# SEMI-DYNAMIC GEOCENTRIC DATUM FOR POSITIONAL ACCURACY AND RELIABILITY IN MALAYSIA

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SEMI-DYNAMIC GEOCENTRIC DATUM FOR POSITIONAL ACURACY AND RELIABILITY IN MALAYSIA

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*To my beloved family*

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# ABSTRACT

Land movements caused by the Earth's natural systems such as tectonic motion and earthquakes have a huge impact on the geodetic datum. The geodetic reference stations that are being used as fiducial points for realizing and maintaining the geodetic datum may shift positions. In a long term, the geodetic datum may suffer more severe coordinate shifts, ultimately resulting in non-geocentric position. The national geodetic datum of Malaysia, the Geocentric Datum of Malaysia (GDM2000), is realised as a static datum which is aligned to the International Terrestrial Reference Frame 2000 (ITRF2000) at epoch January 2000. However, ITRF is currently in version 2014 and Malaysia has experienced several land movements as a result of tectonic motion (secular) and earthquakes (non-secular). This study aims to provide the components needed to enhance the accuracy and reliability of the geodetic datum of Malaysia, outlined in three objectives. First, to investigate the spatio-temporal domain of land deformation in Malaysia. Second, to develop a land deformation model based on secular and non-secular land deformation of Malaysia. Third, to design an appropriate mechanism for the implementation of a semi-dynamic datum in Malaysia and to validate its accuracy over time. In order to achieve these objectives, three phases of methodology have been conducted. In phase one, time series analysis of selected Malaysia Real-time Kinematic Network (MyRTKnet) stations positions has been carried out using linear least squares regression technique. The second phase involves the development of a deformation model using the interpolation approach for secular model and second degree polynomial method for the post-seismic decay model. The third phase provides a timeline for implementing a semi-dynamic datum that consists of information about the applicable epoch and the respective sub-models. In addition, transformation between the new datum GDM2000 at epoch 2009.3055 and the existing datum GDM2000 is generated using the geographic offset method. Based on the time series analysis, it was found that the secular motion of Malaysia can be classified into two periods of time which are 2008-2011 and 2012-2014 and the deformation models for Peninsular Malaysia and East Malaysia have to be separated due to different velocity vectors. Results from assessment of the secular deformation model have found that millimetre-level accuracy can be achieved, i.e. below 6 mm in the horizontal position. For the non-secular deformation model, centimetre-level accuracy can be achieved, i.e. below 7 cm in the horizontal position. It is expected that with the positional accuracy results obtained in this study, it demonstrates the feasibility of implementing a semi-dynamic geocentric datum in Malaysia, thus achieving a reliable position over time.

# ABSTRAK

Pergerakan tanah yang disebabkan oleh sistem semula jadi bumi seperti pergerakan tektonik dan gempa bumi memberi kesan besar kepada datum geodesi. Stesen rujukan geodesi yang digunakan sebagai titik fidusial untuk menubuh dan mengekalkan datum geodesi boleh beralih kedudukan. Dalam jangka panjang, datum geodesi boleh mengalami perubahan koordinat yang lebih teruk, akhirnya mengakibatkan kedudukan tidak geosentrik. Datum geodesi kebangsaan Malaysia iaitu datum geosentrik Malaysia (GDM2000) direalisasikan sebagai datum statik yang selaras dengan kerangka rujukan terestrial antarabangsa 2000 (ITRF2000) pada epok Januari 2000. Walau bagaimanapun, ITRF kini berada dalam versi 2014 dan Malaysia telah mengalami beberapa gerakan tanah akibat gerakan tektonik (sekular) dan gempa bumi (tidak sekular). Kajian ini bertujuan untuk menyediakan komponen-komponen yang diperlukan untuk meningkatkan ketepatan dan kebolehpercayaan datum geodesi Malaysia, yang digariskan dalam tiga objektif. Pertama, untuk menyiasat domain ruang-masa deformasi tanah di Malaysia. Kedua, untuk membangunkan satu model deformasi tanah berdasarkan deformasi tanah sekular dan bukan sekular di Malaysia. Ketiga, untuk mereka bentuk mekanisma yang sesuai untuk pelaksanaan datum separa dinamik di Malaysia dan untuk mengesahkan ketepatannya dari semasa ke semasa. Bagi mencapai objektif-objektif ini, tiga fasa metodologi telah dijalankan. Dalam fasa pertama, analisis siri masa bagi kedudukan stesen-stesen terpilih jaringan masa hakiki kinematik Malaysia (MyRTKnet) telah dijalankan dengan menggunakan teknik regresi linear kuasa dua terkecil. Fasa kedua melibatkan pembangunan model deformasi dengan menggunakan pendekatan interpolasi untuk model sekular dan kaedah polinomial darjah kedua untuk model pasca-seismik. Fasa ketiga menyediakan satu garis masa untuk melaksanakan datum separa dinamik yang mengandungi maklumat mengenai kebolehgunaan epok dan sub-model masing-masing. Tambahan pula, transformasi di antara datum baru GDM2000 pada epok 2009.3055 dan datum sedia ada GDM2000 dihasilkan dengan menggunakan kaedah ofset geografi. Berdasarkan analisis siri masa, didapati bahawa gerakan sekular Malaysia boleh diklasifikasikan kepada dua tempoh masa iaitu 2008-2011 dan 2012-2014 dan model deformasi untuk Semenanjung Malaysia dan Malaysia Timur perlu dipisahkan kerana vektor halaju yang berbeza. Keputusan daripada penilaian model deformasi sekular mendapati bahawa ketepatan tahap milimeter boleh dicapai, iaitu di bawah 6 mm bagi kedudukan mengufuk. Bagi model deformasi bukan sekular, ketepatan tahap sentimeter boleh dicapai, iaitu di bawah 7 sm bagi kedudukan mengufuk. Adalah dijangkakan hasil ketepatan kedudukan yang diperolehi dalam kajian ini, menunjukkan kebolehlaksanaan datum geosentrik separa dinamik di Malaysia, seterusnya mencapai kedudukan yang boleh dipercayai dari semasa ke semasa.

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## LIST OF ABBREVIATIONS

| | | |
|---|---|---|
| APREF | - | Asia-Pacific Reference Frame |
| BIH | - | Bureau International de I'Heure |
| BIPM | - | Bureau International des Poids et Mesures |
| BPE | - | Bernese Processing Engine |
| BT | - | Borneo Triangulation |
| CORS | - | Continuously Operating Reference Stations |
| CTF2000 | - | China Terrestrial Reference Frame 2000 |
| DGFI | - | German Geodetic Research Institute |
| DGRS | - | Differential GPS Reference Stations |
| DMA | - | Defense Mapping Agency |
| DoD | - | Department of Defense |
| DORIS | - | Doppler Orbitography and Radiopositioning Integrated by Satellites |
| DOS | - | Disk Operating System |
| DoY | - | Day of Year |
| DSMM | - | Department of Survey and Mapping Malaysia |
| ECEF | - | Earth-centered Earth-fixed |
| EMSGN97 | - | East Malaysia Scientific Geodetic Network 1997 |
| EOP | - | Earth Orientation Parameter |
| EUREF | - | European Reference Frame |
| FTP | - | File Transfer Protocol |
| GDM2000 | - | Geocentric Datum of Malaysia 2000 |
| GGOS | - | Global Geodetic Observing System |
| GIA | - | Glacial Isostatic Adjustment |
| GIS | - | Geographical Information System |
| 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 |
| IAG | - | International Association of Geodesy |
| ICRF | - | International Celestial Reference Frame |
| IERS | - | International Earth Rotation and Reference Systems Service |
| IGN | - | Institute Geographique National |
| IGS | - | International GNSS Service |
| IRM | - | IERS Reference Meridian |
| IRP | - | IERS Reference Pole |
| ITRF | - | International Terrestrial Reference Frame |
| ITRF | - | International Terrestrial Reference Frame |
| ITRS | - | International Terrestrial Reference System |
| JGD2000 | - | Japan Geocentric Datum 2000 |
| KGD2000 | - | Korean Geodetic Datum 2000 |
| LLR | - | Lunar Laser Ranging |
| MASS | - | Malaysian Active GPS System |
| MRT | - | Malayan Revised Triangulation |
| MyRTKnet | - | Malaysia Real Time Kinematic GNSS Network |
| NDCDB | - | National Digital Cadastral Database |
| NGA | - | National Geospatial-Intelligence Agency |
| NIMA | - | National Imagery and Mapping Agency |
| NNR | - | No-Net-Rotation |
| NRCan | - | Natural Resources Canada |
| NSWCDD | - | Naval Surface Warfare Center Dahlgren Division |
| NZGD2000 | - | New Zealand Geodetic Datum 2000 |
| PCF | - | Process Control File |
| PMSGN94 | - | Peninsular Malaysia Scientific Geodetic Network 1994 |
| PPP | - | Precise Point Positioning |
| QIF | - | Quasi Ionosphere Free |
| RINEX | - | Receiver Independent Exchange Format |

| | | |
|---|---|---|
| SIRGAS | - | Geocentric Reference System for Americas |
| SLR | - | Satellite Laser Ranging |
| TAI | - | International Atomic Time |
| TCG | - | Geocentric Coordinate Time |
| VLBI | - | Very Long Baseline Interferometry |
| WGS | - | World Geodetic System |
| WGS84 | - | World Geodetic System 1984 |

# LIST OF SYMBOLS

| | | |
|---|---|---|
| $X_o$ | - | Position at the epoch of $t_o$ |
| $X_i$ | - | Velocity at the epoch of $t_i$ |
| $t_o$ | - | Reference epoch |
| $t$ | - | Target epoch |
| $dt$ | - | Difference of time |
| $\sum_i dX_i(t)$ | - | The summation includes various "high-frequency" motions affecting site position |
| $e_i^2$ | - | Residuals |
| $Y_i$ | - | Vertical distances between the points of the observed data set |
| $\widehat{Y_1}$ | - | Fitted line |
| $X_i$ | - | X-axis data set (time) |
| $\widehat{\beta_1}$ | - | Slope coefficient |
| $\widehat{\beta_o}$ | - | Intercept coefficient |
| $\sigma^2$ | - | Variance |
| $n$ | - | Number of observation |
| $u$ | - | Number of parameters |
| $A$ | - | Design matrix |
| $L$ | - | Observation matrix |
| $P$ | - | Weight matrix |
| $T$ | - | Tension parameter |
| $\nabla^2$ | - | Laplacian operator |
| $\nabla^4$ | - | Biharmonic operator |
| $dE$ | - | Displacement offset for East component |

| | | |
|---|---|---|
| $dN$ | - | Displacement offset for North component |
| $a$ | - | First coefficient of polynomial |
| $b$ | - | Second coefficient of polynomial |
| $c$ | - | Third coefficient of polynomial |
| $\lambda$ | - | Geographic longitude |
| $\phi$ | - | Geographic latitude |
| $\Delta\lambda$ | - | Difference in the geographic longitude |
| $\Delta\phi$ | - | Difference in the geographic latitude |

# LIST OF APPENDICES



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# CHAPTER 1

# INTRODUCTION

## 1.1 Research Background

A geodetic datum plays an important role as a reference for determining coordinates of points on the earth. From time to time, the geodetic datum has to be improved in accordance with the advances of space-based measurement technology and modernization in the field of Geodesy. One of the elements considered in modern geodesy is Geokinematics, of which the kinematics and variations of the Earth may directly affect the Earth's surface, thus, disturbing the precision of the geodetic datum (or the global datum, i.e. geocentric datum). Therefore, it is essential to understand the movement of the earth that directly affects the geocentric datum and the extent to which these effects may impact positioning accuracy.

Generally, the earth is a complex and dynamic system which is undergoing tectonic plate motion, rotational motion, core-mantel dynamics and changes of mass loads, which include the atmosphere, ocean and crust. One of the most direct economic and social effects is a large destructive phenomenon called earthquake. This phenomenon is usually the result of geological deformation from the slip between tectonic plates (Wang *et al.*, 2012). During an earthquake, also known as the co-seismic period, energy releases instantaneously to the crust and causing a great impact, in the form of displacement, to the land. For instance, the 26 December 2004 Sumatra–Andaman megathrust earthquake significantly affected land displacements up to 10 cm in magnitude with a radius of 400 km away from the earthquake's epicentre (Vigny *et al.,* 2005) during its co-seismic period. In fact, this land displacement, or land deformation, may cause a motion even after the earthquake, in order to return to its equilibrium state, which can last up for a couple of years or decades. A specific term for this phase is the post-seismic motion, resulting in significant amount of land displacement, i.e. centimetres to decimetres per year (Hu and Wang, 2012), over a long period of time, as well as the post-seismic decay motion which is a short term motion after an earthquake. Co-seismic, post-seismic, and post-seismic decay, motions randomly occur and depend on the specific geological deformation pattern, hence, they are typically classified as non-secular motion. A steady-state motion associated with plate tectonic motion is classified as secular motion (Blick *et al.*, 2005). Tectonic plates have a normal internal forcing of heat transported out of the hot core and mantle to the Earth's surface (Hamblin and Christiansen, 2009). Consequently, these plates move gradually and varyingly, with velocities up to a few centimetres annually.

In Malaysia, since the occurrence of the mega earthquake of 2004, the country has been affected by significant land deformation. In fact, Malaysia has experienced heterogeneous land deformation both in spatial and temporal aspects. For example, the northern parts of Peninsular Malaysia, i.e. Arau and Langkawi, have experienced up to 17 cm in land deformation during the 2004 Sumatra–Andaman earthquake (Omar and Jhonny, 2009). In addition, few series of earthquakes such as 2005 Nias, 2007 Bengkulu and 2012 Northern Sumatra also influenced the land deformation in the country. Furthermore, with a significant impact of post-seismic decay motion that occurred from these earthquake events, it will worsen the land deformation and distort the national geocentric datum.

In many countries, a geocentric datum is typically being implemented by adopting a global datum: the International Terrestrial Reference Frame (ITRF). Among the drives for a geocentric datum are the increasing use of satellite-based positioning systems such as Global Positioning System (GPS) and the need of global or unified coordinate system. However, the geocentric datum is only fully compatible with the ITRF at a certain epoch, whereby most of the national geocentric datums remain as a static datum where all site coordinates are fixed or assumed unchanged with time.

Thus, the accuracy of a geocentric datum decreases over the time, if land deformations are not taken into account. It is because tectonic plate motions will dislocate the GPS reference stations over time, thus affecting the geocentric datum causing it to be no longer geocentric (non-geocentric) and does not represent the “true” position of the geodetic stations. The consequence does not only affect the activities of survey and mapping, but will also have a big impact on resource-grade activities, involving socio-economic and environmental activities in general.

In Malaysia, the Geocentric Datum of Malaysia 2000 (GDM2000) was developed by the Department of Survey and Mapping Malaysia (DSMM) to provide a global and homogeneous coordinate system across the country. The realization of the GDM2000 was based on the ITRF2000 at epoch 1$^{st}$ January 2000 (DSMM, 2009). Since Malaysia has experienced land deformation due to plate tectonic motion and a series of earthquakes, thus, there are a number of questions raised: (1) is the current GDM2000 sufficiently reliable to be utilised for present positioning practice when associated with inexorable motion due to tectonic plates and earthquakes? (2) how does the GDM2000 account for heterogeneous land deformations in terms of spatio-temporal? and (3) how to obtain accurate coordinates as function of time? Therefore, there is a need for a comprehensive strategy to enhance and maintain high geospatial accuracy of the geocentric datum in terms of consistency to the ITRF and reliability of the positioning results with respect to time.

Possible options for datum enhancement are by implementing semi-dynamic or dynamic geocentric datum. Both options enable the coordinates to be updated from one epoch to another. The difference between these datum are the reference epoch, whereby the semi-dynamic geocentric datum only updates coordinates at a defined reference epoch and deals with coordinate propagation to/from that reference epoch. Semi-dynamic geocentric datum requires study on the selection of a reference epoch which is within a stable seismic period and requires to determine the appropriate update rate according to the seismic activities and datum accuracy over time. Meanwhile, the dynamic datum is always updating the coordinates based on current epoch and constantly associated to the ITRF. The reference epoch for dynamic datum keeps on changing periodically such as weekly, monthly, or yearly;

thus introducing an array of epochs (Grant and Blick, 1998). Hence, the semi-dynamic geocentric datum is a more practical and reasonable approach to be implemented rather than a dynamic datum so as to avoid confusion at the end-user level, e.g., surveyors, due to continuously changing reference coordinates.

The semi-dynamic geocentric datum includes a land deformation model that enables coordinates to be ‘corrected’ by absorbing the deformation event into the solution. Therefore, the coordinates in a semi-dynamic geocentric datum represents the actual position with respect to the deformation event and time. There are only a few countries that have initiated the implementation of a semi-dynamic geocentric datum, for example, New Zealand (*Blick et al*., 2005) and Papua New Guinea (Stanaway, 2004). It is believed that the number of countries that develop the semi-dynamic geocentric datum is increasing over time, especially when there are significant land deformations in or nearby the country such as Indonesia (Susilo *et al*., 2015) and Taiwan (Ching and Chen, 2015). Nevertheless, Malaysia is presently still adopting a conventional static datum even though it is affected by severe co-seismic and post-seismic motions. Hence, for Malaysia to achieve accurate and reliable positions with respect to time, a semi-dynamic geocentric datum approach is recommended.

The implementation of a semi-dynamic geocentric datum has several issues that need to be properly considered to ensure its feasibility, such as: (1) duration or frequency for updating the geocentric datum, (2) the desired positional accuracy, (3) the deformation model development related to spatial-temporal variation, (4) the appropriate transformation parameters to relate former and later geodetic datums, and (5) cost-benefit of the implementation. There are also several possible challenges that will be raised such as resistant to changes into the new approach and managing the dynamic database.

## 1.2 Problem Statements

The phenomena of secular and non-secular motions will distort the geodetic infrastructures, i.e. Continuously Operating Reference Stations (CORS), up to few centimetres or decimetres, depending on the magnitude of the plate tectonics. Thus, it affects the geocentric datum causing it to no longer be reliable to represent the current (epoch) position of points. In the case of Malaysia, GDM2000 is still implemented as a static datum with more than 10 years of duration without updating the reference datum. Consequently, over time, the national geocentric datum does not represent the real meaning of geocentric anymore and the relation of the national geocentric datum with satellite-based geodetic technology such as GPS would not be truly compatible. Furthermore, if the national geocentric datum is not accurate, it will have profound effects associated with misinterpretation and wrong decision making on land, property and security-related matters. For instance, there is a risk in cadastre that involves disputes in land parcels, whereby if the measurements are not legally traceable to its source, it could be challenged in court. The source for GDM2000 is ITRF2000, of which currently is in version ITRF2014. Therefore, regular datum updates must be carried out on the geodetic infrastructure by considering the land deformation due to plate tectonics.

Even though Malaysia is not situated at the subduction zone, it is still subjected to significant land deformation during the co-seismic and post-seismic as it is nearby the Ring of Fire subduction zone. According to Vigny *et al*. (2005) and Omar and Jhonny (2009), the largest displacement recorded in Peninsular Malaysia during Sumatra-Andaman earthquake was the North-West part (MyRTKnet stations: Langkawi with 17 cm, Arau with 13.7 cm, Sungai Petani with 12.8 cm and Universiti Sains Malaysia, Penang with 12.5 cm). Meanwhile the smallest displacement was at the South-East part (MyRTKnet stations: Tanjung Pengelih with 2 cm, Johor Jaya with 1.9 cm, Pekan with 2.6 cm and Mersing with 3.5 cm). These trends indicate that there are absolutely heterogeneous land deformation in Peninsular Malaysia. Although geodynamics studies in Malaysia have shown the results of its tectonic setting, e.g. Omar and Jhonny (2009), but there is no further research to comprehensively model the land deformation especially in resolving the issue of an outdated geocentric datum. Besides, the study by Jhonny (2010) only used data from December 2004 to December 2008 and did not cover the land deformation in East Malaysia, i.e. Sabah and Sarawak. Hence, the development of deformation model that covers the entire Malaysia is needed by providing specific approach for developing the secular and non-secular sub-models. It is also very important for the effects of post-seismic decay not to be neglected, especially after a strong earthquake, whereby significant effects of land movements, e.g. up to a few centimetres, are able to occur with unique decay patterns which are not linear and can last for several years. Therefore, the inclusion of post-seismic decay motion as part of the non-secular sub-model will significantly contribute to the development of a deformation model, since existing deformation models do not include the post-seismic decay element.

One of the major concerns for implementing a semi-dynamic geocentric datum is the relation between the updated datum and previous datum. In the Malaysian case, it is essential to relate between the new semi-dynamic geocentric datum and the presently used GDM2000 in order to bring all previous database to the new database or vice versa. In terms of time variations, the 14-parameters transformation is typically being used to take into account the rigid plate tectonic motion by the addition of the rates of change of the 7-parameters (Soler and Marshall, 2003). However, further consideration is needed to adopt the 14-parameters in Malaysia since land deformation is heterogeneous across the country which may be inaccurate for high accuracy positioning applications. Hence, this study will find a more specific datum transformation approach that provides high accuracy transformations in Malaysia, such as a 7-parameter datum transformation with a deformation model for coordinate propagation.

Based the above mentioned problem statements and literature reviews in Chapter 2, three main research gaps have been identified. First, Malaysia still implements a static datum which leads to a non-geocentric datum. Preliminary studies in section 2.4.2 have shown that the accuracy of the national datum is out to the extent of decimeter-level from the current position. Second, a land deformation model is not available in Malaysia and there is an opportunity for an improvement to the non-secular model by adding the post-seismic element. Lastly, a semi-dynamic geocentric datum that is suited for Malaysia is needed to cater for high accuracy positioning applications. This includes taking into account the relationship between the new and existing datum through a proper datum transformation approach.

## 1.3 Research Questions

Based on the problem statements and research gaps, several research questions are outlined as follows:

(1) What is the current deformation trend in Malaysia in terms of spatial and temporal aspects, and how has this affected the accuracy of GDM2000?
(2) How to develop a deformation model that comprises a secular and non-secular motion and what techniques are available?
(3) Which epoch is suitable to be a reference epoch for the secular and non-secular models?
(4) What is the appropriate datum transformation model to adopt between GDM2000 and the reference epoch of the deformation model?
(5) How accurate is the semi-dynamic geocentric datum for Malaysia?

## 1.4 Research Objectives

This research aims to provide the components needed to enhance the accuracy and reliability of the geodetic datum of Malaysia. The objectives are specified as follows:

*(1) To investigate the spatio-temporal domain of land deformation in Malaysia.*

This objective was accomplished by carrying out time-series analysis of position variations, using the Malaysia Real Time Kinematic GNSS Network (MyRTKnet) stations all over Malaysia which involves long-term GPS data to represent the spatio-temporal domain of land deformation in Malaysia.

(2) *To develop a land deformation model based on secular and non-secular land deformation of Malaysia.*

This objective focuses on modelling the deformation model that comprises of several sub-models which are secular (steady-state tectonic motion) and non-secular (co-seismic and post-seismic motion) and generate a gradient map (velocity or land displacement) for each sub-model.

(3) *To design an appropriate mechanism for the implementation of a semi-dynamic geocentric datum in Malaysia, and to validate its accuracy over time.*

This objective adopts several elements. First, a timeline to signify how semi-dynamic geocentric datum will be applied over time. Second is the transformation between the semi-dynamic geocentric datum and the existing GDM2000. Third, an execution program will be developed to validate the semi-dynamic geocentric datum.

## 1.5 Research Scope

The scope of this research is as follows:

(1) This study covers the development of semi-dynamic geocentric datum in Malaysia. Thus, the area of study involving land deformation and generating land deformation model encompasses entire Malaysia.

(2) GPS data used in this study consist of MyRTKnet and Malaysian Active GPS System (MASS) as well as International GNSS Service (IGS) stations, which is obtained from the Department Survey and Mapping Malaysia and IGS Central Bureau Information System, respectively. The IGS stations were selected among IGb08 reference frame sites which had been selected by the IGS Reference Frame Working Group for the IGS realization of the ITRF2008. The GPS data used in this study include the available GPS data from December 2004 until December 2014. In terms of GPS data processing, double difference with Quasi Ionosphere Free (QIF) strategy will be used in

this study by using scientific GPS high-precision processing software: Bernese version 5.0.

(3) All the daily coordinate solutions were mapped into ITRF2008. Thus, the development of deformation model and the new geocentric datum were based on the ITRF2008.

(4) This study focuses on the horizontal datum and 2D deformation model. However, map projection and accurate vertical datum transformations are beyond the scope of this research as both of the elements have no major problems with regards to the land deformation in Malaysia (the changes of vertical deformation are below 1 cm which is a very small value).

## 1.6 Significance of Research

This study has several significances:

(1) The semi-dynamic geocentric datum will revolutionize the conventional national geocentric datum in order to dynamically enhance the coordinates by considering the land movement due to plate tectonics and earthquakes over time. Therefore, it provides the 'true' coordinates for a specific epoch.

(2) The semi-dynamic geocentric datum that aligns with the ITRF that leads to compliance with international geodetic standard, seamless integration and homogeneous coordinate reference frame; thus, legally traceable coordinates.

(3) A new land deformation model for Malaysia that is generated by combining secular and non-secular motions, in particular, with the inclusion of post-seismic decay element in the model, will raise awareness and improve the existing deformation models. In addition, this land deformation model will significantly deepen the understanding of the tectonic motion and seismic activities that vary in the spatio-temporal domain in Malaysia.

(4) The design of semi-dynamic geocentric datum will increase the possibility to support wide range of applications. It is expected to benefit geodynamics, environmental hazards mitigation and earth science applications, which crucially require having reliable position information at their desired epoch.

## 1.7 General Research Framework

This section provides the general research methodology that links to several key elements of the research such as problem statements, research questions, and research objectives. Figure 1.1 illustrates the general research framework. The research framework is essential in order to give an overview of how to construct this study. Beginning with literature reviews, several aspects in the study have been reviewed. These include reviews on the dynamic Earth and how it affects the geodetic datum, geodynamics in Malaysia, current status of GDM2000, semi-dynamic geocentric datum and land deformation model. From the literature reviews, it would help to identify the problem statements and research gaps.

Subsequently, 5 research questions and 3 objectives have been derived based on the problem statements and research gaps. These research questions (RQ) have specific relation to the objectives, for example RQ 1 will be answered in the first objective. Then, the research methodology of this study was constructed into three main phases according to three objectives. On the other hand, specific methods and techniques were selected by referring back to the information obtained from the literature reviews. Several assessments on the deformation model have been carried out and the results were presented accordingly. Lastly, conclusion and recommendations were outlined at the end of this thesis. Note that the detailed research framework is illustrated in Figure 3.1, in Chapter 3.

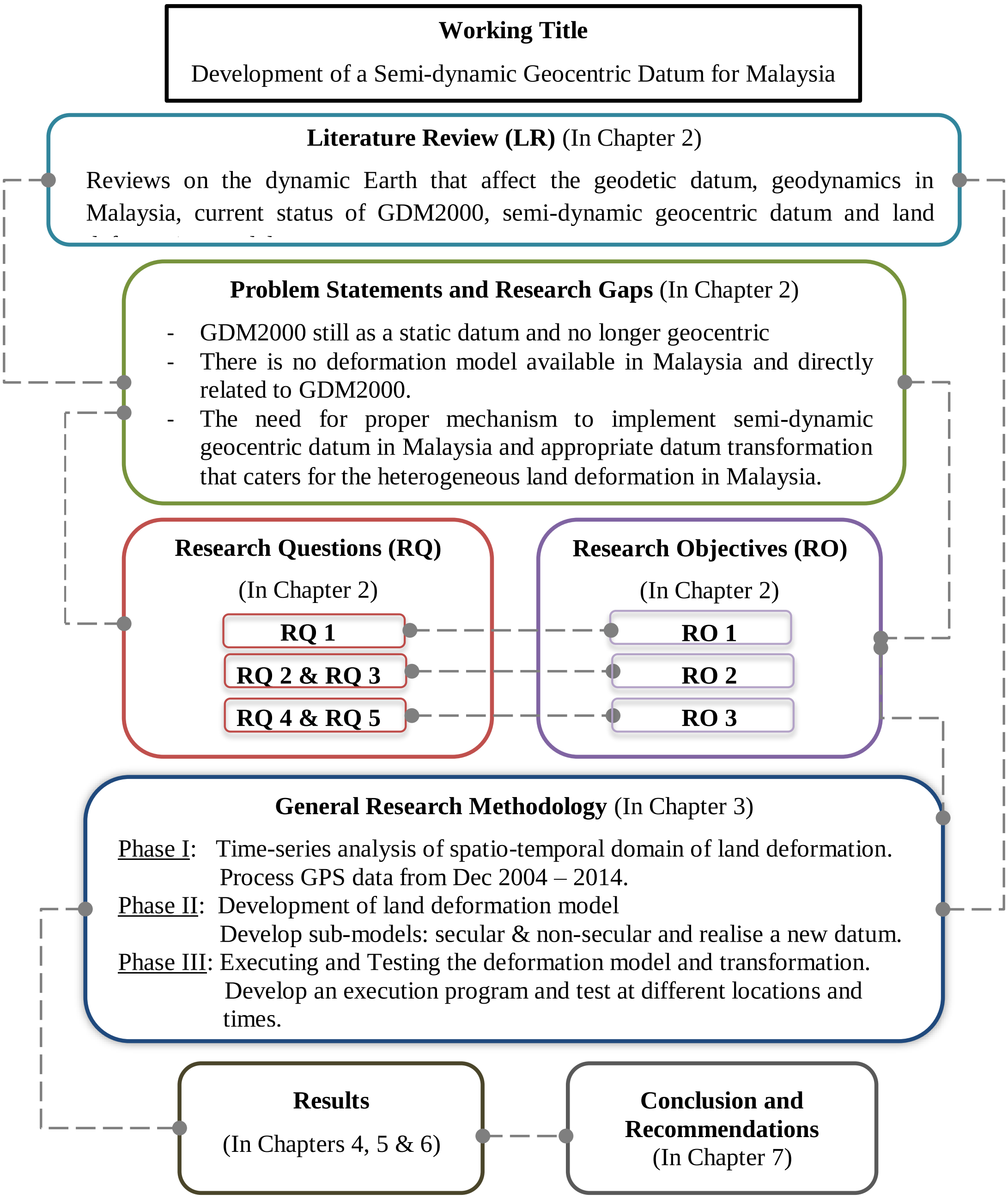


**Figure 1.1 :** The general research framework

## 1.8 Thesis Outline

The contents of this thesis is structured into 7 chapters. Chapter 1 describes the background of the research that consists of the overview of the dynamic Earth and geocentric datum, problem statements, research gaps, research questions, research objectives, research scope, significance of research, and research framework.

Chapter 2 reviews several significant aspects that are related to this study. The overview of the dynamic Earth in the perspective of Geodesy focuses on identifying the secular and non-secular motion factors that affect the geodetic datum. Besides, previous geodynamic studies in Malaysia were also reviewed. Then, the fundamental geodetic reference systems, frames and datum theory were described as the working title is mainly related to these topics. Next, the current deformation trend in Malaysia is described based on previous studies and the accuracy of GDM2000 with relation to the tectonic motion is evaluated in a preliminary study. Lastly, a review on the semi-dynamic geocentric datum was conducted to take into account possible techniques to develop a deformation model as well as several considerations and issues regarding the semi-dynamic geocentric datum. This significantly helps to answer research question 2.

Chapter 3 provides the research methodology of this study in order to achieve the research objectives. Three main phases are structured with their respective procedures. Initially, research materials and tools that consist of information about the GPS data and software used are outlined. Then, the details on the procedures begins with data acquisition, followed by data processing, plotting time-series of MyRTKnet stations and velocities estimation, datum realization, development of deformation model and lastly the execution and testing of the deformation model and datum transformation approach.

Chapter 4 presents the results and analysis of land deformation in Malaysia that are significant to achieve the first objective of this study. Initially, the results of GPS data processing was revealed in order to check the quality of the long-term data processing. Then, a number of selected time series plots of MyRTKnet and MASS stations position were presented and the epoch and period of seismic activities are identified. The time series was then plotted again according to the identified period of seismic activity. This is to estimate the horizontal velocity and land displacement that is beneficial for developing the deformation model in the next chapter.

Chapter 5 discusses one of the contributions of this study, i.e., development of the deformation model based on secular and non-secular land deformation in Malaysia. This model was developed using three different deformation modules which are linear least square regression method, displacement offset and second degree of polynomial. This chapter also presents the results and discusses on each sub-models that has been developed with regard to the secular and non-secular motions in Malaysia. In addition, results for the new datum realization of GDM2000 [@2009.3055] and the datum transformation, i.e. geographic offset, to the existing GDM2000 were indicated.

Chapter 6 contains the framework for implementing a semi-dynamic geocentric datum in Malaysia. Firstly, a timeline for implementing the semi-dynamic geocentric datum in Malaysia was illustrated in order to give an understanding of applying the deformation model as well as geographic offsets involved in the semi-dynamic geocentric datum. Secondly, the development of execution program for velocity estimation and coordinate propagation was described. Then, the results from the assessment of the deformation model were revealed and validated. Lastly, the implication of implementing a semi-dynamic geocentric datum in Malaysia was discussed.

Chapter 7 summarises several factors that drive this study and concludes the major findings from Chapters 4, 5 and 6. Several recommendations are also outlined for future research.

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