GEOID MODELING FOR KLANG VALLEY USING LEAST SQUARE MODIFICATION OF STOKES FORMULA WITH ADDITIVE CORRECTIONS

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requirements for the award of the degree of
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DEDICATION

I dedicated this thesis to my beloved family and their sacrificial made it possible to complete my thesis.

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ABSTRACT

The accuracy of the geoid model is critical in providing accurate earth surface information. Many modification procedures have been developed in recent decades to obtain accurate local geoid models. Furthermore, satellite-based positioning techniques, particularly the Global Navigation Satellite System (GNSS), have been widely used, and more emphasis has been placed on the precise determination of geoid models. The main objective of this study was to improve the quality of the geoid model in a small area. The Klang Valley, with an area 2,500 square kilometres, was selected as an area of interest. A total of 1,258 terrestrial, 878 airborne gravity data, 3-arc Shuttle Radar Topography Mission (SRTM) model and Earth Gravitational Model 2008 (EGM2008) as well as 45 benchmarks were used to develop the Klang Valley Gravimetric Geoid Model ($KTHKVGM2020_{Grav}$). The selection of the Global Gravitational Model (GGMs) was assessed based on terrestrial gravity data and GNSS levelling. The EGM2008 is the best model for this study, with an accuracy of ±0.122m and ±0.851m, respectively. Meanwhile, the SRTM model was assessed based on GNSS and benchmark with an accuracy of ±3.117m and ±3.024m, respectively. The gravity dataset was assessed with anomaly residuals based on ten mGal outliers that caused 181 terrestrials and 41 airborne gravities eliminated. Using the Tscherching/Rapp model and correlated method, the Klang Valley boundary problem value for signal and noise variance on EGM2008 was set at 10,800 maximum degrees. Consequently, the EGM2008 optimum upper limit, M, and upper limit of modification parameter, L was 2,190 maximum degrees. Capsize, ψ_0 of the study area was 0.1 degree as a minimum bias with variance error, ten mGal of the terrestrial gravity anomaly, $\sigma_{\Delta g}$. All datasets were gridded using the Kriging method with patching node encompassing cell interpolation. After additive estimations, the height of the $KTHKVGM2020_{Grav}$ geoid model was estimated between -5.011m and 3.998m, respectively. The $KTHKVGM2020_{Grav}$ geoid model was evaluated with 45 GNSS levelling stations and obtained ±11mm accuracy. Meanwhile, the $KTHKVGM2020_{Grav}$ geoid model successfully fitted into Peninsular Malaysia Geodetic Vertical Datum (PMGVD) using 35 GNSS levelling stations after correlating with four transformations parameters. Klang Valley fitted geoid model ($KTHKVGM2020_{fit}$) succeeded with ±5mm level accuracy. This study has demonstrated that the geoid model developed using the KTH approach provides better quality vertical reference than other methods, especially for a small area, such as Klang Valley.

ABSTRAK

Ketepatan model geoid adalah penting dalam menyediakan maklumat tepat permukaan bumi. Banyak prosedur pengubahsuaian telah dibangunkan dalam beberapa dekad kebelakangan ini untuk mendapatkan model geoid tempatan yang tepat. Tambahan pula, teknik penentududukan berasaskan satelit, khususnya Sistem Satelit Navigasi Global (GNSS), telah digunakan secara meluas dan lebih banyak penekanan telah diberikan kepada ketepatan model geoid. Objektif utama kajian ini adalah untuk meningkatkan kualiti model geoid di kawasan yang kecil. Lembah Klang yang berkeluasan 2,500 kilometer persegi telah dipilih sebagai kawasan kajian. Sebanyak 1,258 data gravity daratan, 878 data graviti bawaan udara, 3-arka model Misi Topografi Radar Ulang-alik (SRTM) dan Model Graviti Bumi 2008 (EGM2008) serta 45 tanda aras telah digunakan untuk membangunkan Model Geoid Gravimetri Lembah Klang (KTHKVGM2020$_{\mathrm{Grav}}$). Pemilihan Model Graviti Global (GGM) dinilai berdasarkan data graviti daratan dan aras GNSS. EGM2008 adalah model terbaik untuk kajian ini masing-masing dengan ketepatan ±0.122m dan ±0.851m. Manakala model SRTM pula dinilai berdasarkan kepada GNSS dan tanda aras dengan hasil ketepatan masing-masing ±3.117m dan ±3.024m. Set data graviti dinilai dengan sisa anomali berdasarkan 10 mGal unsur luaran yang menyebabkan 181 graviti daratan dan 41 graviti bawaan udara dihapuskan. Menggunakan model Tscherching/Rapp dan kaedah kolerasi, nilai permasalahan sempadan Lembah Klang untuk varians isyarat dan hingar pada EGM2008 ditetapkan pada 10,800 darjah maksimum. Justeru itu, had atas bagi optimum EGM2008, M dan had atas parameter pengubahsuaian, L adalah 2,190 darjah maksimum. Telungkup, ψ_0 bagi kawasan kajian ialah 0.1 darjah sebagai bias minimum dan varians ralat, 10 mGal anomali graviti daratan, $\sigma_{\Delta g}$. Semua dataset telah digrid menggunakan kaedah *Kriging* dengan menampal nod yang merangkumi interpolasi sel. Selepas pembetulan, anggaran ketinggian model geoid KTHKVGM2020$_{\mathrm{Grav}}$ masing-masing di antara -5.011m dan 3.998m. Model geoid KTHKVGM2020$_{\mathrm{Grav}}$ telah dinilai dengan 45 stesen aras GNSS dan memperolehi ketepatan ±11mm. Sementara itu, model geoid KTHKVGM2020$_{\mathrm{Grav}}$ berjaya dipadankan ke dalam Datum Tegak Geodesi Semenanjung Malaysia (PMGVD) menggunakan 35 stesen aras GNSS selepas dikolerasikan dengan empat parameter transformasi. Model geoid geometri Lembah Klang (KTHKVGM2020$_{\mathrm{fit}}$) berjaya dihasilkan dengan ketepatan sehingga ±5mm. Kajian ini menunjukkan bahawa model geoid yang dibangunkan menggunakan pendekatan KTH memberikan rujukan menegak yang lebih berkualiti berbanding kaedah lain terutamanya untuk kawasan kecil seperti Lembah Klang.

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LIST OF ABBREVIATIONS

BGI	-	International Gravimetric Bureau
BM	-	Benchmark
BVP	-	Boundary Value Problem
CHAMP	-	CHAllenging Minisatellite Payload
DEM	-	Digital Elevation Model
DOI	-	Digital Object Identifier
DSGM	-	Department of Mineral and Geoscience Malaysia
DSMM	-	Department of Survey and Mapping Malaysia
DTED	-	Digital Terrain Elevation
DTM	-	Digital Terrain Model
DWC	-	Downward Continuous
EGM96	-	Earth Gravitational Model 1996
EGM2008	-	Earth Gravitational Model 2008
EMG03A	-	Gravimetric geoid model for Sabah and Sarawak
EMGEOID05	-	East Malaysia Geoid Model
FFT	-	Fast Fourier Transform
GGM	-	Global Geopotential Model
GOCE	-	Gravity Field and Steady Ocean Circulation Explorer
GM	-	Global Mapper
GNSS	-	Global Navigation Satellite Systems
GRACE	-	Gravity Recovery and Climate Experiment
GRS80	-	Geodetic Reference System 1980
HMS	-	Height Modernization System
IAG	-	International Association of Geodesy
ICGEM	-	International Centre for Global Earth Model
IGS	-	International Geoid School
ITRF	-	International Terrestrial Reference Frame
KTH	-	Royal Institute of Technology
KTHKVGM2020$_{\text{Grav}}$	-	Klang Valley Gravimetric Geoid Model
KTHKVGM2020$_{\text{fit}}$	-	Klang Valley fitted Geoid Model

LSMSA	-	Least Squares Modification of Stokes' Formula
LSC	-	Least Square Collocation
LSD	-	Local Survey Datum
MSL	-	Mean Sea Level
MyGEOID	-	Malaysian Geoid Model
MyRTKnet	-	Malaysia Real Time Kinematic Network
NGVD	-	National Geodetic Vertical Datum
NGM17	-	Northern Region of Peninsular Malaysia Geoid Model 2017
PLN	-	Precise Leveling Network
PMGVD	-	Peninsular Malaysia Geodetic Vertical Datum
PMSGM2014	-	Peninsular Malaysia Seamless Geoid Model 2014
RCR	-	Remove-Compute-Restore
RMKe-9	-	Nineth Malaysia Rolling Planning
RMS	-	Root Mean Square
RMSE	-	Root Mean Square Error
RTM	-	Residual Terrain Model
SOR	-	Successive Over Relaxation
SRTM	-	Shuttle Radar Topographic Mission
SST	-	Sea Surface Topography
WGS84	-	World Geodetic System 1984
WGM2012	-	World Gravity Map 2012
WMG03C	-	Gravimetric geoid model for Peninsular Malaysia
WMGEOID04	-	West Malaysia Geoid Model

LIST OF SYMBOLS

ϕ - latitude
λ - longitude
$\boldsymbol{\vartheta}$ - axis rotation distance
f - centrifugal force of gravity
ω - velocity of earth rotation
p - Distance of rotation axis
Y_n - Legendre polynomials
R - Radius of earth/spherical
ξ,η,ζ - coordinate of mass
Ψ - spherical distance
W - gravitational potential of spherical surface
V - function of gravitational potential
U - normal potential spherical
γ - normal gravity
$S(\Psi)$ - stokes’ function
Δg - gravity anomaly
S_n - modification of parameter
Q_n^L - Molodensky truncation coefficients of limited L
γ_e - normal gravity at equator
h - ellipsoidal height
H - orthometric height
N - geoid height
$\tilde{N}$ - Undulation geoid height
μ - deflection of vertical
$\overline{P}_{\iota m}$ - Legendre polynomials
ι - distance of mass point measurement
ρ - density
σ - surface element/cap
a - semi major axis

b - semi minor axis of ellipsoidal

σ_n^2 - variance terrestrial gravity anomaly error degree of n

e^2 - eccentricity of reference ellipsoid

G - gravitational constant

δN_{comb}^{T} - combined topographic effect

δN^{DWC} - downward continuation effect

δN_{comb}^{a} - combined atmosphere effect

δN^{e} - ellipsoidal effect

$\delta N_{DWC}^{(1)}$ - DWC significant for short wavelength acquisition dataset

$\delta N_{DWC}^{L1,Far}$ - DWC significant for long wavelength acquisition dataset

δN_{DWC}^{L2} - DWC significant for medium wavelength acquisition dataset

δg_{FA} - free air gravity anomaly disturbance

g_{FA} - free air anomaly

ε - residuals

a_i - coefficients

g_{Bp} - Bouguer anomaly with plat anomaly

N_{GGM} - GNSS leveling derived of geoid undulation from GGM

b_n - signal and noise variances

Δg_n^{GGM} - laplace harmonics of degree n from GGM

c_{nm} - disturbing potential of spherical harmonic coefficients by GGM model with degree n and order m

S_{nm} - fully normal spherical harmonic

c_n - gravity anomaly errors

$a_i^T x$ - parametric term of inconsistencies and effects surface

σa_i - standard derivation of each unknown parameter a_i

$Z_{95\%}$ - coefficient of normal distribution for 1dimension arrays at 95% confident level

σ_N - covariant of geoid height

σ_h^2 - variant of ellipsoidal height

σ_H^2 - variant of orthometric height

ζ - Quasi-geoid

CHAPTER 1

INTRODUCTION

1.1 Background

Over the years, the development of the Global Navigation Satellite System (GNSS) technology has become more vital for surveying purposes compared to the spirit of levelling. The use of GNSS technology requires many workforces, time-consuming and quite expensive, compared with the spirit leveling accuracy is better than GNSS levelling (Okeke et al., 2017; Jamil, 2011). The spirit levelling process requires a local vertical datum height with high accuracy of mean sea level (MSL). At the same time, the use of GNSS technology for levelling and ellipsoid height (h) is not reliable for surveying due to disturbing masses, particularly on topographic surfaces. The GNSS ellipsoid height (h) is related to geoid height (N) and orthometric height (H) (Erok and Literacy, 2004). Thus, in order to obtain accurate geoid model, precise orthometric elevation is required. It is a challenging for most developing countries to use the geoid model as the national vertical datum. Therefore, Malaysia has developed a geoid modelling called MyGEOID as the country's vertical datum (DSMM, 2005; Jamil, 2011; Jamil, 2017).

Malaysia has developed a wide area of geoid modelling called MyGEOID in 2004. The model consists of the West Malaysia Geoid Model (WMGEOID04) and East Malaysia Geoid Model (EMGEOID05). Both regional geoid models developed with the remove-compute-restore (RCR) method (DSMM, 2005). Apart from that, other countries developed their own national geoid model. This includes Saudi Arabia (Zaki and Mogren, 2021), Khartoum, Sudan (Abdalla and Green, 2016), South Korea (Lee, 2017), Tanzania (Mayunga, 2016), Turkey (Kilicoglu et al., 2011), Egypt (Saadon et al., 2021) and Japan (Kuroishi, 2000), each with their own national vertical datum. In this regard, Malaysia again developed a Height Modernization System (HMS) project in the Klang Valley area in 2008 using the

RCR method. The HMS project was vital, since it minimise erroneous National Geodetic Vertical Datum (NGVD) information and is relevant for better geoid modelling (DSMM, 2012). The significance of the HMS project reduced erroneous from several factors, including sparsely gathered data, subsidence, and rebound.

Recently, another two (2) famous approaches were used to determine geoid modelling in the world. For instance, the least-square modification of stokes' formulae with additive correction (LSMSA) called the Royal Institute of Technology (KTH) approach and the University of New Brunswick (UNB) approach using stokes' Helmert methodology. The KTH method employs complete gravity anomaly (Sjoberg, 1986; 2003c) and combined additive corrections estimators. KTH approach computes additive corrections with combined direct and indirect effects, such as topography correction, in a simple manner (Sjoberg, 2003c; Kiamerh, 2006b). The computation of the KTH approach was flexible and easy to update on whatever new dataset, mainly terrestrial data (Sjoberg and Bagherbandi, 2017b). Thus, the KTH approach is essential for area that lacks terrestrial datasets and is difficult to access, such as a mountain area (Abbak, 2020). Meanwhile, compared to other methods, the KTH approach was available to minimise the erroneous; particularly the terrestrial dataset (Sjoberg and Hunegnaw, 2000), and terrestrial gravity data fully truncates gravity anomaly in terms of boundary value problem (BVP) (Sjoberg and Hunegnaw, 2000).

The KTH approach is often used by abroad countries to develop as national or local geoid models as vertical references. For instance; Sudan (Abdalla and Fairlead, 2011), New Zealand (Abdalla and Tenzer, 2011), Uganda (Sjoberg et al., 2015), Moldava (Danila, 2012), Greece (Daras, 2008), and Poland (Kuczynska-Siehien et al., 2016). However, in Malaysia only a few numbers of geodesy researchers use the KTH approach to develop their geoid models. For example, the Peninsular Malaysia seamless gravimetric geoid model was developed without using the medium wavelength frequency of the airborne gravity dataset (Sulaiman, 2016). Other than that, regional geoid modelling in northern Peninsular Malaysia was also developed. The model includes the use of marine and airborne gravity datasets (Pa'Suya et al., 2018). Indeed, both geoid models developed using the KTH approach were not excellent as RCR method. However, as previously stated, the KTH has its advantage and not every geoid model developed fit to the same parameter.

Therefore, the need to determine the best geoid parameter for a small area such as Klang Valley area using the KTH approach for further investigation. It is entirely significant for Klang Valley gravimetric geoid model related to local datum as well. Therefore, a suitable geoid modelling that is dependent towards a quality dataset and experience of processing (Verge, 2018), error variance of terrestrial gravity data, capsizes, upper limit modification especially for a small area such as Klang Valley.

1.2 Problem Statement

For the past years, Malaysia managed to develop two geoid models with 5 centimetres level accuracy using the remove-compute-restore (RCR) method. In 2008, Department of Survey and Mapping Malaysia (DSMM) developed Klang Valley geoid model under the Height Modernisation System Project using the RCR method. The Klang Valley geoid modelling provided with 3 centimetres of level accuracy. However, in 2016, the Peninsular Malaysia geoid model has an accuracy of 14.2 centimetres by optioning the KTH approach (Sulaiman, 2016). Meanwhile, a regional Northern Peninsular Malaysia geoid model called the NGM17 was also developed and obtained 27 centimetres in accuracy using the KTH approach (Pa'Suya et al., 2018). Both geoid model accuracy is lower than the existing geoid model that uses the KTH method. Therefore, procedure of computation that's between the RCR or KTH methods has no respective advantages except through scrutiny process for the datasets used.

In practice, the RCR method was a difficult task to understand and seen as complicated computation compared to the KTH approach (Sjoberg, 2003c). According to Varge (2018), the quality data strategy determines optimal and essential geoid model results. There has recently been no one, either locally or internationally, who has developed geoid modelling with a small area using the KTH approach. The study assumes that geoid modelling as a vertical datum in a small area is essential if the dataset is well managed, particularly in the Klang Valley area with approximately 50 kilometres by 50 kilometres. Theoretically, a small area was easy to manage with any newly updated dataset with the KTH approach.

Klang Valley was exposed to earthquake areas such as tsunami on 26th December 2004, 28th March 2005, and 12nd September 2007 at Sumatra, Indonesia, with 9.2, 8.7, and 8.4 magnitudes, respectively (Borrero et al., 2009). Another tsunami sequence occurred on 28 September 2018 at Sulawesi with 7.5 magnitudes (Maya, 2018). All the natural disasters could cause movement over the Sundaland plate (Simons et al., 2007) and cause land displacement until 10 centimetres magnitude for 400 kilometres radius (Jaffar et al., 2019). Indeed, Malaysia is considered a free zone from climate-related disasters (Rahman, 2018). Meanwhile, datasets in multi-format from different platform with optimal accuracy are essentially challenging to handle. For this regard in this study, the small changes due to natural disasters in particular small areas and rapid growth in the developing regions such as Klang Valley supposedly available to obtain an accurate vertical datum within a short period and frequently updated at all times.

The gravimetric geoid was developed using a long-wavelength frequency global Geopotential model (GGM) to determine a local geoid model directly related to the lack of information from gravity anomalies. The gravity anomaly from the empirical ground was estimated with covariance function. The difference in errors between satellite and ground would affect an error called sea surface topography (SST) and cause a circulation error (Barzaghi et al., 2009). As result, a research must be conducted to determine whether the long-wavelength frequency GGM has an effect on a small area. Meanwhile, if terrestrial gravity measurements were sparce, GGM data from satellites provided better information with insufficient coverage.

A benchmark used to fit relevant gravimetric geoid to the local datum and mean sea level (MSL) using water tide gauge are observed with period 18.6 years. Within 18.6 years, several wind stress, storm, and the atmosphere changed (Pugh,

1987) and enacted the inaccurate record information for tide gauge zero frequency situations (Ardalan and Safari, 2005). However, in Peninsular Malaysia, tide gauge observations were based on tidal records from 1984 to 1993 (DSMM, 2005). It's shorter than 18.6 years from a complete cycle lunar. The errors of changing and tide gauge observation information shorter than 18.6 years were caused result in MSL as well. Thus, fitting benchmark (BM) to a local datum, referring to the MSL and related to gravimetric geoid within a small area corresponded to fitted geoid modelling. Therefore, ideal transformation parameters for small areas particularly must be referred and determined in order to achieve optimal accuracy of geoid model for mapping purposes.

1.3 Research Question

Some research questions were addressed to highlight the main idea for this study which includes:

i. What is the ideal dataset used to develop a precise Klang Valley geoid model?

ii. Does the Klang Valley geoid model utilise the KTH approach is a better than option using the RCR approach, even if it covers small area?

iii. How to refine the dataset selection for the optimal parameter to construct Klang Valley geoid model either gravimetric and fitted geoid modeling?

1.4 Aim and Objectives

This study aims to improve the existing local geoid model for the Klang Valley area. There were three main objectives as below:

i. To identify the best geoid parameters for Klang Valley geoid modelling.
ii. To develop a precise local gravimetric geoid model in Klang Valley.
iii. To produce a local fitted geoid model in Klang Valley.

1.5 Scope of Study

The scope of this study is to improve the existing Klang Valley geoid model using the KTH approach.

1.5.1 Study Area

This research focus on a small area in Klang Valley, that is 50 kilometres squares as illustrated in Figure 1.1. This study will look into developing the Klang Valley geoid model, including cap size further to 0.3º to reduce discrepancy and optimise cap size value in the KTH method. In addition, Klang Valley geoid modelling was designed with good performance accuracy for various land surveying activities and geodetic environments under the Height Modernization System project (DSMM, 2012). Thus, this area was selected for this research. The Fast Fourier transforms (FFT) or least-squares collocation (LSC) method will be used to compare the existing geoid modelling under RCR approach development with the model developed in this study using KTH method.

1.5.2 Dataset

Within this research, five types of datasets are used to produce vertical references for Klang Valley.

1.5.2.1 Gravity Dataset

There are two types of gravity datasets involved; terrestrial gravity and airborne gravity datasets. Both gravity datasets were obtained from the National Gravity Database of the Department of Survey and Mapping (DSMM). Those data are verified through fieldwork by DSMM using Ortocor software. There are 1,439 terrestrial gravity and 919 airborne gravity datasets used on this study. The gravity datasets cover 50 by 50 kilometres of square area include approximately 33 kilometres capsize. It’s seeking to truncate drawbacks of geoid undulations nearby and obtain reference information as well as beneficial for future local geoid modelling nearby developing areas.

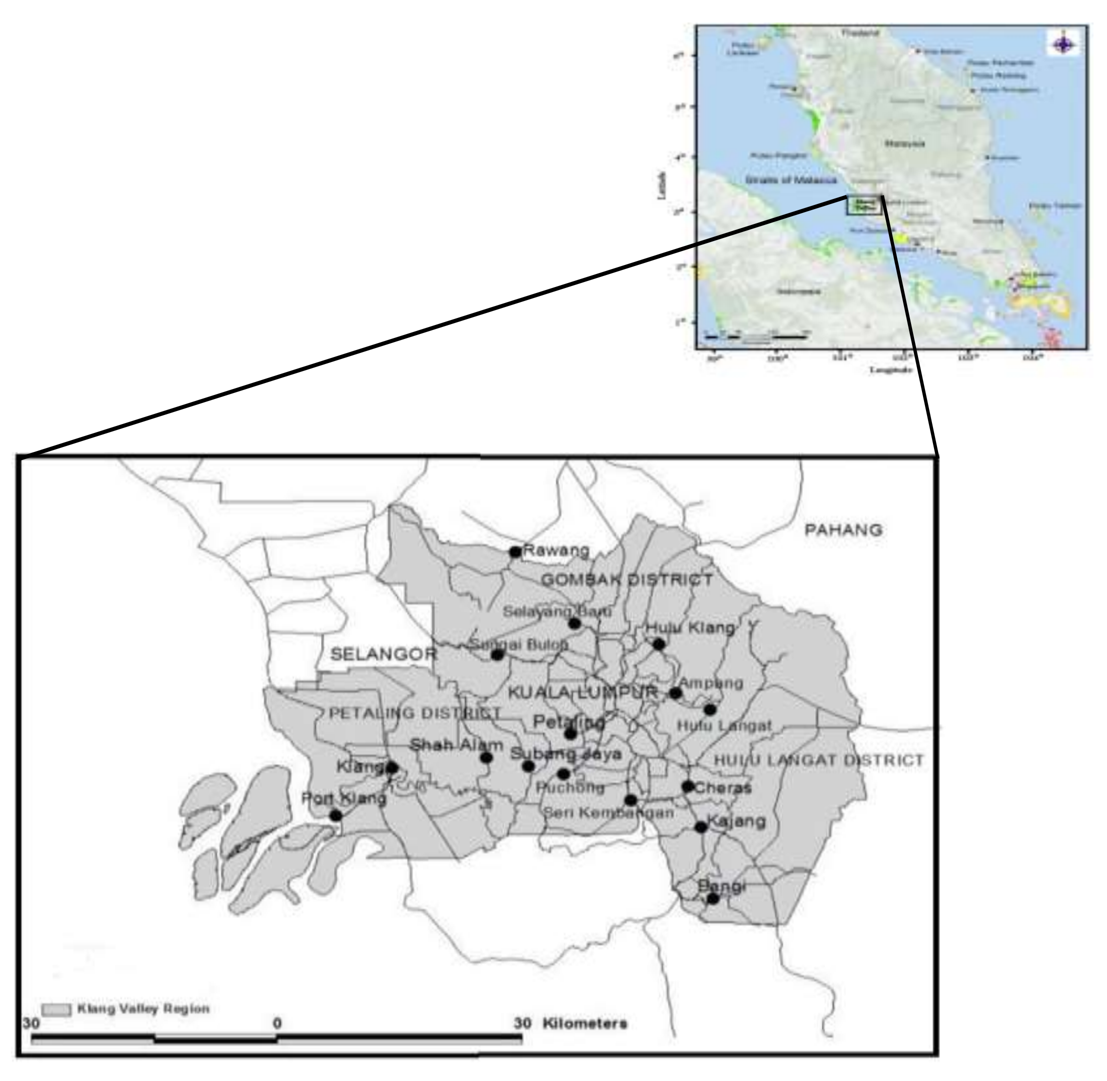

Figure 1.1 Klang Valley Study Area (Modified from Dziauddin et al., 2013)

1.5.2.2 Global Geopotential Models (GGM)

There are twelve (12) long-wavelength frequency global geopotential models (GGM) used in this study (Table 1.1). The GGM models were downloaded from the International Centre for Global Gravity Field website; http://icgem.gfz-potsdam.de (Ince et al., 2019). All GGMs models engaged were based on the Challenging Mini Satellite Payload (CHAMP), Gravity Recovery and Climate Experiment (GRAVE), and Gravity Field and Steady-state Ocean Circulation Explorer (GOCE) satellite orbit data (Doganalp, 2016). The models were evaluated by GNSS levelling and gravity datasets. According to Kiamehr (2010), the long-wavelength frequency GGM model is essential for areas that is lacking dataset and challenging area access.

Table 1.1 List of Global Geopotential Model (GGM) Used

MODEL	**DATA TYPE**	**DEGREE**	**YEAR**	**REFERENCE**
GGM05S	S	240	2015	Bettadpur et al., 2015
GGM03C	S	250	2012	Mayer-Gurr et al., 2012
GOEOO1S	S	220	2010	Pail et al., 2010
GOGRA04S	S	230	2014	Yi et al., 2013
GOSG01S	S	220	2018	Xu et al., 2017
DGM-1S	S	250	2012	Farahani et al., 2013
EIGEN-6C4	S, A, G	2190	2014	Forste et al., 2014
XGM2016	S, A, G	719	2017	Pail et al., 2017
EIGEN-5C	S, A, G	359	2010	Bruinsma et al., 2010
GGM05C	S, A, G	360	2015	Ries et al., 2016
EGM2008	S, A, G	2190	2008	Pavlis et al., 2008
GIF48	S, A, G	360	2011	Ries et al., 2011

S = Satellite A = Altimetry G = Gravity

1.5.2.3 Global Digital Elevation Models (GDEM)

Numerous digital elevation models (DEM) are accessible online from the International DEM services website. The study uses DEM model of Shuttle Radar Topography Mission (SRTM), Global 30 Arc Second Elevation (GTOPO30) and Global Land One-kilometer Base Elevation (GLOBE) model. The global DEM model was closely related to the KTH method, particularly topography surface correction and continuous downward correction (DWC) effects. All GDEM models selected for this study are space between 500 metres to one (1) kilometre. The DEM datasets used for this study is tabulated in Table 1.2.

Table 1.2 List of GDEM Used

GDEM	ARRAY	DATA SOURCES
SRTM	30”	https://earthexplorer.usgs.gov/
GTOPO30	30”	https://gtopo30-science.d1r.de/
GLOBE	30”	https://ngdcnoaa.gov/mgg/topo/globe.html

1.5.2.4 Levelling Dataset

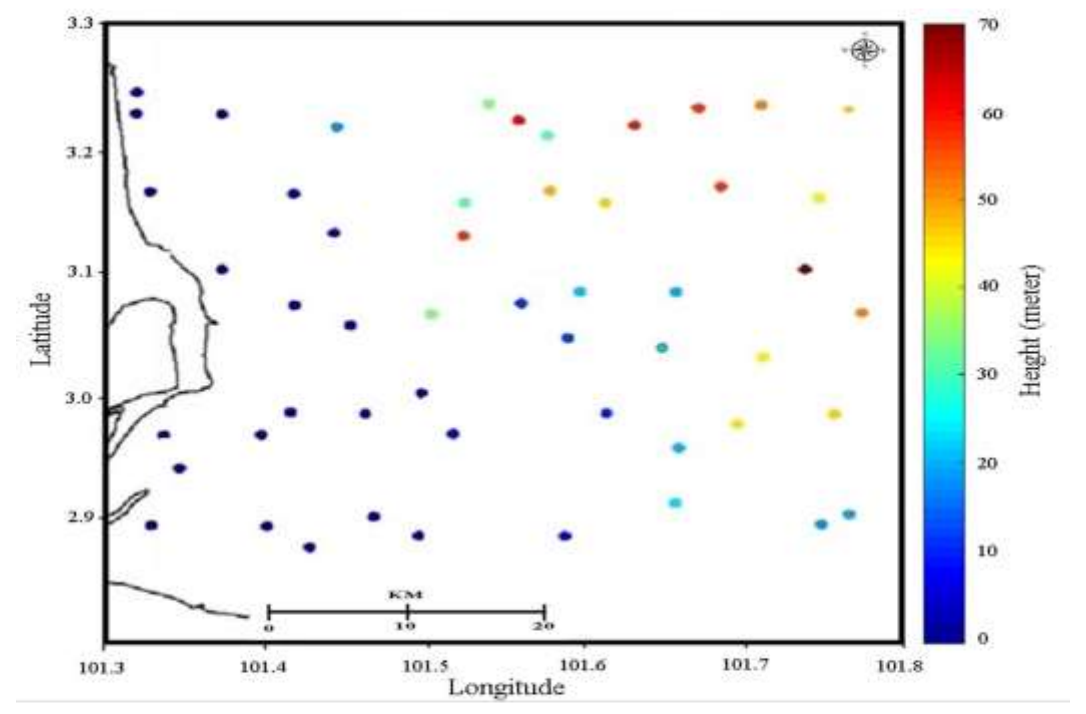

Figure 1.2 The Distribution of GNSS Levelling over the Study Area

This study will include fifty-two (52) benchmarks in the Klang Valley area. The benchmark levelling dataset was obtained from the DSMM database and with root mean square (RMS) that is lesser than 3 millimeters per kilometre in distance (0.003√K). Figure 1.2 depicts a levelling benchmark for this study. After investigation, the levelling datasets could fit the gravimetric geoid model to Peninsular Malaysia Geodetic Vertical Datum (PMGVD) local datum. Meanwhile, the benchmarks involved with GNSS levelling were evaluated with GGM and DEM model for the Klang Valley areas.

1.5.3 Analysis of Outcome

This research study will be divided into four phases. The first phase is cross-validation on investigating and evaluating all of the datasets including gridding scheme process and selecting the best method as well as model will be used. The cross-validation is performed on the spherical surface of the boundary value problem (BVP) for Klang Valley areas using the best gridding scheme.

The second phase included determining signal and noise degree variants during data acquisition, specifically for short or long wavelength frequency datasets. Meanwhile, this determination was seeking to free air and Bouguer anomalies in gravity data for a geoid undulation. The second phase also involves analysing the best optimum modification parameters in the least-squares sense of Klang Valley. The optimum parameters include an upper limit of modification GGM (M) and terrestrial gravity (L), error variance of terrestrial gravity anomaly ($\sigma_{\Delta g}$) as well as capsize (ψ_0). Again, this phase involves additive correction estimators with combined direct or indirect calculation. In the KTH approach, the additive corrections include combined topographic, atmosphere effect, downward continuous, and ellipsoid effect (Sjoberg, 1986). The KTH method's primary goal is to reducing erroneous least-squares estimates for geoid height springing, terrestrial gravity, and geopotential coefficients with greater simplicity and reliability. The KTH approach with rigorous refinement sought to optimise the matching with several error sources or decrease erroneous for undulation geoid height. Meanwhile, it fully uses and utilises gravity anomaly to interpolate and integrate data with a simple solution (Sjoberg and Hunegnaw, 2000; Sjoberg, 1986; 1991; 2003c).

The third phase involves analysing and assessing Klang Valley's gravimetric geoid height and fitted geoid model accuracy from an undulation height. Simultaneously, the best transformation parameter will be selected to fit the Klang Valley geoid model with local datum using verified GNSS levelling.

The fourth phase involves with the results and uses optimum strategy to engage the Klang Valley geoid model. It includes strategic gathering of all the datasets, determining the noise/signal, the best modification parameter, additive correction estimators using least-squares stokes' modification, Klang Valley gravimetric and fitted geoid assessment. The results were aided by KTH Geolab, Microsoft Excel, Surfer, Global Mapper, Ortocor, Geo-com software, and Gravsoft. All these software is essential and able to mobilise computations and presentation of Klang Valley geoid model outputs.

1.6 Significance of Research

The best parameters of the geoid model are best achieved if the dataset is strictly refined. Since there are many datasets available online, additional surveying data were easily obtained. Many Global Geopotential Model (GGM) and Global Digital Elevation Model (GDEM) are accessible online as well. Similarly, the complex area is difficult to access such as mountain and forest areas are lacking terrestrial dataset, which can be obtained with rigorous refines. Meanwhile, a small area geoid modelling is essential to develop and easy to handle with the best vertical datum for that particular area lack of terrestrial datasets. Aside from that, small locations with local defects are not propagated to the surrounding area. As a result, any individual or organisation capable of creating a geoid model of a small area that can be utilised as a local vertical datum.

Consequently, KTH approach employs complete gravity anomalies and parameters with additive Stokes' integral corrections, combined in direct or indirect corrections. KTH approach was simple to implement and dealt well with both new and large datasets and promised to be far superior in terms of geoid modelling computation as well (Kiamehr and Sjoberg, 2010).

Indirectly, the geoid model is easy to develop with the KTH approach since it would positively impact the implementation of GNSS technology. It is well known, GNSS technology was the most popular task for recent surveying field in the geodetic environment. The ellipsoid height (h) is derived from GNSS observation while the geoid height (N) is obtained through the geoid model developed.

Simultaneously, the orthometric height (H) on the topographic surface is generated as well, which presents the geoid surface (Heiskanen and Moritz, 1967; Roman et al., 2010; Gwaleba, 2018). Therefore, corresponds to the study of relationship on geoid height and vertical datum better than one (1) centimeter related with Peninsular Malaysia Geodetic Vertical Datum (PMGVD) as a local datum. Thus, the GNSS technology will obtain plenty of benefits by installing fitted geoid modelling.

1.7 Research Methodology

The methodology of this research within this study is divided into four (4) phases as illustrated in Figure 1.3.

1.7.1 Phase 1: Data gathering and validation

Phase one includes an overview of the existing or previous geoid modelling that has been developed in either a local or foreign country. Meanwhile, several geoid models approach, such as the KTH, RCR, and UNB covered broad areas, regionals, and local areas. Unfortunately, the author found that developing a geoid model with a small area using the KTH approach is still not capable.

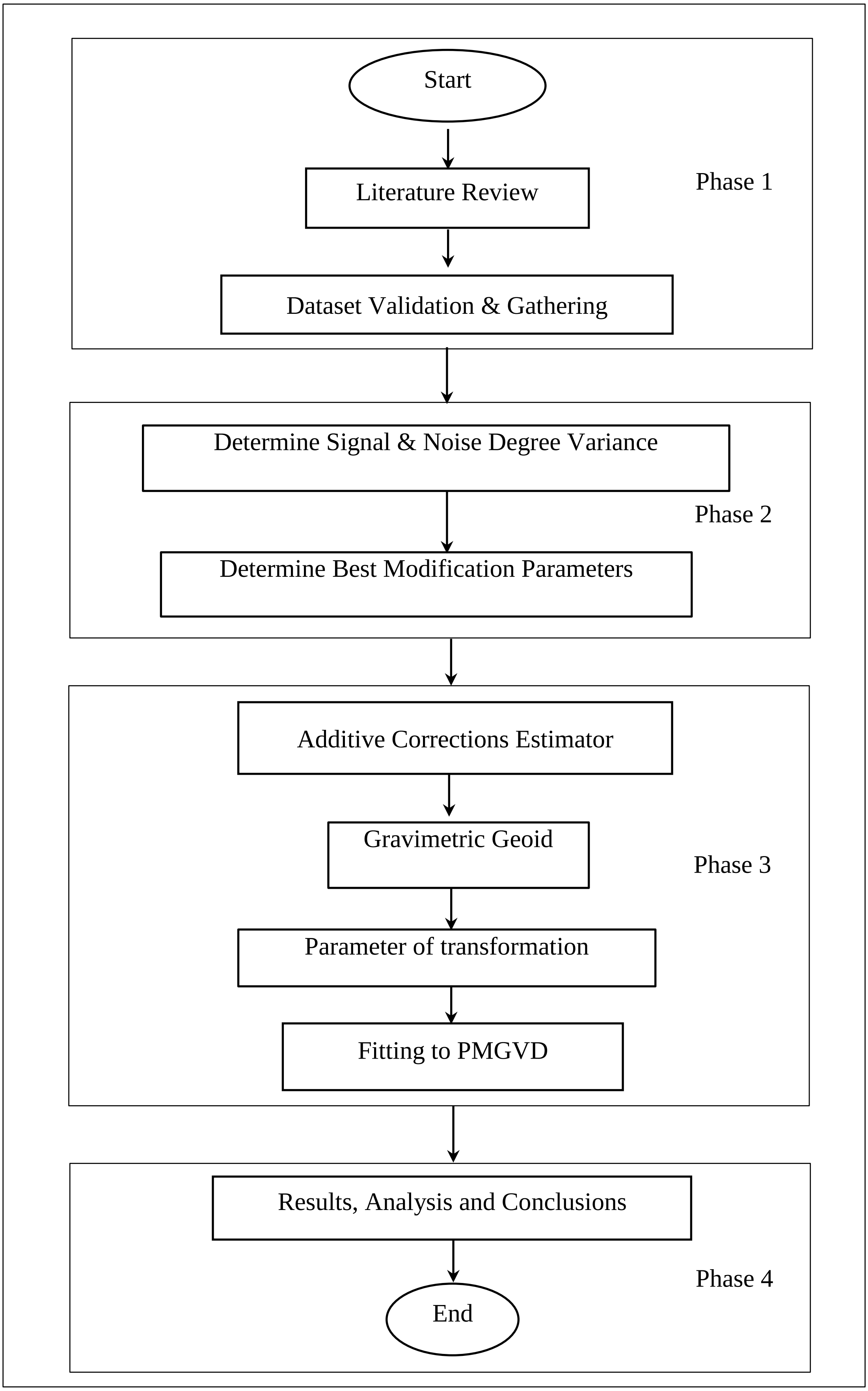

Figure 1.3 General Framework of Research Methodology

There were 1,439 terrestrial gravity datasets endorsed by DSMM and free of masses disturbing as well as free-air gravity anomaly and also Bouguer anomaly order. This study involved 1,439 terrestrial gravity datasets in first-class order that has passed the tolerance. Meanwhile, the study used 919 airborne gravity datasets without any free of mass disturbing for Klang Valley geoid modelling. Simultaneously, the study also involved 52 GNSS levelling datasets from DSMM's database, which is essential evaluate for the GGM and GDEM model. GNSS levelling data from DSMM's database were endorsed and used to engage for fitting Klang Valley gravimetric geoid modelling to the PMGVD local datum. Meanwhile, 12 GGM and 3 GDEM datasets was involved in this study.

1.7.2 Phase 2: Develop Klang Valley gravimetric geoid model

All datasets gathering were gridding using the KTH approach, which involves least-squares modification Stokes' formula, additive corrections procedure and was assessed by GNSS levelling dataset. The long-wavelength frequency of the GGM and GDEM model are bias and noise variants. Thus, fixed-parameter related with long-wavelength frequency model was applied instead of gravity anomaly degree variance, c_n, geopotential harmonic error degree variances, dc_n, modification limitation of M=L, capsize, $\Psi_\circ$ and error variance of terrestrial gravity anomaly, $\sigma_{\Delta g}$ (Wu, et al., 2020; Klees et al., 2019) in the computation procedure. Meanwhile, the procedure is also implemented with additive corrections estimator, called combine topography correction, downward continuous correction, atmosphere correction, and ellipsoidal correction to approximate undulate geoid with least-squares parameters. It is in order to harmonic Klang Valley geoid undulation of height spherical surface.

1.7.3 Phase 3: Fitting Klang Valley gravimetric geoid model to a local datum

The third phase focuses on fitting Klang Valley gravimetric geoid model with Peninsular Malaysia Geodetic Vertical Datum (PMGVD), a local datum with a refined benchmark. The Klang Valley gravimetric geoid model was tested with a transformation parameter model as well.

1.7.4 Phase 4: Results, analysis and conclusion

The fourth phase involves analysis of the results and conclusion. All the outcomes of research and assessment on KTH approaches were analysed as well. The assessment include data gathering, best parameter modification using least-squares modification stokes formula for Klang Valley small area and assessment of accuracy Klang Valley gravimetric geoid and the fitted geoid. Finally, a brief conclusion is made the findings and either or not this research has achieved all the objectives, as mentioned earlier in this chapter. Meanwhile, some recommendations for future studies on designing a better local geoid model, particularly in a small area, will be made as well.

1.8 Structure of Thesis

The structure of the thesis is organised of five chapters as follows.

Chapter 1 describes the introduction, aim and objectives, problem statement, and significance of the study.

Chapter 2 reviews the literature related to the KTH approach applied in other countryand abroad, either theoretical or empirical aspects. Review on RCR and UNB approach was presented as well. Beside from that, this chapter also described the history of geoid model development in Malaysia and the implementation of gravity data collection.

Chapter 3 presented the research methodology for this study. It began with choosing the best parameter for data acquisition, particularly with long-wavelength frequency satellite space data and modification parameters. Subsequently, it also involves processing to truncate data error with additive effects and ends with the fitting Klang Valley geoid model to the local datum procedure.

Chapter 4 discusses results and analyses for every part of evaluations. The goal of this chapter was to go over each step of the output and decision-making process for the best Klang Valley geoid model.

Finally, Chapter 5 presented a conclusion and recommendations for future research along with other efficient approach that can be applied to other fields.

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