American Scientific Research Journal for Engineering, Technology, and Sciences (ASRJETS)
ISSN (Print) 2313-4410, ISSN (Online) 2313-4402

http://asrjetsjournal.org/

A Simple Methodology for Monitoring and Analysis of Vertical Displacement of Buildings

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Abstract

Measurements and monitoring of the engineering structures such as buildings provides information about the health of the structures and their safety aspects as well the safety of the public. This paper explains the development of a method for the monitoring and analysis of vertical deformation of buildings. The proposed method is developed to add a new solution to traditional methods of geometric leveling, leveling routing, least squares technique for level network adjustment and analysis, and global statistical analysis for evaluating the vertical displacement. The proposed method was used for monitoring and analyzing the vertical displacement of official building in Cairo, Egypt. Three local reference stations, five auxiliary points, and twenty monitoring points were used. All measurements were taken using an automatic level with a parallel plate micrometer attachment and a geodetic invar staff. The observations were carried out at eight epochs of one-month interval. Observations were adjusted using least squares adjustment technique to determine the adjusted levels, observations and generating the necessary statistical data. The results of the first epoch were used as reference results such that the subsequent epochs values were compared with them to compute the vertical displacement of monitoring points for each epoch. Furthermore, values of vertical displacement were compared with their corresponding computed 95% confidence intervals to determine the significance of the existing displacement. The results showed the stability of the building during the monitoring period. The case study shows the efficiency of geometric leveling for the monitoring of deformation of the building structures. It is strongly recommended that engineering structures especially high rise buildings should be monitored at regular basis to check their stability and thereby increasing their safety.

Keywords: Deformation Monitoring; Vertical Displacement; Geometric leveling; Accuracy Analysis.

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1. Introduction

The purpose of the deformation determination is to determine whether or not movement is taking place and therefore whether the structure is stable and safe. Deformation can be further studied to know if it is due to seasonal factors, daily variances, etc. and then to use the information for determining future movement of the structure [1]. It is necessary to determine this movement for the purpose of safety studies and as well as preventing any disaster in the future. The advantages of deformation monitoring are the increasing of safety by reducing the risk of structural failure and the refinement of the structural design process for future applications [10]. It is an important tool for risk management. Nowadays, it is possible to use a number of different procedures of deformation monitoring, such as topographic networks for three-dimensional (3D) control using total stations or geometric leveling. These may be combined with more complex procedures such as portable digital photogrammetric stations (DPS) or a terrestrial laser scanner (TLS) system [13]. Specifically, the latter has become an essential tool when dealing with built-heritage buildings, providing very quickly a point cloud that creates a 3D model of the monument [12]. However, in general, these remote sensing technologies require the use of specialized equipment that is not readily available to most surveyors. This equipment is expensive to buy or rent and additional costs can be incurred because of the need to train or hire personnel capable of managing and modeling point cloud data. Additionally, the amount of data acquired by a TLS system makes it difficult to produce models. There are many software systems available to assist in this task, but these consume computing and time resources and again special equipment must be bought or hired. These techniques therefore have significant limitations, confining their application almost exclusively to architectural heritage inspection [6], where the available budgets and resources are both significantly higher. Furthermore, even excluding the issues of cost and complexity, these techniques have other problems, mainly concerning the accuracy of the measurements they produce [2]. Changes in environmental conditions such as humidity and temperature [8], reflectivities of different colors and materials, the effects of angle of incidence [3], and problems due to close-range imaging can generate possible dimensional errors in the model [5]. Depending on these conditions, significant errors in the measurement of vertical displacements can occur, extending sometimes to an order of magnitude of more than 1 cm, compared with direct measurements [9]. This highlights the importance of evaluation procedures that enable the calibration of laser scanners, especially during the development of high-precision surveys in architectural heritage sites. Direct measurement procedures should be used to check typical tests such as deformation monitoring [7]. To avoid some of the above described problems, a cost effective methodology for monitoring vertical displacement of building will be presented in this paper. The obtained results are sufficiently accurate to provide a correct assessment of building safety, thereby improving the diagnostic and decision-making process.

2. Methodology

2.1 Method of Vertical Displacement Measurements

In surveying, leveling is the process of measuring, by direct or indirect methods, vertical distances in order to determine elevations. Two methods are applied: geometric (or direct) leveling and trigonometric (or indirect) leveling. The first method is more accurate, the monumentation is lighter, surveying instruments and fieldwork are more cost-effective and field- and office-works are easier. In geometric leveling, the difference of levels between two points is determined by measuring the readings to the staffs, or ruler, placed on those points. The readings are measured with a leveling instrument. By knowing the elevation of at least one point and the level differences between points, the elevations of all points can be obtained. The points in a leveling line are classified in three categories: i) object points - points that are to be monitored; ii) reference points; iii) auxiliary points. The object points are chosen to be distributed on the building facades and on the necessary walls inside the building. The position of the object points is wisely chosen to verify the stability of each wall in the building. The reference points may be located in the area to be controlled (and therefore might undergo displacements) to determine only relative displacements. If reference points are located outside that area, tied to bedrock or other non-moving structure, absolute displacements can be determined. Although only one reference point is needed in leveling lines, the experience advises to place at least three, the only way to identify unstable reference points. The reference points must be positioned around the building at a safe distance in order to consider that they are not affected by the displacements of the building. Auxiliary points are placed, for instance, to link sectors of a leveling line that, otherwise, would be independent.

2.2 Monumentation

Regarding monumentation, the points are usually materialized by concrete nails sealed on a wall or pegs sealed on the floor using drill and epoxy. All object points must be well tied to the structure preferably to the concrete columns, otherwise, displacements might represent monumentation displacements instead of structure displacements.

2.3 Instrumentation

Automatic levels i. e. optical levels with a built-in compensator, that uses an extremely sensitive pendulum device, which automatically makes the line of sight horizontal, must be used. Accuracy can be improved by fitting a parallel plate micrometer over the telescope objective. The parallel plate micrometer allows direct readings on a staff of one centimeter least count, to 0.1mm, and estimated readings, to 0.01mm. Digital levels are automatic levels with a built-in digital image processing system that permits automatic reading of special staffs (coded bar) and electronic recording. The main advantages of digital levels are the elimination of errors caused by man reading and manual recording and increasing the speed of leveling.

2.4 Field Work

Prior to the observation of the monitoring points, the levels of the reference stations have to be known otherwise the local levels of the reference points may be determined by precise leveling. The leveling of the monitoring points is divided into loops. Each loop starts from a reference station and closed back on the same reference station or another reference station. The levels of the monitoring points are determined at different epochs of specified time interval. After the identification of the reference and monitoring points, and the leveling line route is established, the needed auxiliary points and also an approximate location of the instrument in each leveling line must be marked to assure the precision required by having equal sections of leveling and by having almost the same route of line leveling. Beginning and ending the leveling measurements on reference stations is the only way to control the quality of measurements. The difference between the known level and the computed level is the misclosure (Δ), and is computed by:

$$\text{Misclosure } (\Delta) = \text{Reference}_{\text{Levelknown}} - \text{Reference}_{\text{Levelcomputed}} \quad (1)$$

The misclosure is computed right after the end of the leveling works. Performing this data pre-processing in the field allows the observation team to repeat the measurements with lower costs and, also important, with no changes of the structure conditions.

The allowable misclosure can be obtained as [10]:

$$\text{Misclosure tolerance} = 0.9\sqrt{n} \text{ in mm} \quad (2)$$

where n is the total number of set-up.

When misclosure exceeds the tolerance value all measurements should be repeated. For permissible misclosures, the adjusted levels of all points can be obtained using Least Squares Technique [16].

2.5 Vertical Displacement Determination

LandSurMap software [11] will be used for getting the adjusted level and necessary statistical data of each point in each loop. The software reads the data in the form of the height differences and distances between stations of the network as well as the known elevations of bench mark(s) and uses Least Squares Technique (Mikhail, 1983) for the determination of its output.

LandSurMap offers a great deal of flexibility for level network adjustment which may be summarized as follows:

- Any number of network stations and distribution of bench marks/control points (other than the well known minimum requirements e.g. one control point per level network) are acceptable.
- For practical reasons, the specifications for input data editing have been kept flexible. Various input formats can be accepted if they are consistent.
- Another feature of practical importance refers to the point-numbering. The module has no restriction of any kind about the point-numbering. The point-numbering is natural and virtually free.
- Observations can be weighted. Weighting of observations is desirable from a theoretical point of view. In addition, it helps considerably in locating gross errors.
- Computation of the initial values of levels for unknowns stations which are essential for starting the iterative solution.
- Iterative solution of least squares with the capability of displaying the results of the final iteration or of each iteration.

The output of the software, in the form of ASCII file format, includes variance of unit weight, adjusted levels of unknown stations and their standard deviations (optional), residuals of observations, corrected observations and their cofactor matrix (optional), and statistical data for blunder detection (optional). After getting the adjusted levels of the object points for each epoch, the results of the first epoch are used as reference results such that the subsequent epochs values are compared with them. In this case, the values of vertical displacement of each object point can be obtained as:

$$dZ = Z_{Frist\,epoch} - Z_{Current\,epoch} \quad (3)$$

where,

dZ = vertical displacement of the object point

Z = the adjusted level of the object point

2.6 Displacement Analysis

The classical method for checking stability of reference and object points involves comparing the differences in level obtained in the initial observations (first epoch) and existing (current epoch) as shown in Equation (3). Modern deformation modeling methods involve the application of statistical tests on each epoch of measurements to determine whether point displacements are significant. Determination of the significant of points displacements is based on comparing the computed displacements with their corresponding 95% confidence intervals [4]. If the vertical displacement magnitude of a point j is classified dZ_J (Equation 3) and the maximum dimension of combined 95% confidence ellipse for point j is designated E_J , then, if $|dZ_J| \langle E_J$ it can be concluded that no displacement has occurred in point j and the observed difference is due to errors in measurement. Furthermore, if $|dZ_J| \rangle E_J$ then it can be concluded that point displacement has occurred [15].

E_J can be computed as:

$$E_J = 1.96\sqrt{(m_{\Delta J}^{k+1})^2 + (m_{\Delta J}^{k})^2} \quad (4)$$

in which,

$(m_{\Delta J}^{k+1})$ is the standard error in level of point J in the current epoch and

$(m_{\Delta J}^{k})$ is the standard error in level of point J in the previous epoch.

3. Case Study

The monitored building was a governmental building in Cairo, Egypt. The building is 110.0m in length, 60.0m in breadth and 20m in height. It is a three-story building which consists of various offices.

3.1 Choice of Points

To effectuate the deformation monitoring of the case study building, in the first step the recognition of the field has been made. In this step, three local reference points and five auxiliary points were chosen as shown in Figure 1. These points were positioned around the building at a safe distance in order to consider that they were not affected by the displacements of the building. In the vertical displacement monitoring project of the case study building, 20 object points were positioned on the first floor in order to determinate the stability of the structure. Those object points were positioned on the internal and external walls as shown in Figure 1. The object points on the building walls were about 0.3m above ground level so that the staff can be easily held on them during leveling/observation. The marked monitoring points were made permanent by driving in special nails at the marked points.

3.2 Measurements

All measurements were taken using Leica NA2 automatic level with a Leica (10 mm) GPM3 parallel plate micrometer attachment and a GPLE3 geodetic invar staff with 10 mm graduations [14]. Prior to the observation of the monitoring points, the levels of the reference stations (B1, B2 and B3) must be known. The level of point B1 is assumed as 10.0 m and the levels of points B2 and B3 were determined through loop of level net starting from B1 to reference stations B2 and B3, and the five auxiliary points and closed back on B1.

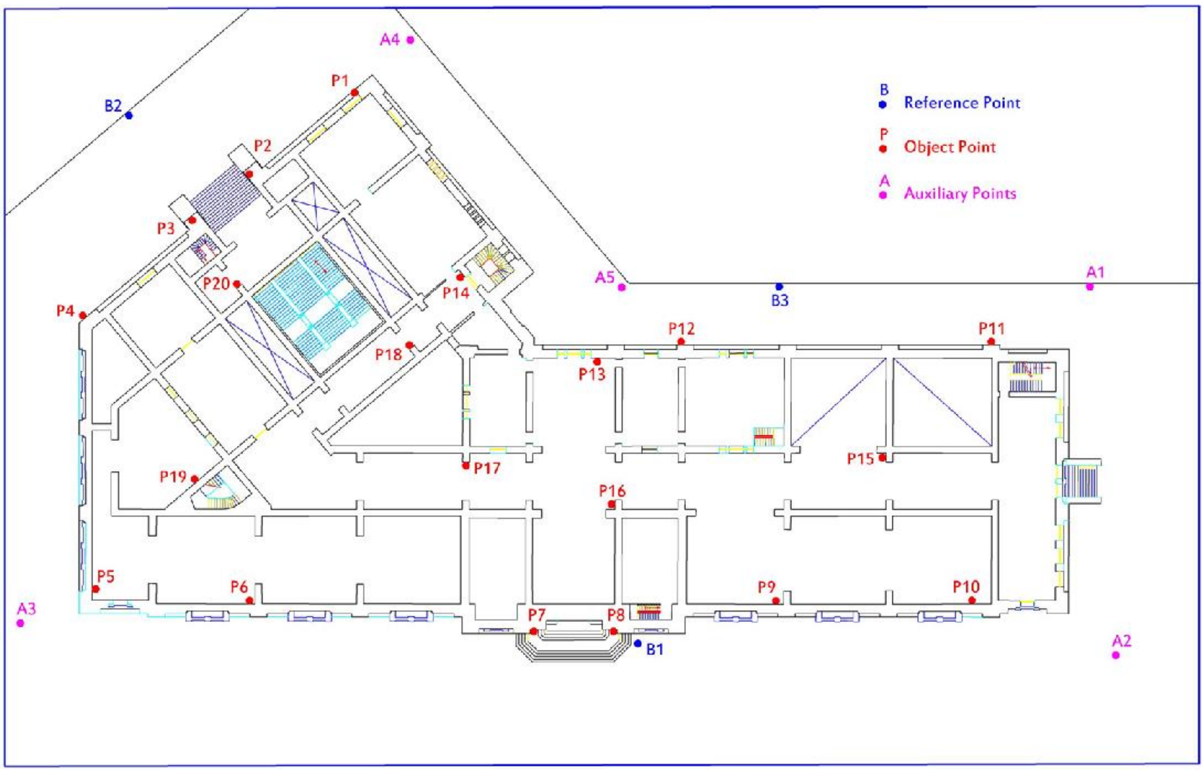

Figure 1: Location of the Chosen Points

Having determined the levels of the reference stations, precise leveling with loops was used to determine the levels of the monitoring points at eight different epochs of one-month interval. All the observations were taken in the morning hours. In all the eight observation epochs that were taken, the misclosure of each leveling line was not higher than 0.4 mm, which is the tolerance accepted for the purpose of this work. The high accuracy of the leveling was as a result of the fairly flat topography of the study area, the observer's experience and equipments used.

3.3 Data Processing and Results

Table 1: The levels and vertical displacement of object points at the observation epochs.

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	10.3086	0.0	10.3089	-0.3	10.3091	-0.5	10.3090	-0.4	10.3089	-0.3	10.3093	-0.2	10.3093	-0.7	10.3091	-0.5
P2	10.4079	0.0	10.4082	-0.3	10.4078	0.1	10.4078	0.1	10.4082	-0.3	10.4079	-0.1	10.4080	-0.1	10.4082	-0.3
P3	10.3114	0.0	10.3112	0.2	10.3109	0.5	10.3110	0.4	10.3110	0.4	10.3108	0.1	10.3109	0.5	10.3110	0.4
P4	10.2954	0.0	10.2952	0.2	10.2953	0.1	10.2949	0.5	10.2950	0.4	10.2952	0.1	10.2950	0.4	10.2951	0.3
P5	10.8162	0.0	10.8162	0.0	10.8159	0.3	10.8158	0.4	10.8161	0.1	10.8159	0.0	10.8162	0.0	10.8163	-0.1
P6	10.8091	0.0	10.8089	0.2	10.8088	0.3	10.8091	0.0	10.8092	-0.1	10.8091	-0.3	10.8094	-0.3	10.8092	-0.1
P7	10.0957	0.0	10.0962	-0.5	10.0962	-0.5	10.0961	-0.4	10.0958	-0.1	10.0959	0.3	10.0962	-0.5	10.0961	-0.4
P8	10.1248	0.0	10.1251	-0.3	10.1252	-0.4	10.1248	0.0	10.1250	-0.2	10.1247	0.5	10.1249	-0.1	10.1252	-0.4
P9	10.8452	0.0	10.8449	0.3	10.8447	0.5	10.8451	0.1	10.8453	-0.1	10.8446	0.1	10.8451	0.1	10.8454	-0.2
P10	10.6501	0.0	10.6503	-0.2	10.6497	0.4	10.6501	0.0	10.6499	0.2	10.6496	0.1	10.6501	0.0	10.6498	0.3
P11	9.2990	0.0	9.2994	-0.4	9.2993	-0.3	9.2988	0.2	9.2991	-0.1	9.2986	0.7	9.2989	0.1	9.2992	-0.2
P12	9.2154	0.0	9.2150	0.4	9.2154	0.0	9.2153	0.1	9.2151	0.3	9.2154	0.0	9.2150	0.4	9.2154	0.0
P13	10.5100	0.0	10.5104	-0.4	10.5101	-0.1	10.5103	-0.3	10.5099	0.1	10.5097	0.4	10.5101	-0.1	10.5096	0.4
P14	10.6028	0.0	10.6030	-0.2	10.6028	0.0	10.6027	0.1	10.6032	-0.4	10.6029	-0.1	10.6033	-0.5	10.6031	-0.3
P15	10.8079	0.0	10.8079	0.0	10.8083	-0.4	10.8082	-0.3	10.8079	0.0	10.8079	0.4	10.8081	-0.2	10.8082	-0.3
P16	10.6048	0.0	10.6053	-0.5	10.6051	-0.3	10.6049	-0.1	10.6047	0.1	10.6048	0.3	10.6051	-0.3	10.6052	-0.4
P17	10.4703	0.0	10.4701	0.2	10.4704	-0.1	10.4699	0.4	10.4697	0.6	10.4699	0.5	10.4695	0.8	10.4701	0.2
P18	10.6609	0.0	10.6611	-0.2	10.6612	-0.3	10.6609	0.0	10.6610	-0.1	10.6608	0.4	10.6607	0.2	10.6608	0.1
P19	10.7991	0.0	10.7986	0.5	10.7988	0.3	10.7987	0.4	10.7991	0.0	10.7993	-0.5	10.7986	0.5	10.7988	0.3
P20	10.6777	0.0	10.6778	-0.1	10.6783	-0.6	10.6783	-0.6	10.6780	-0.3	10.6779	0.4	10.6777	0.0	10.6779	-0.2

Processing the level networks data was performed using LandSurMap software. Measurements and geodetic data e.g. the levels of the reference points and their standard deviations, height differences and distances between stations were entered to the software by editing a suitable data file. Three iterations were required to get the final results of the level net adjustment. The results were received in the form of, as mentioned before, variance of unit weight, adjusted levels of object points and their standard deviations, residuals of observations, and corrected observations and their cofactor matrix. The maximum variances of unit weight of the first to the eight epoch leveling was 1.35 mm2 and the corresponding standard error was 1.16 mm which show the high precision and accuracy of the adjusted observations. The maximum standard error for the adjusted levels in all epochs was 1.22 mm which shows the high accuracy of the adjusted levels. The computed standardized residuals of the eight epochs observations/leveling were all less than their respective standardized residual rejection constants which implies that there were no gross errors or outliers hence, none of the observations was rejected. The observations of the first epoch were used as reference observations such that the subsequent epochs observations were compared with them. The differences in levels between the first and the subsequent epochs adjusted levels and their respective magnitudes were respectively computed. Table 1 shows the level differences and the level of the object points at some of the observation epochs.

The differences in level between the first and the subsequent epochs respective confidence intervals at 95% confidence level were determined using Equations (4). Table 2 presents the vertical displacements values of the object points and their corresponding confidence intervals at 95% confidence level. The vertical displacements magnitudes of the monitoring points/building at each epoch were computed and compared with their corresponding confidence intervals at 95% confidence level to determine if the computed displacements were actual movements of the structure (significant) or they were due to measurement errors.

Table 2: Analysis of the vertical displacement for 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	0.3	1.8	0.5	2.1	0.4	1.9	0.3	2.3	0.2	1.3	0.7	1.8	0.5	1.9	NO
P2	0.3	2.1	0.1	2.4	0.1	1.8	0.3	1.8	0.1	2.0	0.1	1.7	0.3	1.5	NO
P3	0.2	2.2	0.5	2.3	0.4	1.7	0.4	2.2	0.1	1.9	0.5	1.7	0.4	1.6	NO
P4	0.2	1.9	0.1	2.1	0.5	2.2	0.4	2.1	0.1	1.5	0.4	2.0	0.3	1.6	NO
P5	0.0	1.5	0.3	2.3	0.4	1.9	0.1	1.9	0.0	1.9	0.0	1.5	0.1	1.6	NO
P6	0.2	1.3	0.3	2.1	0.0	1.5	0.1	2.1	0.3	1.8	0.3	1.5	0.1	1.9	NO
P7	0.5	1.7	0.5	2.0	0.4	1.9	0.1	2.5	0.3	1.6	0.5	1.5	0.4	1.8	NO
P8	0.3	2.3	0.4	1.9	0.0	2.2	0.2	2.0	0.5	2.0	0.1	1.6	0.4	1.4	NO
P9	0.3	2.1	0.5	2.2	0.1	1.4	0.1	2.0	0.1	2.4	0.1	2.0	0.2	1.4	NO
P10	0.2	1.9	0.4	2.6	0.0	1.4	0.2	2.4	0.1	2.0	0.0	2.1	0.3	2.0	NO
P11	0.4	2.2	0.3	2.1	0.2	2.3	0.1	1.9	0.7	2.2	0.1	1.5	0.2	1.4	NO
P12	0.4	1.8	0.0	1.6	0.1	1.9	0.3	2.4	0.0	1.4	0.4	2.2	0.0	1.9	NO
P13	0.4	2.1	0.1	2.3	0.3	1.6	0.1	2.6	0.4	1.9	0.1	1.4	0.4	2.2	NO
P14	0.2	2.3	0.0	2.2	0.1	1.9	0.4	1.7	0.1	2.0	0.5	1.4	0.3	1.9	NO
P15	0.0	1.8	0.4	1.6	0.3	1.9	0.0	2.5	0.4	1.7	0.2	1.6	0.3	1.6	NO
P16	0.5	1.9	0.3	2.2	0.1	2.0	0.1	2.4	0.3	1.6	0.3	1.5	0.4	1.6	NO
P17	0.2	2.0	0.1	1.7	0.4	2.3	0.6	2.4	0.5	1.5	0.8	2.2	0.2	2.2	NO
P18	0.2	2.0	0.3	1.9	0.0	2.1	0.1	2.1	0.4	1.9	0.2	1.9	0.1	1.6	NO
P19	0.5	1.8	0.3	1.8	0.4	1.9	0.0	1.8	0.5	1.5	0.5	2.5	0.3	1.5	NO
P20	0.1	1.7	0.6	1.5	0.6	1.8	0.3	2.5	0.4	1.8	0.0	2.0	0.2	1.5	NO

It can be concluded from Tables 1 and 2 that the evaluated displacements magnitudes were all less than their corresponding confidence intervals showing that the building did not undergo any vertical displacement during the period of monitoring.

4. Conclusions and Recommendations

The proposed method is accurate and efficient for the determination of the vertical displacement of the structures. The case study shows that geometric leveling is always one of the best methods for the determination of vertical displacement of a building. This method is recommended for vertical displacement monitoring with the precision of under 0.4 mm. Geometric leveling is not considered a modern technique of vertical displacement monitoring but it is an accurate, precise, and inexpensive method. For these reasons, geometric leveling can be widely applied in the deformation monitoring of structures. The main limitation of the proposed method lies in the application areas of its use. The proposed method can only be used to monitor vertical movements but horizontal movements are unable to be monitored. It is strongly recommended that engineering structures especially high rise buildings should be monitored at regular basis to check their stability and thereby increasing their safety.

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