Determination of Vertical Movement for Deformation Monitoring of a Bridge Using GPS Technique

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Abstract

Deformation analysis using height differences is imperative to the determination of vertical movements in engineering structures, landslide areas and crustal deformations. GNSS technology and data processing software have made these observations much more convenient, accurate and cost-effective tool for monitoring of natural and man-made structures. Here, we determine the vertical movement of a bridge with respect to control network established on stable grounds. These include pre-analysis, survey design, data collection, data reduction, adjustments determination of maximum expected displacement and its accuracy requirement. The observations are carried out in geodetic monitoring network in three epochs (2017, 2018 and 2019), and by this way stable network are verified. The instrument employed is Pro-mark3 and its accessories for measuring planimetric positions and elevations of points. Once the survey have been conducted, GNSS Solutions provides accurately determine site locations within the parameters establish. Least squares adjustment was used for rigorous adjustment of GPS carrier-phase measurements. The statistical test was carried out using Fisher Table and by computing T- test values. Finally the results obtained portrayed that the bridge, even though has minor vertical movement is found to be stable.

Keywords: Engineering Structure, Vertical Movement, Deformation Monitoring, GNSS, T-test

INTRODUCTION

Height is the most important parameter in deformation monitoring of engineering structures due to pressures from overload of vehicles and natural events such as landslides due to crustal movements, tsunamis etc. Previously, deformation studies depended on use of in situ-based equipment such as Total Stations and theorolites. However, contemporary works on deformation monitoring employs the use of global navigation satellite system (GNSS) and its post-processing software that improves the results (Chen *et al*., 2000; Kutoglu, 2010). This makes the studies more convenient, accurate and cost-effective for monitoring deformation of natural and man-made structures. These, however depend on good control points and reference network (Rutledge *et al.*, 2001; Kaloop and Li, 2009). Bridges and flood control structures are subject to external forces that affect them right from foundation. This is as result of deflection in horizontal axis of structure and/ or settlement in vertical direction. Hence, any indication of instability either on the horizontal or vertical axis may threaten the safety of the structure. Therefore, careful monitoring of the external forces on a structure and its responses can aid in determining abnormal behavior of that structure. Thus careful monitoring of vertical movement of the structure is required to determine the abnormal behavior of the structure in order to avoid risk of lives and properties.

Geotechnical structural measurements of local deformations uses tilt meters, strain meters, extensometers, joint meters, laser distance gauge method, etc. Each type of the measurements has its own advantages and drawbacks (Erol, 1999; Beshr, 2004). The acceleration integration method integrates the acceleration, which is measured by acceleration gauge, to obtain the displacement. But its error is relatively large. The laser distance gauge method is often influenced by the weather. Furthermore, the geotechnical structural measurements often need to stop the traffic, which brings a lot of costs. So these methods are suitable for some structures whose survey distance is relatively short and the displacement is relatively small, but to structures such bridges, these methods are difficult to use.

GPS (now called GNSS because of the use of other satellite positioning systems such as GLONAS, EGNOS that are currently active) has the potential for employing fewer manpower for conducting surveys. The limitations of large-scale GPS applications to structural deformation monitoring are the relatively high cost of dual frequency GPS receivers, effects of a number of potential errors, large volumes of GPS data due to high sampling rate, and high precision requirements (Kutoglu, 2010).

GPS has been used to monitor engineering structures for a number of reasons. One important reason for monitoring high rise buildings and other engineering structures is their safety assessment in events of extreme loading, such as earthquakes and storms (Raziq, 2009). Monitoring is necessary because engineering structures are liable to movements and failures (Stewart and Tsakiri, 2002). Deformation Monitoring refers to the determination of movements of a structure obtained by referring those movements to a network of control points outside the structure (Ndlovu, 2014). The location of the sensors or the observed targets must include points where maximum or critical deformations are expected (Chrzanowski, 1993) while the location of reference stable points must be based on the knowledge of the boundaries of the deformation zone. Thus, the investigated deformable object must be treated as a mechanical system, which undergoes deformation according to the laws of continuum mechanics (Szostak - Chrzanowski *et al* 2006). The GPS is a satellite-based positioning and navigation service used to obtain geodetic coordinates at a user location in the 1984 World Geodetic System (WGS84). In the global test, after the free adjustment calculations of the networks separately, the combined free adjustment is applied to both epoch measurements (e.g. Ayan, 1982; Ayan *et al* 1991).

This study focuses on GNSS techniques to monitor vertical movement of a bridge. We aim to determine the vertical movement of the bridge with respect to control network previously established on stable ground. This is achieved through determining maximum expected displacement and its accuracy requirement, pre-analysis, survey design, data collection, data reduction and adjustments of results. The purpose of monitoring and analysis of Jimeta Bridge is to provide technical guidance with the use of the Global Positioning System (GPS) for measuring and monitoring three-dimensional (3D) displacements on the structures. Technical guidance on procedures, standards, and specifications recommended for data collection and analysis are considered. These are employed to check whether the behavior of the bridge and its surrounding area follow the predicted pattern. As a result, this paves way for detection of possible vertical movements at an early stage. Interpretation of deformation status is used for the determination of causative factors that trigger the vertical movement.

Jimeta Bridge had been constructed since four (4) decades, and to our knowledge, no previous studies has been undertaken to examine its vertical movement. The processes of field work, office planning and reconnaissance as well as criteria for monitoring network are considered. Surveying requirements for accuracy, system performance, and equipment are of geodetic requirement. Procedures and specifications for planning, fieldwork and data collection are covered based on Surveyor’s Council of Nigeria regulations. Data processing procedures are described as well as the software and processing requirements for baselines and networks that include least squares.

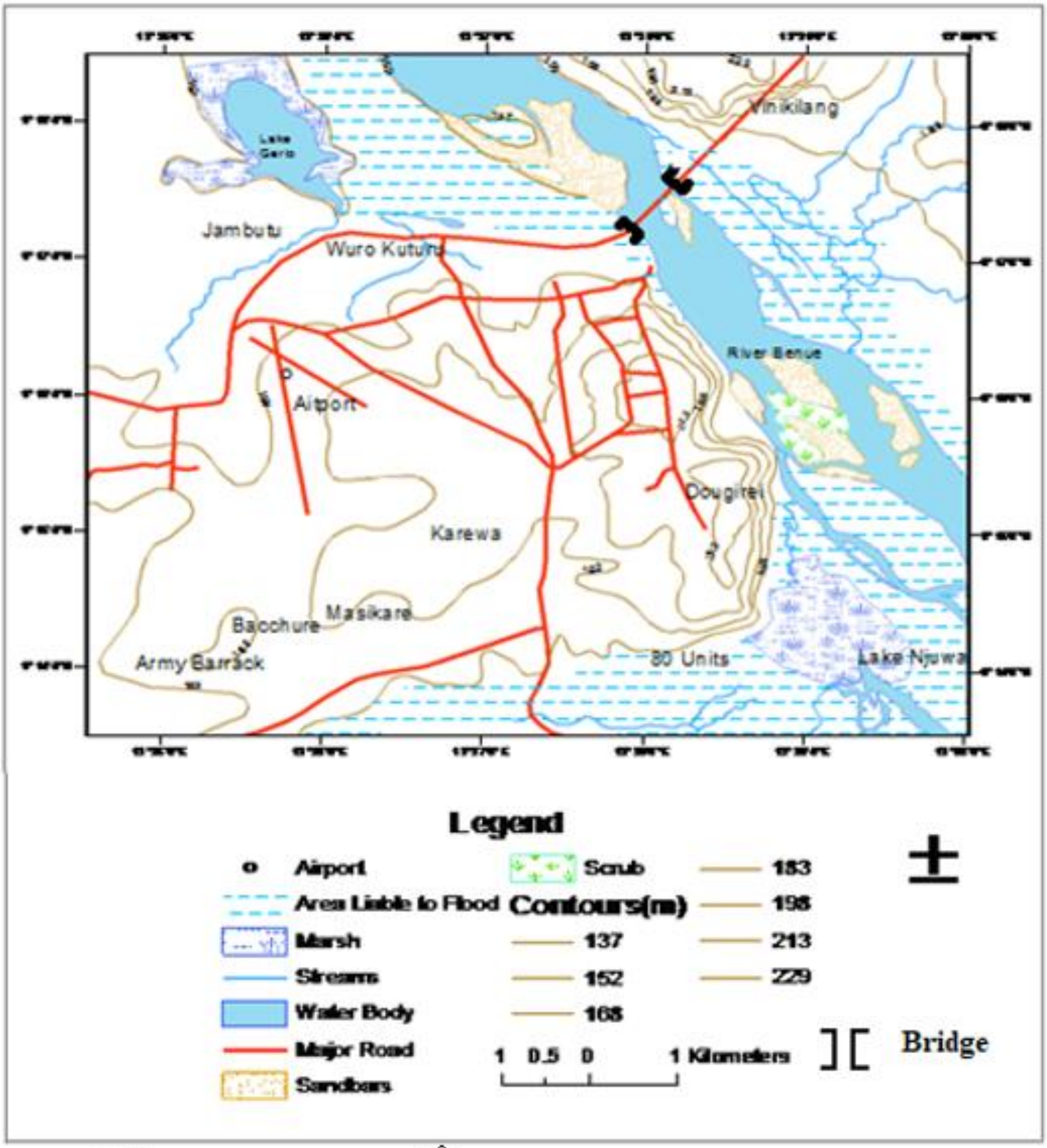

Figure 1: Jimeta town showing the location of the bridge (top). Map of Nigeria showing location of Jimeta (red dot - bottom).

Study Area/Site

Jimeta Bridge is about 1.2km long with location and centre point coordinate as 9.2974E and 12.47216N. It has been built across River Benue at entry of Jimeta from Mubi. The river is approximately 1,400 kilometers (870 mi) long and is almost entirely navigable during the summer months. It rises in the Adamawa Plateau of northern Cameroon Republic, from where it flows west, and through the town of Garoua and Lagdo Reservoir, into Nigeria south of the Mandara mountains. It reaches Jimeta and passed through Ibi and Makurdi before meeting River Niger to form a confluence at Lokoja. Large tributaries are the Gongola River and the Mayo Kébbi, which connects it with the Logone River (part of the Lake Chad system). It has a mean discharge of 3400 m^3/s. During the following decades, the runoff of both rivers decreased markedly due to irrigation. The Lagdo Dam, a 40m high dam, has been built across the river about 50km upstream of Garoua. It classified as tropical climate condition that is Girei Local Government Area in general. The summer is much rainier than the winter with average annual temperature of 27.5˚C and 940mm of precipitation falls annually. Below is study area;

METHODOLOGY

The observations are carried out on an established geodetic monitoring network in three epochs (2017, 2018 and 2019) after verifying the stability of these network stations. The stable networks are the control points established previously by Takana and Buba (2017) on the stable terrain completely away from monitoring stations. This provides way to determine the changes on the observed structure or area following Demirel (1987). Rigorous adjustments using least square as standard for monitoring scheme has been carried out on each set of observation and this was achieved using GNSS software. The instruments used were GPS (Promark 3) and its accessories for measuring elevations of points. The position of a pin-point location of the monitoring points were fixed on the flank of the bridge within a few millimeters (±5 mm over distances averaging between 5 and 10 km). The differential mode of observation with 30 minute semi-static mode had considerably portrayed a geodetic standard for deformation monitoring. Thereafter, the data had been processed using GNNS solutions to improve upon accuracy. More over rigorous geodetic observation technique and quality control protocols were adhered to for adjusting the data. All monitoring points were observed in multiple (pre-selected number).

In general, the deformation analysis was evaluated in three steps in a geodetic network. In the first step, the measurements, which were carried out in the measured epochs, are adjusted separately according to free adjustment method, and outliers and systematic errors are detected and eliminated. In the second step, global test procedure is carried out and by this test it is ensured that the network point was assumed as stable points. Once the survey have been conducted, GNSS Solutions accurately determine site locations within the parameters establish. Least squares adjustment was used at two different stages in processing GPS carrier-phase measurements; first, it is applied in the adjustment that yields baseline components between stations from the redundant carrier-phase observations. The second stage where least squares adjustment procedure was employed is in processing GPS observations in adjusting baseline vector components in networks.

Concept of Vertical Movement (Height)

This work focuses on vertical height measurements using both the master and rover of the instrument. The master was set at the control point on tripod stand. The height of instrument is measured with a steal tape that is from center of GPS to the control point. The measured height value is imputed in the setting of master receiver. The rover is vertically on the graduated rod of known height and it height is also imputed in rover`s receiver. The GPS would reduce the two heights to the height of control points and monitoring points respectively using the equation 1 below. For two stations occupied for an observing station that, one station is a control point and the second station is a point of unknown position on the bridge. Observation equations are written that relate station coordinates to the coordinate differences observed and their residual errors. The observation equation are written for each baseline component observed as follows;

$$Z_C = Z_A + \Delta Z_{AC} + V_{ZAC} \tag{1}$$

Similarly, the observation equations for the baseline components of line CD were

$$Z_D = Z_C + \Delta Z_{CD} + V_{ZCD} \tag{2}$$

The observation equations can be expressed in matrix form as;

$$Z_C = Z_A + \Delta Z_{AC} + V_{ZAC} \tag{3}$$

Similarly, the observation equations for the baseline components of line CD were

$$Z_D = Z_C + \Delta Z_{CD} + V_{ZCD} \tag{4}$$

It's should be noted that, because GPS networks contain redundant observations, they must be adjusted to make all coordinate differences consistent. In applying least squares to the problem of adjusting baselines in GPS networks, the observation equations can be expressed in matrix form as:

$$AX + L = V \tag{5}$$

Determination of the Deformation Values

Since the established control network would serve as a bench mark for subsequent monitoring observations, the scheme had required to introduce relationships for progressive determination of deformation vectors in subsequent epochs. The deformation values were computed as explained below. The deformation vector for any point was given as;

$$\underline{d} = \begin{bmatrix} x_k^j - x_k^i \\ y_k^j - y_k^i \\ z_k^j - z_k^i \end{bmatrix} = \begin{bmatrix} d_x \\ d_y \\ d_z \end{bmatrix}$$

And the magnitude of the vector is given as

$$d = \sqrt{\underline{d}^T \underline{d}} \tag{6}$$

To determine the significance of these deformation vectors, which are computed according to above equations, the H_o null hypothesis is carried out as given as;

$$Ho : d = 0 \tag{7}$$

From equation 4 above the deformation model for computing the deformation values in each epoch is given in table 1.

Table 1 Deformation Vector Model of Vertical Movements

Station	Z_k^j - Z_k^i = $\underline{d}z$
TP01	Z_1^k - 185.431 = $\underline{d}$
TP02	Z_2^k - 187.720 = $\underline{d}$
TP03	Z_3^k - 190.024 = $\underline{d}$
TP04	Z_4^k - 192.477 = $\underline{d}$
TP05	Z_5^k - 194.809 = $\underline{d}$
TP06	Z_6^k - 197.061 = $\underline{d}$
TP07	Z_7^k - 196.058 = $\underline{d}$
TP08	Z_8^k - 189.049 = $\underline{d}$
TP09	Z_9^k - 192.270 = $\underline{d}$
TP10	Z_{10}^k - 199.319 = $\underline{d}$
TP11	Z_{11}^k - 200.304 = $\underline{d}$
CP12	Z_{12}^k - 197.949 = $\underline{d}$
TP13	Z_{13}^k - 195.588 = $\underline{d}$
TP14	Z_{14}^k - 193.255 = $\underline{d}$
TP15	Z_{15}^k - 190.882 = $\underline{d}$
TP16	Z_{16}^k - 188.552 = $\underline{d}$

Where, Z= height, j=number of stations, i=number of observations, k is the number of epochs and d=residuals (vector of deformation). Also the Statistical test values would be computed using:

$$T = \frac{\underline{d}^T \underline{Q}_{dd}^{-1} \underline{d}}{3s_0^2} \tag{8}$$

Where;

$$s_0^2 = \frac{\underline{v}_1^T \underline{P}_1 \underline{v}_1 + \underline{v}_2^T \underline{P}_2 \underline{v}_2}{f_1 + f_2} \tag{9}$$

$$Q_{dd} = Q_{H_1H_1} + Q_{H_2H_2} \tag{10}$$

Where Q is the cofactor and is given by;

$$Q_{(6,6)} = W_{(6,6)}^{-1} = diag\left[\sigma_{S_1}^2, \sigma_{S_2}^2, \sigma_{\alpha_1}^2, \sigma_{\alpha_2}^2, \sigma_{\gamma_1}^2, \sigma_{\gamma_2}^2\right] \tag{11}$$

In which σ^2_{s1}, σ^2_{s2}, σ^2_{s3}, σ^2_{s4}, σ^2_{s5}, and σ^2_{s6}, are the standard deviations of the observations. The test values T, standard deviation σ^2_{si} and RME vectors σ_{si} are computed. In this model, all observations were assumed to be independent and uncorrelated. Statistical test analysis for structural deformation observations is carried out using F-Fisher criterion with a confidence level of 95%. Test values T_i above are computed in dependence on the resulted values of coordinate displacements vector and vector of its accuracy (RME vector). While this test value is compared with critical value, If the test value T is greater than the critical value, i.e. $T \geq F$ (h, f, 1- α), (where1- α is the confidence level), it is said that there is a significant vertical deformation in that point (Denli, 1998). Statistical test was done for each monitoring point.

RESULTS AND DISCUSSION

The observations yielded results for all the stations comprising 16 stations (see figure 2). Vertical movements are observed from all stations, ranging from negative to positive values. Some stations indicate upward movement of the bridge while others show the pillars sinking.

Highest positive values that indicate upward movement reaches 0.04m at CP12, while sinking appears in TP06 and TP07 both having values of approximately -0.09m for 2017 and 2019. These two columns are at the centre of the deepest water level. Interestingly, TP11 shows a fairly firm and stable column.

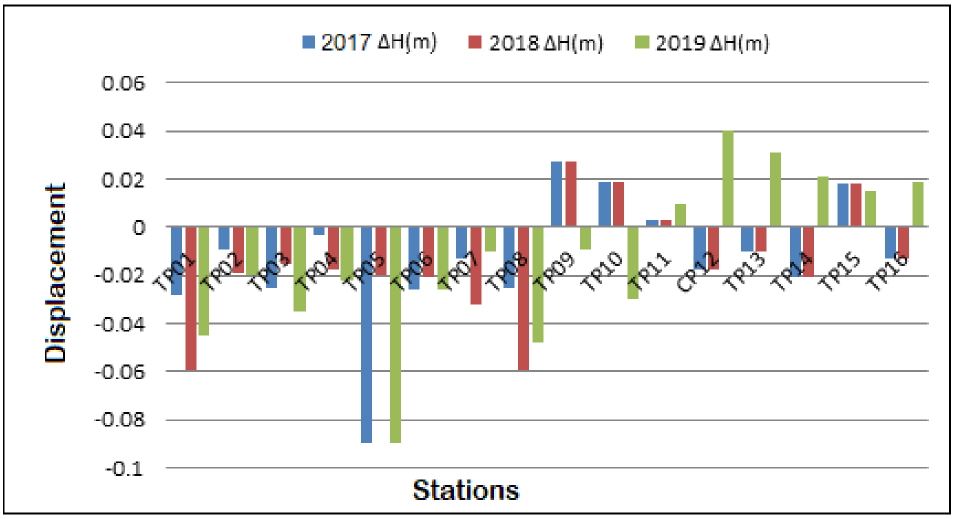

Figure 2: Deformation vector in across the stations for the three epochs.

Table 2 presenting the deformation vectors is computed using equation 4 as in the model (table 1). Figure (3) showed the displacement vectors on map. There were no significant movements detected and all stations' displacements are under threshold at all epochs. Next, GPS processed data were analyzed continually using the aforementioned method. The results of stability analysis show all the stations are stable despite little movements. The fluctuation of monitoring stations is revealed through plotting ΔH in three epochs (2017, 2018 and 2019). Analyzes was performed also based on the column chart (fig. 4) the displacement range.

Table 2: the deviation of reference stations coordinates between three observations epochs and the calculated test values.

Station	Standard deviation	Deformation vector	T-test Values(m) vs critical values(m)	Status
TP01	0.02539	-0.044	0.000645 < 3.68	Stable
TP02	0.009416	-0.016	8.87E-05 < 3.68	”
TP03	0.01493	-0.025	0.000223 < 3.68	”
TP04	0.010874	-0.01433	0.000118 <3.68	”
TP05	0.046904	-0.06667	0.0022 < 3.68	”
TP06	0.012393	-0.02433	0.000154 < 3.68	”
TP07	0.044485	-0.04833	0.001979 <3.68	”
TP08	0.026166	-0.044	0.000685 < 3.68	”
TP09	0.0155	0.015	0.00024 < 3.68	”
TP10	0.037968	0.002667	0.001442 < 3.68	”
TP11	0.016701	0.005333	0.000279 < 3.68	”
CP12	0.025915	0.001333	0.000672 < 3.68	”
TP13	0.022066	0.003667	0.000487 < 3.68	”
TP14	0.020106	-0.007	0.000404 < 3.68	”
TP15	0.021777	0.017	0.000474 < 3.68	”
TP16	0.015213	-0.00233	0.000231 < 3.68	”

* 3.68 is the critical value obtained from the F-distribution table.

CONCLUSION AND RECOMMENDATION

Since the least square adjustment technique was applied, the adjusted coordinates and its associated accuracy of each point were calculated for all epochs. The standard deviations vary from 0.9mm to 44mm in the vertical components. Practically, the overall data analysis has shown that the qualities of the observation for all campaigns are indicated high precision and accuracy. Prior to this, the deformation values shown in the table 1 expressed random movement as portrayed using the graph (figure 2). This random movement is significantly small and may be attributable partly due to seasonal overflow of rainfall and debris that affect the bridge as we as random errors associated with field observations. The computed T- test values as compared with the critical value using the Fisher Table revealed the bridge is stable. It is recommended that important bridges such as this long 1.2km be monitored using continuously operating reference stations (CORS) to examine longer time series of observations.

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