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Structural Deformation Monitoring Using GPS and Conventional Surveying Methods

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Abstract: ***This paper describes the application of Global Positioning System (GPS) and trigonometric levelling for structural settlement monitoring at the Botswana International University of Science and Technology (BIUST). The research provides an overview of previous research on structural deformation monitoring techniques, including the analysis of the advantages and disadvantages of the measurement techniques used. In addition, this paper examined the structural deformation monitoring using GPS and trigonometric levelling and determine the parameters subjected to heavy loads of the structure after being completed. The GPS observation and deformation data were processed and analysed by using the Least Squares Adjustment software. The results showed a correlation coefficient of 0.998, and the*** **computed coordinates of reference and monitoring points** ***revealed a standard deviation of 19.6 cm and a RMSE of 0.131.***

Keywords: Structural Settlement, Foundation, Surveying, Monitoring, GPS, TOTAL STATION

1. Introduction

According to (1), deformation is the term used to describe changes in an object's size, shape, or position from its initial state or design. It is a typical occurrence in engineering structures like bridges, dams, and tall buildings. Numerous factors, such as seismic activity, construction stresses, and extreme weather events like hurricanes or flooding, can cause these structures to fail or sustain damage. For example, after Hurricane Laura, Caroline Habetz and the KPLC Digital Team reported significant damage to the Capital One Tower in Lake Charles, Louisiana, on September 11, 2020 [2]. The 39-year-old structure was abandoned and eventually demolished because of the extent of the damage. Similarly, Typhoon Yagi in Northern Vietnam caused infrastructure damage, including broken glass doors, to the Novotel Ha Long Hotel (3). Furthermore, CNN reported in September 2024 that Hurricane Helene had caused major damage in Western North Carolina, with homes, businesses, and major roads all severely flooded (4). These examples underscore how cumulative effects from natural hazards and construction stresses can lead to critical levels of deformation. If not addressed, such deformation compromises the structural integrity and safety of buildings, endangering occupants and shortening the lifespan of structures. While modern engineering has introduced advanced design and reinforcement methods to reduce the effects of deformation, repairing damage after it has occurred remains a complex challenge. Therefore, continuous and real-time monitoring of engineering structures is crucial for early detection and timely intervention.

Deformation assessments relied on conventional techniques that monitored material responses under various conditions. However, the integration of GPS technology into geodesy and surveying has revolutionized deformation monitoring by enabling more precise measurements. Measurement techniques for deformation are broadly categorized into geodetic and non-geodetic methods (5)

Geodetic methods, such as GPS, total stations, and photogrammetry, measure absolute displacements of specific points with respect to reference locations. Among these, GPS is particularly valued for its high-accuracy 3D positioning capabilities. However, GPS-based vertical positioning is generally less accurate than horizontal positioning due to geometric weaknesses and atmospheric errors (6). To overcome these limitations, special techniques like the rapid static method for short baselines and the use of forced centring equipment are employed (7).

In deformation monitoring of engineering structures, these models include static, kinematic, and dynamic models. A static model that is not dependent on time provides the determination of deformations on the characteristic points of the area or the structure, which is monitored. In this paper, baseline data is established using accurate geodetic and trigonometric levelling methods. The X, Y, and Z coordinates of reference and monitoring points for deformation monitoring of the student centre building at Botswana International University of Science and Technology. The intention of using trigonometric levelling is to find the accurate positions of points on the building. In Botswana, there are many public buildings with different designs that have a great effect on Botswana people and the economy. These buildings are constructed using different materials. In this paper, the laying out of baseline information for deformation monitoring of public buildings at BUST is presented. The need for deformation monitoring is underscored by recent cases of unexpected building collapses, both in Botswana and internationally. For instance, a church that was being built in Mogoditshane experienced a partial wall collapse during a storm in 2015, which led to one person's death and another person's injuries (8). Most recently, a four-story building collapsed in Dar es Salaam, Tanzania, in November 2024, killing and injuring several people. The collapse in Dar es Salaam is a stark reminder of how failure to address underlying structural weaknesses can have tragic consequences, even in bustling urban areas (9).

2. Objectives

To determine the baseline parameters for structural deformation monitoring of a building.

3. Materials and Methods

3.1 Setting out Reference Points

Four reference points around the Student Centre were marked on stable ground as they were suitable positions for measurement. Since these sites are less likely to change over time, the reference points for regular monitoring will stay constant. GPS surveys were carried out to ascertain the ellipsoidal heights of the four points identified within the study area. Using the Real Time Kinematic approach, the GPS readings were obtained using Hi-target DGPS receivers. As a fixed base, the reference receiver was installed on BM5, a well-known reference station. MJ, the known surveyed point, was directly above the base station GPS antenna, which was mounted on a level tripod. The height of the base station antenna phase centre above the surveyed point was measured as part of the standard protocol. To receive correction data from the base station, the GPS rover was placed on a survey point equipped with a radio receiver.

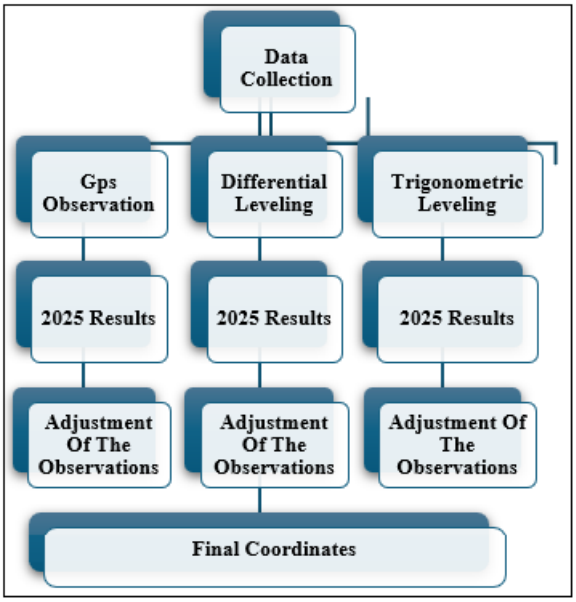

Figure 1: Shows the Flowchart of the methodology.

3.2 Differential Leveling observations

Differential leveling is one of the most accurate methods used to determine the vertical distance between two points on the Earth's surface. This technique is employed in geodetic surveys, construction projects, and deformation monitoring (10). In this method, a level instrument is used to measure the height difference between a benchmark (a point with a known elevation) and an unknown point (11).

The primary advantage of differential leveling is its high accuracy. It can be used over short to medium distances and is particularly effective in monitoring local deformations or small-scale elevation changes, such as those that may occur in large buildings (12). This method is often preferred in situations where precision is critical, such as when identifying potential structural settling, shifting, or foundation issues in buildings (13).

3.3 Trigonometric Levelling

Trigonometric leveling, also known as angular leveling, is a technique to determine the height differences between points on Earth's surface. It uses angles and distances to make these calculations. This method is useful in surveying and geodetic measurements where traditional leveling might be impractical due to long distances, difficult terrain, or when dealing with large-scale projects like the monitoring of structural deformation in buildings.

This approach calculates the height difference by applying trigonometry. It uses the angle of elevation or depression observed between a fixed reference point and the spot to be measured.

To calculate the elevation difference, the following trigonometric relationship is used:

$$\Delta h = d \times tan(\theta) \quad \text{.....(1)}$$

Where:

- Δh is the height difference between the two points.
- d is the horizontal distance between the points.
- θ is the observed angle (either elevation or depression).

The elevation difference between two points can be determined using trigonometric leveling by measuring the horizontal distance (H) between them and the vertical angle (V) or zenith angle (z). At point A, whose elevation is known, a total station is positioned. At point B, whose horizontal distance from point A is established, a leveling staff is positioned. With these parameters, the elevation of point B can be easily determined.

4. Results and Analysis

After the determination of the coordinates of reference and monitoring points, the coordinates were stored in the internal memory of the GPS receiver and were downloaded into the computer and adjusted by the least squares adjustment software. The least squares adjustment was conducted based on the following mathematical relationship:

Let line ij be from the point $(i)\ to\ (j)$ the least squares observation equation is expressed as:

$$X_j = X_i + \Delta X_{ij} + vx_{ij} \quad \text{.....(2)}$$

$$Y_j = Y_i + \Delta Y_{ij} + vy_{ij} \quad \text{..... .(3)}$$

$$Z_j = Z_i + \Delta Z_{ij} + vz_{ij} \quad \text{..... (4)}$$

Equations 2,3 and 4 can be compressed in matrix format such as:

$$\begin{pmatrix} x_1 \\ x_2 \\ x_3 \\ \dots \\ x_n \end{pmatrix} = \begin{pmatrix} l_1 \\ l_2 \\ l_3 \\ \dots \\ l_n \end{pmatrix} + \begin{pmatrix} v_1 \\ v_2 \\ v_3 \\ \dots \\ v_n \end{pmatrix} \quad \text{.....(5)}$$

$$AX = L + V \quad \text{..... (6)}$$

Where:

A is the design matrix.
X is the vector of the unknown
L is the vector of observations and
V is the vector of residuals.

By inserting a weight (w) and a priori variance $\sigma^2{}_o$ for the observations in equation 4, the cofactor matrix can be given as:

$$Q_L=\frac{1}{\sigma_o^2}Sum_L \quad \ldots\ldots (7)$$

Therefore,

$$W= Q_L^{-1} \quad \ldots\ldots (8)$$

The solution becomes well-defined by Least Squares principle of V^TWV = minimum. From the above observation equations, the least squares principle becomes:

$$(A^TWA)X = A^TWL \quad \ldots\ldots (9)$$

The vector of unknowns can be computed as:

$$X = (A^TWA)^{-1}(A^TWL) \quad \ldots\ldots (10)$$

The matrix equation can be computed as:

$$V = AX - L \quad \ldots\ldots (11)$$

The standard deviation of the measurements of unit weight for the weighted observations is given as:

$$\sigma_0=\sqrt{\frac{v^TWV}{r}} \quad \ldots\ldots (12)$$

Where σ_0 is the degree of freedom in the adjustment, which is equal to the number of observations minus the number of unknowns.

Table 1: Shows GPS Coordinates for established Reference Points

Point No	Y coordinates	X Coordinates	Z Coordinates
BM 41	-127559	2499031	979.225
MB42	-12866	2499049	979.125
BM 43	-12843	2499122	979.325
BM 44	-12750	2499132	979.055
BM 5	-13034	2499305	982.771

Table 2: Shows the results of the differential leveling results

Station	Backsight (BS/m)	Foresight (FS/m)	Rise (+) (m)	Fall (-) (m)	Reduced Level (m)
BM 5	1.065				982.771
1	0.745	1.865		0.8	981.971
2	0.680	1.995		1.25	980.721
BM43	1.431	2.100		1.42	979.301
BM44	1.280	1.386	0.045		979.346
BM41	1.055	1.570		0.29	979.056
3	0.965	0.883	0.172		979.228
BM42	1.541	1.220		0.225	979.134
4	1.115	1.380	0.161		979.134
BM43	1.231	0.901	0.214		979.348
5	2.440	1.128	0.103		979.451
6	1.985	1.061	1.379		980.830
7	1.998	0.909	1.076		982.779
BM5		1.125	0.873		982.779
TOTAL	17.531	17.523	4.023	4.015	

Table 3: Shows results for trigonometry leveling results

Reference Point	Monitoring Point	Vertical Angle (a)	Horizontal Distance (H(m))	Difference in Height(m)	Elevation of Monitoring Point from Instrument Axis (V(m))	Elevation of Monitoring Point (m)
BM43 Height of instrument =1.44m Backsight=1.069m Height of benchmark=979.301m	P1	65˚32′57″	13.5852	6.0080	29.878	1009.550
	P2	68 ˚ 16′48″	15.4927	6.0046	38.892	1018.564
	P3	71˚55′01″	18.8928	6.0020	57.861	1037.533
	P4	74˚42′44″	22.5631	6.0004	82.546	1062.218
BM44 Height of instrument =1.489m Backsight=1.343m Height of benchmark=979.346m	P5	78˚47′41″	32.2150	7.7149	162.619	1142.111
	P6	79˚40′15″	34.9355	7.7003	191.683	1171.175
	P7	81˚10′43″	40.9467	7.6877	263.848	1243.340
BM41 Height of instrument =1.495m Backsight=1.301m Height of benchmark=979.056m	P8	64˚47′00″	12.9062	7.4108	27.406	1006.656
	P9	73˚31′11″	20.4587	7.3855	69.155	1048.405
	P10	77˚31′52″	27.3595	7.3829	123.729	1102.979

5. Conclusion

Four reference points (B41, BM42, BM43, and BM44) were strategically selected based on their stability and long-term accessibility. From Table 2 above, the total backsight and foresight readings were 17.531 m and 17.523 m, respectively, yielding a minimal difference of 0.008 m. This small discrepancy confirms the accuracy of the leveling operation and reflects acceptable instrumental and observational tolerances. The rise and fall summary calculated using the BS-FS method showed 4.023 m of rises and 4.015 m of falls, again yielding a total difference of 0.008 m, which further supports the reliability of the data.

BM43 experienced a slight rise of 0.045 m, while BM44 showed a fall of 0.29 m. These minor fluctuations are consistent with natural ground variation or minor instrument error and are within acceptable limits for deformation monitoring. Other benchmarks, such as BM41 and BM42, also exhibited 0.29 m and 0.225 m, respectively.

The established baseline parameters serve as a reference for future surveys. By repeating the same procedures using the same benchmarks, any vertical movement, whether due to settling, environmental influences, or structural strain, can be identified and tracked over time. Regular monitoring using these established benchmarks will allow for accurate trend analysis and early warning of potential structural issues.

The precision and accuracy of the reference and monitoring points were determined by calculating the correlation coefficient of the observations for the first epoch. The correlation coefficient, denoted by ρ, was used to indicate how the X, Y, and Z coordinates of the reference and monitoring points were determined. The linear equation describes the linear equation of the correlation coefficient.

a) If $\hat{\boldsymbol{\rho}}$ =1 or $\hat{\boldsymbol{\rho}}$ = -1, then the data set is perfectly aligned. Data sets with values of ρ *is* close to zero shows no straight-line relationship.

$$\hat{\boldsymbol{\rho}}\frac{(n\Sigma xy-\Sigma x\Sigma y)}{\sqrt{(n\Sigma x^2-(\Sigma x)^2)(n\Sigma y^2-(\Sigma y)^2)}}\ldots\ldots\ldots\ldots(18)$$

$$\rho\frac{(70\times 66.7\times 10^6-4.67\times 10^9)}{\sqrt{(70\times 66.7\times 10^6-4.7\times 10^9)(70\times 66.7\times 10^6-4.7\times 10^9)}}$$

Therefore, $\hat{\boldsymbol{\rho}} = 0.998$

Based on the result obtained, it shows that the correlation coefficient is within the acceptable range of -1 to +1.

Table 4: Shows the difference in Z Coordinates between GPS and Differential

Point No	GPS Z Coordinates (m)	Differential Leveling Z Coordinates (m)	GPS (Z) – Diff.(Z) (m)
BM 41	979.225	979.174	0.051
BM 42	979.125	979.134	0.009
BM 43	979.325	979.327	0.002
BM 44	979.055	979.042	0.013

Table 5: Shows the residuals between GPS height and Differential leveling

Point Name	ΔH (m)GPS Height (m) – Differential Levelling
BM 41	0.009
BM 42	0.051
BM 43	0.013
BM 44	0.002

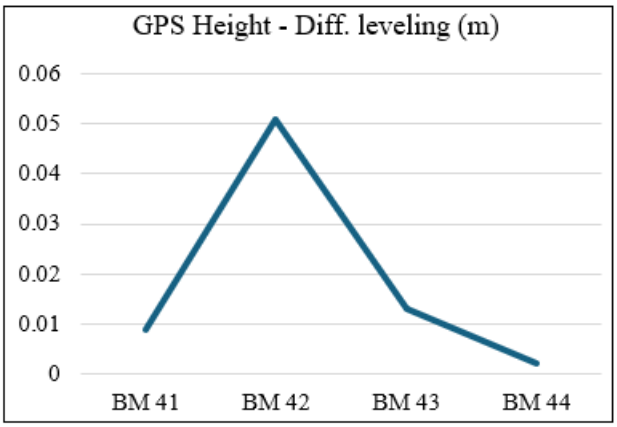

Figure 22: 1 Shows a graphical presentation of the height differences (ΔH) between GPS and differential levelling measurements

6. Conclusion

The result of the study shows that the baseline parameters for structural deformation monitoring were determined at the BIUST Student Centre building in Palapye, Botswana. Four reference control points and ten monitoring points were established on the ground and on the first floor of the building, respectively. The GPS observations were processed and analysed by using the Least Squares Adjustment software. Statistical analyses were conducted to evaluate the quality of points defined (Objective 4). ρ=0.998 is the correlation coefficient between GPS and levelling data was determined. The result shows that there is a linear correlation, which indicates the reliability of the results.

Additionally, comparing the Z values of GPS and differential levelling as shown in Table 4, revealed insignificant differences (usually <0.015 m) except for BM42 (0.051 m. The computed coordinates of reference and monitoring points revealed a standard deviation of 19.6 cm and a RMSE of 0.131 m, indicating the accuracy of the height difference measurements.

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