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Deformation Monitoring of Lotsane Bridge Using Geodetic Method

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Abstract: ***Civil engineering structures such as dams, bridges, tunnels, high rise buildings etc. are susceptible for deterioration over a period of time. Bridges in particular deteriorate after being constructed due to loading conditions, environmental changes, earth movement, material used during construction, age and widespread corrosion of steel. Bridge deformation monitoring is most important as it determines quantitative data, assesses the state of the structure and detects unsafe conditions at early stages and proposes necessary safety measures before can threaten the safety of vehicles, goods and human. Despite government's efforts to construct roads and highways in most African countries, bridge deformation monitoring is not given priority and ultimately causes some bridges to collapse unexpectedly. In this paper we present a geodetic approach of bridge deformation monitoring of Lotsane bridge in Palapye, Botswana. The horizontal positions of reference and monitoring points were determined using Global Positioning System (GPS) while the height components were determined using precise leveling. The accuracy of the adjusted control points in x, y and z were 0.020m, 0.146m and 0.33m respectively. The final adjusted coordinates of the reference and monitoring points are presented and will be used for deformation monitoring of the bridge for the first epoch in 2020.***

Keywords: Structural health monitoring, GPS, Precise Leveling, Bridge deformation

1. Introduction

Structural Health Monitoring (SHM) is a new concept in civil engineering which aimed at assessing the behavior and safety of constructed structures. The behavior assessment of civil engineering structures includes observation and analysis of points on the structure over different periods of time to determine the current state of the structure. Civil engineering structures such as bridges, high-rise buildings, dams, etc. are essential to social, human and economic development of any country. Bridges in particular are key infrastructures to settlements, towns and cities where either waterways or land barriers prevent transportation and other economic activities. Bridges after being constructed are susceptible to deterioration although are built to have life spans above three decades Beshr, A. A (2004). Deterioration is a failure of civil engineering structures which is mainly caused by environmental and non-environmental factors such as erosion, earthquake, floods, loading conditions and construction materials which may have been overlooked during design and construction periods Beshr, A. A (2010). The environmental and non-environmental factors are considered during design and construction stages as they help to understanding the status of a bridge within a specified period of time. It is imperative to understand that after construction a bridge has to undergo static load test to verify the load deformation response. Therefore, bridge monitoring is important aspect in obtaining quantitative data about the structure for safety of people, goods, social and economic aspects. Deformation is defined as the process of distorting or changing the original position, shape or dimensions of a structure in horizontal or vertical Brownjohn (2017) Deformation monitoring of engineering structures helps to detect defects at early stages or abnormal behavior and propose necessary safety measures before it can threaten the safety of vehicles, goods and human. Daniele, I., et al (1999) pointed out that continuous monitoring for civil engineering infrastructures is considered to be a valuable tool to complement other nondestructive methods in improving reliability and extending lifetime of bridge structures.

Structural deformation is grouped into two major parts namely long term and short term deformation Erol, S. (2004). Long term deformation monitoring is caused by bridge foundation settlement, deck creep and stress relaxation, while short term deformation is caused by the dynamic effects such as wind, temperature, traffic, age and earthquake Erol, S. and Ayan, T. (2003). Based on the analysis of data obtained after deformation monitoring, proper repair or rehabilitation can be conducted to keep the bridge much longer. The cost for monitoring and repair is much lower as compared to reconstruction cost of new bridge. Therefore, monitoring of civil engineering structures is very vital for safety and economy growth of any country. In order to effectively monitor the abnormal behavior of a bridge, a precise measuring mechanism is required. The output of monitoring is to provide information on the state of the bridge despite of its age and operational environments.

In recent years we have witnessed bridges collapsing in many parts in the world. For example, in Italy for example, a bridge at Genoa collapsed killing dozens of people and damaged vehicles and other properties (https://www.euronews.com/tag/italya-daki-kopru-kazas-).

In South Africa, a pedestrian bridge which was under construction collapsed along M1 highway and damaged vehicles and properties. In the Southern District Council of Botswana a bridge collapsed as a result of failed culvert structure which gave-in from water pressure at a site of construction. According to a statement issued by the Roads Department blamed the contractor for a failed culvert structure which caused the bridge to collapse. The collapsed bridges cause the government loss of property and resources for reconstruction of new bridges. Indeed, lack of short and long term bridge monitoring mechanism is a major factor for this phenomenon.

There are several techniques have been employed for bridge deformation monitoring. These techniques are categorized into two major group's namely geodetic and no-geodetic techniques. Geodetic and non-geodetic methods have their own advantages and disadvantages John, O. O. (2015). Geodetic techniques are based on connected points who's angular, linear and height measurements are observed. Based on these points the behavior of a structure can be easily detected. In addition, geodetic techniques it includes also conventional leveling, bearing and distance measurements, photogrammetry (aerial and digital photogrammetry), and the use of satellite positioning (Global Positioning System-GPS, GPS and InSAR). The advantages of geodetic method include the capability of providing horizontal and vertical information that can quantify the magnitude of behavior of the bridge at any location with respect to some reference points.

Non-geodetic techniques or commonly known as geotechnical techniques include the application of sensors, laser, tilt-meters, strain-meters, extensometers, joint-meters, plumb lines, micro-meters, and Linear Vibrating Displacement Transducers etc. The limitations of non-geodetic techniques include provision of local information of a bridge without detailed errors analysis of the behavior of the structure. In addition, non-geodetic methods provide one dimension solution. Park, H. S et al., (2008)detected and localized damages in the superstructure of the concrete box bridge whereby numerical and experimental modal parameters were used as input to localize the damage in the bridge superstructure. The results shows that environmental conditions, such as the extreme differences in moisture conditions may have significantly affect the accuracy of the damage locations of the bridge.

For decades, the roads department at the Ministry of Infrastructure Development in Botswana has been collecting data on roads and bridge conditions. Data collected includes visual inspection of cracks, raveling, bleeding and rutting. However, visual inspection has serious shortcomings which include limited accuracy, subjective results, time consuming and cost ineffective. Based on visual inspection carried out in 2019 it shows that some of the bridges in the Central district have visible signs of damages. Apart from visual bridge inspections there has been no attempts made by the department to develop bridge monitoring mechanism. Lack of bridge monitoring mechanism may have been caused by limited resources, tools and advanced techniques. In this paper we present a geodetic approach of deformation monitoring of Lotsane bridge along heavy traffic highway in Palapye, Botswana. The reference and monitoring points were established using GPS and precise leveling was used to determine height components of reference and monitoring points.

2. Methodology

2.1 Study Area

Lotsane Bridge along Botswana A1 highway was selected as a case study for the purpose of establishing geodetic points for deformation monitoring. Lotsane Bridge is situated in Palapye 260km north from Gaborone city, 168km south of Francis town and 28km from Serowe village. The bridge was constructed across Lotsane River and it is a link between Gaborone Capital city and neighboring city of Bulawayo in Zimbabwe. The bridge has 37.7m long, 12m wide and 9.6m high. The bridge has two lanes in two way directions and was constructed using reinforcement concrete in three spans and supported with 3 pillars. Fig.1 shows the photograph of Lotsane bridge.

Figure 1: Lotsane Bridge, Palapye

2.2 Geology of Palapye

Lotsane bridge is on the Central District of Botswana whereby a weathered zone lies under the Gaborone – Francis Town road (A1). The rocks and soils found around the study area is silty sand, sandy calcrete, mudstone, calcrete, siltstone, siltstone, carbonaceous shale, coal, carbonaceous shale.

2.3 Planning and Establishment of reference and Monitoring Points

The established points at the bridge were 8 reference and 14 monitoring points. The reference points were established and fixed on a stable ground away from the bridge. The monitoring points were fixed on the bridge with at equal intervals of 6m at all sides of the bridge. The advantages of separating these points were to ensure that the reference points are well spaces for relative and absolute accuracy. In addition, configuration of eight reference points was located on a four braced quadrilaterals (Figure 2) whereby each quadrilateral consists of 4 points. Two baselines were selected and their coordinates were determined using Sokkia GPS equipment. The GPS receiver was first set over a known point BM5 in Palapye and the rover was then centered over the control points on both sides for 20 minutes to measure the coordinates for these points. The GPS was then set over the 8 reference points LT01, LT02, LT03, LT04, LT05, LT06, LT07 and LT 08 and BR8. The same process was repeated using a known point PMR33. The monitoring points were fixed on bridge using aluminum sheets inserted inside the concrete about 6cm The monitoring points were BR1, BR2, BR3, BR4, BR5, BR6, BR7, BR8, BR9, BR10, BR 11, BR 12, BR 13 and BR 14., BR12, BR13 and BR14. The coordinates of reference and monitoring points were determined using Global Positioning System (GPS). GPS utilizes network satellites by sending carrier-phase signals to receivers on earth to obtain the exact position of something in real-time. Not only GPS measures the magnitude of deflection, it also measures the frequency of the movements of structures.

GPS has the ability to provide real-time 3D positioning through triangulation between satellites and it can be used under all weather conditions. In addition, GPS have advantages as it provides high accuracy coordinates (millimeter accuracy) although height information being the least accurate of the 3D coordinates. As stated above, however, general achievable accuracies with GPS in horizontal component are in the order of 1cm. The accuracy is slightly bad in the height component which is mainly due to inherent geometric weakness and atmospheric errors which tend to increase when parts of the space is obstructed by other features and structures Featherstone, W. et al., (1998); Celik, et al., (2001). The 8 reference and 14 monitoring points were established and fixed on a stable ground away from the bridge. The monitoring points were fixed on the bridge at equal intervals of 6m at all sides of the bridge. Figure 2 below shows the configuration of reference and monitoring points. The advantages of separating these points were to ensure that the reference points are well spaces for relative and absolute accuracy. In addition, configuration of eight reference points was located on a four braced quadrilaterals (Figure 2) whereby each quadrilateral consists of 4 points.

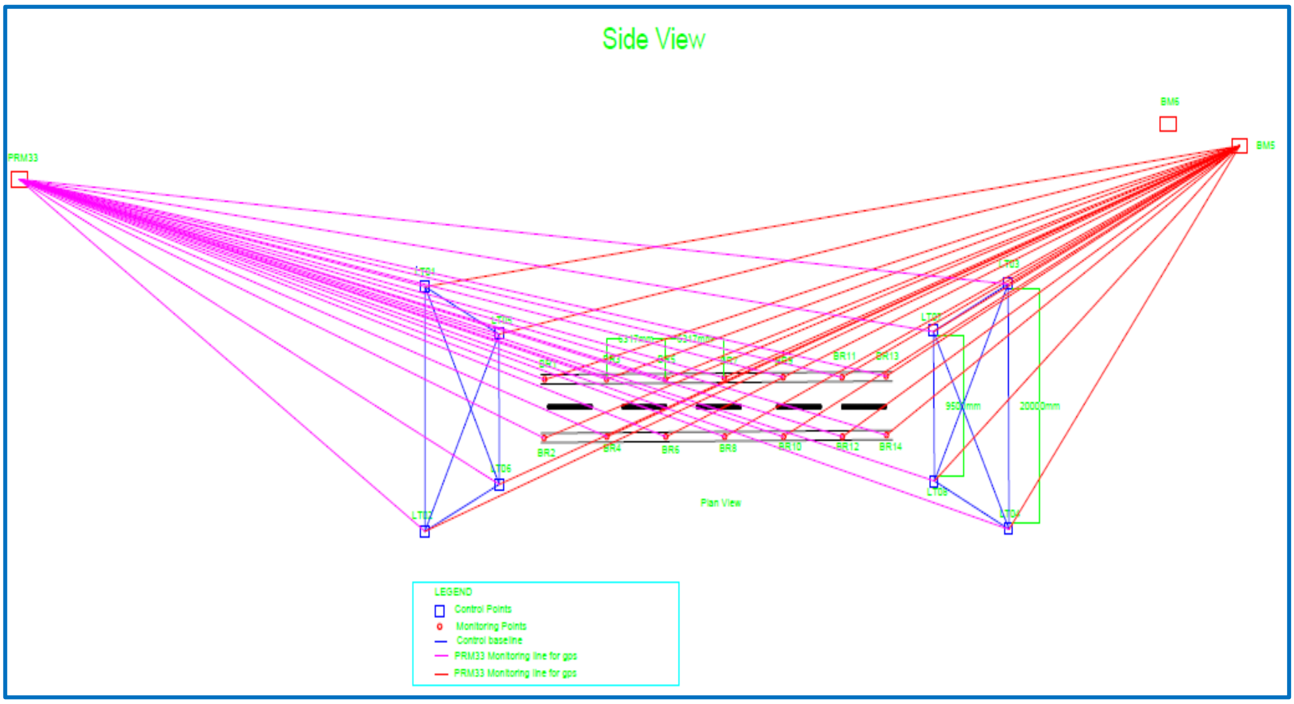

Figure 2: Configuration of Reference and monitoring points

2.3 Data Collection

2.3.1 Coordinates of Reference Points

A major consideration for data collection was data quality which aimed at obtaining high quality data and minimizes low quality data [10]. One Sokkia GPS receiver was used to fix both reference and monitoring points whereby one baseline was established and coordinated. After fixing the baseline points, the rover of the GPS was set at reference point LT01, LT02, LT03, LT04, LT05, LT06, LT07 and LT08 while the base GPS was positioned at point PRM 33. After fixing the reference points, the rover was used to coordinate points BR1, BR2, BR3, BR4, BR5, BR6, BR7, BR8, BR9, BR10, BR11, BR12, BR13 and BR14.

2.3.2 Leveling of Reference and Monitoring points

As stated above, GPS provides better accuracy in x and y components but has inferior accuracy in height component. In order to improve the accuracy of GPS height component of reference and monitoring points, precise leveling was carried out. The precise leveling was carried out to provide data as independent check of the vertical height determined by GPS solutions. Precise leveling was conducted starting from Bench Mark PZ1 through all reference and monitoring points and closed on Bench Mark PZ4. Figure 3 below shows the leveling route from PZ1 to PZ4.

2.4 Data Processing

2.4.1 Least Squares Adjustment

After GPS observations of reference and monitoring points (zero epoch), raw data were stored into the internal memory of the receiver and downloaded into the computer derived and adjusted by least squares adjustment using Magnet processing software to determine the reliability of the adjusted coordinates. The GPS observations were adjusted based on equations (1) and (2) as described below:

$$\begin{pmatrix} v_1 \\ v_2 \\ v_3 \\ \cdots \\ v_m \end{pmatrix} = \begin{pmatrix} a_{11} a_{12} \ldots a_{1n} \\ a_{21} a_{22} \ldots a_{2n} \\ \ldots \ldots \ldots \ldots \ldots \\ a_{m1} a_{m2} \ldots a_{mn} \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \\ \cdots \\ x_n \end{pmatrix} - \begin{pmatrix} l_1 \\ l_2 \\ \cdots \\ l_m \end{pmatrix} .. \quad (1)$$

$$\text{Where: } V = \begin{pmatrix} v_1 \\ v_2 \\ v_3 \\ \cdots \\ v_m \end{pmatrix}, \text{ A=} \begin{pmatrix} a_{11} a_{12} \ldots a_{1n} \\ a_{21} a_{22} \ldots a_{2n} \\ \ldots \ldots \ldots \ldots \ldots \\ a_{m1} a_{m2} \ldots a_{mn} \end{pmatrix}$$

$$\text{X=} \begin{pmatrix} x_1 \\ x_2 \\ \cdots \\ x_n \end{pmatrix} \text{ and } L = \begin{pmatrix} l_1 \\ l_2 \\ \cdots \\ l_m \end{pmatrix}$$

A is a design Matrix, X is a Vector of unknowns, L is different between calculated and observed values and V is residual Matrix.

$$\text{X= } (A^T W A)^{-1} (A^T W L)^{-1}) \ldots \ldots \ldots \ldots \ldots .. (2)$$

Where: A is design matrix, L is observation matrix, and W is the weight matrix of the adjusted GPS observations. The weights were determined based on the standard deviation of each measurement as shown in equation 3.

$$W_i = \frac{1}{\sigma_i^2} \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots .... (3)$$

Where:

W_i *is the observation weight*

σ_i is the standard deviation of the measurement. The standard deviation of unit weight for the weighted observations (σ_i) is given as:

$$\sigma_i = \pm\sqrt{\frac{V^T PV}{r}} \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots (4)$$

V *is the vector of residuals*
P is the weight
r is the degree of freedom

Based on equation (4) above, the standard deviations for x and y are 0.038m and 0.146 in y respectively.

3. Analysis of the Results

After adjustment, the horizontal displacement were computed whereby the magnitudes of displacement in x, y and z were determined and shows that there were within the tolerable limits and that the monitoring points were accurately established. Table 2 below shows that the magnitude of displacement of horizontal coordinates. The adjusted vertical coordinates of reference and monitoring points were compared with the height obtained from precise leveling to determine their displacement magnitude. Table 4 shows the magnitude of displacement of vertical height of GPS and precise leveling.

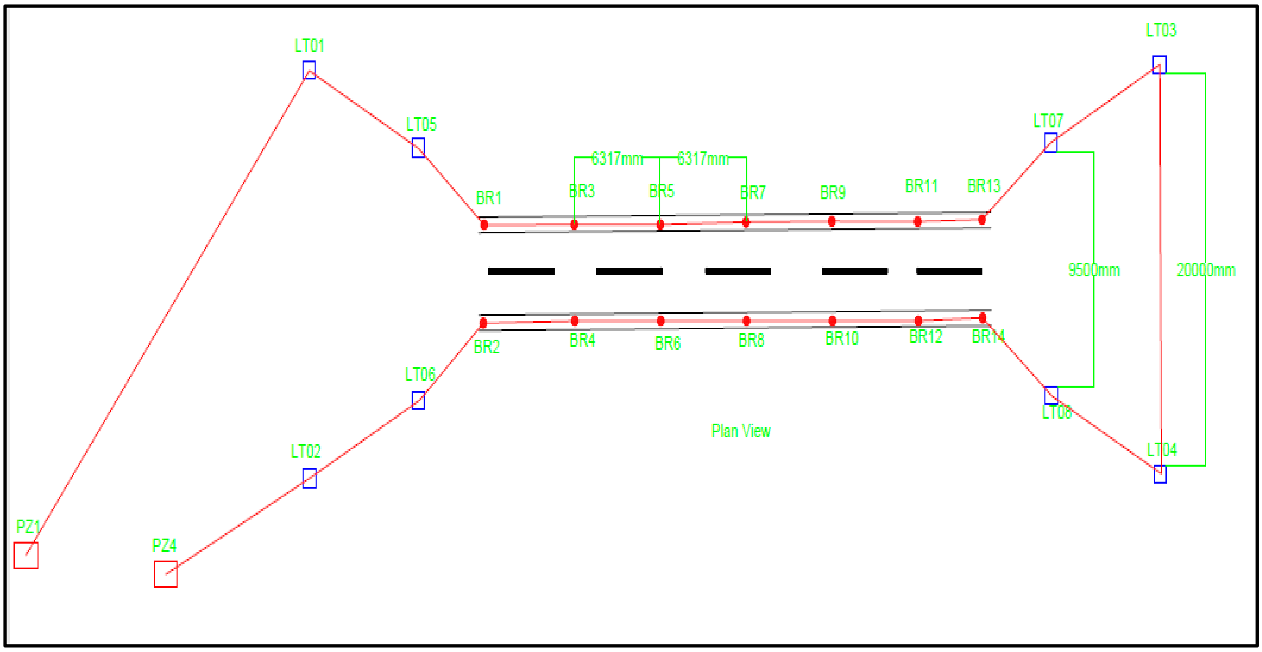

Figure 3: Leveling route of reference and monitoring points …

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Table 2: Magnitude of displacement in x, y and z

Name	dN (m)	dE (m)	dHt (m)	Horz RMS	Vert RMS
PRM33−PRM30	-367, 537	-158, 898	1, 108	0, 002	0, 003
PRM33−LT-01	1110, 753	565, 95	-4, 814	0, 002	0, 003
PRM33−LT-02	1084, 198	615, 635	-5, 225	0, 002	0, 003
PRM33−LT-03	1073, 134	551, 819	-5, 675	0, 002	0, 003
PRM33−LT-04	1052, 963	577, 216	-5, 91	0, 002	0, 003
PRM33−LT-05	964, 715	452, 686	-4, 482	0, 002	0, 003
PRM33−LT-06	929, 053	494, 268	-4, 627	0, 002	0, 003
PRM33−LT-07	985, 661	472, 596	-5, 67	0, 002	0, 003
PRM33−LT-08	966, 419	508, 971	-5, 688	0, 002	0, 003
PRM33−BR-01	1025, 88	540, 308	-3, 637	0, 002	0, 003
PRM33−BR-02	1030, 82	534, 022	-3, 628	0, 002	0, 003
PRM33−BR-03	1020, 911	536, 461	-3, 592	0, 002	0, 003
PRM33−BR-04	1025, 871	530, 129	-3, 582	0, 002	0, 003
PRM33−BR-05	1015, 973	532, 647	-3, 576	0, 002	0, 004
PRM33−BR-06	1020, 942	526, 286	-3, 559	0, 002	0, 003
PRM33−BR-07	1011, 012	528, 83	-3, 573	0, 002	0, 003
PRM33−BR-08	1015, 953	522, 445	-3, 538	0, 002	0, 003
PRM33−BR-09	1006, 102	524, 945	-3, 573	0, 002	0, 003
PRM33−BR-10	1011, 048	518, 613	-3, 554	0, 002	0, 003
PRM33−BR-11	1001, 171	521, 103	-3, 601	0, 002	0, 003
PRM33−BR-12	1006, 051	514, 821	-3, 577	0, 002	0, 003
PRM33−BR-13	996, 177	517, 282	-3, 651	0, 002	0, 003
PRM33−BR-14	1001, 183	510, 896	-3, 623	0, 002	0, 003

Table 3: Comparison of GPS height and precise leveling

	Reference point=PRM33			Reference Point=BM5			Coordinate Differences		
	2493259.640	-9131.200	930.26	2499267.47	-13034.15	982.77			
Name	**Northing (m)**	**Easting (m)**	**H**	**Northing (m)**	**Easting (m)**	**Ht**	**ΔNorthings (m)**	**ΔEastings (m)**	**ΔH (m)**
LT01	2494370, 393	-8565, 25	925, 255	2494370, 416	-8565, 398	925.635	0, 023	0, 148	0, 380
LT02	2494343, 838	-8515, 565	924, 843	2494343, 859	-8515, 711	925.224	0, 021	0, 146	0, 381
LT03	2494332, 774	-8579, 381	924, 394	2494332, 817	-8579, 517	924.77	0, 043	0, 136	0, 376
LT04	2494312, 603	-8553, 984	924, 158	2494312, 558	-8554, 124	924.492	0, 045	0, 140	0, 334
LT05	2494224, 355	-8678, 514	925, 587	2494224, 395	-8678, 677	925.964	0, 04	0, 163	0, 377
LT06	2494188, 693	-8636, 932	925, 442	2494188, 715	-8637, 084	925.804	0, 022	0, 152	0, 362
LT07	2494245, 301	-8658, 604	924, 399	2494245, 336	-8658, 744	924.759	0, 035	0, 140	0, 360
LT08	2494226, 059	-8622, 229	924, 38	2494226, 117	-8622, 365	924.839	0, 058	0, 136	0, 459
BR01	2494285, 52	-8590, 892	926, 432	2494285, 54	-8591, 044	926.794	0, 02	0, 152	0, 362
BR02	2494290, 46	-8597, 178	926, 441	2494290, 495	-8597, 329	926.81	0, 035	0, 151	0, 369
BR03	2494280, 551	-8594, 739	926, 477	2494280, 594	-8594, 882	926.836	0, 043	0, 143	0, 359
BR04	2494285, 511	-8601, 071	926, 487	2494285, 561	-8601, 216	926.859	0, 05	0, 145	0, 372
BR05	2494275, 613	-8598, 553	926, 493	2494275, 643	-8598, 705	926.851	0, 03	0, 152	0, 358
BR06	2494280, 582	-8604, 914	926, 51	2494280, 6	-8605, 055	926.879	0, 018	0, 141	0, 369
BR07	2494270, 652	-8602, 37	926, 495	2494270, 687	-8602, 521	926.86	0, 035	0, 151	0, 365
BR08	2494275, 593	-8608, 755	926, 531	2494275, 651	-8608, 891	926.9	0, 058	0, 136	0, 369
BR09	2494265, 742	-8606, 255	926, 496	2494265, 773	-8606, 413	926.857	0, 031	0, 158	0, 361
BR10	2494270, 688	-8612, 587	926, 515	2494270, 728	-8612, 744	926.871	0, 04	0, 157	0, 356
BR11	2494260, 811	-8610, 097	926, 468	2494260, 844	-8610, 24	926.834	0, 033	0, 143	0, 366
BR12	2494265, 691	-8616, 379	926, 492	2494265, 731	-8616, 527	926.838	0, 04	0, 148	0, 346
BR13	2494255, 817	-8613, 918	926, 418	2494255, 859	-8614, 062	926.79	0, 042	0, 144	0, 372
BR14	2494260, 823	-8620, 304	926, 446	2494260, 843	-8620, 455	926.795	0, 02	0, 151	0, 349

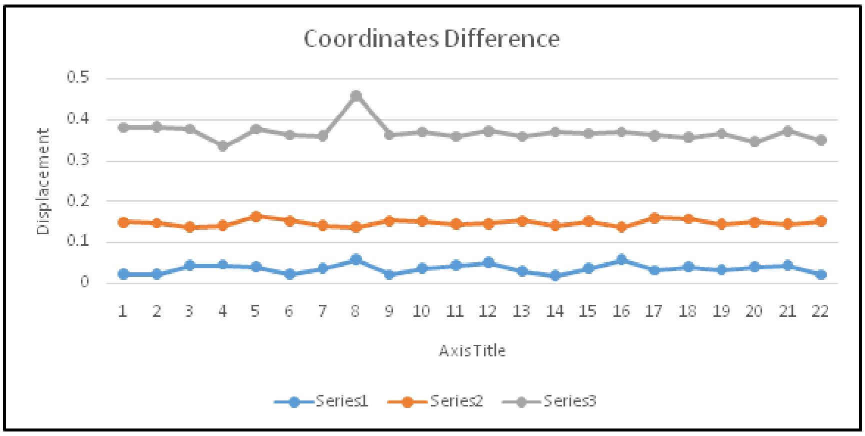

Table 4: Comparison of GPS height and precise leveling

Point	GPS height (m)	Precise Levelling (m)	Difference ($\Delta H_{GPS} - \Delta H_{LEVEL}$) (m)
LT01	925.255	919.341	5.914
LT02	924.843	918.928	5.915
LT03	924.394	918.478	5.916
LT04	924.158	918.238	5.920
LT05	925.587	919.688	5.899
LT06	925.442	919.631	5.811
LT08	924.399	918.489	8.910
BR01	924.380	918.748	5.632
BR02	926.432	920.522	5.910
BR03	926.477	920.562	5.917
BR04	926.487	920.581	9.906
BR05	926.493	920.575	5.924
BR06	926.510	920.586	5.924
BR07	926.531	920.590	5.905
BR08	926.531	920.590	5.927
BR09	926.496	920.590	5.906
BR10	926.515	920.595	5.920
BR11	926.468	920.567	5.901
BR12	926.492	920.570	5.922
BR13	926.418	920.510	5.908
BR14	926.446	920.527	5.919

Table 5: Final Coordinates of Reference and Monitoring points

Name	Northing (m)	Easting (m)	Heights (m)
LT01	2494370, 393	-8565, 25	919, 341
LT02	2494343, 838	-8515, 565	918, 928
LT03	2494332, 774	-8579, 381	918, 478
LT04	2494312, 603	-8553, 984	918, 238
LT05	2494224, 355	-8678, 514	919, 688
LT06	2494188, 693	-8636, 932	919, 631
LT07	2494245, 301	-8658, 604	918, 489
LT08	2494226, 059	-8622, 229	918, 748
BR01	2494285, 52	-8590, 892	920, 522
BR02	2494290, 46	-8597, 178	920, 521
BR03	2494280, 551	-8594, 739	920, 562
BR04	2494285, 511	-8601, 071	920, 581
BR05	2494275, 613	-8598, 553	920, 575
BR06	2494280, 582	-8604, 914	920, 586
BR07	2494270, 652	-8602, 37	920, 59
BR08	2494275, 593	-8608, 755	920, 604
BR09	2494265, 742	-8606, 255	920, 59
BR10	2494270, 688	-8612, 587	920, 595
BR11	2494260, 811	-8610, 097	920, 567
BR12	2494265, 691	-8616, 379	920, 57
BR13	2494255, 817	-8613, 918	920, 51
BR14	2494260, 823	-8620, 304	920, 527

3.1 Discussion of the results

After least-squares adjustment, small corrections were applied to the observations to obtain the best fit of the observations producing one solution for all points. These small corrections are residuals from the computed coordinates. For each point there were three residual components namely ($\Delta x, \Delta y,$ and Δz) for reference and monitoring points respectively. The result shows that the computed coordinates were free from blunders because in both cases the residuals were very small (Table 3). The minimum and maximum values in northings were 0.020m and 0.580m and 0.136m and 0.163m in easting respectively, while the standard deviation for x, y and z are 0.038m, 0.146m and 0.376m respectively. The GPS heights of reference and monitoring points show similar pattern. It can be seen from the Table 4 that height values from GPS observations are larger as compared to the height values obtained from precise leveling. However, it is important to mention that horizontal accuracy of both reference and monitoring points from GPS observation continued to be better.

4. Conclusion and Recommendations

Bridges are susceptible to deterioration due to heavy traffic, tectonic disturbances, corrosion of steel, erosion, age and type of construction materials. All these factors have tremendous effect on horizontal and vertical movement of the bridge which cannot be discovered by visual inspection. Therefore, it is imperative to monitor bridges and other civil engineering structures to determine quantitative data. Quantitative data will help to assess the state of the structure and detect at early stages unsafe conditions and propose necessary safety measures before it can threaten the safety of vehicles, goods and human. Eight reference stations and 14 monitoring points were established on a stable ground around the bridge. The horizontal positions of reference and monitoring points were determined using GPS while their corresponding height information was determined using precise leveling. The accuracy and reliability of reference and monitoring points were analyzed and the result shows that both points were established within the required accuracy. The 8 established reference and 14 monitoring points were accurate and reliable and will be used to determine bridge deformation for the first epoch which is expected to take place in 2020. It has been established that GPS observations provides accurate data in horizontal component but vertical component must be supplemented by precise levelling Based on the results the following are specific recommendations:

1. The coordinates of reference and monitoring points determined from this study be used for deformation monitoring of bridges using GPS measurements.
2. In order to eliminate height GPS errors, GPS measurements must be supplemented with Precise Leveling measurements or the use of GPS and laser system.

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