MODERN TECHNIQUES OF LANDS AND CONSTRUCTIONS DEFORMATION MONITORING

Cătălin Ionuţ VINTILĂ, Eng. PhD. Student – S.C. Total Topographic Survey S.R.L.-D., catalin.vintila@ymail.com
Andreea Carmen RĂDULESCU, Eng. PhD. Student – Technical University of Civil Engineering Bucharest, andreea3radulescu@yahoo.ro
Petre Iuliu DRAGOMIR, Prof. Eng. PhD. – Technical University of Civil Engineering Bucharest, petreiuliu.dragomir@gmail.com

Abstract: It's well known that any land or construction has long term movements, those movements can only be measured with high precision by using topographical instruments. In the past years, the technique and technology of lands and constructions monitoring has been greatly expanded.

The main purpose of monitoring constructions behavior in time is to learn the displacements and deformations that constructions suffers in comparison to a number of known point (reference points) that are situated around the construction, at a well calculated distance so they couldn't be affected by the building deformations.

This paper presents several modern techniques of lands and constructions monitoring, such as: high precision geometrical leveling, GOCA – GNSS/LPS based Online Control and Alarm Systems and 3D laser scanning and ends with a case study of high precision geometrical leveling.

Keywords: Deformation monitoring, Geometric levelling, GOCA, GNSS technology, Laser scanning.

1. Introduction

In search of the elements that reduce the incertitude of projection calculations and also to verify different structures, the knowledge of geometrical forms modifications and displacements, which lands and constructions suffers more or less as time goes by, has a very big importance. The measurement of those modifications is one of the most interesting problems in experimental researches which allows us to obtain precious indications of the elastic behavior and material's endurance and of the field's behavior on which the construction is situated. Also the deformation monitoring can bring useful contributions to improvement of the constructions techniques, by allowing a confrontation between the theoretical assumptions, the studies made in specialized labs and the practical results obtained.

The Deformation monitoring of a land or construction represents a systematic action of observation, measurement and analysis of the way they respond to influence of surrounding agents, taking permanently in consideration the projection parameters of functionality, stability and safety. For a proper monitoring of constructions behavior in time, constructions that are subjects to experimental solicitations or exploitation, obtaining observations in a relative short time is highly required.

The tasks in deformation monitoring survey require acquisition of observation data obtained from at least two campaigns of field measurements. Type of instruments used in data

acquiring is depending on the nature of works and also on logistical consideration. Normally, for a small network the use of total station seems good enough in measuring the required directions or horizontal angles and distances. The subsequent task is to perform the least squares adjustment to determine the coordinates of all the reference as well as the object points in the network for each epoch of measurements.

2. High precision geometric levelling

Geometric levelling is the oldest method of geodetic surveying, used to measure differences of elevation between two or more points at the Earth's surface. Experience has shown geometric levelling to be a reliable and very precise vertical displacement measurement method. Modern electronic levels, with automatic reading and recording, have significantly improved geometric levelling operational performances. [1]

In surveying, levelling is the process of measuring, by direct or indirect methods, vertical distances between two or more points in order to determine elevations. Two methods are applied: geometric levelling and trigonometric levelling. The first one is usually more precise, equipment and fieldwork are less expensive and operation procedures are easier. In geometric levelling the difference of height between two points is determined by differences of readings to the staffs placed on those points. The readings are made with a levelling instrument, digital or optical level.

The points in a levelling line could be classified in three categories: 1) object point; 2) reference points; 3) auxiliary points – intermediate points between reference points and object points. When the reference points are located in the close proximity, and therefore they might suffer displacements themselves, the displacements recorded are relatives. If reference points are located outside the monitored object surrounding, tied to bedrock or other secured structures, absolute displacements can be determined. Although, in theory, only one reference point is needed in levelling line, for deformation monitoring at least three reference points must be placed to identify the misclosure and eventually unstable reference points. A geotechnical expert is the person qualified to choose the position of the reference points and object points.

For high precision geometric levelling, digital levels should be used. Those levels are automatic levels with a system of digital image processing that allows automatic reading from a special rod, coded bar, and electronic recording. This way all the errors caused by man reading and by manual recording are eliminated and also the speed of levelling increases. In levelling line rigid invar staffs must be used. Invar is a nickel-steel alloy that has a linear thermal expansion coefficient of 0.7×10^{-6} ^{o}C, a very important characteristic especially when measurements must be made in extreme temperature conditions.

From all the methods used in levelling line, the most recommended and accepted one, in which level differences from two points are measured with one level and readings are made on both invar rods in two different horizons of the instrument. This procedure is recommended to ensure the proper accuracy required to measure the level differences between two points. Consequently, the level difference will be calculated as the result of the arithmetic mean of the values determined with both horizons of the instrument. [2]

$$h_i = \frac{1}{2}(h_i^{t1} + h_i^{t2})$$ (1)

Where, h_i^{t1} is the level difference measured in the first horizon of the instrument and h_i^{t2} is the level difference measured in the second horizon of the instrument.

The most important errors that affect geometric leveling are due to:

- Non horizontal line of sights (vertical collimation error);
- Reading errors of staff and level micrometer;
- Errors made during manual recording;
- Tripods placed on unstable surfaces like sandy ground or mud;
- Thermal effects of the sunrays incidence on the level;
- Influence of magnetic field on automatic levels;
- Non verticality of the staff;
- Temperature;
- Refraction;
- Crustal movements.

Due to those errors made during measurements, each reading has an error, unknown, associated, so that:

$$\mu = R + \varepsilon \tag{2}$$

Where, R is the reading and μ the true value, unknown.

The error ε can be split into three errors:

- Θ_i - Instrumental error due to errors of the measuring equipment;
- Θ_e - Environmental error due to measuring conditions
- δ - Accidental errors.

$$\varepsilon = \Theta_i + \Theta_e + \delta \tag{3}$$

While instrumental and environmental errors are systematic errors and they have the same values when observation conditions are repeated, the accidental errors have a random distribution. For high precision geometric levelling, special care is required during measurements in order to reduce these errors. One is to place the instrument at almost equal distances from the rods (at least ±1m), this care reduce the effect of collimation error. If the instrument is not positioned at equal distances between the rods, the height difference, as being a difference of readings, is affected by this error.

$$E_a \neq E_b \tag{4}$$

E_a, E_b, are readings errors from point A, respectively point B.

Equal distances between instruments and staff also eliminate the effect of curvature of the earth and normal refraction, the coefficient of refraction is the same for both lines of sight. On slopes, backsights have different distances from the ground than foresights and, therefore, light rays undergo different paths and so the back and fore readings are differentially affected. This situations could be avoided or by placing additional points or by standing the level higher in order that the line of sight will not be less than 50 cm above the ground. To ensure equal atmospheric conditions on both sightseeing the maximum length of one line of sight should not be more than 20 m.

3. GOCA – GNSS/LPS based Online Control and Alarm Systems

With the use of newer and efficient construction methods, the geodetic supervision is demanded more often. In the past decades, buildings were constructed with big effort regarding safety and stability. Today, however, for the planning of constructions, new methods are introduced which are edging technical feasibility. These new methods require an increase of accuracy and also a decrease of the observation time, aiming to a continuous online geodetic monitoring of the construction. Otherwise, the security for man and building cannot be guaranteed properly. [3]

Modern geodetic monitoring starts with the storage of original measurements, continues with network adjustments and deformation analysis and ends with their report or in case of emergency with the alarming of the responsible people.

The GOCA, which is a part of expert monitoring systems, applies GNSS as well as classical local positioning sensors (LPS), such as motorized total stations, for a real-time deformation monitoring. The system may be used as a warning system for natural calamities (landslides, volcanos eruptions) and also for the monitoring of and constructions (mining, tunnelling activities, bridges). [4]

The GOCA system consists of GNSS and LPS sensors, which are set up in the monitoring area as a permanent system or as a mobile monitoring system. The GOCA hardware-control and communication software modules collect, in different kind of communication modes, the GNSS and the LPS data in a user defined sampling rate.

GOCA deformation-analysis software is responsible for a further processing of that data in a three steps sequential adjustment procedure. Both least squares and robust estimation techniques are applied. A first focus is set on the robust online displacement estimation, statistical testing and alarm setting.

The GOCA system consists of a set of GNSS/LPS sensors and communication units that are set up in the area of the monitored object and two software packages, the GOCA sensor communication software and the GOCA deformation analysis software. The GOCA computation unit, the "GOCA-Center" is a computer where these two software components are running.

This system of control and alarm system sets up a classical geodetic deformation network online, which is parted into a stable reference point frame and the domain of moving objects points. The sensors observations, GNSS observations and total stations observations, enable the permanent estimation of the deformation.

The structure of the GNSS and LPS data interface for the GOCA deformation analysis software, the so-called GKA files, are adapted to the GNSS baseline standard output of respective coordinates and covariance matrices and the LPS data standard (zenith angles, distances, directions, height differences). Any local GOCA-center may be linked over a long distance to another PC, which serves as a remote control station.

4. 3D Laser Scanner

The use of terrestrial laser scanners is a new and promising way for monitoring the deformations of artificial and natural objects. These new sensors offer distance measurements with reflectorless technology. The result of such a scan is a very dense point cloud which enables more precise object models. Two main problems exist if dense point clouds from laser scanner measurements are used for deformation analysis: the huge data volume which has to be handled, and the lack of fully automated analysis methods. As in a typical deformation scenario the shape of the objects changes due to bending and flexing, a thorough but information preserving parameter reduction is needed by a set of a few characteristic parameters. [5]

The use of laser scanning techniques for 3D point determination is well known from airborne surface acquisition where an oscillating laser beam is measuring the angle and the distance to the ground in a section orthogonal to the plane's flight direction. In engineering geodesy this type of sensors has been available since a few years. Up to now, terrestrial laser scanners have become important tools for solving tasks such as cultural heritage or as-built documentation or object monitoring. Similar to airborne devices, terrestrial laser scanners use a laser beam to determine the slope distance s to an object's surface, either by time-of flight or

phase-shift method. Usually the laser beam is moved in a raster-shaped way over the object with two rotating or oscillating mirrors which are placed perpendicularly to one another. The vertical angle φ and horizontal angle λ are also registered. For a better handling, the polar coordinates are usually transformed into rectangular coordinates. The result of such a scan is a so called point cloud, the data volume of which can easily exceed 100 million points. [6]

3D Laser Scanners can reach a scanning accuracy up to 5 mm, so that they can be successfully used to track the behavior of certain constructions, where the required precision is not very high and the ground situation allows for their use; they have the disadvantage that the scanned image acquisition should be done from the smallest distance possible from the building - to achieve the highest accuracy of determination, which means that the land around the building is stable in time. Using Terrestrial Laser Scanners (TLS), although it is a more recent technology, proves to be promising for the near future, in the vast process of determining and monitoring deformations of constructions under investigation. Although the first TLS were marketed over a decade ago, currently there is still no ISO standard to regulate the field testing procedures of such devices.

5. High precision geometric levelling used for deformation monitoring of Sky Tower infrastructure, from Floreasca City Center, Bucharest

To meet the growing demand for office space in crowded cities as Bucharest, but also because of the smaller and smaller buildable area in these cities, Raiffeisen Property Holding International decided to build the highest block for office spaces in Bucharest. Sky Tower has 5 basements, ground floor and 37 upper floors with a total area of 50400 square meters and held a footprint of just 1300 square meters.

Tower block is located between two of the most important streets in the north of Bucharest, Floreasca and Barbu Văcărescu street, as can be seen in Fig. 1. The building has a total height of 137 meters, is visible from almost every part of the city, being the highest construction for office spaces ever built in Romania.

The Sky Tower provides state of the art office spaces with unique panoramic views over Bucharest, a first class restaurant with a sky bar, a conference area on the top floors and a prime location in the north of Bucharest. [7]

Fig. 1. Sky Tower, Bucharest
(Source: www.skytower.ro)

To effectuate the deformation monitoring of Sky Tower building in the first step the recognition of the field has been made. In this step there were identify and verify three reference points that are part of the state levelling network. The three reference points that were used were positioned around the building at a safe distance in order to consider that they were not affected by the displacements of the construction.

For the measurements of the height differences digital level Leica DNA03 has been used. This level is a product of Leica Geosystems, is a part of the second generation of digital levels by Leica (the inventors of the first digital level), has a modern and ergonomic design, cutting edge electronic technology and excellent optical and mechanical system. For height measurements with invar staff, the standard deviation per km double levelling is 0.3 mm. [8]

In the deformation monitoring project of the Sky Tower building 28 object points were positioned at the 5th basement in order to determinate the stability of the structure. Those object points were positioned on the key points of the infrastructure, on the piles and on the diaphragm walls, as it can be seen in *Fig. 3*.

In order to be able to realize the measurements between reference points positioned outside the area of the construction and the object points positioned in the 5th basement of the building, measurements has been divided in two parts. In the first part there were made measurements from the reference points to a group of auxiliary points positioned near the building and then measurements were made at the ground floor and the 5th basement with the combined method. In the second part there were made measurements between al of the object points positioned in the 5th basement.
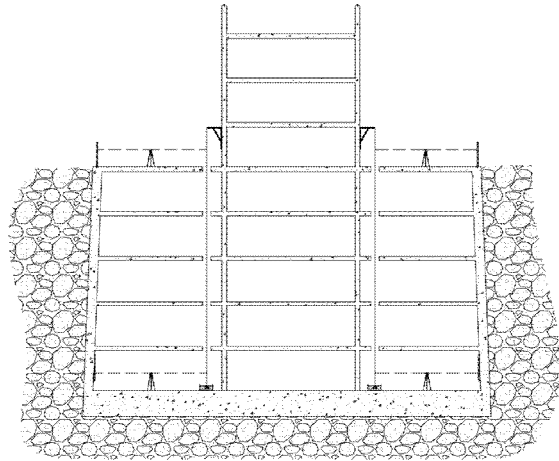

Fig. 2. The combined method
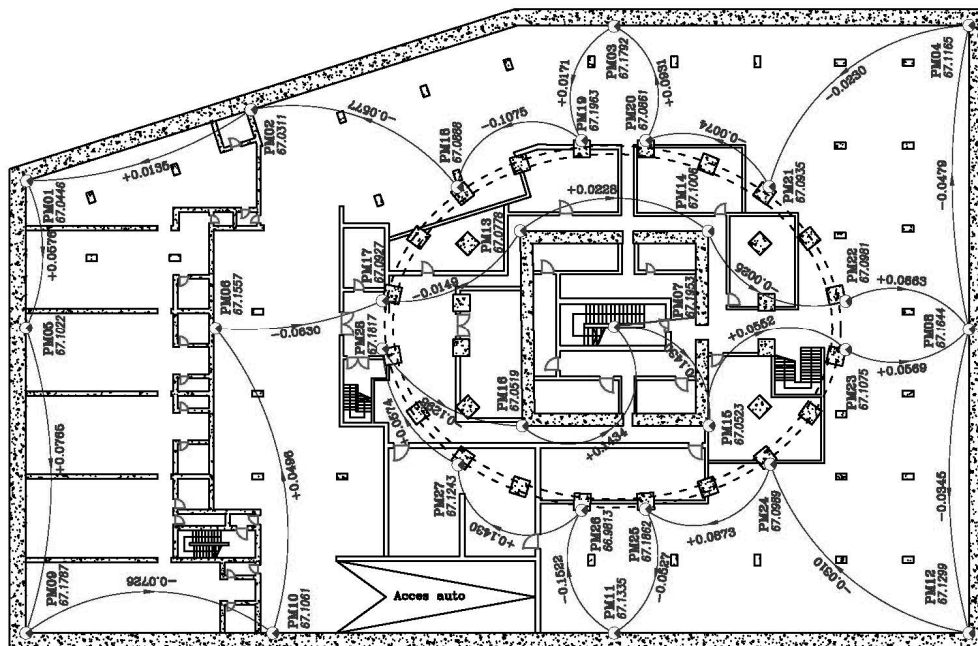
Fig. 3. Object points positioned in the 5th basement

To realize the combined method there were installed, in two parts of the building, two measurement steel tapes from the ground floor to the 5th basement and systematic readings were made in the same time with two digital levels of the same precision to assure the accuracy of the method (*Fig. 2*). Also another levelling line was made from the ground level, through the auto access, down to the 5th basement to verify if the method used meets the required precision.

Since October 2011 until May 2013 a total of 18 measurement runs has been effectuated, according to the given measurement program. The first measurement was done when all the basements were constructed and then at the end of construction of every three floors (almost one month), when the construction was built entirely a measurement run was made at every three months. In present the measurement runs are made at every six months.

At every observation run the compensation of the levelling lines were made separately for the levelling line made at the ground floor and for the levelling line made at the 5th basement using the free network adjustment. After the compensation of each observation run the networks were statistically tested using the global congruence test and displacements were identify using the "student test" and "multiple F test". In the table below are shown the height differences and the level of the object points at some of the observation runs.

Table 1 Height differences between observation runs

No. of observation run:	Observation run "0"			Observation run "1"			Observation run "12"			Observation run "18"		
Date:	24/10/2011			24/11/2011			28/10/2012			15/5/2013		
Physical state of the buiding:	5S			5S+P			5S+P+36E			5S+P+36E		
	Level of object point	Height difference since		Level of object point	Height difference since		Level of object point	Height difference since		Level of object point	Height difference since	
		last	first		last	first		last	first		last	first
Object point:		reading			reading			reading			reading	
	m	mm		m	mm		m	mm		m	mm	
PM1	67.0446	0	0	67.0437	-0.9	-0.9	67.0165	-1.3	-28.1	67.0104	0.2	-34.2
PM2	67.0311	0	0	67.0303	-0.8	-0.8	67.0037	-1.2	-27.4	66.9976	0.1	-33.5
PM3	67.1792	0	0	67.1783	-0.9	-0.9	67.1500	-1.3	-29.2	67.1439	0.5	-35.3
PM4	67.1165	0	0	67.1155	-1.0	-1.0	67.0879	-1.4	-28.6	67.0818	0.3	-34.7
PM5	67.1022	0	0	67.1011	-1.1	-1.1	67.0725	-1.4	-29.7	67.0664	0.5	-35.8
PM6	67.1557	0	0	67.1548	-0.9	-0.9	67.1280	-1.5	-27.7	67.1219	0.0	-33.8
PM7	67.1953	0	0	67.1944	-1.0	-1.0	67.1611	-1.3	-34.3	67.1518	-0.9	-43.5
PM8	67.1644	0	0	67.1634	-1.0	-1.0	67.1373	-1.2	-27.1	67.1312	0.2	-33.2
PM9	67.1787	0	0	67.1776	-1.1	-1.1	67.1505	-1.4	-28.2	67.1444	0.6	-34.3
PM10	67.1061	0	0	67.1050	-1.1	-1.1	67.0781	-1.2	-28.0	67.0720	0.5	-34.1
PM11	67.1335	0	0	67.1323	-1.2	-1.2	67.1050	-1.1	-28.5	67.0989	0.2	-34.6
PM12	67.1299	0	0	67.1289	-1.0	-1.0	67.1015	-1.3	-28.4	67.0954	0.6	-34.5
PM13	67.0778	0	0	67.0767	-1.1	-1.1	67.0434	-1.2	-34.4	67.0342	-1.6	-43.6
PM14	67.1006	0	0	67.0995	-1.1	-1.1	67.0652	-1.1	-35.4	67.0559	-1.7	-44.7
PM15	67.0523	0	0	67.0514	-0.9	-0.9	67.0186	-1.2	-33.7	67.0094	-1.7	-42.9
PM16	67.0519	0	0	67.0510	-0.9	-0.9	67.0174	-1.3	-34.5	67.0082	-1.7	-43.7
PM17	67.0927	0	0	67.0918	-0.9	-0.9	67.0591	-1.2	-33.6	67.0498	-1.5	-42.9
PM18	67.0888	0	0	67.0879	-0.9	-0.9	67.0558	-1.3	-33.0	67.0465	-1.6	-42.3
PM19	67.1963	0	0	67.1953	-1.0	-1.0	67.1621	-1.3	-34.2	67.1529	-1.7	-43.4
PM20	67.0861	0	0	67.0851	-1.0	-1.0	67.0522	-1.3	-33.9	67.0430	-1.5	-43.1
PM21	67.0935	0	0	67.0924	-1.1	-1.1	67.0594	-1.2	-34.1	67.0502	-1.5	-43.3
PM22	67.0981	0	0	67.0970	-1.1	-1.1	67.0642	-1.2	-33.9	67.0550	-1.5	-43.1
PM23	67.1075	0	0	67.1065	-1.0	-1.0	67.0743	-1.4	-33.2	67.0651	-1.5	-42.4
PM24	67.0989	0	0	67.0979	-1.0	-1.0	67.0647	-1.3	-34.2	67.0555	-1.6	-43.4
PM25	67.1862	0	0	67.1849	-1.3	-1.3	67.1525	-1.3	-33.7	67.1433	-1.5	-42.9
PM26	66.9813	0	0	66.9801	-1.2	-1.2	66.9470	-1.2	-34.3	66.9378	-1.5	-43.5
PM27	67.1243	0	0	67.1231	-1.2	-1.2	67.0894	-1.2	-34.9	67.0802	-1.5	-44.1
PM28	67.1817	0	0	67.1805	-1.2	-1.2	67.1471	-1.1	-34.6	67.1379	-1.5	-43.8

In all the 18 observation runs that were taken, the misclosure of the levelling lines were not higher than 0.2 mm, which is under the tolerance accepted for the purpose monitorisation. The vertical displacements of the object points measured were between 33.2 mm and 44.7 mm (as you can see in *Table 1*), which tells us, from the position of the object points, that the construction had bigger vertical displacements in the middle area of the construction. This thing was predicted in the deformation monitoring project because the area of the basements is bigger than the area of the tower and the tower's position is in the middle of the basements.

6. Conclusions and recommendations

In this paper modern techniques of lands and constructions deformation monitoring has been presented. The GOCA system, part of expert monitorisation systems, is a modern technique that can determine real time displacements and it's highly recommended for huge constructions or landslides monitoring, which is an extraordinary fact that allow us to take urgent action in cases of emergency.

The 3D laser scanner is a new promising way of monitoring with the precision of under 1 cm of natural and artificial objects with reflectorless technology, which in many cases can be helpful.

In the case study has been shown that geometric levelling is still one of the best method to determine the deformation of a building. This method is recommended for the high precision of positioning and for vertical deformation monitoring with the precision of under 0.3 mm.

Although geometric levelling it's not considered a modern technique of deformation monitoring, it is a non-intrusive, inexpensive, accurate and highly precise method. In this paper has been also shown that if we take care of most of the errors that could happened during the monitoring process by geometric levelling, it becomes a precious way of deformation monitoring and a high precision method and that in some cases it's the only viable way of vertical deformation monitoring.

These are good reasons for geometric levelling to be the surveying method most applied in the deformation monitoring of construction and lands.

7. Abbreviations

GOCA – GNSS/LPS based Online Control and Alarm Systems
GNSS – Global Navigation Satellite System
LPS – Local Positioning Sensors
GPS – Global Positioning System
TLS – Terrestrial Laser Scanners

8. References

1. *Henriques, M. J., Casaca, J. – Monitoring vertical displacements by means of geometric levelling – Historical Constructions, Guimaraes-Portugal, 2007*
2. *Nistor, Gh., Nistor, I. – Direct algorithm for the calculation of vertical displacements and deformations of constructions using high-precision geometric levelling, Alba-Iulia, Romania, 2007*
3. *http://www.goca.info*
4. *Jager, R., Gonzalez, F. – GNSS/LPS Online Control and Alarm System (GOCA) – Mathematical Models and Technical Realization of a System for Natural and Geotechnical Deformation Monitoring and Hazard Prevention, Karlsruhe, Germany, 2007*
5. *Hesse, C., Kutterer, H. – Automated Form Recognition of Laser Scanned Deformable Objects, Hannover, Germany, 2007*
6. *Onu, C. – Current Trends on Monitoring the Deformations of Studied Constructions, Alba-Iulia, Romania, 2011*
7. *http://www.skytower.ro*
8. *Http://www.leica-geosystems.com*