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# Deformation Monitoring of Dam Using GPS: Case Study Letsibogo Dam, Botswana

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**Abstract:** All civil engineering structures are susceptible for deterioration over a period of time after been constructed. Dams, bridges, tunnels, high rise buildings deteriorate due to different factors such as stress, unstable slopes, low foundation shearing strength, settlement, expansion from temperature changes, and age. As a results of these effects, long and short term deformation monitoring of these structures is very important to validate the construction specifications and safety measures. Long term deformation monitoring is mainly based on measurements of horizontal and vertical movement of the entire structure to ensure that every part of the structure is stable. In this work we present the first deformation monitoring of Letsibogo dam in Botswana by establishing baseline points using Global positioning Systems (GPS) which is capable of detecting structural movement in three dimension. The results obtained shows that the established reference and monitoring points measured by using GPS are reliable with standard deviations of 0.004m and 0.007m in x and y respectively and horizontal displacement of 1cm. In addition, the correlation coefficient for the observations $was\ \hat{\rho} = 0$ which confirms that the GPS measurements of reference and monitoring points are correlated. The position accuracy obtained is suitable for dam deformation monitoring for the first epoch which is expected to take place in 2020.

**Key words:** Dam deformation, geodetic technique, global positioning system.

## 1. Introduction

Civil engineering structures and dams in particular are susceptible to deterioration after being constructed. The deteriorations are caused by reservoir water pressure, unstable slopes low foundation shearing strength, tectonic movements, dam settlements and age [1]. As the results of deterioration, long term deformation monitoring after construction is very important aimed at validating the construction specifications and safety. Long term monitoring is referred to as measurements of dam structural movement in x, y and z to ensure that every part of the structure is functioning as constructed. Generally, dams have different displacement characteristics based on construction materials, soil types and environmental conditions. In addition, dams have different monitoring systems installed to monitor pressure, chemical properties, and stress within the ground surface [1]. Therefore, each dam must be monitored independently using different types of methods and instruments [2]. Dam structural movement can be categorized into horizontal and vertical movements. Horizontal movement includes movement of an entire dam mass relative to its abutments or foundation while vertical movements is a result of consolidation of embankment or foundation materials resulting in settlement of the dam [3]. All of these movements can be effectively measured using different instruments and techniques. Dams are mainly constructed in different parts of the world to preserve water for drinking, irrigation and hydro-electric schemes to generate power.

There are several techniques being used to monitor deformation of dams which are categorized into two major group's namely geodetic and no-geodetic techniques. Geodetic and non-geodetic methods have their own advantages and disadvantages [4]. Geodetic techniques are based on measurements of connected points whose angular, linear and height measurements

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are determined. Based on these network points the behavior of a structure can be easily determined in x, y and z directions. Geodetic techniques include conventional levelling, bearing and distance measurements, photogrammetry (aerial and digital photogrammetry), Global Positioning Systems-(GPS), and remote sensing. Geodetic techniques are reliable and capable of providing horizontal and vertical information that can quantify the magnitude of behavior of the dam at any location.

Non-geodetic techniques include the application of sensors, laser, tilt-meters, strain-meters, extensometers, joint-meters, plumb lines, micro-meters, and Linear Vibrating Displacement Transducers. These instruments normally provides global results on one dimension of the movements of the structure which becomes very difficult to measure horizontally and vertically [5]. In order to improve the accuracy, reliability and capability of dam deformation monitoring techniques, the instruments and methods must be capable of measuring both horizontal and vertical movement of the structure [6]. Therefore, selecting dam deformation monitoring technique is a vital requirement in validating designers' assumptions and assessment of the behavior of the structures. Lack of reliable deformation monitoring technique and framework may not provide reliable results. The effect of unreliable results and monitoring framework may cause a dam to collapse or bust unexpectedly causing damages of properties and even loss of life. Therefore, reliable technique and monitoring framework is vital and authorities responsible for water have an obligation to take all necessary precautions to prevent such catastrophe to happen. One important precaution for such catastrophe to happen is to establish a reliable monitoring framework capable of assessing the behavior of the dam in vertically and horizontally.

For the past two decades, we have witnessed advances in measuring instruments which has greatly improved the methods of point positioning. These instruments are capable of measuring points simultaneously in three dimension and are very fast than conventional land surveying methods. Conventional land surveying methods, include triangulation, traversing and leveling which have been widely used to monitor displacements for dams [7]. However, João Casaca and Dr. Maria João Henriques (2014) [7] later noted that integration of the GPS with conventional surveying methods is important improving the results. In recent years, GPS has been used for various applications such as tectonic measurement and geodynamics of active lithospheric and volcano hazards [8]. Typical examples of the application of GPS include Levent T. (2008) [9] who analyzed whether GPS measurements could meet the accuracy requirements for dam deformation measurements. The deformation experiment used 6 reference points and 11 monitoring points. The measurements were made 4 times over a period of two years using dual frequency GPS receivers with static method. It was established that the displacement was 4 mm in x and y and was accepted. Wei L. and Chang W. (2011) [10] used GPS to observe 27 monitoring points to monitor the tailing dam, and used Pinnacle software to calculate observation data. From statistical analysis of several observations, it was found that the largest horizontal displacement was 9.6 mm while the vertical displacement was 4.9 mm. It was concluded that, the displacement of monitoring points were within the acceptable error requirements.

Other deformation monitoring studies include the monitoring of Atinkaya Dam in Turkey using GPS [11, [12]. It is evident that, the accuracy that GPS can reach in the order of 1cm in x and y components but height component has slightly inferior accuracy. There are two main reasons for inferior GPS height accuracy which includes satellite geometry and unmodelled error. For decades, the water Department at the Ministry of Water and Environment in Botswana has been visually monitoring dams. Visual inspection of dams include cracks, settlement and overflow. However, visual inspection of cracks, settlement and overflow has serious shortcomings which include limited accuracy and subjective results. Lack of comprehensive monitoring framework of dams in Botswana may be due to limited resources, tools and advanced techniques. In this study, we present the first deformation monitoring framework of Letsibogo dam in Botswana using Global positioning Systems (GPS) which is capable of detecting structural movement in three dimensions.

## 2. Study Area

The Study Area is Letsibogo Dam which is located in the Central District of Botswana near Mmadinare Village, Bobirwa Sub District. The dam lies along the Motloutse River flowing from west to east. The dam has a capacity of 104 million cubic meters, height of 28 m from ground level and covering an area of 18 km$^2$ and the coordinates are 21.844819°S, 27.734608°E. [14].

### *2.1 Climate*

The Letsibogo dam is situated in Mmadinare village and both are classified under the 2D3 Agro Climatic region of the hard veld as per Botswana land systems Climate classification criteria. This region extends from Palapye to Francistown with an overall crop season of 81-1000 days. The dry days being 31-40 while the humid period is of 20-40 days with an occurrence of less than 50%. There is a high risk of crop failure. The water catchment schemes in the area allow to capture water into the dam. The area falls under a hard veld topographical profile that overlays Precambrian rocks which is prominent in the Eastern part of Botswana. It bares the characteristics of the “late tertiary and quaternary erosion surface [13]. This kind of topography is practically flat, with the occurrence of delicately undulating plains, mostly at the boundaries. The dam is located along the plate boundary between the Limpopo belt and the Zimbabwe craton. Fig. 1 shows satellite image of Letsibogo dam.

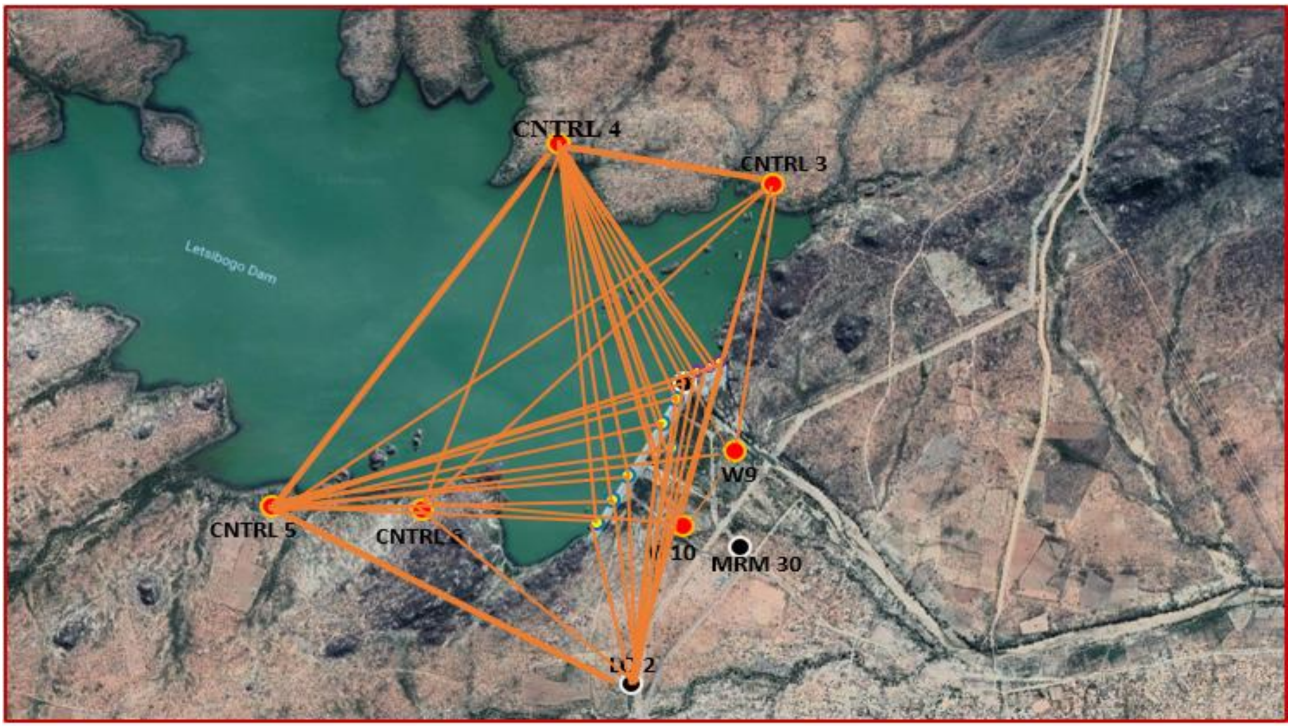

**Fig. 1 Satellite image showing the configuration of reference and monitoring points.**

## 3. Data Collection

The datum points around the dam were selected that are part of the National control datum that was used to coordinate reference and monitoring points. The selected control points were MRM 30 and MRM8 on L20 Cape datum and are established on a permanent and stable ground. A total of 6 reference points were established on stable ground away from the dam. Two reference points being in front of the dam wall, two on the left side and two being on the right side of the dam wall. In addition, thirteen monitoring points established along the edges of the dam wall and along the wall at regular intervals of 6 m. Fig. 1 shows the configuration of reference and monitoring points.

### *3.1 GPS Observation of Reference and Monitoring Points*

The oobservations of both reference and monitoring points were carried out using dual frequency GPS based on datum points MR 20 and MRM 8. The GPS base station was first placed at MR 20 and rover was positioned at reference points CNTRL 01, CNTRL 02, CNTRL 03, CNTRL 04, CNTRL 05, CNTRL06 and monitoring points MP01, MP02, to MP20. The observation time spend on each station was 30 minutes with a sampling rate of 10 seconds. The satellite elevation mask was selected at 15° so as to minimize multi-path effect and cycle slip error. Then after the GPS base station was shifted to MRM8 and the same procedure was repeated to coordinate reference and monitoring points. After GPS observation, the raw GPS data were logged onto the hard disks of the SOKKIA GPS receivers and downloaded and post-processed using magnet Tool GPS processing software package.

### *3.2 Data Processing*

After GPS observations, the raw data were downloaded from the Sokkia data logger and processed using Magnet Tool 2.0 software to adjust the observations. The two sets of observations from M8 20 and MRM 8 datum points were adjusted to determine the coordinates of reference and monitoring points. Since GPS measurements are in WGS 84 coordinates system, were aligned with the local coordinate system. All WGS-84 coordinates were transformed to a local coordinate for compatibility with the physical ground. Fig. 2 below shows the configuration of adjusted reference and monitoring points. Least Squares Adjustment was used to adjust the observations. The GPS observations were adjusted based on Eqs. (1) and (2) as described below.

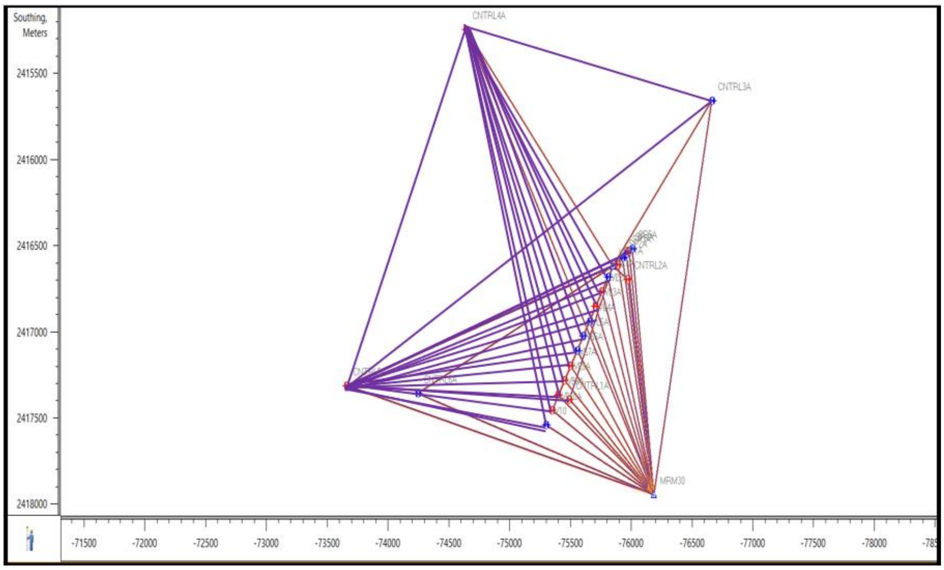

**Fig. 2 Network configuration of reference and monitoring points.**

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

Where:

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

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

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

$$X = A^{T}WA)^{-1}(A^{T}WL)^{-1} \qquad (2)$$

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 Eq. (3).

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

Where:

$W_i$ is the observation weight

$\sigma_i$ is the standard deviation of the measurement. Table 1 shows the adjusted points observed using GPS.

For Dam deformation monitoring areas, the position accuracy less than +1 cm is sufficient for earth–rock fill dams [13]. The precision of the observed data can be defined by the variance. The sample variance gives an unbiased estimate of the population and it is computed as shown in Eq. (4) below:

$$\sigma = \sqrt{\frac{\sum_{n=1}^{n} v_i^2}{n-1}} \qquad (4)$$

Where:

n = sample

v = residuals

Therefore, the standard deviation for horizontal and vertical components are 0.004 m and 0.007 m respectively. Fig. 3 shows the horizontal and vertical displacements of reference and monitoring points. From GPS observations, Correlation was also determined to validate whether the measurements are correlated. If the correlation coefficient is close to +1 then the measurements are correlated else if close to -1 then they are inversely related. The correlation coefficient is expressed as:

$$\hat{\rho} = \frac{s_{xy}}{s_x s_y} \qquad (5)$$

Where:

$$s_{xy} = \sum \frac{(x - \bar{x})(y - \bar{\bar{y}})}{n-1}$$

$$s_x^2 = \sum \frac{(x - \bar{x})^2}{n-1}$$

$$s_y^2 = \sum \frac{(x - \bar{x})^2}{n-1}$$

Therefore, the correlation coefficient $\hat{\rho} = 0$ which confirms that the measurements of reference and monitoring points are correlated.

## 4. Discussion of the Results

The results acquired from this study are satisfactory because the coordinates obtained are within the tolerable GPS Accuracy level of 1 cm in horizontal component. However, there are large residuals spotted at points 2, 26, 27 and 28 as shown in Fig. 3. The suspected reasons for spotted high residuals could be systematic errors caused by either the instrument, operator, or environment that could have affected the survey observations. The standard deviations $\sigma$ for horizontal and vertical components are 0.004 m and 0.007 m respectively. Finally, the computed correlation coefficient $\hat{\rho} = 0$ for the observations confirms that the GPS measurements of reference and monitoring points are correlated. Table 2 shows the final adjusted coordinates of the network of reference and monitoring points from both observations.

**Table 1 Adjusted coordinates.**

| Point Name | dN(m) | dE(m) | Dh(m) | Horz RMS | Horz RMS |
|---|---|---|---|---|---|
| L02-CNTRL 1A | 772.734 | 355.576 | -17.824 | 0.005 | 0.012 |
| L02-CNTRL 2A | 73.142 | -124.216 | -21.759 | 0.004 | 0.007 |
| L02-CNTRL 3A | -961.392 | -816.417 | -5.211 | 0.004 | 0.006 |
| L02-CNTRL 4A | -1374.87 | 1203.307 | -5.765 | 0.005 | 0.008 |
| L02-CNTRL 5A | 693.901 | 2186.334 | -6.008 | 0.004 | 0.006 |
| L02-CNTRL 6A | 735.967 | 1602.06 | -6.153 | 0.004 | 0.005 |
| L02-SP1A | -10.207 | -47.613 | -18.454 | 0.006 | 0.009 |
| L02-SP2A | -51.715 | -82.271 | -18.472 | 0.003 | 0.006 |
| L02-SP3A | -74.872 | -111.285 | -18.472 | 0.003 | 0.006 |
| L02-SP4A | -90.342 | -135.86 | -18.522 | 0.003 | 0.006 |
| L02-SP5A | -103.302 | -162.433 | -18.511 | 0.003 | 0.006 |
| L02-WL1A | 59.89 | 37.751 | 0.336 | 0.004 | 0.008 |
| L02-WL2A | 145.657 | 88.896 | 0.327 | 0.004 | 0.008 |
| L02-WL3A | 231.716 | 140.096 | 0.362 | 0.004 | 0.008 |
| L02-WL4A | 317.688 | 191.172 | 0.344 | 0.005 | 0.01 |
| L02-WL5A | 403.658 | 242.287 | 0.357 | 0.004 | 0.006 |
| L02-WL6A | 489.569 | 293.431 | 0.31 | 0.004 | 0.006 |
| L02-WL7A | 575.492 | 344.481 | 0.333 | 0.004 | 0.006 |
| L02-WL8A | 661.418 | 395.54 | 0.349 | 0.004 | 0.006 |
| L02-WL9A | 747.416 | 446.783 | 0.313 | 0.004 | 0.006 |
| L02-WL10A | 833.343 | 497.947 | 0.246 | 0.004 | 0.006 |
| MRM30-CNTRL1 | -549.054 | 697.243 | -3.746 | 0.004 | 0.008 |
| MRM30-CNTRL2 | -1248.64 | 217.441 | -7.693 | 0.004 | 0.007 |
| MRM30-CNTRL3 | -2283.15 | -474.764 | 8.802 | 0.004 | 0.007 |
| MRM30-CNTRL4 | -2696.66 | 1544.986 | 8.313 | 0.004 | 0.006 |
| MRM30-CNTRL5 | -627.88 | 2527.989 | 8.087 | 0.006 | 0.013 |
| MRM30-CNTRL6 | -585.797 | 1943.741 | 7.945 | 0.006 | 0.013 |
| MRM30-SP1 | -1331.99 | 294.048 | -4.395 | 0.005 | 0.011 |
| MRM30-SP2 | -1373.35 | 259.628 | -4.415 | 0.004 | 0.007 |
| MRM30-SP3 | -1396.65 | 230.362 | -4.392 | 0.004 | 0.007 |
| MRM30-SP4 | -1412.12 | 205.794 | -4.412 | 0.004 | 0.008 |
| MRM30-SP5 | -1425.08 | 179.212 | -4.421 | 0.004 | 0.007 |
| MRM30-W1 | -1261.89 | 379.39 | 14.397 | 0.003 | 0.006 |
| MRM30-W2 | -1176.13 | 430.548 | 14.394 | 0.003 | 0.006 |
| MRM30-W3 | -1090.09 | 481.771 | 14.427 | 0.003 | 0.006 |
| MRM30-W4 | -1004.1 | 532.82 | 14.436 | 0.004 | 0.006 |
| MRM30-W5 | -832.23 | 635.08 | 14.385 | 0.003 | 0.006 |
| MRM30-W6 | -746.319 | 686.147 | 14.423 | 0.004 | 0.008 |
| MRM30-W7 | -660.385 | 737.203 | 14.435 | 0.003 | 0.006 |
| MRM30-W8 | -574.38 | 788.44 | 14.393 | 0.003 | 0.006 |
| MRM30-W9 | -488.463 | 839.618 | 14.313 | 0.004 | 0.007 |
| MRM30-W10 | -402.519 | 890.601 | 14.334 | 0.003 | 0.005 |

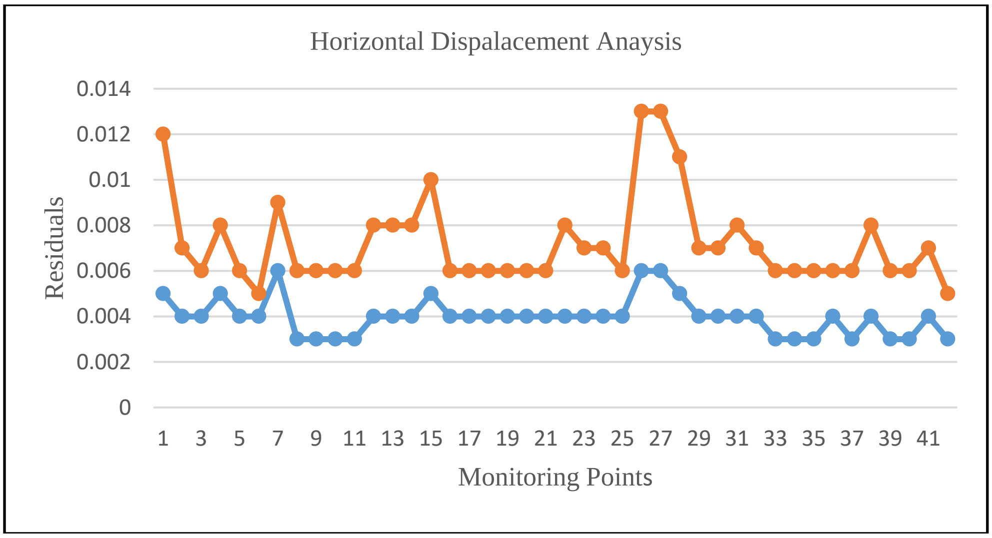

**Fig. 3 Horizontal displacement.**

**Table 2 Final adjusted coordinates of the network of reference and monitoring points from both observations.**

| Point Name | N(m) | E(m) | Horz RMS |
|---|---|---|---|
| L02-CNTRL 1A | 2417398.2 | -75491.33 | 836.223 |
| L02-CNTRL 2 | 2416698.6 | -75971.14 | 832.515 |
| L02-CNTRL 2A | 2416698.6 | -75971.13 | 832.288 |
| L02-CNTRL 3 | 2415664.1 | -76663.34 | 849.010 |
| L02-CNTRL 3A | 2415664 | -76663.33 | 848.837 |
| L02-CNTRL 4 | 2415250.6 | -74643.59 | 848.521 |
| L02-CNTRL 4A | 2415250.6 | -74643.6 | 848.283 |
| L02-CNTRL 5 | 2417319.3 | -73660.59 | 848.295 |
| L02-CNTRL 5A | 2417319.3 | -73660.58 | 848.040 |
| L02-CNTRL 6 | 2417361.4 | -74244.84 | 848.153 |
| L02-CNTRL 6A | 2417361.4 | -74244.85 | 847.895 |
| SP1 | 2416615.2 | -75894.53 | 835.812 |
| SP1A | 2416615.2 | -75894.52 | 835.594 |
| SP2 | 2416573.9 | -75928.95 | 835.793 |
| SP2A | 2416573.7 | -75929.18 | 835.575 |
| SP3 | 2416550.6 | -75958.22 | 835.816 |
| SP3A | 2416550.5 | -75958.19 | 835.576 |
| SP4 | 2416535.1 | -75982.78 | 835.796 |
| SP4A | 2416535.1 | -75982.77 | 835.526 |
| SP5 | 2416522.1 | -76009.37 | 835.787 |
| SP5A | 2416522.1 | -76009.34 | 835.537 |
| W1 | 2416685.3 | -75809.19 | 854.604 |
| W2 | 2416771.1 | -75758.03 | 854.602 |
| W3 | 2416857.1 | -75706.81 | 854.635 |
| W4 | 2416943.1 | -75655.76 | 854.644 |
| W5 | 2417115 | -75553.5 | 854.593 |

**(To be continued)**

**(Table 2 continued)**

| | | | |
|---|---|---|---|
| W6 | 2417200.9 | -75502.43 | 854.631 |
| W7 | 2417286.8 | -75451.38 | 854.643 |
| W8 | 2417372.8 | -75400.14 | 854.601 |
| W9 | 2417458.7 | -75348.96 | 854.521 |
| W10 | 2417544.7 | -75297.98 | 854.542 |
| WL1A | 2416685.3 | -75809.16 | 854.384 |
| WL2A | 2416771.1 | -75758.01 | 854.375 |
| WL3A | 2416857.1 | -75706.81 | 854.409 |
| WL4A | 2416943.1 | -75655.74 | 854.391 |
| WL5A | 2417029.1 | -75604.62 | 854.405 |
| WL6A | 2417115.0 | -75553.48 | 854.358 |
| WL7A | 2417200.9 | -75502.43 | 854.381 |
| WL8A | 2417286.8 | -75451.37 | 854.396 |
| WL9A | 2417372.8 | -75400.13 | 854.361 |
| WL10A | 2417458.8 | -75348.96 | 854.294 |

## 5. Conclusion

In order to monitor and determine possible displacements of a structure, a deformation network of reference and monitoring points has been established at Letsibogo dam and the surrounding area. GPS was used to establish the baseline points as it is an effective and efficient technique for deformation monitoring. The raw data obtained from GPS observations were downloaded and processed using Magnet 2.0 software and adjusted using least squares solution at a confidence level of 95%. The results shows that the coordinates of reference and monitoring points differs by 1 cm in x and y and 2 cm in z component. The reference and monitoring points meet the Botswana network accuracy requirements which state that “all networks should meet a minimum requirement of 2cm accuracy, which is an acceptable accuracy for project control surveys. Therefore, the position accuracy of the reference and monitoring points at zero epoch show that they are reliable with standard deviations of 0.004 m and 0.007 m in x and y respectively. The established points can be used for determination of displacement of points for the first epoch which is expected to take place in 2020. However, based on the results obtained, height component determined using GPS is weak and must be supplemented by precise levelling before being used for deformation monitoring in the first epoch.

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