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**PENILAIAN APLIKASI DATUM TEGAK GEODETIK DI
AMERIKA, AUSTRALIA, TAIWAN, NEW ZEALAND, KOREA
SELATAN AND SEMENANJUNG MALAYSIA**

*THE ASSESSMENT OF GEODETIC VERTICAL DATUM APPLICATION IN
AMERICAN, AUSTRALIA, TAIWAN, NEW ZEALAND, SOUTH KOREA, AND
PENINSULAR MALAYSIA*

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Abstrak:

Ketinggian atau kedalaman atas permukaan bumi adalah unsur penting dalam sistem koordinat tiga dimensi. Kebiasaannya, nilai ketinggian atau kedalaman merujuk kepada permukaan rujukan yang tertentu dikenali sebagai datum tegak. Secara konvensional, datum tegak dibahagikan kepada dua kategori utama iaitu Geoid, Purata Aras Laut dan Pasang Surut Astronomi Terendah. Kajian ini merupakan satu usaha untuk mengkaji semula aplikasi datum tegak geodetik daripada negara Amerika, Australia, Taiwan, New Zealand, Korea Selatan dan Semenanjung Malaysia. Gambaran keseluruhan datum tegak geodetik diringkaskan untuk menyokong aplikasinya pada masa hadapan. Oleh

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itu, kajian semula yang mengandungi pengumpulan data, input data dan kaedah analisis dalam aplikasi datum tegak akan dibincangkan dan digariskan. Usaha ini adalah penting untuk perancangan dan kemajuan pembangunan datum tegak pada masa hadapan di Malaysia.

Kata Kunci:

Ketinggian, Geoid, Datum tegak, Purata Aras Laut, Pasang Surut Astronomi Terendah.

Abstract:

Height or depth on the surface of the Earth is the crucial element in the three-dimensional coordinate system. Commonly, the height or depth value will denote a particular reference surface known as a vertical datum. Conventionally, the vertical datum is divided into two major categories which are Geoid/ Mean Sea Level and Lowest Astronomical Tide. This paper is an effort to review the applications of geodetic vertical datum from American, Australia, Taiwan, New Zealand, South Korea, and Peninsular Malaysia. An overview of geodetic vertical datum will be summarised to support the future application. Thus, a review consisting of a data gathering, data input, and analysis approach in vertical datum applications will be discussed and outlined. This initiative is significant for the planning and advancement of future vertical datum development in Malaysia.

Keywords:

Height, Geoid, Vertical Datum, Mean Sea Level, Lowest Astronomical Tide

Introduction

The vertical datum of a height network is defined by consigning the zero height to the Mean Sea Level (MSL) based on a certain period at a defined tide gauge in the past 200 years. Conventionally, this reference height surface is adopted in many countries to define the vertical datum at their region. The determined MSL value from the tide gauge measurement is transferred from the benchmark to another point through the conventional spirit level. Conventional spirit levelling has been performed over 200 years ago for determining height differences former surveyors and it is a remarkable and inherently accurate method (Odumosu et al., 2016). Nevertheless, it is costly and challenging particularly in a large area with an enormous point's number towards the requirement of height practically.

A seamless reference surface indicates a continuous and time-invariance surface. Due to the irregular topographic surface of the Earth, the geodetic computations are complicated to be accomplished. To solve this problem, geodesists implements a smooth mathematical reference surface to estimate the irregular shape of the surface of the Earth, hence, precisely describes as to estimate geoid height. Jekeli (2016) interprets geoid as an equipotential surface of the Earth's gravity field closely approximates with mean sea level. The equipotential surface is described as a constant value of the gravity potential on the surface. Nevertheless, Sjoberg and Bagherbandi (2017) defines geoid as the equipotential surface of the Earth's gravity field that best fits to the mean sea level.

In this era of survey and mapping activities has achieved their revolution through Global Navigation Satellite System (GNSS), which has become more demanding than conventional levelling measurement (Amirrudin, et al., 2020). The advancement of GNSS in expressing a position with good accuracy up to mm level has been proven but the deficiency of physical definition. Thus, height transformation procedure is required with the availability of high resolution and precise gravimetric geoid model. The GNSS ellipsoidal height is transformed to orthometric height (H) reference to geoid height by subtracting geoid heights (N) from the GNSS ellipsoidal heights (h).

GNSS levelling is significance in providing a good accuracy of geoid model. Recently, most of the countries have revolutionized the height system through geoid modelling for determining orthometric height using GNSS levelling instead of conventional levelling with the prompt intensification in the comprehensive augmentation of GNSS users. The initiation of new gravity from satellite gravity missions which produce an accurate Global Geopotential Model (GGMs) to be merged with the terrestrial gravity data either from land or marine area which the gravity data can also be merged with several technique that need to be optimised properly in order to provide a good accuracy of geoid model.

Thus, this paper attempts to review the techniques applied towards the development of geodetic vertical datum implementation for a region. Six (6) countries are selected in this study in order to review the geodetic vertical datum techniques implements in Malaysia, United States of America, Australia, Taiwan, New Zealand and South Korea.

Geodetic Vertical Datum Implementation

There are six countries will be reviewed in this section which consist of the geodetic vertical datum in Malaysia, United States of America, Australia, Taiwan, New Zealand and South Korea.

Overview of Geodetic Vertical Datum in Malaysia

There are numerous vertical datum are implemented for land and marine area in the determination of height or depth. However, the reference datum is derived based on tidal observation, entirely (Din et al., 2016). Survey and mapping in Peninsular Malaysia is referred to Peninsular Geodetic Vertical Datum (PMGVD) via First Order Precise Levelling Network (FOPLN) as a vertical datum. However, local CD via LAT are implemented for charting activities. Nevertheless, there are also surveying, mapping and charting activities implements local MSL as a vertical in preparing map, plans and charts since 1900's. The information about the inconsistency of height or depth at the coastal areas become tremendously vital due to rapid development (Hassan and Rahmat, 2016). The vertical network establishment in Peninsular Malaysia, Sabah and Sarawak are established discretely. Besides, the levelling networks in Sabah and Sarawak are not unified and referred to numerous vertical datum (Ismail et al., 2018).

Peninsular Malaysia Seamless Geoid Model 2014 (PMSGM2014) by Sulaiman (2016) became the first geoid model in Peninsular Malaysia, which is computed using the LSMSA method of KTH approach. Nevertheless, this model is computed implementing terrestrial and marine gravity without the airborne gravity data hence providing two types of geoid model known as the gravimetric and hybrid (fitted) geoid models. The validation is accomplished using GNSS-

levelling points with an accuracy of the geoid model about 10cm of the standard deviation of residual.

However, an accuracy of a hybrid geoid model with a mean parametric surface corrector model developed by Sulaiman (2016) represent high Root Mean Square (RMS) of 7 cm as compared with the official geoid model over Peninsular Malaysia, MyGEOID. This is very challenging as the computation of PMSGM2014 without the adaption of airborne gravity data. Besides, the sparse of terrestrial gravity data also will influence a geoid model accuracy. Then, Pa'suya (2020) has been established a new height reference system modernisation in Peninsular Malaysia using LSMSA technique recently by incorporating the airborne gravity data known as Peninsular Hybrid Geoid 2020 (PMHG2020). The hybrid geoid models were evaluated using GNSS levelling points while the hybrid geoid models represented that the optimum two parameters consisted of 50 km correlation length and 0.03 m with approximate standard deviations with an RMSE of 0.04716 m.

Overview of Geodetic Vertical Datum in United States of America

There is currently ongoing project related to American Vertical Datum (GRAV-D) related to redefine the vertical datum of the United States by 2022 with airborne gravity, terrestrial gravity, latest satellite gravity and altimetry data from DTU13 known as XGEOID2020 (NOAA, 2020). GRAV-D is a proposal by the National Geodetic Survey (NGS) to re-evaluate the vertical datum of the United States by 2022. The goal of this project is 2 cm accuracy level of the gravity-based vertical datum. The proposal is official policy for NGS and is comprised in the NGS 10-year plan.

The NGS has a distinctly mentioned mission to delineate, maintain and provide retrieve to the National Spatial Reference System (NSRS). This mission is initiated in Congressional mandates and Executive orders and has been the fundamental mission of NGS since its commencement as part of the Survey of the Coast in 1807. The main constituent of the NSRS is the height determinations with respect to the ellipsoidal height, orthometric height and dynamic height which any points in the United States or its territories. This is due to NGS describes these heights in the official datums of the United States. Besides, NGS has the crucial responsibility of providing the fundamental information for federal mapping activities in the nation due to federal mapping activities are currently referred on these datums.

The changes of the ellipsoidal heights in the United States have been tracking and predicting by NGS for some time with the implementation of GPS Continuously Operating Reference Stations (CORS). Furthermore, the existing gravity information for United States has been collected by NGS, then the geoid model is computed to determine orthometric heights from GPS. However, these attempts are inadequate at the maximum levels of accuracy, because of tremendously incongruent type of the available data. Due to apathetic large-scale tracking of gravity changes over time being performed by agencies in United States, this condition will degrade as crustal motion continuously change the condition of the land.

The nation needs to conduct a gravity survey due to the existing national gravity holdings are inadequate for NGS to appropriately conduct its mission to the degree of accuracy significance for accomplishing its requirement to the enormous NOAA mission. The high-resolution gravity survey needs to perform in recognition of the requirement to predict changes to heights which derived from predicted changes in the gravity field, particularly the geoid). Hence, the dual-

mode approach is an appropriate solution. Firstly, high resolution snapshot to repair and enhance current gravity fields which is a one-time survey with dense spatial coverage, but with a short temporal span. Next, low-resolution movie to track the temporal changes to the gravity field on a broad scale which a re-occurring survey with very coarse spatial coverage and a long temporal span. Lastly, a terrestrial partnership surveys to measure and track localised gravity value of particular significance to the fine-scale local determination of heights.

Thus, based on a new survey, there are few problems being addressed such as data gaps, aged data, discontinuities, imbalance of spatial coverage, lack of information regarding gravity change over time and inability to maintain the current vertical datum realization. As a solution in order to develop a geoid model accurately and track the changes through time, hence, a supporting information in addition to the gravity survey will be crucial. Which are, digital elevation models (DEM), geoid slopes from co-located (temporally and spatially) levelling and GPS surveys over large regions, rock densities of the largest mountain ranges of the United States, bathymetry of main lakes and near-shore regions of the United States, deflection of the vertical for testing upward continuation algorithms as required, gravity gradiometry and satellite derived gravity models.

Overview of Geodetic Vertical Datum in Australia

Currently, many countries applied a technique known as fitting gravimetric geoid or quasi-geoid models to GPS-levelling data. This technique is vital in Australia due to distortions in the Australian Height Datum (AHD). Hence, Australia took a consideration to fit the Australian Gravimetric Quasigeoid 2017 (AGQG 2017) (Featherstone et al., 2018a) model to a nationwide GPS-levelling dataset (Featherstone et al., 2018b) to develop a model of the separation between the GDA2020 ellipsoid and the AHD, thus permitting a direct transformation between ellipsoidal and AHD heights. This approach is a combined gravimetric-geometric model or other terms known as “hybrid quasigeoid model”.

According to Kotsakis and Sideris (1999), combined gravimetric-geometric models are influenced by errors in GPS ellipsoidal heights, estimations in the determination of heights, errors in the levelling data and systematic errors in the geoid. Subsequently, the geometric component is computed and its complementary grid of improbability values implementing least squares prediction (LSP) (Mysen, 2014). A new AUSGeoid model known as AUSGeoid2020 is developed based on a combined gravimetric-geometric model be associated with a 1' by 1' grid of uncertainty values propagated from input data into the LSP-gridded surface, giving users with location-specific ambiguity approximates.

Thus, Australian geodetic datum is changed from GDA94 to GDA2020. GDA2020 is referenced to International Terrestrial Reference Frame 2014 (ITRF2014) (Altamimi et al., 2016) extrapolated to epoch 2020.0 using Australian GPS station velocities (ICSM 2018). The geometric component of AUSGeoid2020 was developed by implementing least squares prediction (LSP) based on 7624 co-located GPS-levelling points across Australia. Hence, 40 points were established to misfit AUSGeoid2020 by more than five standard deviations from the average after conducting an initial cross-validation test. Then, the points were eliminated and the geometric component redetermined. The details regarding to the procedure of AUSGeoid2020 combined gravimetric-geometric model was described in detail in Brown et al., (2018).

Based on the findings in Brown et al., (2018), AUSGeoid2020 represents a method to convert between GPS-derived ellipsoidal heights and AHD heights then to compute the differences of AHD height. AUSGeoid2020 is also followed by a location-specific combined uncertainty of the GPS, AHD and quasi-geoid components applied in a development. Pseudo-independent examining of AUSGeoid2020 has represented that it is able of supporting GPS users to convert from ellipsoidal heights to AHD heights with an absolute uncertainty of ± 27 mm. Thus, by referring to the output, AUSGeoid2020 is equal to, or improved than conventional third-order levelling in Australia at distances beyond ~ 3 km.

Overview of Geodetic Vertical Datum in Taiwan

A substantial effort in gravity data collection and statistical techniques is required in a development of a high-resolution geoid model in Taiwan. Taiwan is bounded by the Pacific Ocean to the east with deep trenches, the South China Sea to the south, the Taiwan Strait to the west and the East China Sea to the north. The terrain of Taiwan is mostly rugged (up to 4000m high), with flat regions only on its coastal plans. Land-based gravity surveys can only be conducted along mountains treks and areas appropriate for walks or vehicle transportation.

Hence, a precise geoid model is required due to these issues. In order to solve these issues, three-dimensional, real-time cm-level positioning has been conducted by implementing a continuous GNSS network. Next, the Kuroshio Current east of Taiwan and the surrounding seas conduct large gradients in the dynamic ocean topography over Taiwan that can affect great variances in the vertical datums between Taiwan and its offshore islands. The variances cannot be solved without a precise geoid model. Lastly, Taiwan's ellipsoidal heights and most divisions of Taiwan's offshore islands have been observed and surveyed by LiDAR. A conversion procedure from ellipsoidal heights to orthometric heights needs a precise geoid model. The accuracy of a geoid model in low-lying areas and foothills will be crucial to weighing flooded zones and geohazards because of high sloping terrains.

In geoid modelling, there are three categories of data implemented specified to terrestrial (land and near shore) gravity data as follows:

1. Land gravity data

This data set is classified into two sub-sets:

- a) Subset 1: gravity measurements composed over year 1980 until 2003 at Taiwan's horizontal control points and first-order benchmarks
- b) Subset 2: gravity measurements collected over 2004 until 2006 except gravity measurements based on horizontal control points (Hwang et al., 2003).

2. Airborne gravity data

Over year 2004 until 2009, three airborne gravity surveys were conducted to measure and survey gravity data over Taiwan (Hwang et al., 2012; Hwang et al., 2014)

3. The offshore gravity data

The gravity data were measured within 50km to the five tide gauges and over waters 20 km offshore Taiwan. This is vital to enhance vertical datum connection between Taiwan and islands and for improving coastal geoid model.

However, the altimeter-derived sea surface heights (SSHs) were utilised in order to occupy the data gaps in the shipborne gravity data at sea and along the coasts of Taiwan. Then, the gravimetric geoid model is modelled by using the "modern" approach that is based in gravity

anomalies on the ground and the implement of planar terrain corrections. Where, at first, height anomalies are computed followed by conversion to geoidal heights. Hence, Taiwan's regional gravity values, a global geopotential model and a Digital Elevation Model (DEM) were required in Taiwan's regional gravity values. Then, a gravimetric geoid model in Taiwan is developed which is utilised to conduct the hybrid geoid model using the determined geoid heights, Thus, the remove-compute-restore technique were implemented in this computation. The hybrid geoid is developed by combining the "corrections", η to the gravimetric geoid as follows:

$$N_{hybrid} = N_{geoid} + \eta \quad (1)$$

N_{hybrid} is the hybrid geoid model, N_{geoid} is the gravimetric geoid model and η , the corrections. The details regarding to the procedure of new gravimetric-only and hybrid geoid models has been explained in Hwang et al., (2020). Based on the findings in Hwang et al., (2020), the combining of gravimetric geoid with the GPS and tidals records provides the errors identifications of about 40 to 50 cm in the current vertical datums.

Overview of Geodetic Vertical Datum in New Zealand

New Zealand officially utilised a gravimetric quasi-geoid model as the fundamental of its national vertical datum known as NZVD 2009 in year 2009. 13 different local vertical datum were implemented formerly, each of local vertical datum were referenced to different tide-gauge-based on the estimation of local mean sea level. Consequent to that, there were offsets of up to 0.4 m amongst the NZ local vertical datum. The NZGeoid2009 was crucial to merge the local vertical datum by determining offsets from the iteratively computed gravimetric quasigeoid model (Amos 2007; Amos and Featherstone, 2009; Claessens et al., 2011).

The gravity data implemented to determine NZGeoid2009 have some objectionable qualities for quasigeoid modelling. The terrestrial gravity data largely consist of historical measurements of varying accuracy and are unevenly distributed, typically isolated to valley through areas of rough topography. On the other hand, satellite altimetry data are recognised to be erroneous in coastal areas, and the large survey vessels commonly implemented for shipborne gravimetry cannot navigate near to the coast. Hence, a proper set of gravity measurements with a regular spatial distribution (seamlessly onshore and offshore) and consistent precision is required in order to provide precise quasi-geoid modelling.

In order to solve this issues, airborne gravimetry gives large data coverage over difficult areas such as coastal areas and in rough topography where terrestrial gravity measurements are sparse, and in coastal areas where the altimetry data are erroneous and shipborne data are sparse. It is a suitable technique for the determination of regional geoid computations, hence, to enhance the gravimetric quasi-geoid model (Hájková, 2011).

The terrestrial, shipborne, altimeter and airborne gravity measurements were reduced to refined Bouguer gravity anomalies and then merged onto a single grid at the topographic surface using least squares collocation. The gridded data were then converted to estimate Molodensky gravity anomalies, by combining the Bouguer plate term. The modified Stokes integration Wong and Gore (1969) was utilised to determine quasigeoid heights and the remove-compute-restore technique with the EIGEN-6C4 global gravity model as the reference field. The quasigeoid

model was fitted to 1422 independent GPS-levelling-derived quasigeoid heights the best, after elimination of offsets between the different levelling datums in New Zealand.

Hence, the standard deviation of the differences between the gravimetric quasigeoid and the GPS-levelling data represents 4 mm more precise than EIGEN-6C4 and 14 mm more precise than NZGeoid2009. However, the largest magnitude change in quasigeoid heights after involvements of airborne data was 0.122 m. The determination of quasigeoid heights by combining with the airborne gravity data were more precise than with the GPS-levelling data for each set of integration parameters.

Overview of Geodetic Vertical Datum in South Korea

The National Geographic Information Institute (NGII) has developed three Korean national geoid (KNGeoid) models known as KNGeoid13, KNGeoid14 and KNGeoid18 utilising the Earth's gravity field model, satellite-altimetry-derived gravity data, land and ocean gravity data, airborne gravity data and digital elevation model (DEM) data. These geoid models are hybrid geoid models established by NGII to enhance the height measurement accuracy based on GNSS surveying.

Firstly, the KNGeoid13 model is established by NGII for land part was made on gravity data provided from several national control points (unified control point, benchmark and triangulation point), airborne gravity data provided since year 2008 (Baek et al., 2014), DTU10 satellite altimetry data, EGM 2008, and 5m gridded topographic data with residual of standard deviations 3.41 cm. Then, in 2014, KNGeoid13 model was established utilising the similar approach as KNGeoid13 model by combining the gravity data in year 2014 and shipborne gravity data from Korea Hydrographic and Oceanographic Agency (KHOA) to the gravity data developed on KNGeoid13 with 3.3cm of residual's standard deviation (Lee et al., 2015). Lastly, the KNGeoid18 model was established using Experimental Gravity Field Model 2016 (XGM2016) made on GOCE gravity data (Pail et al., 2018) produced as primary sort of Earth Gravitational Model 2020 (EGM2020) with standard deviation of residual about 2.33 cm. Hence, EGM2008, EIGEN-6C4 and GECO have been utilised as a Global Geopotential Model (GGM) with coefficients up to degree 2190.

The accuracy of the geoid heights derived from the recently released Earth gravity model based on gravity data computed from the Gravity Recovery and Climate Experiment (GRACE) and the Gravity Field and Steady-State Ocean Circulation Explorer (GOCE) satellites was validated by assessing with the geoid heights derived from the Global Navigation Satellite System (GNSS)-levelling on the 1182 unified co(GNSS)-levelling on the 1182 unified control points (UCPs) installed by the National Geographic Information Institute (NGII) all over South Korea.

Hence, based on the output obtained from Kim et al., (2020), the geoid heights derived from the three high-degree global geopotential models (GGMs) and the three Korean National Geoid (KNGeoid) models presented similar distributions ranging from 17 to 33 m around South Korea. Secondly, the EGM2008 model represented a rather stable result for the root-mean-square-error (RMSE) of the residuals that were considered in terms of relative geoid heights accuracy. Thus, the EGM2008 model is a more suitable model than the GECO and EIGEN-6C4 models as compared with the GNSS/leveling geoid heights all over South Korea. As a result, the EGM2008 model could be selected as the suitable GGM from among the three

GGMs for determining a gravimetric geoid model for South Korea. Lastly, among the three KNGeoid models, the most recently developed KNGeoid18 model represented good results as a gravimetric geoid model all over South Korea than the KNGeoid13 and KNGeoid14 models as compared with the GNSS/levelling-derived geoid heights.

Results and Discussions

As discussed in the previous section, every country comprised of a regional geodetic vertical datum. Each geodetic vertical datum is established based on different approach as represented in Table 1. Where, the geodetic vertical datum of Malaysia is developed using Least Squares Modification of Stokes with additive corrections (LSMSA) approach. While, other countries such as United States of America and New Zealand implement Remove-Compute-Restore (RCR) approach. However, Australia represents a new technique known as combined gravimetric geometric model known as hybrid quasi-geoid model.

Thus, based on the discussions of other countries, it can be illustrated that airborne gravimetry provides a good data coverage especially over inaccessible areas like coastal areas and in rough topography. As discussed in geodetic vertical datum in New Zealand, the terrestrial data largely consist of historical measurements of varying accuracy and are unevenly distributed, typically isolated to valleys through areas of rough topography. Additionally, satellite altimetry data are known to be unreliable in coastal areas (Vignudelli et al., 2011), and the large survey vessels typically used for shipborne gravimetry cannot navigate close to the coast. For more precise quasigeoid modelling, a dedicated set of gravity observations with a regular spatial distribution (seamlessly onshore and offshore) and consistent precision is needed.

It is a suitable gravity data for a regional geoid computation. Due to this reasons, airborne gravimetry appears well suited to account for the shortcomings of the existing gravity data in each country to enhance the gravimetric quasigeoid model (Mc Cubine et al., 2017).

Table 1: The Vertical Datum Applications in American, Australia, Taiwan, New Zealand and Peninsular Malaysia

Researcher	Study Area	Data Gathering	Data Input	Analysis Approach
NOAA (2020)	United States of America	Airborne gravity, latest satellite gravity models, Terrestrial gravity	Gravity data Timeline: from year 2014 to 2020 (NGS published annual experimental geoid (XGEOID) models.	-R-C-R (Fitted geoid) -Limitation: Data gaps, aged data, discontinuities, imbalance of spatial coverage, lack of information regarding gravity change over time and inability to maintain the current vertical datum realization.

Brown et al., (2018)	Australia	GPS ellipsoidal height, gravimetric quasigeoid, altimeter-derived gravity anomalies, levelling	Gravimetric quasi-geoid, ellipsoidal height	-A combined gravimetric geometric model known as hybrid quasi-geoid model. -Limitation: The combined gravimetric-geometric models are influenced by errors in GPS ellipsoidal heights, estimations in the determination of heights, errors in the levelling data and systematic errors in the geoid.
Hwang et al., (2020)	Taiwan	Airborne gravity, shipborne gravity, terrestrial gravity and satellite altimetry data, 5 major tide gauges	Gravity data (land and marine), gravimetric geoid	-Merging land and marine gravity using LSC. Fitted geoid. -Limitation: The combining of gravimetric geoid with the GPS and tidal records provides the errors identifications of about 40 to 50 cm in the current vertical datums.
McCubbine et al., (2018)	New Zealand	Land gravity, DEM, GPS levelling, shipborne gravity, satellite altimetry, scalar airborne gravity and GGMs	A one arc-minute resolution gravimetric quasigeoid model, EIGEIN-6C4 (GGM)	-Modified Stokes integration using R-C-R -Limitation: A proper set of gravity measurements with a regular spatial distribution (seamlessly onshore and offshore) and consistent precision is required to provide precise

				quasi-geoid modelling.
Kim et al., (2020)	South Korea	Global Geopotential Models (EIGEN-6C4, EGM2008 and GECO), GNSS levelling, land gravity and DTU10 altimetry data	Gravity data	-The combinations of gravity data from satellites and land gravity data (blank area of gravity data is filled with DTU10 altimetry data). -Remove-Compute-Restore -Limitation: The accuracy assessment of the geoid model over South Korea by adding gravity data and collocating the GNSS/leveling-derived geoid heights.need to be performed.
Sulaiman (2016)	Peninsular Malaysia	Terrestrial land gravity data, Ship track marine gravity data from International Gravimetrics Bureau GGM and Satellite altimetry data from DTU10	Gravity data, geoid heights, othomertic heights and ellipsoidal heights	-LSMSA and Fitted geoid -Limitation: There are blank area of terrestrial gravity data in the middle of Peninsular Malaysia.
Pa'suya (2020)	Peninsular Malaysia	Terrestrial gravity, airborne gravity, satellite gravity data from GGM, shipborne gravity, satellite altimetry from DTU13, GNSS levelling	Gravity data, ellipsoidal heights, orthometric heights	-LSMSA -Fitted geoid/hybrid geoid (fitted to PMGVD and MSL) -Limitation: The study area is specified to the Peninsular Malaysia only.

Conclusion

As a conclusion, the suitable technique for merging and integrating land and marine gravity data can be optimized which is significance for modelling the gravity potential field in Malaysian region. Hence, multi-mission gravity data from terrestrial gravity data, airborne, shipborne, satellite altimetry and satellite gravity from GGM can be implemented to determine seamless vertical datum for Malaysian region. Then, the suitable technique for merging and integrating land and marine gravity data will be optimized which is significance for modelling the gravity potential field.

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