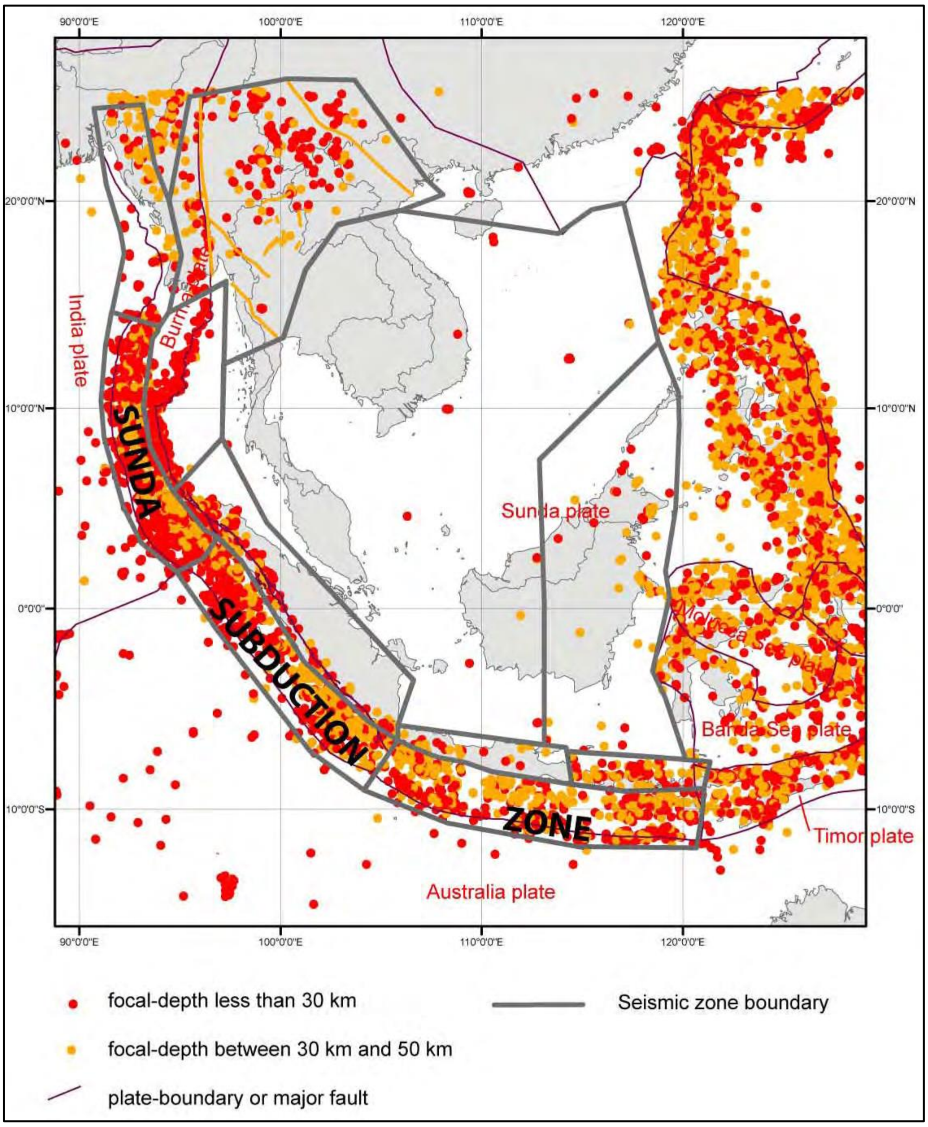

Figure 1.1 Map depicting the epicenters of shallow-depth earthquakes in Southeast Asia

Evidence data from JMG reported that Ranau has strong topographic relief and even moderate magnitude earthquakes would generate large-scale mass movements of land; landslides and mud-flood (Sali et al., 2017). These issues transmit urgent needs by the general population, especially for the people living in the affected zone, and required immediate solutions towards disaster recovery and preparedness; prompting research-based outputs (Bakar et al., 2016).

Consequently, the historical earthquake data recorded in this area shows that seismic risk is steadily increasing in this moderate seismicity region with weak to moderate magnitude earthquakes recently occurred on 3 August 2019, 30 June 2020, 13 May 2021, and 4 September 2021 with the magnitude of 4.5 M_b, 4.9 M_b, 2.7 M_L and 3.4 M_L respectively (USGS, 2021a). The distribution of major earthquakes in Sabah extracted from Incorporated Research Institutions for Seismology (IRIS) database from the year 1973 to 2021 with magnitude > 4 is shown in Figure 1.2. Based on these events, a seismic risk assessment map of Ranau, Sabah at different probability levels is deemed required. The map would incorporate updated information that represents the recent seismic activities with newly devise methodologies that can be used as a policy standard in developing a uniform hazard assessment across the country. The best approaches that can be followed were based on the methodologies developed by Petersen et al. (2008a) from the Documentation of United States National and Southeast Asia seismic hazard map which evaluates the seismic risk that not just focus on the hazard elements but also on the other relevant factors at risk (in physical, social, economic and environmental terms) and their vulnerability to probable seismic impacts (Liu et al., 2020).

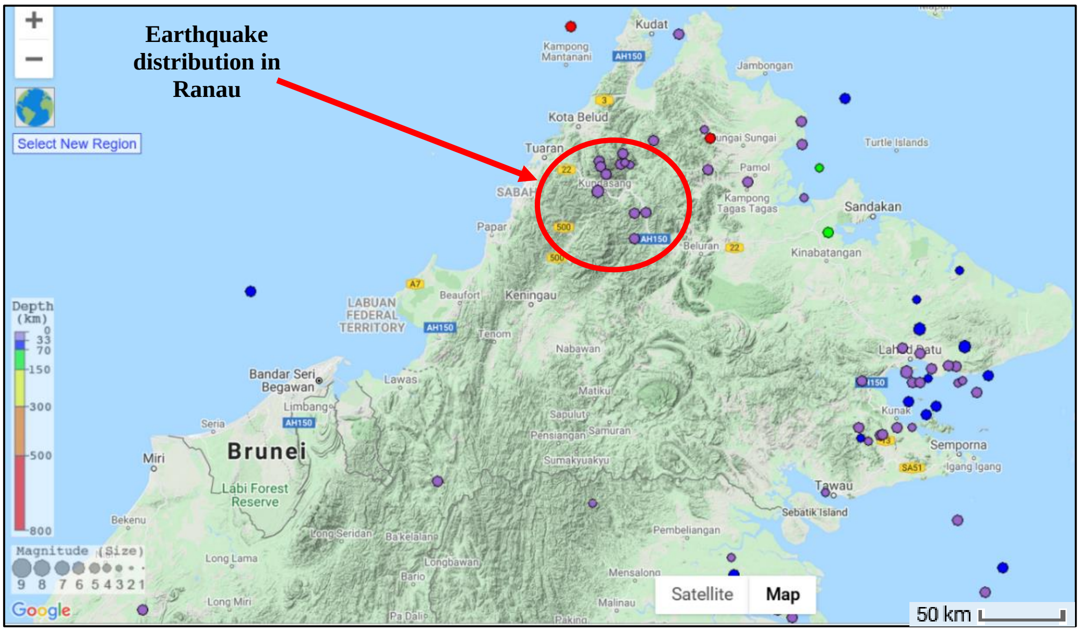

Figure 1.2 The distribution of major earthquakes in Sabah from 1973-2021

Thus, the conceptual design approach to the problem of risk analysis required a proper hazard, vulnerability and exposure evaluation (Gallina et al., 2016). Whereby, in the first phase of research activities, it is necessarily crucial to understand the differences between the definition of risk, hazard and vulnerability themselves as the risk concept is derived from hazard and vulnerability. In terms of a disaster event originating from seismic activity, seismic risk can be defined as the probability or likelihood of a particular element or group of elements acquiring damage and loss subsequent to the seismic event over a specific period (Fell and Hartford, 2018; Pavić et al., 2020). Hazard can be referred to as a potential threat to humans and their welfare and is essentially associated with any natural phenomenon investigated (Smith, 2013; Gilard, 2016). Vulnerability is usually represented as a given hazard severity level or the degree of loss sustained from a disaster event; the possibility to sustain damage and loss in terms of sensitivity, reliance, and reliability (Sarris et al., 2010; Fell and Hartford, 2018).

Hence, this study focused on seismic risk assessment and analysis using Ranau, Sabah as an application model aimed at incorporating information from historical earthquake data of the area, GIS datasets, attenuation relationship, or GMPE coupled with GIS-based analysis. The conceptual framework of the developed GIS-based approach for the risk analysis includes the combination of vulnerability and hazard assessments. The findings would be useful for policymakers, local government and authorities to ensure the community's resilience to seismic-related events.

1.2 Problem Statement

In this region, several seismic vulnerabilities, hazard and risk assessment models and maps have been developed. However, this past information currently has become obsolete due to non-updated data and methodologies based on the current seismicity events. In 2007, triggered by the 2004 Indian Ocean Earthquake and Tsunami event, seismic hazard models and maps in this region were produced by the United States Geological Survey (USGS) using methodologies developed by Petersen et al. (2007) as shown in Figure 1.3 for Indonesia and Thailand (Petersen et al., 2008b).

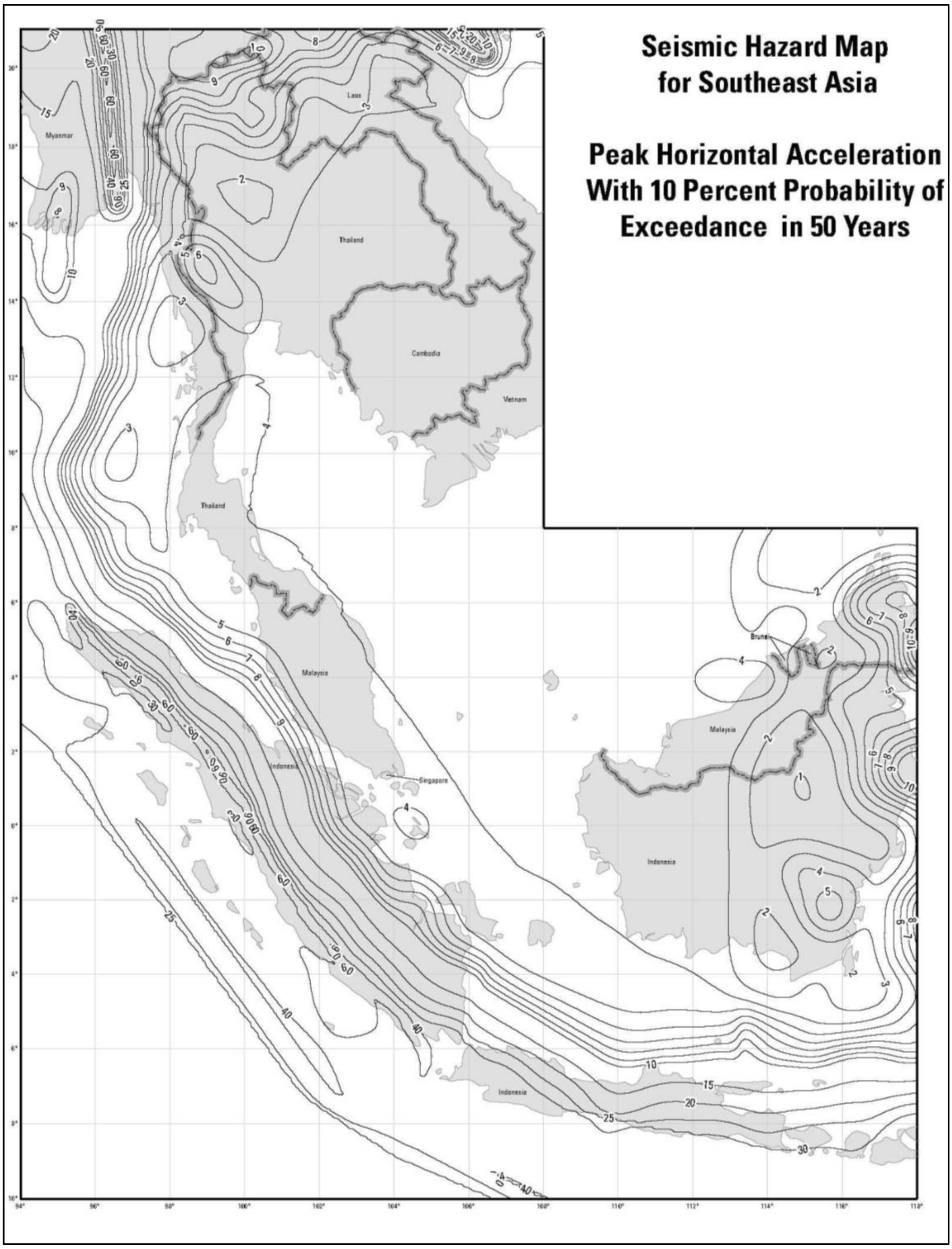

Figure 1.3 Southeast Asia seismic hazard map for 10% probability of exceedance (PE) in 50 years

For Malaysia, only hazard maps; PGA and Spectral Acceleration were compiled for Peninsular Malaysia and Sabah, and Sarawak. There have been few studies on seismic vulnerability maps that involved the combination of various indicators such as physical, environmental, social and other indicators in Malaysia.

Seismic vulnerability map (e.g., Ghafar et al., 2015; Mansor et al., 2017; Roslee et al., 2018; Jainih et al., 2020; Kassem et al., 2020) mostly focused on physical indicators such as buildings and other man-made structures like a dam, bridge and other related structures. With no updated seismic risk assessment related model and no standardized methodologies have been developed to produce such a model, Malaysia and especially the Ranau region in Sabah urgently needed a new risk map using the currently updated input parameters for earthquake sources based on the new design model and methodologies.

Seismic-related studies using GIS analysis are not a new form of research. Several GIS studies related to the seismic risk or merely focusing on seismic hazard or seismic vulnerability have been done in past years. Some of these studies involve the application of emergency support systems for better emergency disaster management for pre, during or post-earthquake disasters (Harris and Anitha, 2017; Hossain et al., 2020;) or simulation and modeling of earthquake disaster episodes in anticipating and preparing for an unforeseen future event (Muhammad et al., 2016; Sahin et al., 2016; Ismail-Zadeh et al., 2018) or the development of earthquake information systems, decision support systems or hazard mitigation databases (Yepes-Estrada et al., 2016; Matassoni et al., 2017; Newman et al., 2017; Wang, 2020). Seismic risk analysis is mainly focused on the potential of human and economic damages in case of a seismic episode. Currently, there are a few GIS-based tools such as Hazards United States (HAZUS) and Risk Assessment Tools for Diagnosis of Urban Areas under Seismic Disasters (RADIUS) that performed seismic risk assessment either from generalized expert information or localized observations and measurements. However, the data input required is enormous and they are often difficult to be applied in regions that lack the necessary information background (Sarris et al., 2010) such as Ranau.

1.3 Research Questions

1. What are the factors that can be considered for seismic vulnerability study other than the physical factors and how can these factors affect the vulnerability of the study area?
2. What are the required parameters needed to develop a new attenuation relation equation that approximately represents the ground motion of the study area?
3. How to develop a new seismic risk model that can combine vulnerability and hazard factors in the study area?

1.4 Research Goal

The purpose of this study is to create a seismic risk map depicting the seismic vulnerability and ground motions of the study area.

To meet the research goal, the following objective has been defined;

1. To identify a suitable hybrid model for the seismic vulnerability with acceptable accuracy.
2. To develop a local attenuation relation equation that approximately represents the ground motion of the study area.
3. To produce a seismic risk map based on the seismic vulnerability map in (1) and ground motion in (2) of the study area.

1.5 Significance of the Research

This study emphasized the importance of these subjects;

1. Well-informed and better seismic risk and hazard management in decision and policy making in Malaysia.

As highlighted by Wang (2006), seismic risk refers to a plethora of interpretations among different professions and stakeholders. Seismic risk as being understood by seismologists is considered as the probability or likelihood of an earthquake or multiple earthquakes with a certain magnitude or greater striking at least once in a region during a specific period. Structural engineers defined seismic risk as the probability that ground motion (a consequence of an earthquake or multiple earthquakes) at a site of interest exceeds a specific level at least once in a given period (Choudhur and Kaushik, 2015; Caterino et al., 2018). For an asset owner, the seismic risk is the probability of damage (loss) caused by an earthquake or multiple earthquakes in a specific period. Seismic hazard on the other hand describes earthquakes or consequences of the earthquakes and their occurrence frequencies (Wang, 2006). By looking at the different perspectives of each expert and 'cataloging' their respective views regarding seismic risk assessment, this study reviews the methodologies developed by the previous research on seismic risk alongside seismic vulnerability and hazard analyses to create a hybrid and simple methodologies of seismic risk assessment map in Ranau, Sabah.

2. Assessment and analysis of the probability of risk posed by seismic hazard with the magnitude of >5 in Ranau, Sabah Seismic Zone.

An in-depth seismic hazard analysis is required as the risk posed by ground motion in the study area is at large. The Seismic Zone in Sabah particularly in the Ranau area is faced with frequent seismic activities with the largest ever occurring was VII intensity earthquake on June 5, 2015 (M_W 6.0) as well as the largest recent earthquake on March 8, 2018 (M_W 5.2). The earthquakes caused a chain event that triggered other forms of natural hazards such as; rockfall, mudflow, landslides, and liquefaction to occur, as well as building destructions and cracks, loss of life and injuries, water shortage and disturbance in daily life (Indan et al., 2018).

3. Simple methodologies for accessing seismic risk over time.

A combination of powerful tools (e.g., GIS software and machine learning model) and designed processes (combination of hybrid modeling process of seismic vulnerability with ground motion algorithms) for assessing the seismic risk and prioritizing needs will help in the implementation of simple methodologies to support emergency preparedness (pre-earthquake event) (Matassoni et al., 2017). The risk assessment will enhance risk evaluation and performs analyses that would not otherwise be possible in the event of an earthquake. Critical information such as infrastructure locations (e.g., buildings and roads) can greatly affect the probability of success during the post-earthquake event efforts as saving lives and protecting property depends on how quickly and efficiently people and other subjects of interest can be safely handled after the earthquake (post) (Iqbal et al., 2021).

1.6 Scopes and Limitations

1. Statistical models that were used to develop a seismic vulnerability map in Ranau, Sabah.

Scope: 4 hybrid statistical models using GIS techniques were employed to produce a seismic vulnerability map in Ranau, Sabah, and their respective results were compared in terms of their reliability and accuracy in the validation process. In addition, the methodologies used in the seismic vulnerability assessment process can also be adopted in other regions.

Limitation: Although the methodologies adopted can be employed in other study areas for other research-related purposes, the seismic vulnerability result is only applicable to the study area; Ranau, Sabah. The uses of different models (e.g., NB, Artificial Neural Network (ANN), or other models) would also affect the seismic vulnerability assessment results.

2. Data collection and processing in seismic vulnerability assessment

Scope: For the seismic vulnerability assessment in Ranau, the main steps involved data collection and analysis from various agencies and sources. The relevant seismic conditional factors and their classes were then extracted using the relationship between seismic conditional factors and the past seismic activities in the study area.

Limitation: As the is no exact standard to determine the minimum or maximum conditional factors required to develop the required seismic vulnerability mechanism, the number of factors used was limited to the available data-sets obtained from the various agencies. Thus, adding or subtracting a number of conditional factors used in this research would affect the seismic vulnerability map produced.

3. GMPE computation for seismic hazard assessment

Scope: The parameters used in all GMPEs computation in this study were obtained from the historical catalog of the seismic activities in the study area.

Limitation: The prediction model was largely affected by the distribution of the past seismic activities in the study area. New seismic data, as well as the occurrence of large magnitude earthquakes, would affect the model created as it is a ‘fitted’ GMPE model of the study area. In addition, the GMPE model computed from this research is unique and applicable to the study area only as it was a ‘localized’ model and not a ‘universal’ model.

4. Seismic risk map model development

Scope: This study used 2 risk parameters for the model development which are vulnerability and hazard parameters.

Limitation: Due to data availability, only 2 risk parameters were employed in this study; vulnerability and hazard. The actual concept of risk consists of 3 parameters which are vulnerability, hazard and exposure. According to Simmons et al. (2017), depending on the objective of risk analysis and data availability, risk assessment methods can be varied in formalization and rigor. In addition, many researchers have performed seismic risk studies using various methodologies without exposure parameters in them such as Jena et al. (2020a) and Wei et al. (2022).

1.7 Thesis Structure

This study revolved around seismic risk modeling and analysis in Ranau, Sabah which involved designing the methodologies for 2 main seismic risk parameters; vulnerability and hazard assessment. Detailed review, reporting, explanation and illustration of the research were compiled in 6 separate chapters which are;

1. Chapter 1; provides background and a general idea of the study and presents the issues and problems that brought the cause of this research. This chapter also included the main purpose, objectives, scope and limitation as well as the main questions in designing methodologies and resolving the issues emphasized in the research.

2. Chapter 2; reviews the existing literature or past research that is related to the research design and objectives.

3. Chapter 3; describes the research design and flow of process. This chapter presented the methodologies adopted to satisfy the 3 research objectives. The 4 seismic vulnerability assessment models used and the equations involved were discussed. This chapter also included the computation of 6 GMPEs used in the study and the development of the fitted GMPE for the study area. The combination of both seismic vulnerability and hazard results was also discussed to create the final seismic vulnerability map of the study area.

4. Chapter 4; delivers the results and suitable analysis of the research outcome. A seismic vulnerability map, new fitted GMPE with hazard map and seismic risk map produced were presented. Suitable analyses were performed to justify and validate the research outcome which was also discussed in this chapter. Discussions on several important aspects of the research were also elaborated

on in this chapter. The discussion included identifying the relationship between tectonic settings and seismic risk in Ranau, comparison with past research on seismic vulnerability assessment, the relevance of the vulnerability assessment results and evaluation of the developed attenuation relationship of the study area. The relationship between selected conditional factors such as buildings and PGA with the final seismic risk map was also discussed.

5. Chapter 5; the conclusion of the research was addressed here. Recommendations on the future research direction and improvement on the current research were also emphasized.

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LIST OF PUBLICATIONS

Journal with Impact Factor

1. **Razak, J.A.A.**, Rambat, S., Che Ros, F., Zhongchao, S. and Mazlan, S.A. (2021). Seismic vulnerability assessment in Ranau, Sabah, using two different models. *ISPRS International Journal of Geo-Information, 10(5),* 271. https://doi.org/10.3390/ijgi10050271. **(Q2, IF:2.899)**

Non-Indexed Conference Proceedings

1. **Razak, J.A.A.,** Rambat, S. and Shariff, A. R. B. M. (2018). SAR Interferometry Analysis from 2015 M_w 6.0 Earthquake in Ranau, Sabah Using Alos Palsar-2 Data. In 2018 7th International Graduate Conference on Engineering, Science and Humanities (IGCESH). *Sharing Visions and Solutions for Better Future*, p.26.