LOCALIZED GLOBAL POSITIONING SYSTEM DERIVED STRAIN MAP OF MALAYSIA

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DEDICATION

This thesis is dedicated to all those whom help essentially:

Every challenging work, needs, self-efforts as well as guidance of elders especially those were very close to my hearts.

My humble efforts I dedicate to my loving family, especially my parents for their endless love, support and encouragement.

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ABSTRACT

Located on the Sunda tectonic block which encompasses a major part of the Southeast Asia region, Malaysia was considered lying in a relatively safe zone, as events caused by tectonic plate movement such as earthquakes, tsunamis and volcanic eruptions had never hit her. However, several regional earthquakes such as the Sumatra-Andaman, Nias, Bengkulu and the most recent Sabah earthquake have resulted in a long-term post-seismic deformation within the Sunda plate; these entail the need for Malaysia to have seismic hazard assessment for the prediction of risks attached to possible future earthquakes in the country. Strain or deformation at the earth's surface is often a consequence of large-scale tectonic forces such as earthquakes. When earthquakes happen, the accumulated strain on the crust is released, thus the strain rate can proxy for earthquake potential. This study aims to characterize the state of current seismic deformation in Malaysia through three objectives: 1) to estimate Global Positioning System (GPS) velocity vectors from the Continuously Operating Reference Station (CORS) network; 2) to generate localized GPS-derived strain map of Malaysia, and 3) to assess the GPS-derived strain map from seismic data. Three research methodologies were adopted to achieve these objectives. The first phase of the study estimated velocity vectors using linear least squares regression analysis from the time series of daily solutions of 88 CORS throughout Malaysia over a period of 7 years from 2010 to 2016. It is found that Peninsular Malaysia moves south-east at an average velocity of -0.43 ±0.09 cm/year for the north component, and 2.90 ±0.22 cm/year for the east component. Meanwhile, Sabah and Sarawak also move south-east at an average velocity of -1.07 ±0.09 cm/year for the north component and 2.50 ±0.02 cm/year for the east component. In the second phase, continuous strain field patterns over the Malaysia region were generated by employing the least square collocation technique. Extension and shortening strain up to 300 nanostrain/year is found in Peninsular Malaysia while extension and shortening strain up to 230 nanostrain/year is found in Sabah and Sarawak. For the final phase, the reliability of the GPS-derived strain map was verified from the estimated strain rate from seismic moment tensor. There is a good correlation between the strain rates obtained from seismic data and the strain rates estimated from GPS. The extension and shortening strain rates show slightly similar results, except for the azimuth which shows slightly different direction in the range of 12^0-19^0. In conclusion, the analysis of the localized strain can provide important information on active faults and also ongoing internal plate deformation for seismic hazard assessment in Peninsular Malaysia and Sabah and Sarawak.

ABSTRAK

Terletak di blok tektonik Sunda yang merangkumi sebahagian besar dari rantau Asia Tenggara, Malaysia dianggap berada di zon yang agak selamat, kerana peristiwa yang disebabkan oleh pergerakan plat tektonik seperti gempa bumi, tsunami dan letusan gunung berapi tidak pernah melandanya. Walau bagaimanapun, beberapa gempa bumi serantau seperti Sumatra-Andaman, Nias, Bengkulu dan yang terkini, gempa bumi di Sabah telah mengubah deformasi seismik jangka panjang di plat Sunda; ini membuktikan bahawa terdapat keperluan untuk Malaysia melakukan penilaian bahaya seismik bagi memastikan risiko yang berkaitan dengan kemungkinan berlakunya gempa ada di negara ini pada masa depan. Ketegangan atau deformasi di permukaan bumi sering kali merupakan akibat dari insiden tektonik berskala besar seperti gempa bumi. Apabila gempa bumi terjadi, ketegangan terkumpul di kerak bumi dilepaskan, sehingga kadar ketegangan boleh menjadi proksi untuk potensi gempa bumi. Kajian ini bertujuan untuk mencirikan keadaan deformasi seismik semasa di Malaysia melalui tiga objektif; 1) untuk menganggarkan vektor halaju Sistem Penentudududukan Global (GPS) daripada jaringan Stesen Rujukan GPS yang Berterusan (CORS); 2) untuk menjana peta ketegangan bagi Malaysia berasaskan GPS setempat dan 3) untuk menilai peta ketegangan GPS daripada data seismik. Tiga metodologi penyelidikan digunakan untuk mencapai objektif ini. Fasa pertama kajian menganggarkan vektor halaju menggunakan analisis regresi kuasa dua terkecil dari masa penyelesaian harian 88 CORS di seluruh Malaysia dalam tempoh 7 tahun dari 2010 hingga 2016. Di dapati bahawa Semenanjung Malaysia bergerak ke arah tenggara dengan halaju purata -0.43 ± 0.09 cm/tahun bagi komponen utara, dan 2.90 ± 0.22 cm/tahun bagi komponen timur. Sementara itu, Sabah dan Sarawak juga bergerak ke arah tenggara dengan kelajuan purata -1,07 ± 0.09 cm/tahun untuk komponen utara dan 2.50 ± 0.02 cm/tahun untuk komponen timur. Dalam fasa kedua, corak bidang terikan berterusan di rantau Malaysia dihasilkan dengan menggunakan teknik kolokasi kuasa dua terkecil. Penambahan dan pemendekan ketegangan sehingga 300 nanostrain/tahun di dapati di Semenanjung Malaysia sementara penambahan dan pemendekan terikan hingga 230 nanostrain/tahun boleh didapati di Sabah dan Sarawak. Untuk fasa akhir, kebolehpercayaan peta ketegangan daripada GPS telah disahkan dari anggaran kadar ketegangan dari tensor momen seismik. Terdapat korelasi yang baik antara kadar ketegangan yang diperoleh dari data seismik dengan kadar ketegangan yang dianggarkan daripada GPS. Kadar penambahan dan pengurangan ketegangan menunjukkan hasil yang hampir sama kecuali azimut yang menunjukkan arah yang sedikit berbeza dalam julat 12^0-19^0. Kesimpulannya, analisis ketegangan setempat dapat memberikan maklumat penting mengenai sesar aktif dan juga deformasi plat dalaman yang berterusan untuk penilaian bahaya seismik di Semenanjung Malaysia dan Sabah dan Sarawak.

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LIST OF ABBREVIATIONS

2D	-	2-Dimensional
3D	-	3-Dimensional
ANGKASA	-	National Space Agency
ANSS		Advance National Seismic System
APC		Antenna Phase Centre
CORS	-	Continuously Operating Reference Station
CTS	-	Coordinate Time Series
DD	-	Double-Difference
DSMM	-	Department of Survey and Mapping Malaysia
DoD		US Department of Defense
DoY		Day of Year
EPS		Encapsulated PostScript File
FES		Finite Element Solution
GEODYSSEA		Geodynamics of South and Southeast Asia
GITSA		GPS Interactive Time Series Analysis
GMT		Global Mapping Tools
GNSS	-	Global Navigation Satellite System
GPS	-	Global Positioning System
GSHHG		Global Self-consistent, Hierarchical, High-resolution Geography Database
GUI	-	Graphical User Interface
IGS		International GNSS Service
IONEX		Ionospheric Map Exchange
ITRF		International Terrestrial Reference Frame
InSAR		Interferometric Synthetic Aperture Radar
JMG		Mineral and Geoscience Department of Malaysia
MATLAB		Matrix Laboratory
MMD		Malaysian Meteorological Department
MY Network		Malaysia National Seismic Network
MyRTKnet		Malaysian Real-Time Kinematic GNSS Network

NMF	Niell Mapping Function
NRC-net	National Research and Development (R&D) network
QIF	Quasi-Ionosphere-Free
RINEX	Receiver Independent Exchange Format
RMS	Root Mean Square
SEAMERGES	Southeast Asia: Mastering Environmental Research with Geodetic Techniques
SINEX	Solution Independent Exchange
SD	Single-Difference
SV	Space Vehicles
TEC	Total Electron Content
USGS	United States Geological Survey
UTM	Universiti Teknologi Malaysia
ZPD	Zenith Path Delay

LIST OF SYMBOLS

$u^{[T]}$	-	Sum of Translation
$u^{[D]}$		Sum of Dilatation
$u^{[R]}$		Sum of Rotation
$u(x)$		Displacement Field
$x(t_1)$		Vector of Position at Time
dx_k		Displacement Vector
Ω		Strain Rotation Tensor
ω		Strain Rotation Element
φ		Latitude
λ		Longitude
R		Average Curvature Radius
μ		Shear Modulus
V		Cell Volume
M0		Seismic Moment
m_{ij}		Unit Moment Tensor
$\widehat{\beta_1}$		Slope Coefficient
$\widehat{\beta_o}$		Intercept Coefficient
ε_{xy}		Shear Strain

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CHAPTER 1

INTRODUCTION

1.1 Geodynamic of Malaysia

Malaysia is located on the Sunda tectonic block situated on the zone of convergence between Indian–Australian, Philippines and Eurasian plates which covers major part of the Southeast Asia region. Previously, Malaysia was considered in relatively risk-free zone, as it was far from fatal events caused by tectonic plate movement such as earthquakes, tsunamis and volcanic eruptions. However, an occurence whereby an earthquake had a disastrous effect on Malaysia was the 9.2 Mw 2004 Sumatra-Andaman earthquake which resulted in long-term post-seismic deformation within the Sunda plate (Paul *et al.*, 2012). This effect continues with the 8.6 Mw 2005 Nias, the 8.4 Mw 2007 Bengkulu and the 8.6 Mw 2012 Indian Ocean earthquake (see Figure 1.1). Most recently, the 6.0 Mw 2015 Sabah earthquake which was considered small but significant earthquake affecting Malaysia since 1976.

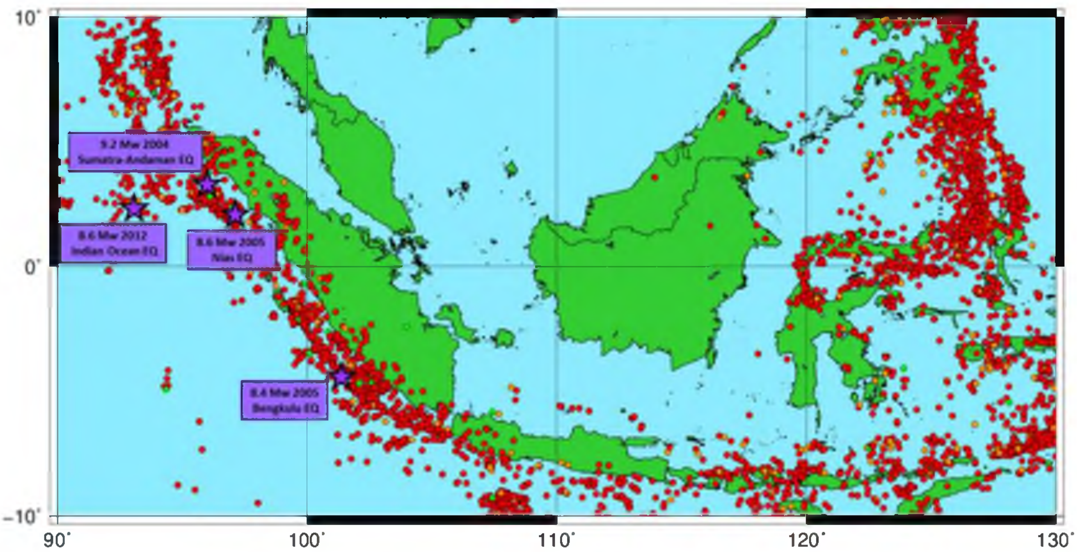

Figure 1.1 Location of all earthquake's epicentre with Mw > 5 from the year 2000 to 2018. (Adapted from https://earthquake.usgs.gov)

Historically, Sunda Plate shows low seismicity as its progressive collision with the Eurasian Plate was relatively slow (Baroux *et al.*, 1998). It is believed that the axis of rotation of the Sunda block is 49.0ºN to 94.2ºE with a clockwise rotation of 0.34 degree/million years. The block moves eastwards at a slow-rate of 6 ± 1 mm/year and 10 ± 1 mm/year in its southernmost and northern boundaries, respectively (Simons *et al.*, 2007). Figure1.2 shows estimated relative and absolute velocities of plates and main blocks surrounding Sundaland based on study by Mustafar (2017). However, a study by Loi (2018) summarizes that even when Malaysia was located on a stable continental region, ground motions due to earthquakes was still being experienced in the country.

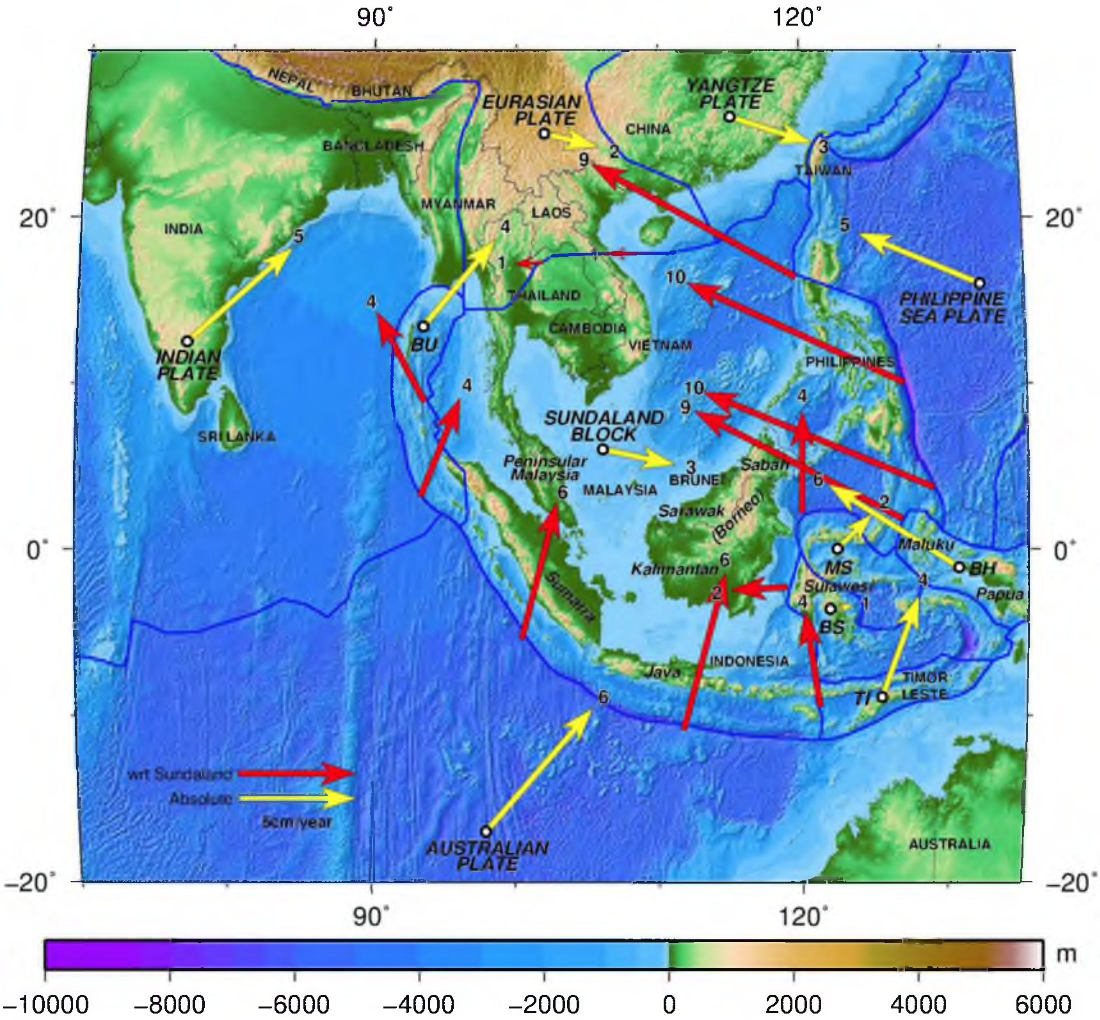

Figure 1.2 Estimated relative and absolute velocities of plates and main blocks surrounding Sundaland (Mustafar, 2017).

1.1.1 Global Positioning System (GPS) for Geodynamic Application

Geodynamic is one of the scope of geophysics which deals with the dynamics of the Earth. Hwang *et al.*, (2014) once stated that experts in geodynamics commonly utilize data from various sources such as GPS, Interferometric Synthetic Aperture Radar (InSAR) and seismology, along with numerical models to study the evolution of the Earth's condition. For the past decades, the swift development of modern space geodesy techniques and technologies such as GPS can provide the motion and velocity of tectonic plates, to detect the earthquake occurrence, fault movement and others. GPS satellite technology was originally introduced for navigation, but as its high accuracy was soon recognized, it was utilized for geodynamics and other geological applications to replace the old conventional survey techniques which is usually time-consuming. This continues especially with the development of the International Global Navigation Satellite System (GNSS) Service (IGS) network, which realized an accurate and reliable global reference frame for measurements. GPS Continuously Operating Stations (CORS) in particular, has been proven to provide accurate and long term inter-seismic, co-seismic and post-seismic measurements (Ozener *et al.*, 2013).

1.2 Problem Statement

The earth was considered dynamic in nature as its topographical features change continuously when it experiences multiple geological processes. The alteration in the shape of the earth is significant in geodynamic study especially in subjects related to plate tectonics and significant geological phenomena. Thus, it is important to have clear comprehension and understanding on the details of deformation in the region and its effects on nearby fault zone to figure out which faults are most likely to produce the next earthquake (USGS, 2020).

According to the Advance National Seismic System (ANSS), the western edge of Sunda plate (Sumatran plate boundary) was seismically inactive from 1963 to 2003 (Feng *et al.*, 2015). However, several regional earthquakes such as the Sumatra-

Andaman, Nias, Bengkulu and most recently the Sabah earthquake, has resulted in significant seismic deformation within the Sunda plate. A study by Vigny *et al.*, (2005) and Omar *et al.*, (2010) showed that the largest displacement recorded in Peninsular Malaysia during Sumatra-Andaman earthquake was the North-West part (MyRTKnet stations: LGKW with 17 cm, ARAU with 13.7 cm, SGPT with 12.8 cm and USMP with 12.5 cm. Meanwhile the smallest displacement was at the South-East part (MyRTKnet stations: TGPG with 2 cm, JHJY with 1.9 cm, PEKN with 2.6 cm and MRSG with 3.5 cm). These trends indicate that there is absolutely heterogeneous land deformation in Peninsular Malaysia. Although geodynamic studies in Malaysia have shown the results of its tectonic setting, e.g. by but there is no further research to comprehensively shows the current seismic deformation occurs in Malaysia.

Besides the far epicentre earthquake effect, there are several minor fault zones identified within Malaysia which are mostly generating non-lethal tremors for the time being. In Peninsular Malaysia, a series of moderate seismic activities by Malaysia Meteorological Department (MMD) occurring in recent years such as tremors around Bukit Tinggi and Jerantut, and sink holes around Batu Gajah and Ipoh are believed to be originated from these earthquakes (Azlan *et al.*, 2005). This event raises question on the reactivation of major faults in Peninsular Malaysia, especially in Raub-Bentong suture and Bukit Tinggi Area. For East Malaysia, there has been a low amount of moderate earthquake activity across this region that has caused casualties, damage to properties and created narrow fissures in the ground (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).

Although these seismic activities can be considered weak in intensity, there is a need for constant precaution and monitoring action. Investigation on tectonic movement for each fault zone is needed for a better deformation analysis in Malaysia. Thus, there was a need for Malaysia to have seismic hazard assessment especially for the prediction of the risks attached to future earthquake in the country. Strain or deformation on the earth's surface is often a consequence of large-scale tectonic forces such as earthquakes. When earthquakes happen, the accumulated strain on the crust is released, thus the strain rate can proxy for earthquake potential. The aim of this research is to characterize the state of current seismic deformation in Malaysia. In doing so, GPS data from CORS network within the period of seven (7) years between year 2010-2016 will be processed to obtain strain field patterns over the Malaysia region. The analysis of the localized strain fields such as normal and shear strains can provide insights on the seismic deformation including the tectonic motion and location of the main faults for future seismic hazard assessment of Malaysia.

1.3 Research Questions

The research questions identify the essential elements to be studied, primarily in the methodological context, based on the research gaps. The research questions for this study are as follows;

(a) What is the current crustal deformation trend with respect to the tectonic motion of Malaysia?

(b) How to characterize the state of current seismic deformation in Malaysia?

1.4 Research Aim and Objectives

The aim of this research is to develop a localized GPS-derived strain map for characterizing the state of current seismic deformation thus supporting geodynamic and seismological studies in Malaysia. The aim can be achieved through these following objectives:

(1) To estimate GPS velocity vectors from the CORS network.

(2) To generate GPS-derived strain map of Malaysia.

(3) To assess the GPS-derived strain map from seismic data.

1.5 Research Scope

The research focuses primarily on the development of a localized GPS-derived strain map for Malaysia. The scope of this study is given as following:

(a) Research area: Research area covers within local CORS network, namely Malaysia Real Time Kinematic GNSS network (MyRTKnet) and National Research and Development (R&D) CORS network (NRC-net) which are situated in Peninsular Malaysia and East Malaysia (Sabah and Sarawak) region, as shown in Figure 1.3 and Figure 1.4, respectively. This area involves in the study on long term continuous crustal deformation trend, co-seismic as well as the strain tensor analysis.

(b) Data employed and time span: GPS data comprises of L1 and L2 signal observation from seventy-eight (78) MyRTKnet stations and eight (8) NRC-net stations with selected thirty-two (32) IGS stations in the period of seven (7) years with data spanning from January 2010 to December 2016 was utilized.

(c) Adopted Reference Frame: All the daily coordinate solutions were estimated in a single reference frame, ITRF2008. Thus, the continuous crustal deformation trend and development of GPS-derived strain map were based on ITRF2008 reference frame.

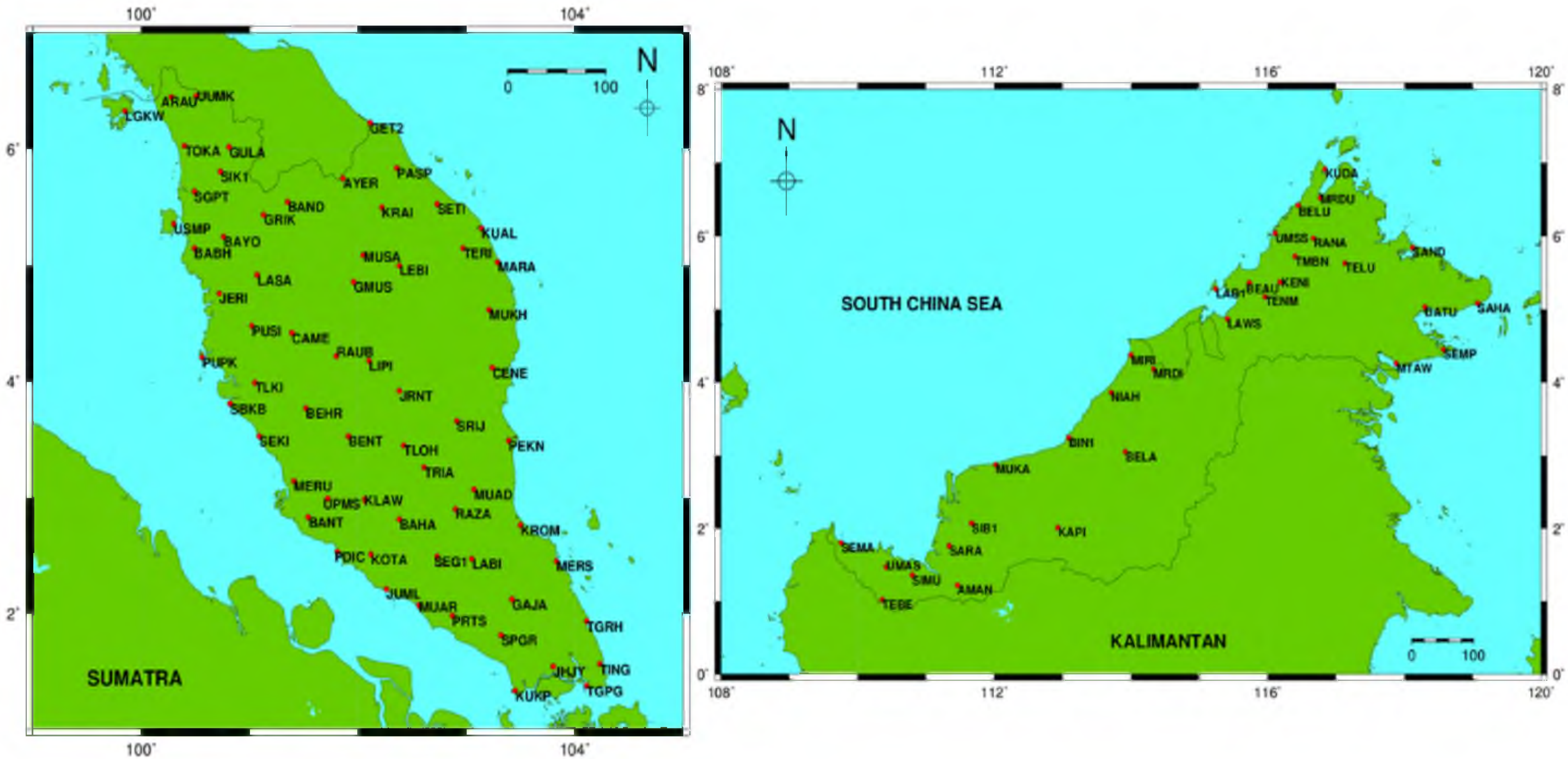

Figure 1.3 Distribution of 78 MyRTKnet stations around Malaysia.

Figure 1.4 Active NRC-net stations throughout Malaysia.

1.6 General Research Framework

A general research framework can be portrayed in four phases as shown in Figure 1.5. This framework function as links to the key elements of the research, such as research objectives and also provide an overview of the research methodology.

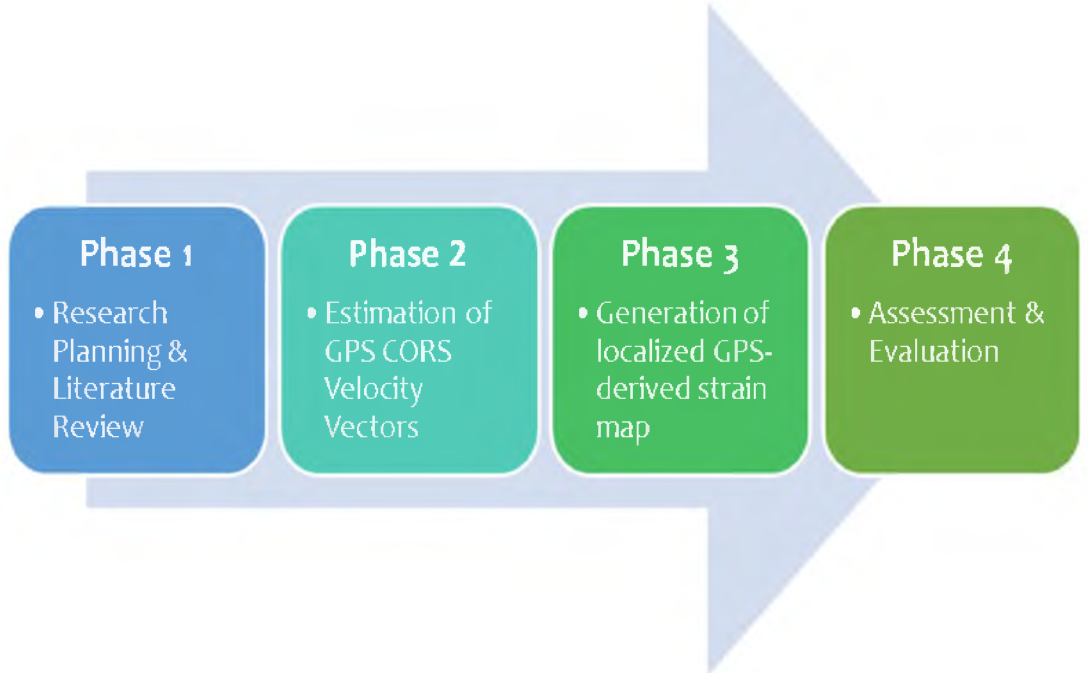

Figure 1.5 Research Framework of this study.

1.6.1 Phase 1: Research Planning and Literature Review

Phase 1 covers the literature review and the research planning element of this study. In this phase, the literature review is carried out to establish a theoretical framework for this study. By conducting literature review, research planning can be drawn and formulate. Other than that, it will give guidance to related topics in this study.

1.6.2 Phase 2: Estimation of GPS Velocity Vectors of CORS

Phase 2 presents the research activities towards achieving the first objective of the study. The research activities can be described as follows:

(a) Data Acquisition: GPS observation data from available MyRTKnet stations, along with NRC-net stations and also selected IGS stations were collected in the RINEX format with sampling rate of 30 seconds for 24-hour period. Simultaneously, general parameters such as satellite ephemeris (EPH), earth rotation parameter (ERP), ionospheric information (ION), station information (STA) and differential code biases (DCB) were also prepared for GPS data processing.

(b) GPS/GNSS Data Processing: Daily solutions of all MyRTKnet and NRC-net stations were estimated by using high-precision GPS/GNSS processing software, Bernese 5.0 (Dach *et al.*, 2007). 78 MyRTKnet stations, 8 NRC-net stations and 32 IGS stations were chosen with data spanning from January 2010 to December 2016.

(c) Estimation of Site Velocity Vectors – The Bernese 5.0 software were utilized to obtain each station's precise coordinates and its velocity, consecutively. Velocity vectors were estimated by employing linear least squares regression analysis from the time series of daily solutions.

1.6.3 Phase 3: Generation of localised GPS-derived strain map

Phase 3 presents the research activities towards achieving the second objective of the study. The output from previous phase such as CORS coordinates, velocity and its uncertainties were used to generate continuous strain field. The GPS-derived strain map in this study was generated using least square collocation method. The tensor analysis displayed different aspects of deformation, which include the estimation of their magnitudes and directions for GPS-derived strain rates.

1.6.4 Phase 4: Assessment and Evaluation

Phase 4 presents the research activities towards achieving the third objective of the study. The reliability of the GPS-derived strain map was verified and evaluated from seismic strain rates derived from seismic moment tensors using the Kostrov summation equation. Seismic data was obtained from Malaysia National Seismic Network (MY network) operated by Malaysian Meteorological Department (MMD).

1.7 Significance of Research

The significance of this study can be described as follows:

(a) To provide a clear comprehension and understanding on tectonic motion of Malaysia through the estimation of GPS-derived velocities from CORS network.

(b) GPS-derived strain map for Malaysia generated could provide important information on the location of the main faults and current strain accumulation for future hazard assessment which can be useful for seismic catalog of the region.

(c) In addition, by-products of this research such as the site-specified coordinate time series from the GPS CORS network is also useful in maintaining geodetic reference frame of Malaysia which will be of benefits to the Department of Surveying and Mapping Malaysia (DSMM).

1.8 Thesis Outline

The contents of this thesis are structured into six (6) chapters. Chapter 1 describes the background of the research that consists of the overview of the geodynamic of Malaysia and the uses of GPS for geodynamic applications, problem statements, research aim and objectives, research scope, significance of research, and research framework.

Chapter 2 provides the various literature review on the fundamental of GPS including the error and its role in determining the crustal deformation. Other related past or ongoing research on the strain tensor analysis and its effect on the crustal deformation are covered as well in this chapter.

Chapter 3 discusses on the methodology used in this study to achieve the aim and objectives. Three main phases are structured with their respective procedures. Firstly, research materials and tools that consist of information about the GPS data and software involved are outlined. Then, the details on the procedures including data acquisition, followed by data processing, generating coordinate time-series of each stations and velocities estimation, strain calculation, development of GPS-derived strain map and lastly the assessment and evaluation of said strain map against the seismic data.

Chapter 4 reveals the results and analysis which are significant to achieve the first objective of this study. This includes the results of GPS data processing and its quality checking. Then, all coordinate time series of MyRTKnet and NRC-net stations were plotted and used to estimate the velocity vectors which is beneficial for developing the GPS-derived strain map in the next chapter. Other results such as the co-seismic displacement of major earthquake was shown as well.

Chapter 5 discusses the results and analysis which are significant to achieve the second and third objective of this study. These comprises of the calculation for estimating the strain rate from GPS velocity estimated in previous chapter, the generation of the strain map and its tensor analysis such as the normal and shear strains, including their magnitude and direction. In addition, the results from the evaluation of the strain map generated against the seismic data are shown as well.

Chapter 6 summarizes this research and draws some conclusions. Several improvements are suggested and further steps of studies are discussed.

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LIST OF PUBLICATIONS

Indexed Journal

1. **Johari, N. N**., Musa, T. A., Din, U., & Aris, W. A. W. (2019). Analysis of NRC-net GPS-derived velocity vectors for tectonic movement in Malaysia. *Jurnal of Computational and Theoretical Nanoscience* (Indexed by SCOPUS)

Non-Indexed Conference Proceedings

1. **Johari, N. N**., Musa, T. A., & Din, U., (2019). Velocity vectors of MyRTKnet stations for year 2016. *1st International Graduate Conference of Built Environment and Surveying 2019 (GBES 2019)*