MONITORING TECHNOLOGIES OF DYNAMIC PHENOMENA OF "BUCHAREST ONE" TOWER

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Abstract: *It is well known that every construction, especially new ones, suffers, more or less, long term displacements, these displacements can be determined with high accuracy by using together geodesic or non-geodesic technologies.*

In the past years many modern technologies have been developed for real time and online deformation monitoring, but in order to assure the precision required, the monitoring method has to be wisely chosen. This paper presents the monitoring technologies, the network adjustment and the interpretation of obtained data, used to establish the displacements of one of the tallest construction build in Romania, the Bucharest One Tower.

1. Introduction

In the battle of finding the elements that certifies the correctness of projection calculations, the knowledge of geometrical form's modifications and the displacements of studied objects has considerable importance. The analysis of those modifications is one of the most interesting problems in experimental researches which allow us to obtain important indications of the elastic behaviour and material's endurance. 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 results obtained through monitorisation.

The deformation monitoring of a land or construction represents a systematic action of measurement and analysis of the way they react to influence of surrounding variables, taking permanently in consideration the projection parameters that refer to functionality, stability and safety. For a proper monitoring of constructions behaviour in time, constructions that are subject to experimental solicitations or even exploitation, obtaining observations in a relative short time and with higher precision is highly recommended.

The deformation monitorisation of constructions behaviour in time can be divided in two categories: normal monitorisation and special monitorisation.

Normal monitorisation consists in observing and recording issues that could indicate changes in the capacity to meet the strength, stability and durability established in the project. The normal monitorisation is planned in the project.

Special monitorisation takes place in case of natural disasters (earthquakes, floods) and explosions.

Analysis of deformations of constructions or lands includes geometric analysis and physical interpretation. The goal of the geometrical analysis is to determine in the whole deformable object the displacement and strain fields in the space and time domains. Physical interpretation is to establish the relationship between the causative factors and the deformations.[1]

2. The purpose and location of the work

To meet the growing demand for office spaces in cities as Bucharest, but also because of the smaller buildable area available in these cities, Global Worth decided to build one of the highest tower for office spaces in Bucharest. *Bucharest One Tower* has 3 basements, ground floor, mezzanine and 23 upper floors with a total area of 53920 square meters and held a footprint close to 2000 square meters.

Bucharest One Tower has a total height of 120 meters, is visible from almost every part of the city, being the 2nd highest construction for office spaces ever built in Romania.

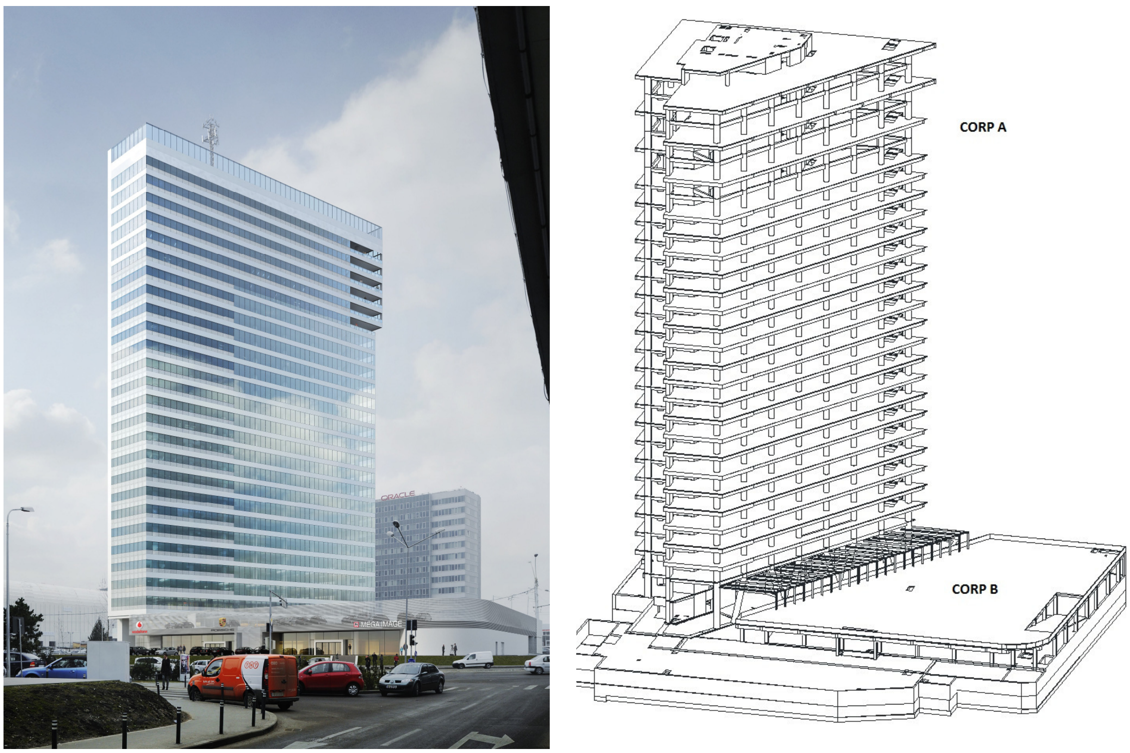

Fig. 1 – Bucharest One Tower

Bucharest One Tower is a landmark "class A" development in Bucharest located in the northern part of the city in the Calea Floreasca / Barbu Văcărescu area. The location is one of the country's most dynamic within the office segment and the property is situated at the heart of it. The property has excellent visibility and is situated at the junction of 3 main streets, Barbu Văcărescu Street, Pipera Road and Calea Floreasca. [2]

2.1. Recognition of the field

To effectuate the vertical displacements of Bucharest One Tower in the first step the recognition of the field has been made. In this step there were identified and verified three reference points that are part of the state levelling network (RN01, RN02, and RN03). 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. Also the reference points used were sealed in 15 years old constructions with two or three levels, at 20 to 30 metres from roads with heavy traffic, so it can be considered that the displacements of those constructions faded and the vibrations caused by traffic are insignificant.

In order to verify the stability of the reference points, a levelling line was made between them in the first step. Measurements were made with the digital level Leica DNA03, a high precision digital level with a standard deviation per Km double levelling of 0.3 mm.

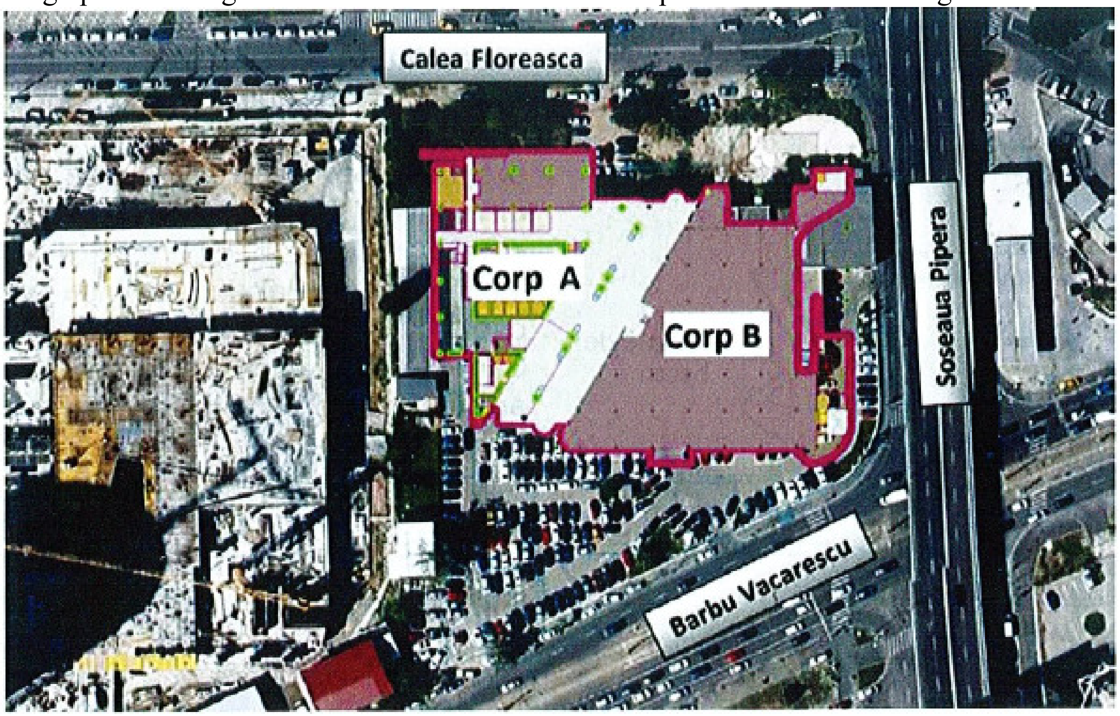

Fig. 2. – Location of the work

2.2. Digital level Leica DNA03

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.

The main reason for using a digital level is that it applies corrections from the measuring step. By measuring with the program back-front-front-back is no longer necessary to run double levelling lines with different line of sight. One of the most important correction applied is earth curvature correction (*E*):

$$E = \frac{D^2}{2R} \quad (1)$$

Where *D* is the measured distance from the instrument position to the staff and *R* is 6.378.000 – earth radius.

Another correction applied by the digital level is the Line-of-sight correction:

$$\alpha = \frac{A_1 - B_1 + B_2 - A_2}{d_1 - d_2 + d_3 - d_4} \quad (2)$$

In the formula above A_1, B_1, B_2, A_2 are staff height and d_1, d_2, d_3, d_4 are distances from the instrument to the staff. [3]

3. The measurement program

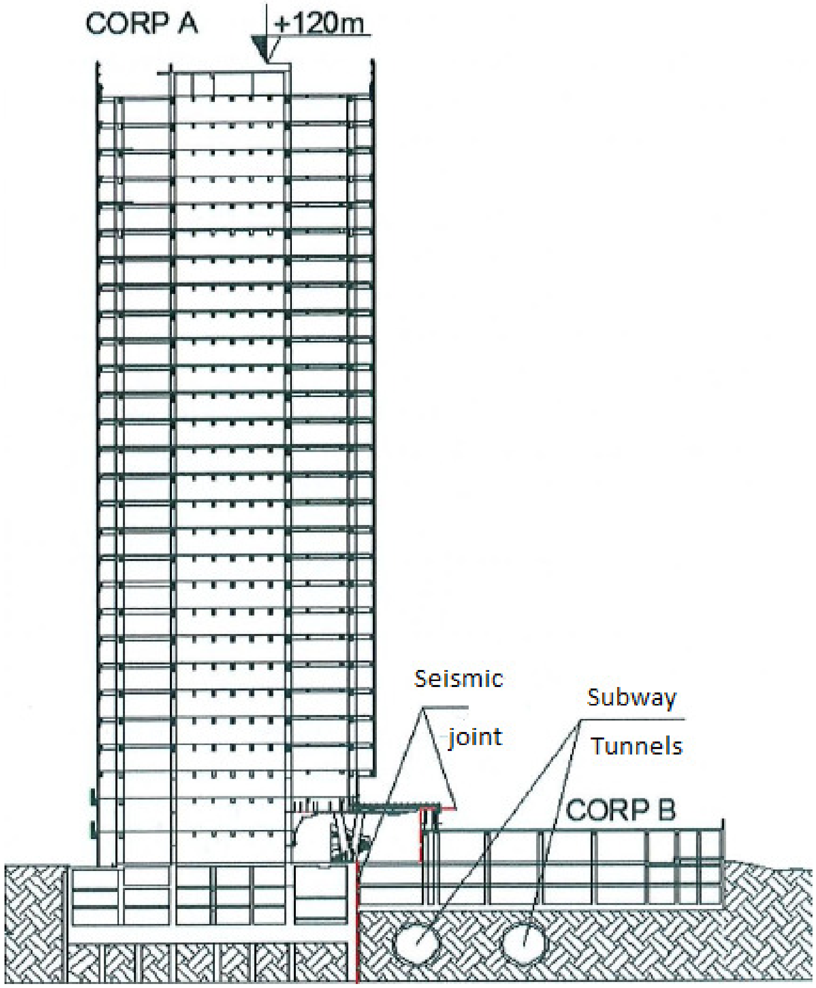

Fig. 3 – Cross section between A and B buildings

After the recognition of the field phase was completed, phase in which the reference points were identified and the levelling line route has been established, there were marked all the intermediate points needed and also an approximate location of the instrument in each levelling line was marked to assure the precision required by having equal sections of levelling and by having almost the same route of line levelling.

3.1. Positioning the object points

In the monitoring project of the Bucharest One Tower 30 object points were positioned in the sidewalk around the building yard and on the nearby buildings, another 20 object points were positioned at the 3rd basement of the A building and at the 2nd basement of the B building for the proper determination of 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.

The position of the object points was wisely chosen to verify the stability of each pile and diaphragm wall and also to observe, as soon as possible, an eventual inclination of the tower construction.

Additional measurements have been made in the subways tunnels, of the M2 metro line between Aurel Vlaicu and Pipera rail stations. The monitorisation of the subway tubes was made by measuring on reflectorized targets mounted inside the tubes as shown in the next figure with motorised total station by traverse method closed on known points. The displacements of the tubes were smaller than expected, the highest displacement being a few millimetres.

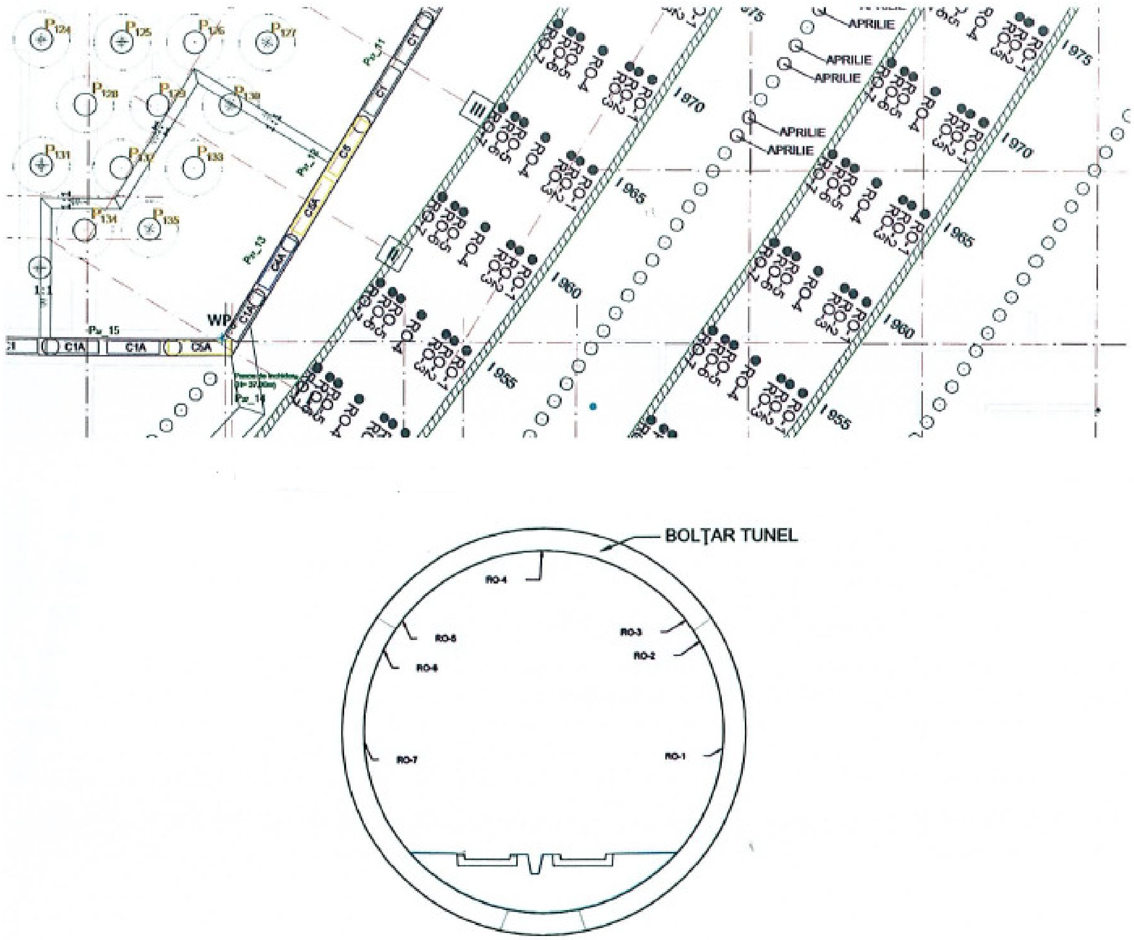

Fig. 4 – The position of the object points inside the subway tubes

3.2. Displacements determination

The measurement program was divided into two parts because the reference points were sealed in old buildings near the construction site and the object points had to be positioned in the 2^{nd} and 3^{rd} basement of the monitored construction, according to the monitoring project. In the first part measurements were made from the reference points, through all the intermediate points (sidewalk points) established in the monitoring program. Second determination was made by performing a levelling line through the auto access, from the ground floor down to the 2^{nd} and 3^{rd} basement to assure the accuracy of the method used.

Since December 2014 until September 2015 a total of 9 measurement runs have 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 four floors (almost one month), when the construction was built entirely a measurement run was made at every three months. In all the 9 observation runs that were taken, the misclosure of the levelling lines were not higher than 0.2 mm, which is the tolerance accepted for the purpose monitorisation.

4. Deformation analysis

The classical method for checking stability of reference and object points involves comparing the differences in level obtained in the initial observations (run "0") and existing (current run). Modern methods involve the application of statistical tests on each run of measurements, resulting conclusions on the stability of the measured points. If the measured level differences in the initial and current run differ by less than the measurement error then the reference and objects points can be considered stable.

In a monitoring network measurements are carried out in two different runs. Measurements made in the first run are to determine the geometry of the network. After the measurements from the second run are completed, for the study of deformation the two networks are overlapped and their congruence is analysed as following:

- Networks are congruent if there is no deformation;
- Networks are non-congruent if errors occur due to changes in the position of the points.[4]

4.1. Calculation algorithm

Calculation algorithm involves measuring the level differences in a levelling network at different stages. To establish if the networks are congruent, the parameters resulted from processing are analyzed. The results are analyzed as follows:

- If the results do not fall within the safe limits set, the two networks are not congruent, which means that deformation occurred;
- If these differences are within the safe set, the two networks are congruent, and differences are only due to errors in measurement, not because of movement points.

The first step of the realization algorithm is the calculation of the corrections vector, it requires the following calculations:

$$v_{ij} = x_j - x_i + l_{ij}; P_{ij} \quad (3)$$

Where:

- v_{ij} is the corrections vector;
- x_i, x_j – terms of coefficients matrix;
- l_{ij} – free terms;
- P_{ij} – weight.

The free terms calculation:

$$l_{ij} = (H_j^0 - H_i^0) - \Delta h_{ij}^0 \quad (4)$$

In the relation above the notations means:

- H^0 – provisional elevation;
- Δh_{ij}^0 – provisional elevation difference.

The weight of correction equations P_{ij} is determined by the following relation:

$$P_{ij} = \frac{1}{n} \tag{5}$$

Where n is the total number of stations effectuated in the levelling line.

After the corrections vector has been calculated, the compensated elevations are determined, as follows:

$$H_i = H_i^0 + x_i \tag{6}$$

Following the calculation of corrections with elevation differences and provisional elevation differences can be calculated compensated elevation differences - Δh_{ij} .

$$\Delta h_{ij} = \Delta h_{ij}^0 + v_{ij} \tag{7}$$

Evaluation of measurement accuracy for each stage:

$$s_{0i} = \pm\sqrt{\frac{[Pvv]}{n-u+d}} \tag{8}$$

In which:

- s_{0i} is empirical standard deviation in the phase "i" of measurements;
- n – number of equations;
- u – number of unknown values;
- d – rank defect.

4.2. The global test of congruence

Global test of congruence is applied if in the phases of measurements, deformations occurred or not, very useful information, but the application of this test cannot achieve localization of deformations.

The global test of congruence is based on the assumption that there are no deformations:

$$H_0 : E\{\hat{X}_2\} = E\{\hat{X}_1\} \tag{9}$$

Applying global congruence test is performed using the elements calculated at each stage of measurements. The discrepancy vector d is calculated, cofactors matrix Q_{dd} and the empirical standard deviation s_0 of the deformation model.

$$d = X_J - X_i \tag{10}$$

$$Q_{dd} = Q_{xxi} + Q_{xxj} = N_i^+ + N_j^+ \tag{11}$$

$$s_0 = \pm\sqrt{s_{0i}^2 + s_{0j}^2} \tag{12}$$

After calculating the discrepancy vector, cofactors matrix and the empirical standard deviation of the deformation model, the Fisher F test value can be calculated:

$$F = \frac{d^T Q_{dd}^+ d}{s_0^2 h} \tag{13}$$

Fischer test decision is determined based on the calculated value of the test Fischer - F and its theoretical value - F_{lim}, value extracted from Fischer tables, as follows:

- If $F \le F_{lim} = F_{h,f,1-\alpha} \Rightarrow E\{\hat{X}_2\} = E\{\hat{X}_1\} \Rightarrow$ hypothesis H_0 is true (there are no deformations)
- If $F \ge F_{lim} = F_{h,f,1-\alpha} \Rightarrow E\{\hat{X}_2\} \ne E\{\hat{X}_1\} \Rightarrow$ hypothesis H_0 is false (there are deformations)

With the formulas presented, the Fischer test value has been calculated, as shown in the table below:

4.3. Locating the deformations

Locating the deformations can be achieved through statistical test "Student" and the statistical test "Multiple F".

The Student test

The Student test is based on the assumption that there is no movement in the monitored network:

$$H_0 : E\{d_j\} = 0 \quad (14)$$

For Student statistical test application use the following formulas:

$$s_j = s_0\sqrt{Q_{dd}} \quad (15)$$

$$t_j = \frac{d_j}{s_j} \quad (16)$$

$$t_{lim} = t_{f,1-\alpha} \quad (17)$$

Student test decision is determined by the following relations:

- If $t \le t_{f,1-\alpha} = t_{lim} \Rightarrow (H_0)$ is true, $E\{d_j\} = 0 \Rightarrow$ point is considered stable (there are no deformations)
- If $t > t_{f,1-\alpha} = t_{lim} \Rightarrow (H_0)$ is false, $E\{d_j\} \neq 0 \Rightarrow$ point is considered displaced (there are deformations)

According to the formulas above, the t value of the test has been calculated for each point of the network and it shows that the reference points are stable and the additional object points sealed in the basements of the buildings are unstable.

The Multiple F test

In the Multiple test F, the same hypothesis H_0 is carried out, in which case there is no movement, points are considered stable.

$$H_0 : E\{\hat{X}_2\} = E\{\hat{X}_1\} \quad (18)$$

For this test is used the following formula:

$$F_k = \frac{d_j^T Q_{ddj}^+ d_j}{s_0^2 * 2} \quad (19)$$

Decision of the Multiple F test statistic is determined by the following relations:

- If $F_k \le F_{lim} = F_{2,f,1-\alpha} \Rightarrow E\{\hat{X}_2\} = E\{\hat{X}_1\} \Rightarrow$ hypothesis H_0 is true (there are no deformations)
- If $F_k \ge F_{lim} = F_{2,f,1-\alpha} \Rightarrow E\{\hat{X}_2\} \neq E\{\hat{X}_1\} \Rightarrow$ hypothesis H_0 is false (there are deformations)

5. Non-geodesic monitoring technologies

Tachometric measurements have the purpose of deformation monitoring of the ground from the building yard. Tachometers are made by two plastic tubes, one rigid tube inside and one flexible tube outside on which are mounted magnetic sensors.

Fig. 5 – Tachometric scheme

For the A building a 60m deep tachometer has been installed, for the B building two tachometers have been installed at 60m, respective 40m deep. [5]

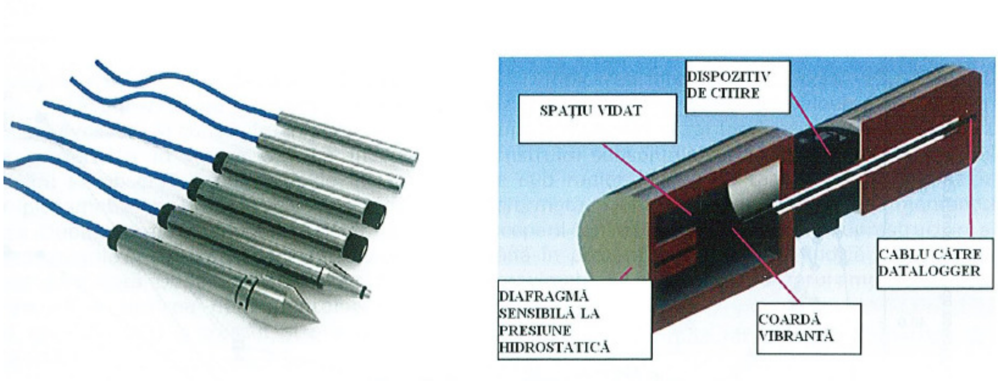

Fig. 6 – Casagrande piezometer

For the hydrostatic level monitorisation Casagrande piezometer has been used, as shown in figure 6.

The sensor inside the piezometer has a stainless steel diaphragm which is sensible to water variation. The piezometer with vibrant main truss (Casagrande) has been installed in the building yard on the B building area, above the subway tubes by pressure down to 15m deep.

To assure the monitorisation on the execution phase of tilt works support 14 inclinometers have been installed at deeps of 12m down to 50m in the drilled piles.

6. Conclusions

To achieve accurate monitoring, reference points used must be placed at a considerable distance from the monitored building in order to consider that their elevation is not influenced by the constructions displacements.

Regarding the effect of temperature on measurements made it can be said that the measurements were not affected by this, object points being made of a special metal resistant to temperature variations.

The level of hydrostatic also had no effect on compaction since there were no significant differences between the hydrostatic level one phase to another. Pressure of the weight of the building affected mostly the displacements.

Although geometric levelling it's not considered a modern technique of deformation monitoring, it is an inexpensive, accurate and highly precise method. In this paper has been also shown that if it is considered most of the errors that could happen during the monitoring process by geometric levelling, it becomes a precious way of vertical displacements monitoring.

Bucharest One Tower is in an advanced stage of execution and we learned that the parameters followed by the monitoring program falls within accepted values resulting from the calculation and the current technical regulations.

7. References:

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[2] http://www.globalworth.com/investments/bucharest-one.aspx

[3] http://www.leica-geosistems.com

[4] Vintilă, C. I., Dissertation: Monitoring Technology of Time Behavior for Infrastructure Tower Block "Sky Tower" from Floreasca City Center, Bucharest, Faculty of Geodesy Bucharest, 2013

[5] Saidel, T., Raileanu, I., Draghici, S., Butulescu, G., Modruj, A., Stanciu, T., Poenaru, A., Arion, D., Marcu, A., - Proiectarea si monitorizarea sistemului de fundare si a incintei adanci pentru cladirea inalta "Bucharest One", realizata in imediata vecinatate a galeriilor de metrou, AICPS, Bucharest, 2015