An Efficient Methodology for Detecting the Vertical Movement of Structures

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ABSTRACT

Details regarding the public safety of engineering structures can be gleaned from measurements and monitoring. The development of a methodology for monitoring and analyzing structures' vertical displacement is explained in this paper. The developed methodology aims to add a new dimension to geometric leveling, and leveling routing, by applying a least squares solution for level network adjustment and performing statistical analysis to assess the change in vertical displacement. To monitor and analyze the vertical deformation of a building in Cairo, Egypt, the proposed methodology was utilized. Twenty monitoring points, five auxiliary points, and three local reference stations were utilized. All the measurements were taken with a geodetic invar staff and an automatic level with an attachment of a parallel plate micrometer. The observations were made for an interval of 81 months. The least squares adjustment technique was applied to obtain the adjusted levels and observations and to generate the required statistical data. The results of the subsequent epochs were compared to the results of the first epoch to determine the vertical movement of the monitoring points for each epoch. In addition, the significance of the present displacement was ascertained by comparing the values of vertical displacement to the determined 95% corresponding confidence intervals. The findings demonstrated that the building remained stable throughout the monitoring period. The case study demonstrates how effectively geometric leveling with least square adjustment can be used to monitor the vertical displacement of structures.

Keywords-stability and safety of engineering structures; geometric leveling; vertical displacement monitoring; least squares adjustment; accuracy analysis

I. INTRODUCTION

The aim of measuring a structure's movement is to decide whether the structure is safe and stable. Deformation can be subjected to more analysis to determine whether it is caused by seasonal factors, daily variations, or other factors and then utilize the data to estimate how the structure will move in the future [1-5]. This movement must be identified for the purposes of safety studies and the prevention of future disasters. Deformation monitoring has the advantages of improving the design process of structures for use in the future and increasing safety by lowering the possibility of structural damage [6]. It is a crucial risk management tool. Presently, there are many techniques for deformation monitoring. Modern techniques often use geometric leveling and total stations for three-dimensional (3D) control [7]. The above-mentioned techniques can be used in conjunction with a Terrestrial Laser Scanner (TLS) system [8-12] or Portable Digital Photogrammetric Stations (DPSs) [13-15]. In particular, TLS has evolved into a crucial tool for working with historical structures, supplying a point cloud that quickly generates a three-dimension model of a monument [8]. However, the majority of surveyors do not have access to the specialized equipment required by these remote sensing technologies. It is costly to purchase or rent this equipment, and it could cost even more to train or hire employees who can manage and model point cloud data [9, 10]. A TLS system's data acquisition capacity also makes model creation challenging [10, 11].

Numerous software systems can help with this, but they consume time and computing resources and require an additional instrument that must be purchased or hired. As a result, these methods are severely constrained and can only be used for architectural heritage inspection [12, 16], where resources and budgets are significantly available. In addition, these methods have other issues, including the accuracy of the measurements they produce [17] despite the cost and complexity issues. Potential dimensional errors in the model can be caused by issues with close-range imaging [18], as well as variations in temperature and humidity [19], the reflectivity of various materials and colors, and the effects of incidence angle [20].

Comparing to direct measurements, significant errors in measuring vertical deformations can happen based on the above-mentioned conditions, sometimes exceeding one centimeter in magnitude [21, 22]. This emphasizes the significance of evaluation techniques that allow calibrating laser scanners, particularly as high-precision surveys development in architectural heritage sites. Typical tests like deformation monitoring should be checked using direct measurement methods [12].

To overcome some of the issues listed above, this paper aims to:

- develop a cost-effective methodology based on a mathematical model for determining the accurate levels from measurements at individual monitoring points,
- adjust redundant measurements and get their precision using the least squares solution,
- develop software based on the derived mathematical model and the least squares solution for determining the adjusted levels and required statistical data of deformation points, and
- use the developed methodology for detecting the vertical displacement of a building as a case study at a particular time interval.

II. THE PROPOSED METHODOLOGY

A. Development of the Mathematical Model

Leveling is the method of measuring vertical distances, either directly or indirectly, to determine elevations. There are two approaches: geometric and trigonometric leveling [23]. Geometric leveling is more accurate, the required surveying instruments are more cost-effective, and the work in the field and office is easier. In geometric leveling, the difference in levels between two points can be obtained by taking the readings of the staffs, or rulers, placed on the points. A leveling instrument is used to measure the readings. The elevations of all points can be determined by knowing at least one point's elevation and the level differences between points. To apply the method of least squares in leveling adjustments, an observation equation is first written for any elevation difference [23]. Figure 1 illustrates the geometrical relationship for the elevation difference observed between two stations, A and B. The equation is written as:

$$\delta_{hAB} + v_{\delta hAB} = h_B - h_A \qquad (1)$$

which can be rewritten as:

$$v_{\delta hAB} - h_B + h_A = -\delta_{hAB} \qquad (2)$$

The observation equation (2) gives the relation between the unknown elevations of any two stations, A and B, the differential levelling observation δ_{hAB} and its residual. This equation is essential in applying least squares adjustments of level nets. Equation (2) is linear and can be written directly in the form [24]:

$$V + B.\Delta = \varepsilon \qquad (3)$$

where Δ is the vector to the current values set for the unknowns (elevations of the deformation points) in the iterative solution, B is the matrix of the partial derivatives of (2) in relation to the unknowns, V is the vector of residuals, i.e. the correction vector to the observations (height difference), and ε is the vector of discrepancies.

The solution of (3) using least squares method is [23,24]:

$$\Delta = N^{1}.C \qquad (4)$$

where:

$$\left.\begin{aligned} N &= B^t.W.B \\ C &= B^t.W.\varepsilon \end{aligned}\right\} \qquad (5)$$

The variance of unit weight is obtained by:

$$\hat{\sigma}_o^2 = V^t.W.V \,/\, (N-U) \qquad (6)$$

where $\hat{\sigma}_o^2$ is the variance of unit weight, N is the number of observations, W is the weight matrix observations, U is the number of unknowns and equals to the number of deformation points, and (N-U) present the degrees of freedom.

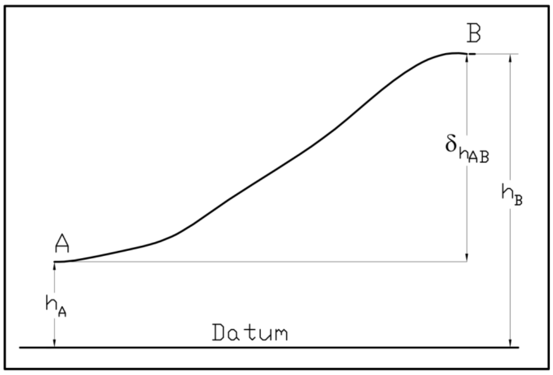

Fig. 1. Geometric depiction of the proposed model.

B. Developing the Necessary Software

The software for determining the adjusted level and desired statistical data for each deformation point in every loop is being developed as part of the current research. The least squares method, as explained above, is used to determine the output of the developed software, which makes use of the data in the form of level differences and distances between network points in addition to the known levels of the benchmark(s). The variance of unit weight, adjusted levels of stations and their standard deviations (optional), residuals of observations, corrected observations, and their cofactor matrix (optional), and statistical data for gross error detection (optional) are all included in the software's ASCII file output. The software provides flexibility in level network adjustment as follows:

- Any number and distribution of network points is acceptable.
- The editing of input data specifications has remained flexible for practical reasons. If the input formats are consistent, they can be accepted.
- The point-numbering is another important practical feature. Point-numbering is not restricted in any way by the software. The point-numbering is easy and almost natural.

- Weighting observations is possible. From a theoretical standpoint, it is desirable to weight the observations because it greatly aids in the detection of gross errors.
- Determination of the necessary initial levels for unknown points in order to initiate the iterative process.
- An iterative least-squares solution that can show the results of each iteration or the final iteration.

The software makes use of effective methods like Data Structuring [25, 26], Random File Access, and Dynamic Memory Allocations [27] for the purpose of automatically processing and representing the data and the results. The software was created with window-driven user interfaces in mind to make it easier to use [28].

C. Classification of Leveling Points

Three categories of points are proposed in the leveling line: i) monitoring points, ii) reference or benchmark points, and iii) auxiliary points. The monitoring points are selected to be placed on the building's exterior walls and required interior walls. To ensure that each building's wall is stable, the monitoring points are strategically placed. In order to determine only relative displacements, the reference points can be situated in the controlled area and undergo displacement. Absolute displacements can be obtained if the reference points are attached to solid foundation or other stationary structures outside that area. Even though leveling lines only require one reference point, experience suggests placing at least 3 of them in order to recognize unstable reference points. In order to ensure that they are unaffected by the building's movements, the reference points need to be positioned at a safe distance from it. Auxiliary points are positioned, for example, to connect independent sections of a levelling line.

D. Fixing the Points

Regarding fixing the points, they are typically secured by utilizing drill and epoxy to seal concrete nails on a wall or floor. All monitoring points must be well connected to the structure, particularly the concrete columns otherwise the displacements might be more accurately described as displacements of the points rather than structural displacements.

E. Leveling Instruments

It is necessary to use automatic levels, also known as optical levels, that have a built-in compensator that automatically makes the line of sight horizontal. Accuracy can be improved by mounting a parallel plate micrometer over the telescope objective [29]. The parallel plate micrometer permits estimated readings up to 0.01mm and direct readings up to 0.1mm on a staff of 1cm least count. Digital levels may also be used. Digital levels are automatic levels that have a digital image processing system built in. These levels allow for electronic recording and automatic reading of coded bars staff. The speed of leveling and the elimination of the errors brought on by human reading and recording are the main benefits of digital levels [30].

F. Field Work

It is necessary to know the reference station levels before monitoring points can be observed. Otherwise, precise leveling can be used to obtain the local levels of reference stations [29]. Loops are used for the leveling of the monitoring points. Each loop begins at a reference station and ends at either the same or another reference station. At various epochs of a predetermined time interval, the levels of the monitoring points are obtained. After the reference and monitoring, points have been selected and the leveling line route has been established, the necessary auxiliary points and an approximate location of the instrument in each leveling line must be marked in order to guarantee the precision required by having equal sections of leveling and by following almost the same route of line levelling. Starting and stopping leveling measurements at reference stations is the only way to control the quality of the measurements.

The misclosure (Δ) is the difference between the determined level and the known level, and it is calculated by :

$$\text{Misclosure } (\Delta) = \text{Reference}_{\text{Levelknown}} - \text{Reference}_{\text{Levelcomputed}} \quad (7)$$

Following the completion of the levelling work, the misclosure is computed. The fieldwork team is able to repeat the measurements at a lower cost and, most importantly, without altering the conditions of the structure by carrying out this data pre-processing in the field. The permissible misclosure can be calculated as [6]:

$$\text{Misclosure tolerance} = 0.9\sqrt{n} \ \text{(mm)} \quad (8)$$

where n is the number of set-ups.

All measurements ought to be repeated when the misclosure is more than the tolerance value. In case of permissible misclosure, the points' adjusted levels can be determined applying the least squares technique as explained above.

G. Vertical Displacement Determination

The developed software is utilized for computing the adjusted levels of the monitoring points for each epoch. In order to compare the results of the subsequent epochs with those of the first epoch, the results of the first epoch are used as a reference. The vertical displacement of each monitoring point can be determined as follows:

$$dZ = Z_{\text{first epoch}} - Z_{\text{current epoch}} \quad (9)$$

where dZ is the vertical displacement of the monitoring point and Z the adjusted level of the monitoring point.

H. Displacement Analysis

Comparing the level differences between the observations of the first epoch and the current epoch is the traditional method for determining the stability of reference and monitoring points, as shown in (9). In recent deformation modeling techniques, statistics are applied to each epoch of measurements to get the significance of point movements. Comparing the obtained displacements to their respective 95% confidence intervals is used to obtain the significance of point displacements [31]. In case the value of the vertical movement of a point K is classified as dZ_K and the maximum dimension of the combined 95% confidence ellipse for point K is specified as E_K, two cases will arise [32]:

- In the first case if $|dZ_K| < E_K$, then no movement has happened in point K and the observed difference is due to measurement errors.
- If $|dZ_K| > E_K$ then point displacement has occurred.

  E_K can be obtained as:

$$E_K = 1.96\sqrt{(m_{\Delta K}^{i+1})^2 + (m_{\Delta K}^{i})^2} \qquad (10)$$

where $(m_{\Delta K}^{i+1})$ is the standard error in level of point K in the current epoch and $(m_{\Delta K}^{i})$ is the standard error in level of point K in the previous epoch.

III. CASE STUDY

A building in Cairo, Egypt, was selected as a case study for monitoring the vertical displacement. The building is 110.0m long, 60.0m wide, and 20m high. There are various offices in this 3-story structure.

A. *Choosing Points*

The field has been identified in the initial step in order to carry out the vertical displacement monitoring of the studied building. As shown in Figure 2, 3 local reference stations and 5 auxiliary points were chosen. In order to ensure that the local reference stations were unaffected by the building's displacements, these points were fixed around it at a secure distance.

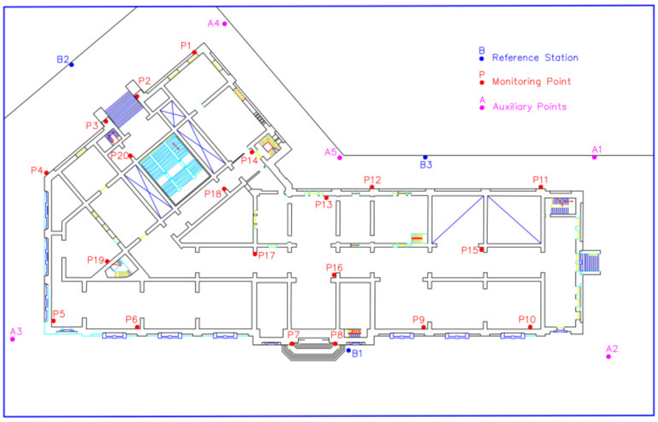

Fig. 2. Location of the case study points.

Twenty monitoring points were fixed on the first floor of the case study building as part of the vertical movement monitoring project to determine the structure's stability. Figure 2 depicts the positions of those monitoring points on the internal and external walls. The staff could easily hold on to the monitoring points on the building walls during levelling and observation because they were about 0.3m above the ground. Special nails were driven into the marked monitoring points to make them permanent.

B. *Measurements*

Measurements were acquired with a Leica NA2 automatic level, a GPLE3 geodetic invar staff with 1cm graduations, and an attachment for a Leica (10mm) GPM3 parallel plate micrometer. Before the monitoring points can be observed, it is necessary to know the levels of the reference stations B1, B2, and B3 as explained above. The level of point B1 is assumed to be 15.0m. The levels of points B2 and B3 were obtained by looping a level net from B1 to 5 auxiliary points, B2 and B3, and then closing back on B1. After determining the reference station levels, loops utilizing precise leveling were utilized to get the levels of monitoring points at 8 distinct 1-month interval epochs. Observations were made in the early morning. Each leveling line's misclosure did not exceed 0.4mm across all 8 observation epochs, which is an acceptable tolerance for the purposes of this work. The relatively flat topography of the study area, the experience of the observer, and the instruments used all contributed to the leveling's high accuracy.

C. *Data Processing and Results*

The developed software was used to process the data from the level networks. The necessary data and measurements such as the levels of the reference stations and their standard deviations, height differences, and distances between stations, were inserted into the software by editing the data file. The final results, for each epoch, were obtained from the adjustment of the level network. As previously mentioned, the variance of the unit weight, the adjusted levels of the monitoring points and their standard deviations, the residuals of the observations, and the corrected observations with their cofactor matrix comprised the received results. The high precision of the adjusted observations can be seen by the fact that the first to eighth leveling epochs had maximum variances of unit weight of 1.02m^2 and standard errors of 1.01mm. The high accuracy of the adjusted levels is demonstrated by the fact that their maximum standard error was 1.06mm across all epochs. All 8 epochs' computed standardized residuals for observations or levels were less than their rejection constants of the respective standardized residual which indicates that none of the observations were rejected due to gross errors or outliers.

The adjusted values of levels of monitoring points for each observation epoch and the differences in levels between the first and the subsequent epochs were respectively computed with (9) and are tabulated in Table I. Equation (10) was used to calculate the 95% confidence level differences between the first and respective confidence intervals of the subsequent epochs. The vertical displacement values of monitoring points and the confidence intervals that correspond to them at a 95% level of confidence are shown in Table II.

At a 95% confidence level, the magnitudes of the vertical movement of the monitoring points at each epoch were obtained and compared to their identical confidence intervals to decide whether the obtained displacements were actual (significant) displacements of the structure or caused by measurement errors. According to Tables I and II, all the evaluated movement values were less than their related confidence intervals, indicating that there was no vertical movement of the building within the monitoring period.

TABLE I. THE ADJUSTED LEVELS AND VERTICAL DISPLACEMENT OF THE MONITORING POINTS

Point	Epoch (1)		Epoch (2)		Epoch (3)		Epoch (4)		Epoch (5)		Epoch (6)		Epoch (7)		Epoch (8)	
	Level m	**dZ mm**	**Level m**	**dZ mm**	**Level m**	**dZ mm**	**Level m**	**dZ mm**	**Level m**	**dZ mm**	**Level m**	**dZ mm**	**Level m**	**dZ mm**	**Level m**	**dZ mm**
P1	15.3092	0	15.3093	-0.10	15.3095	-0.30	15.3094	-0.20	15.3093	-0.10	15.3097	-0.50	15.3097	-0.50	15.3095	-0.30
P2	15.4085	0	15.4086	-0.10	15.4082	0.30	15.4082	0.30	15.4086	-0.10	15.4083	0.20	15.4084	0.10	15.4086	-0.10
P3	15.3120	0	15.3116	0.40	15.3113	0.70	15.3114	0.60	15.3114	0.60	15.3112	0.80	15.3113	0.70	15.3114	0.60
P4	15.2960	0	15.2956	0.40	15.2957	0.30	15.2953	0.70	15.2954	0.60	15.2956	0.40	15.2954	0.60	15.2955	0.50
P5	15.8168	0	15.8166	0.20	15.8163	0.50	15.8162	0.60	15.8165	0.30	15.8163	0.50	15.8166	0.20	15.8167	0.10
P6	15.8097	0	15.8093	0.40	15.8092	0.50	15.8095	0.20	15.8096	0.10	15.8095	0.20	15.8098	-0.10	15.8096	0.10
P7	15.0963	0	15.0966	-0.30	15.0966	-0.30	15.0965	-0.20	15.0962	0.10	15.0963	0.00	15.0966	-0.30	15.0965	-0.20
P8	15.1254	0	15.1255	-0.10	15.1256	-0.20	15.1252	0.20	15.1254	0.00	15.1251	0.30	15.1253	0.10	15.1256	-0.20
P9	15.8458	0	15.8453	0.50	15.8451	0.70	15.8455	0.30	15.8457	0.10	15.8450	0.80	15.8455	0.30	15.8458	0.00
P10	15.6507	0	15.6507	0.00	15.6501	0.60	15.6505	0.20	15.6503	0.40	15.6500	0.70	15.6505	0.20	15.6502	0.50
P11	14.2996	0	14.2998	-0.20	14.2997	-0.10	14.2992	0.40	14.2995	0.10	14.2990	0.60	14.2993	0.30	14.2996	0.00
P12	14.2160	0	14.2154	0.60	14.2158	0.20	14.2157	0.30	14.2155	0.50	14.2158	0.20	14.2154	0.60	14.2158	0.20
P13	15.5106	0	15.5108	-0.20	15.5105	0.10	15.5107	-0.10	15.5103	0.30	15.5101	0.50	15.5105	0.10	15.51	0.60
P14	15.6034	0	15.6034	0.00	15.6032	0.20	15.6031	0.30	15.6036	-0.20	15.6033	0.10	15.6037	-0.30	15.6035	-0.10
P15	15.8085	0	15.8083	0.20	15.8087	-0.20	15.8086	-0.10	15.8083	0.20	15.8083	0.20	15.8085	0.00	15.8086	-0.10
P16	15.6054	0	15.6057	-0.30	15.6055	-0.10	15.6053	0.10	15.6051	0.30	15.6052	0.20	15.6055	-0.10	15.6056	-0.20
P17	15.4709	0	15.4705	0.40	15.4708	0.10	15.4703	0.60	15.4701	0.80	15.4703	0.60	15.4704	0.50	15.4705	0.40
P18	15.6615	0	15.6615	0.00	15.6616	-0.10	15.6613	0.20	15.6614	0.10	15.6612	0.30	15.6611	0.40	15.6612	0.30
P19	15.7997	0	15.7990	0.70	15.7992	0.50	15.7991	0.60	15.7995	0.20	15.7997	0.00	15.7990	0.70	15.7992	0.50
P20	15.6783	0	15.6782	0.10	15.6787	-0.40	15.6787	-0.40	15.6784	-0.10	15.6783	0.00	15.6781	0.20	15.6783	0.00

TABLE II. DETECTING THE VERTICAL DISPLACEMENT OF THE MONITORING POINTS

Point	Epoch (2)		Epoch (3)		Epoch (4)		Epoch (5)		Epoch (6)		Epoch (7)		Epoch (8)		Point displacement
	|dZ| mm	***E* mm**	**|dZ| mm**	***E* mm**	**|dZ| mm**	***E* mm**	**|dZ| mm**	***E* mm**	**|dZ| mm**	***E* mm**	**|dZ| mm**	***E* mm**	**|dZ| mm**	***E* mm**	
P1	0.10	1.67	0.30	1.97	0.20	2.01	0.10	2.41	0.50	1.39	0.50	1.89	0.30	1.81	None
P2	0.10	1.97	0.30	2.27	0.30	1.91	0.10	1.91	0.20	2.09	0.10	1.79	0.10	1.41	None
P3	0.40	2.07	0.70	2.17	0.60	1.81	0.60	2.31	0.80	1.99	0.70	1.79	0.60	1.51	None
P4	0.40	1.77	0.30	1.97	0.70	2.31	0.60	2.21	0.40	1.59	0.60	2.09	0.50	1.51	None
P5	0.20	1.37	0.50	2.17	0.60	2.01	0.30	2.01	0.50	1.99	0.20	1.59	0.10	1.51	None
P6	0.40	1.17	0.50	1.97	0.20	1.61	0.10	2.21	0.20	1.89	0.10	1.59	0.10	1.81	None
P7	0.30	1.57	0.30	1.87	0.20	2.01	0.10	2.61	0.00	1.69	0.30	1.59	0.20	1.71	None
P8	0.10	2.17	0.20	1.77	0.20	2.31	0.00	2.11	0.30	2.09	0.10	1.69	0.20	1.31	None
P9	0.50	1.97	0.70	2.07	0.30	1.51	0.10	2.11	0.80	2.49	0.30	2.09	0.00	1.31	None
P10	0.00	1.77	0.60	2.47	0.20	1.51	0.40	2.51	0.70	2.09	0.20	2.19	0.50	1.91	None
P11	0.20	2.07	0.10	1.97	0.40	2.41	0.10	2.01	0.60	2.29	0.30	1.59	0.00	1.31	None
P12	0.60	1.67	0.20	1.47	0.30	2.01	0.50	2.51	0.20	1.49	0.60	2.29	0.20	1.81	None
P13	0.20	1.97	0.10	2.17	0.10	1.71	0.30	2.71	0.50	1.99	0.10	1.49	0.60	2.11	None
P14	0.00	2.17	0.20	2.07	0.30	2.01	0.20	1.81	0.10	2.09	0.30	1.49	0.10	1.81	None
P15	0.20	1.67	0.20	1.47	0.10	2.01	0.20	2.61	0.20	1.79	0.00	1.69	0.10	1.51	None
P16	0.30	1.77	0.10	2.07	0.10	2.11	0.30	2.51	0.20	1.69	0.10	1.59	0.20	1.51	None
P17	0.40	1.87	0.10	1.57	0.60	2.41	0.80	2.51	0.60	1.59	0.50	2.29	0.40	2.11	None
P18	0.00	1.87	0.10	1.77	0.20	2.21	0.10	2.21	0.30	1.99	0.40	1.99	0.30	1.51	None
P19	0.70	1.67	0.50	1.67	0.60	2.01	0.20	1.91	0.00	1.59	0.70	2.59	0.50	1.41	None
P20	0.10	1.57	0.40	1.37	0.40	1.91	0.10	2.61	0.00	1.89	0.20	2.09	0.00	1.41	None

IV. SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

The aim of measuring a structure's movement is to decide whether there is actually a movement and whether the structure is safe and stable. Deformation monitoring has the advantages of improving the design process of structures for use in the future and increasing safety by lowering the possibility of structural damage. It is a crucial risk management tool.

This paper explains the development of a methodology for monitoring and analyzing structures' vertical displacement. The developed methodology aims to add a new dimension to the well-known ones for geometric leveling and leveling routing. The proposed methodology is accurate and effective in determining the vertical displacement of structures. The case study demonstrates that geometric leveling is always effective for determining the vertical displacement of structures. For vertical displacement monitoring with a precision of less than 0.4mm, this approach is suggested. Geometric leveling is an accurate, precise, and cost-effective method of vertical displacement monitoring but it is not considered to be cutting-edge. Geometric leveling is recommended to be used extensively to monitor structures' deformation for the above-mentioned reasons.

The proposed method is subjected to limitations in its application areas. The proposed method can only be utilized to monitor displacements in the vertical plane, it cannot be utilized to monitor displacements in the horizontal plane. The developed software and methodology are very adaptable, affordable, and of great interest to students and researchers. They provide a helpful tool for engineering firms to monitor the safety of structures. It is strongly recommended that engineering structures, especially high-rise buildings, should be monitored at a regular basis to check their stability and thereby increasing their safety.

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