Quantification of Geographical Variations of Solid Earth Tidal Effects for Geodetic Deformation Monitoring in Ghana*

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Abstract

Tidal forces arise from the gravitational attraction of external bodies changing over the volume of a body. The solid earth tides cause deformation of the Earth's shape due to the tidal forces from the Moon and Sun. This causes displacement in the positions of higher engineering structures that can result in loss of lives, loss of property, and economic cost to the nation. The Earth's response to the tide generating potential can be determined analytically by the driving forces, with the knowledge of the orbital motion of the Earth and the Moon, the Sun and other external objects, combined with the Love numbers which are partially related to the rheological properties of the Earth. By using Navier's equations of motion, the tidal deformation of the Solid Earth can be quantified numerically. In this paper, the tidal effect on the earth crust is quantified for five (5) Regions of Ghana using the theory of Love. The results reveal that an average tidal deformation value for all the points were within the range of 1.81×10^{-3} m to 2.70×10^{-3} m. The average deformation values is an indication that tidal deformation of the earth crust should be considered in daily deformation monitoring of the earth crust and all relevant engineering structures.

Keywords: Deformation, Love Parameterization, Navier Equation of Motion, Tidal Potential

1 Introduction

The partially elastic body of the earth is deformed as a result of the effects of tides of the solid earth (Torge, 2001). The solid earth tides epitomise one of the largest sources of noise in terms of magnitude which must be considered to safeguard long-term stability of engineering structures since a strong gravitational wave might result in deformation of a structure (Kurinsky, 2013). Tidal effects studies have become obligatory in recent times because the surface loading of the earth due to the weight of the ocean tides cause a time-varying deformation of the solid earth, which is called ocean tide loading (Rafiq and Santos, 2004; Straser, 2008a). The recent disastrous casualties that have struck various zones of the earth, producing victims and provoking huge damage to buildings and the economy, has call for urgent experimentation with methods that might help to mitigate risk (Straser, 2010; Consoli *et al.*, 2013; Shiki *et al.*, 2008; Straser, 2008b; Zhao *et al.*, 2008; Nakamura, 2003; Goulty, 1979; Lammlein, 1974).

Even though the mechanisms that trigger the earth and being provoked by lunar/solar gravitational interaction are not yet clear, various studies have been already conducted to determine the relationship between lunar cycles and terrestrial cycles (Kolvankar *et al.*, 2010; Omori, 1908; Bagby, 1973; Straser, 2009a; Straser, 2009b; Gross *et al.*, 1997). Several studies have applied both numerical analysis and the usage of high sensor instruments for studying the tidal effects on the earth crust for geodetic deformation modelling. Notable among these instruments are: Global Navigation Satellite Systems (GNSS) (Rafiq and Santos, 2004), Advanced Laser Interferometer Gravitational Wave Observatory (aLIGO) (Kurinsky, 2013), Seismicity (Straser, 2010; McGehee and McKinney, 1995; Shimizu *et al.*, 2006; Beltrami and Di Risio, 2011; Bressan and Tinti, 2012) and Superconducting Gravimeters (Heping *et al.*, 2005). Mathematical methods such as Artificial Neural Networks (ANN) (Beltrami; 2008; Beltrami *et al.*, 2001; Beltrami, 2011; Sergio *et al.*, 2013; Flinchem and Jay, 2000; Sun *et al.*, 2006; Zhong and Ogadiji, 2013; Deo and Chaudhari, 1998; Tsai and Lee, 1999; Lee *et al.*, 1998; Lee *et al.*, 2002; Lee, 2004; Huang *et al.*, 2003; Cox *et al.*, 2002; Lee, 2006; Lee and Jeng, 2002; Liang *et al.*, 2008; Deo, 2010; Wang *et al.*, 2012), Numerical Analysis (Munk and Cartwight, 1966; Godwin, 1972; Foreman, 1977; Barber and Wearing, 2016; Mirfenderesk and Tomlinson, 2007; Poulsen, 2009; Lisitzin, 1974; Wahr, 1995; Catwright, 1999), Harmonics (Vaziri, 1997; Pawlowicz, 2002; Parker, 2007; Doodson, 1921), and Interpolation Techniques (Kalman, 1960; Ghil *et al.*, 1981; Miller and Cane, 1989; Chen and Cane, 2008; Yen *et al.*, 1996; Choi *et al.*, 2000; Sorensen *et al.*, 2006, Altaf *et al.*, 2013; Yen *et al.*, 1996). These methods are mostly used in geodetic sciences for tides predictions and modelling, but these mathematical methods have also yielded a good solution to many problems within the Geoscientific community.

In this paper, the authors were motivated to quantify tidal effects in coastal and non-coastal

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areas within Ghana to see how significant the values are and its implementation in geodetic deformation using a numerical analysis, that is, Navier's equations of motion and Love theories as proposed by Torge (2001) and Kurinsky (2013). This is because it is normally significant to quantify these tidal effects and their implementation on the position of monitoring point objects. In recent times in Ghana, deformations of engineering structures are normally attributed to mining, construction activities and poor engineering constructions. There is therefore the need to quantify the effects of tidal waves on the earth crust to ascertain if the deformations being recorded at the monitoring station are actually not coming from the effect of tides or otherwise. This can be done by creating a model from the quantified results so as to incorporate it into daily deformation monitoring values. The mathematical theories by Love (2011) were adopted to determine the radial direction in which the earth is deforming. According to Torge (2001) and Kurinky (2013), the deformations of the horizontal direction are proportional to the horizontal tidal accelerations and this can be achieved by numerical methods.

In this paper, a mathematical relationship of Love (2011), Torge (2001) and Kurinsky (2013) was applied for quantifying the effects of tides in five Regions (Central, Greater Accra, Western, Eastern and Ashanti) of Ghana. The authors were motivated to apply the mathematical relationship because the applicability and performance valuation of these numerical methods for quantifying tides effect in Ghana has not been evaluated. Therefore, this study will quantify the effects of tides in the five Regions of Ghana.

2 Resources and Methods Used

2.1 Study Area and Data Source

Data used for this study was obtained from Survey and Mapping Division in Ghana and it covers the areas of interest (Fig. 1). Ashanti Region covers a total land surface area of about 24 389 km^2 of the total land area in Ghana (Opoku, 2015). It lies between longitude 2.25˚ W and latitudes 7.46˚ N. This region has thick forests with no sea but have different rivers and lakes. Eastern Region covers an area of 19 323 km² which is about 8.1% of Ghana's total landform (Opoku, 2015). Average temperature ranges from 30°C during the night and 24 °C during day time. Relative humidity is generally high ranging from highest of 85% to 77% (Mohammed, 2015). Western Region covers an area of roughly 23 921 km² (Opoku, 2015). The topography is generally described as a series of ridges and valleys parallel to one another (Ziggah, 2007) with few low lands. The region is instituted within the South-Western Equatorial Climatic Zone of Ghana with the uppermost mean temperature being 34°C which is chronicled between March and April, while the lowest mean temperature of 20 °C is veteran in August (Opoku, 2015) and its relative humidity is very high, between 75% and 85% in the rainy season and 70% to 80% in the dry season (Karpeta, 2000). Central Region covers an area of 9 826 km² in lieu of 4.1% of Ghana's land area (Opoku, 2015). The region is sited along the shoreline zone of Ghana which makes the region experience high temperatures year-round. The invariability in climate in the region is influenced more by rainfall than temperature (Mohammed, 2015). The climate is of the moist semi-equatorial type. The mean monthly temperature ranges from 26°C in the coolest month of August to about 30°C in the hottest months, March to April (Mohammed, 2015). Greater Accra is the smallest region in Ghana lodging a total land surface of 3 245 km² or 1.4% of the total land size of Ghana. The climate is mainly tropical. The effects of climate change in the southern part of Ghana, especially Accra, results in droughts in the dry season, severe floods in the rainy season, high temperatures, the incursion of pest and diseases taking away human lives and properties (Danquah, 2013). The absolute maximum temperature is 40°C (Mohammed, 2015).

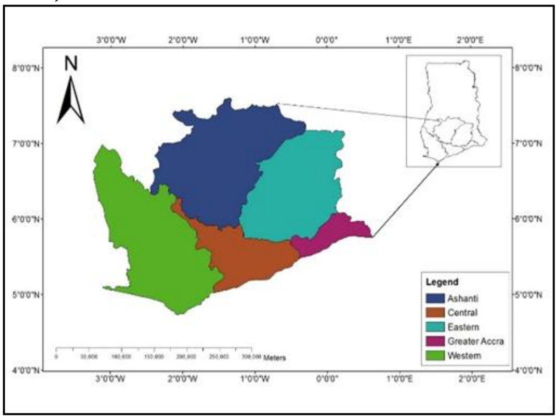

Fig. 1 Study Area

Table 1 Sample of Data Used

LATITUDE	LONGITUDE
5.66600000000	-0.42333333330
5.69666666670	-0.31500000000
5.70383333330	0.07933333330
5.68833333330	0.05000000000
5.82783333330	0.06566666670
5.82000000000	0.18833333330
5.93683333330	0.05216666670
5.95116666670	0.19383333330
5.92283333330	0.20916666670
5.78666666670	0.43666666670

Data used for this present study is in latitude and Longitude. The data was collected during GPS receivers by the Survey and Mapping Division across the whole country. The collected data focuses on the areas of study that is the coastal areas and the non-coastal areas to quantify tidal effects on the stability of controls. Table 1 shows a sample of the data used to embark this study.

2.2 Methods Used

2.2.1 Tidal Potential

A functional form for the tidal potential was attained by projecting the geometric potential (well-defined in a moderately modest manner from Fig. 2 into the space of spherical harmonics). The first two terms can then be eradicated in the consequential sum, due to the first term being a constant (giving rise to no force and the second term being the orbital force (Kurinsky, 2013). The third term is thus the overriding tidal component of the gravitational force due to supplementary $\frac{r}{d}$ terms, wherein this present study $r \le d$. This yields in the following potential as denoted by Equation (1) (Kurinsky, 2013; Torge, 2001):

$$T(Q) = D\left(\frac{r}{a}\right)^2 \left(\frac{p}{d}\right)^3 \begin{bmatrix} \cos^2\varphi \cos^2\delta \cos 2H \\ +\sin 2\varphi \sin 2\delta \cos H + \\ 3(\sin^2\phi - \frac{1}{3})(\sin^2\delta - \frac{1}{3} \end{bmatrix} \quad (1)$$

where *p* is the average object distance, ϕ and λ are the latitude angle and longitude correspondingly, ϕ is the colatitude of the position, and δ is the declination of the external body (as shown in Fig. 2) (Kurinsky, 2013; Torge, 2001; Poulsen, 2009).

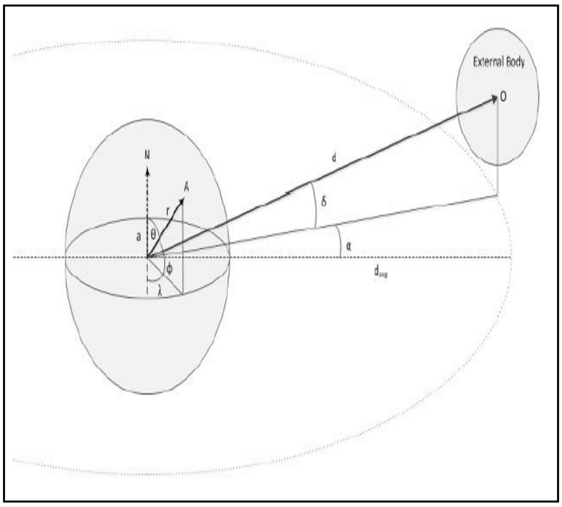

Fig. 2 Model of the Three-Dimensional System (Kurinsky, 2013)

The two other terms introduce here are Doodson's constant, denoted by (Kuirnsky, 2013):

$$D = \frac{3}{4} G M_o \frac{a^2}{p^3} \quad (2)$$

The local hour angle H is given by (Kurinsky, 2013):

$$H(T) = wT - \alpha - \lambda \quad (3)$$

where w is the sidereal velocity of the earth, *T* is the sidereal time and α is the right ascension of the body (Kurinsky, 2013). The core features to memorandum before working with the potential are the time dependences. It can be noticed that there are two obvious sinusoidal disparities with respect to time of day, and one term which is in value constant. If the outward bodies were motionless, the constant term could be disregarded when considering varying potential, as it is done, and merely compute the magnitude of each potential module one.

The orbit of the moon about the earth and the orbit of the earth around the sun are joined with the tilt of the earth's rotational axis. This means that the terms do diverge with a time necessity correlated to these two cycles. Explicitly, twice monthly and twice-yearly patterns should be seen at the very least and at times the moon and the sun may cross out while at other times the may reinforce each other. For this reason, in modelling, highly accurate position data is employed for all external bodies.

2.2.2 Love Parameterization

In order to employ the functional potential to model solid earth tides, a model which is linked to the shape of the tidal potential to the earth deformation must be adopted. Ensuring the prevailing literature, the parameterization of Love, 2011 was adopted, and the earth was designated as a solid, isotropic, elastic solid, whose shape can be linked to the potential by two-dimension parameters, l and h, which is called love numbers according to the following formulae (Kurinsky, 2013; Torge, 2001):

$$X_r = h\frac{T(Q)}{g}, X_\varphi = \frac{l}{g}\frac{T(Q)}{\partial\varphi}, X_\lambda \frac{l}{g\sin(\varphi)}\frac{\partial T(Q)}{\partial\lambda} \quad (4)$$

where the variables are as well-defined in the potential, g is the gravitational acceleration at $r \approx \alpha$, and l and h are in the range (0,1) with typical values $h \approx 0.6$ and $l \approx 0.08$ (Kurinsky, 2013). From this parameterization, a way to calculate the deformation of earth's shape in physically useful quantities is made possible.

2.2.3 Displacement

The tidal deformation of the earth is solved numerically. These displacements can be added to the position of the points in geocentric coordinates to get the new location of the points. This section elaborates the tidal equations as employed for displacement computations. The displacement formed are straightforward calculations from the equations presented in the main text (Kurinsky, 2013). The equations adopted include:

$$X_r = \frac{3hGM_o r^2}{4gd^3}\begin{pmatrix}\cos^2(\varphi)\cos^2(\delta)\cos(2H) \\ +\sin(2\varphi)\sin(2\delta\end{pmatrix} * \cos(H) + 3(\sin^2(\varphi) - \frac{1}{3})(\sin^2(\delta) - \frac{1}{3})) \tag{5}$$

$$X_\varphi = \frac{3lGM_o r}{4gd^3}(-\sin(2\varphi)\cos^2(\delta)\cos(2H) + 2\cos(2\varphi)\sin(2\delta)\cos(H) + 3\sin(2\varphi)(\sin^2(\delta) - \frac{1}{3})) \tag{6}$$

$$X_\lambda = \frac{3lGM_o r}{4gd^3\cos(\varphi)}(2\cos^2(\varphi)\cos^2(\delta)\sin(2H) + \sin(2\varphi)\sin(2\delta)\sin(H) \tag{7}$$

In the above equations, M_o is object mass, and all other terms have been defined in the text. The units of radial displacement is metres while the other two terms are in radians (Kurinsky, 2013).

2.2.4. Accuracy Assessment of Models

In order to determine the accuracies of the models used, various statistical indicators were employed to determine the working efficiency of the models. Hence, to make an unprejudiced valuation of the models, statistical indicators such as Root Mean Square (RMSE), Mean Biased Error (MBE) and Mean Absolute Error (MAE) were used. Their individual mathematical relationships are given by Equations (8) to (10) respectively.

$$RMSE = \sqrt{\sum \frac{E^2}{n}} \tag{8}$$

where n is the number of observation points and E^2 is the square of the error. The MBE was calculated using the formula below:

$$MBE = \sqrt{\sum \frac{E}{n}} \tag{9}$$

where E is the error and n is the number of observation points. The MAE was calculated using the formula:

$$MAE = \sqrt{\sum \frac{|E|}{n}} \tag{10}$$

where $|E|$ is the absolute error and n is the number of observation points.

3 Results and Discussion

The results for the effects of tides by the lunar and solar cycles for Western Region (WR) are used to compute the resultant effects. The resultant effects by the solar and lunar tides on Western Region are tabulated in Table 2. From Table 2 it can be observed that there is displacement of position as a result of tidal effects on the solid earth crust. Hence the need to quantify tidal effects for geodetic deformation monitoring for all areas cannot be overemphasized.

From Table 3, Ashanti region is not situated along the coast, but from the results, it can be seen that both the solar and lunar tides caused displacements in the positions of the points.

From Table 4, Central region is situated along the coast and from the results, it can be observed that there is displacement in the position of points as a result of tides.

From Table 5, Eastern region is a non-coastal area but there is a shift in the position of points as a result of tides.

From Table 6, Greater Accra Region is situated along the coast, it can be seen that there are displacements in the positions of the points due to tidal effects. The statistical analysis is tabulated in Table 7.

Table 2 Resultant Effects of Solar and Lunar Tides for Western Region

Points Locations	Radial (radians)	Δ latitude	Δ Longitude	Displacement (m)	Radial (m)
WR 1	-4327.78	0.002038	0.000296	0.002058858	-247931
WR 2	-3396.87	0.002216	3.65E-05	0.002215988	-194601
WR 3	-8198.13	-0.00079	-4.71E-05	0.000794119	-469658
WR 4	-8758.03	8.19E-06	1.22E-06	8.28275E-06	-501733
WR 5	-8637.22	0.000369	4.69E-05	0.000372145	-494812
WR 6	-2645.98	0.002304	-0.00029	0.00232327	-151584
WR 7	493.4831	0.002616	-0.00023	0.002626475	28270.83
WR 8	10719.05	0.002392	-0.00028	0.002408132	614076.4
WR 9	4388.376	0.002674	-0.00064	0.002749402	251402.8
WR 10	-606.778	0.002537	-0.00018	0.002543673	-34761.3

Table 3 Resultant Effects of Solar and Lunar Tides for Ashanti Region

Points Locations	Radial (radians)	Δ Latitude	Δ Longitude	Displacement (m)	Radial (m)
AS1	-4232.47	0.0019	0.000837	0.002076347	-242471
AS2	-6173.31	0.001201	1.11E-03	0.001637799	-353659
AS3	11430.86	0.000938	2.12E-03	0.002319861	654854.9
AS4	6176.985	1.18E-03	2.46E-03	0.002723638	353869.3
AS5	13338.86	0.000885	1.81E-03	0.002010867	764161.2

Table 4 Resultant Effects of Solar and Lunar Tides for Central Region

Points Locations	Radial (radians)	Δ Latitude	Δ Longitude	Displacement (m)	Radial (m)
CR 1	-7966.82	0.000881	0.000326	0.000939782	-456406
CR 2	-4343.32	0.002056	3.11E-05	0.002055923	-248821
CR 3	4391.747	0.002632	-7.94E-04	0.002749352	251595.9
CR 4	13176.26	-4.86E-04	-1.98E-03	0.002042035	754846.4
CR 5	-1346.64	0.002291	9.35E-04	0.002474521	-77146.9
CR 6	-2047.05	0.001292	0.00202	0.002397983	-117272
CR 7	-1035.53	0.00044	0.002466	0.002504989	-59323.8
CR 8	-2023.67	0.000272	0.002385	0.002400717	-115933
CR 9	-3852.67	0.001402	0.00162	0.002142699	-220713
CR 10	734.6678	-0.00018	0.002635	0.002641421	42087.91

Table 5 Resultant Effects of Solar and Lunar Tides for Eastern Region

Points Locations	Radial (radians)	Δ Latitude	Δ Longitude	Displacement (m)	Radial (m)
ER 1	9531.474	-0.0025	0.000371	0.002529013	546042.4
ER 2	8908.36	-0.0024	9.53E-04	0.002580812	510345.3
ER 3	8022.166	-0.0024	1.10E-03	0.002641541	459576.7
ER 4	6838.451	-2.48E-03	1.06E-03	0.002700751	391763.6
ER 5	7618.481	-0.00229	1.36E-03	0.002664487	436450.2
ER 6	-2047.05	0.001292	0.00202	0.002397983	-117272
ER 7	-1219.55	0.001035	0.002262	0.002487206	-69866.1

Table 6 Resultant Effects of Solar and Lunar Tides for Greater Accra Region

Points Locations	Radial (radians)	Δ Latitude	Δ Longitude	Displacement (m)	Radial (m)
GR 1	2143.373	4.58E-05	0.002709	0.002709232	122790.3
GR 2	3704.351	-0.00045	2.71E-03	0.002745726	212216.2
GR 3	4232.373	-0.00223	1.61E-03	0.002749129	242465.7
GR 4	4457.509	-2.14E-03	1.73E-03	0.002749172	255363.3
GR 5	4579.579	-0.00216	1.70E-03	0.002748994	262356.5
GR 6	2985.304	-0.00247	0.001162	0.002733703	171023.2
GR 7	5007.791	-0.00211	0.001759	0.002746152	286888.1
GR 8	3035.765	-0.00248	0.001157	0.002735021	173914.0
GR 9	2740.942	-0.0025	0.001087	0.002727805	157024.0
GR 10	-1844.130	-0.00241	0.000197	0.002421189	-105647.0

Table 7 Statistical Analysis of Models

Region	Mean (m)	RMS (m)	MAE (m)	MBE (m)
Western	0.001810	0.000181	0.004254	0.004254
Ashanti	0.002154	0.000431	0.009282	0.009282
Central	0.002235	0.000223	0.004728	0.0047228
Eastern	0.002572	0.000367	0.007245	0.007245
Greater Accra	0.002707	0.000271	0.005203	0.005203

All bodies' response to the universal law of gravitation, the intensity of the effects of tides depends upon the mass of the bodies and the distance separating them. The Earth and the celestial bodies revolve in equilibrium round their common centre of gravity which is situated in the earth's centre. Every day, the earth experience two tides, that is, the lunar tides in the evening and the solar tides during the day. The moon being the nearest celestial body to the earth is a major tide-producing body. The sun gives rise to two oppositely situated wave crests, but because the sun is far from the Earth, its tide-raising force is only about 46 percent that of the Moon. It can be seen from the statistical analysis that the quantification model performs well in both the coastal and non-coastal regions.

4 Conclusions

The solid earth tides introduce noise into the position of structures at a magnitude within the ranges of 1.81×10^{-3} m to 2.70×10^{-3} m which indicates that, without proper quantification of tidal effects based on geographical location and incorporating this into monitored values of engineering structures, will result in misrepresentations of the actual cause of deformation of structures. The present study has quantified the effects of tides on the earth crust for the selected regions of Ghana through numerical quantities. From the analysis of the results, it can be concluded that deformation of structures within the study area can partly be attributed to the effects of tides.

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