Review on the Height Datum Unification in Sri Lanka

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Abstract*: Single or Multiple Tide Gauges (TGs) observations are typically used to observe the sea level changes and those observations are used to define the vertical datums/Local Vertical Datums (LVDs) in an Island-wide or continental-wide. The national geodetic datum is the most significant framework for any surveying work like construction, engineering, mapping, or hydrographic in any country. This network usually should consist of both horizontal (latitude and longitude) and vertical (height) components with a higher order of accuracy to fulfil the survey and mapping needs within the country. Vertical datums are based on the geopotential whereas horizontal datums are geometric. Vertical datums are mostly based on the equipotential surface like the geoid, an equipotential surface that coincides with the Mean Sea Level (MSL) of the oceans. Currently, there are numbers of LVDs existing in the world and usually, those are used to define using spirit levelling, gravimetric observations, and TGs observations and it was continuously described within the geodetic literature over the past decades. Sometimes within that, it can be identified Global Vertical Datums (GVDs) which were based on the low-resolution geoids. According to the International Association of Geodesy (IAG) one of its main tasks is to create unification of the existing LVDs around the world through the Global Geodetic Observing System (GGOS). The main objective of this study is to identify a suitable vertical datum unification method that can be applied for the vertical datum in Sri Lanka which was formed in early 1930 and it is highly needed to re-observe it in order to fix the potential datum bias due to various geodynamic effects. The concept of the Unification of height/vertical datum is increasingly interesting nowadays which makes the comparison of various datums in different regions possible. Our study revealed that the Geodetic Boundary Value Problem (GBVP) approach is the most appropriate process that can be used for the unification process of the vertical datum in Sri Lanka.*

Keywords: *Geodetic Boundary Value Problem, Mean Sea Level, Unification, Vertical Datum, Tide Gauge*

1. Introduction

The national geodetic control system is the most vital framework for any surveying like engineering, construction, hydrographic and mapping purposes. This framework should consist of both horizontal (latitude and longitude) and vertical components with higher-order accuracy. Horizontal datums are normally identified as geometrical and vertical datums are mostly known as equipotential. The vertical datum is a reference system used for determining the physical heights (elevations) of a point on, above, or below the surface of the earth. It may be a LVD based on MSL or a GVD built on low-resolution geoids. Single or multiple TGs observations of the MSL were used to define most of the LVDs. However, it can be clearly stated, that the local MSL does not exactly coincide with the global equipotential surface like geoids, which was used to determine the

LVDs for island-wide or continental-wide. According to Amin et al., (2019), a geoid is defined as a particular equipotential surface of the gravity field of the Earth that gives the best-fitted model for the undisturbed MSL (Amjadiparvar et al., 2015; Vu et al., 2021) with the sense of least square adjustment. Further, this undisturbed sea level is not possible to achieve because of the sea currents, external gravity forces, atmospheric pressure, etc. and for that convention, MSL should also be needed. Until recent years, these LVDs were consistent in time, and reference stations are normally considered as steady and consistent over the decades.

The height of a point or elevation is an important component for the positioning, and it should reference to some height datum. To determine the vertical component, the spirit levelling is adopted with reference to some equipotential surface (Balasubramania, 1994). An equipotential surface was defined as the geopotential value W_0 (Sánchez et al., 2016), which is taken as the base surface for the measurements of the physical heights, normally known as a vertical/height datum. To define the potential value of W_0 and the origin of the vertical levelling network, the fundamental TGs were used, and zero level height was defined (Amjadiparvar et al., 2015; Balasubramania, 1994; Dayoub et al., 2011; Hayden, 2013; Hayden et al., 2012; Sjöberg 2013).

Within the world, there are more than hundred LVDs exist and those are based on the reference surfaces and the adopted height systems, which differ between the countries and the regions. Most of them are based on the averaging sea level observations of a single or multiple primary TGs, assuming that the MSL at these TGs coincides with the geoid (Balasubramania, 1994; Dayoub et al., 2011). Balasubramania (1994), mentioned that the vertical datums adopted for the different countries or regions are based on their computed average MSL observations over 19 years of tidal observations, different methods, and different time epochs. He further mentioned that the observations of MSL of later epochs will not coincide with this reference vertical surface or datum.

Ihde et al. (2000) mentioned that the Global Positioning System (GPS) can also be used for levelling purposes if the geoid is precisely known enough to concern the relationship between the levelling reference system and the GPS reference system. But still, precise geoids yet to be achieved for the European region with a few centimetres' accuracies for practical consideration can be used for the GPS/levelling purposes for the existing vertical networks.

According to Sánchez (2007, 2009), the global potential value assigned to the zero-height level should be adopted to have a precise explanation and realization for the unified height system. In the geodetic literature, it can be identified different strategies and approaches are used to define the unified vertical datums around the world and it is one of the most significant tasks of the GGOS of the IAG. With the improvement of science and technology, it was observed and identified the changes on the surface of the earth and pointed toward having high-accurate unified vertical datums that can be used for any kind of surveying activities. The main objective of this study is to identify a suitable method that can be used for the height datum unification of the Sri Lankan level net named Ceylon Level Net established in 1930 using multiple TGs observations and two-way spirit leveling. To fulfill the above-mentioned objective, already published research papers were reviewed and various strategies that can be used to get the solution for the unification of the height datums are studied in the following paragraph.

2. Vertical/Height Datum Unification Strategies

Unification of vertical datum has been broadly discussed and examined in the geodetic literature and the physical geodesy within the last centuries and still it is investigated to develop unified vertical datums for some countries for the purpose of all kinds of survey activities. A number of geodesists examined and introduced different tactics that can be used for the unification process (Ardalan & Grafarend, 2004; Ardalan et al., 2010; Ardalan & Safari, 2005; Ebadi et al., 2019; Gerlach & Rummel, 2013; Gruber et al., 2012; Rummel & Ilk, 1995; Rummel, 2000; Sansò, 1981; Zhang et al., 2009; Zhang et al., 2020). Those are spirit levelling and gravimetric observations, the oceanographic approach, and the GBVP approach.

Strategy – Spirit Levelling with the Combination of Gravimetric Observation Approach

This strategy was used to connect two or more LVDs in some countries. As an example, the United European Levelling Network 1995/1998 (UELN95/98) was used as the vertical datum for the twenty-seven (27) countries in the European region since 1990. Later by using the spirit leveling and the geopotential numbers derived from the gravimetric observation were used to upgrade the LVD to centimeter-level accuracy and formed the European Vertical Reference Network (EUVN) (Ihde et al., 2000). Another typical case study is the height datum adjustment of North American Vertical Datum 1988 (NAVD88) in Canadian, Mexico, and the United State using the above-mentioned strategy (Amjadiparvar et al., 2015; Zilkoski et al., 1992).

Strategy ii – The Oceanographic Approach

Different LVDs even if they were not connected by the points on the ground, can be connected using the oceanographic approach (Rummel & Ilk, 1995; Thompson et al., 2009; Woodworth et al., 2012). Oceans are the fundamental obstacles to the height datum unification (Rummel & Ilk, 1995), because it is not possible to conduct direct spirit levelling on the surface of the oceans. To overcome this problem, potential differences were derived from ocean levelling using geostrophic and steric levelling methods.

Woodworth et al. (2012) show that the application of ocean levelling can be used for the vertical datum unification, and for the determination of mean dynamic topography (MDT) at the coast area such that North Atlantic coastlines, and islands, North American Pacific coast and Mediterranean and obtained sub-decimeter level accuracy. As explained by Amjadiparvar et al. (2015), MDT is used for the oceanographic approach to determine the changes in MDT at the primary TGs of the datum and shows that the differences are equivalent to the datum parameters. They further mentioned that MDT can be calculated using satellite altimetry based on mean sea surface or MSL at the TGs joint with a geoid model. Hayden et al. (2014), give a better explanation of the determination of the MDT using a geographic approach also.

The MSL records at the selected TGs are integrated into the levelling network, in combination with oceanographic models of sea surface topography, which can provide independent control for the network (Rummel and Teunissen, 1988). This sort of control, on the other hand, makes sense only if the oceanographically determining potential differences are of higher quality than the levelled ones.

Strategy iii – The GBVP Approach

The GBVP approach is an important strategy that can be used for the unification of the height datums and this method is commonly used to define the unified vertical datums over the countries or continental-wide. The solution given by this approach is used to connect different LVDs and can be used to define the datum parameters furnish with the global potential surface.

A number of geodesists investigated and studied the different quantities of the gravity field and introduced different methods to define the unified vertical datums (Balasubramania, 1994; Colombo, 1980, 1981; Heck, 1990; Heck & Rummel, 1990; Rummel & Teunissen, 1988; Tengstrom, 1965; Xu, 1992). And different boundary value problem approaches were developed and introduced for the height datum unification by Fernando Sanso since 1981. Furthermore, different overviews of the GBVP approach were studied and presented for the unification process (Sansò, 1981, 1993, 1995; Sansò & Venuti, 2002).

According to Sansò (1981), if considered the shape of the boundary and the value of the potential, it gives the Dirichlet problem, and if considered value of the potential as well as the gravity vector all over the boundary, it gives the Molodensky problem. According to Sansò (1995), the boundary value problem formulation can be used to perform a gravimetric calculation of the geoid. The general idea of removing the first-degree spherical harmonics from the gravitational potential, for the regularization of the downward continuation of a high-frequency part of the gravity, can be used to test the existence of a solitary solution to the boundary value problem for the determination of gravimetric geoid (Martinec, 1998).

As mentioned by Heck (1990), the Stokes function is commonly used to compute the geoid or quasi-geoid models for the unification of LVDs, because using the Stoke function can compute the gravity anomalies referring to the LVDs which are biased with the global equipotential surface defined by the different Global Gravity Models (GGMs). For example, vertical datum unification done in New Zealand which was originally based on normal-orthometric-corrected-precise-levelling can be taken. For this process regional gravimetric quasi-geoid model and GPS/levelling points on 13 different LVDs were used by combining the iterative process with the GBVP approach. In this case, the iterative process was used due to datum offsets which were affected by gravity anomaly bias, and each iteration step was updated with offsets computed at the previous process (Amos & Featherstone, 2009). With this iterative process, Earth Gravity Model 2008 (EGM2008) and satellite-only gravity model from Gravity field steady-state Ocean Circulation Explorer (GOCE) mission data were used to compute the datum offsets (Pavlis et al., 2012).

Another GBVP approach is the use of the highest degree satellite-only global gravity model (GGM) in grouping with terrestrial gravity differences and applying the modified Stokes kernel. According to Gerlach & Rummel (2013), if use GGM which was not based on satellite gives a 1 – 2 m error globally. But when the satellite-based GGM of a spherical harmonic degree and order 200 was used for the computation, this inaccuracy could be decreased to the level of 1 cm, and indirect bias terms may be disregarded for the GBVP approach when applying for datum unification. The findings of this study were supported by (Gatti et al., 2012) also.

Different types of GBVP approaches were proposed and studied by several other researchers to find an applicable method for vertical datum unification all over the world. Some of them are (Ardalan & Grafarend, 2004; Ardalan et al., 2010; Ardalan & Safari, 2005; Zhang et al., 2009; Zhang et al., 2020).

As mentioned Ardalan and Grafarend (2004), were presented a new theory for the computation of the high-resolution regional geoid without using Stroke's formula. For the process, they have formulated a fixed-free two-boundary-value problem with respect to a reference ellipsoid. Ardalan and Safari (2005), also used this fixed-free two-boundary-value problem to propose a method for vertical datum unification.

A new methodology to unify the vertical datum in Shenzhen and Hong Kong is proposed, and it is based on the linearized fixed GBVP method (Zhang et al., 2009). The geodetic leveling is within a few centimeters of the height differences found using this unique method.

A bias-free GBVP approach was formulated to unify the vertical datum by (Ardalan et al., 2010), based on potential and gravity differences considered free from the datum shift.

The height datum offset values between the local and the global vertical datum are defined using the Remove-Compute-Restore (RCR) process, which is based on the GBVP approach (Zhang et al., 2020). The RCR approach was utilized to remove and restore the long wavelengths of the gravity field, and the GRACE and GOCE satellite missions were used to obtain the very accurate medium-long gravity field.

3. Sri Lankan Vertical Datum

The geodetic vertical control network of Sri Lanka, originally named Ceylon Level Net was started in 1926 and was completed in 1930. The primary level network consisted of 27 two-way level lines and 59 primary benchmarks. The zero MSL was observed using the discretely located self-recording TGs based in Colombo, and Trincomalee from 1923 to 1933. These MSL observations were used to define the origin point of the Ceylon Level Network (Jackson, 1936). But, before that, three discretely located harbors in Colombo, Trincomalee, and Galle were used to observe the tidal observations, because those locations were given the daily prediction of the tidal data of the Indian Ocean. The Great Trigonometrical Survey of India was used above harbors to determine the MSL readings using the self-recording TGs within the following periods: at Colombo and Galle 1884 – 1890, at Trincomalee 1890 – 1895. It was initially decided to use the Colombo and Trincomalee as the zero-height location for the precise leveling network because when it was undertaken, it was decided to re determine the MSL at both places within the same period and the leveling process is ongoing. Anyway, with these observations ongoing at both Colombo and Trincomalee, the Level Net of Ceylon was adjusted in 1932 by using the MSL value of Colombo as observed by the Great Trigonometric Survey of India observed by the five years observations during the 1884 – 1889 (Price, 2013).

When it considers the crustal changes and other global geophysical changes like melting of the glaciers (post glacier rebound), sea-level changes, land subsidence, etc. MSL observations done in the 1884 – 1889 period are not sufficient for the present-day work and those discretely located three TGs were used for MSL observations are not appropriate for fixing the vertical datum in Sri Lanka and also this was pointed out by (Abeyratne et al., 2009) and further mentioned the possibility of ellipsoidal height bias in Sri Lankan GPS datum.

Also, the recent research done by Prasanna et al. (2021), developed a model for the height changes to determine the relationship between the LVD and the Lowest Astronomical Tide (LAT) around Sri Lanka. This model was analyzed using IDW spatial interpolation with the assumption of spatial autocorrelation. Additionally, they stated that the absence of gravity data over Sri Lanka was a major concern for this type of study and that this global-based local geoid was suggested as a result.

4. Discussion

Many LVDs in the world were used to define the unified vertical datum using three different strategies mentioned above for all kinds of surveying and mapping purposes.

When it comes to Sri Lanka, still Sri Lankan surveyors use the level data observed in the 1884 – 1889 period for any type of surveying activities within the country and its surrounded sea area. Two horizontal control networks such that Kandawala and Sri Lanka Datum 1999 (SLD99) are utilized to get horizontal controls, but for the vertical controls, it is still using the above-mentioned MSL-based vertical datum which was based on Colombo within the 1884 – 1889 period and having the normal orthometric height system. Those MSL observations which were established more than 130 years ago are still used for all types of surveying activities.

According to IPCC, (2014), the present global mean sea level rising rate is approximately 3.2mmyr^{-1}and Sri Lanka faced a huge Tsunami effect in 2004 due to the plate tectonic movements that happen on the Burma plate and Indian plate. Therefore, when considering the above-mentioned factors and other global geophysical changes the MSL observations done in the 1884-1889 period are not sufficient for the present-day surveying and hydrographic activities within the country and the surrounded sea area.

5. Conclusion

According to the above-mentioned geodetic literature, and the history of the Ceylon Level Network, the unification of the LVD is an important work for the present-day survey and mapping activities. The remedy for this is incorporating continuous equipotential surface like geoid as the vertical datum. Therefore, it is possible to say as for Sri Lanka, it is better to use the GBVP approach method to find the datum offset between LVD and the global geopotential model (geoid).

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I am KP Manuranga, Have completed my basic degree in B.Sc in Surveying Sciences (Specialized in Surveying & Geodesy). I would like to do my future studies regarding in Gravity, Height Datum Unification, and GNNS. All my studies are related to surveying and geodesy, and I like to make some effort to generate new solutions for the problems in the above-mentioned research interests.