Monitoring Vertical Displacements by Means of Geometric Levelling for Sky Tower Building from Floreasca City Center, Bucharest

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Abstract: - It is widely known that any construction, old or new, suffers, more or less, long term displacements, these displacements can be measured with high precision by using topographical methods. Displacements are mainly influenced by the kind of the soil, where the building stands, by the material’s endurance and elasticity, temperature variation, time and by the pressure generated by the construction’s own weight. The main purpose of monitoring constructions’ behaviour in time is to learn the displacements and deformations that construction suffers in comparison to a given number of known points (benchmarks) situated near the construction but at a well calculated distance so their stability couldn’t be affected by the building movements.

Nowadays 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 high precision geometric levelling method, the network adjustment and the interpretation of obtained data, used to establish the displacements of the tallest construction ever made in Romania, the Sky Tower building, from Floreasca, Bucharest.


1 Introduction

In the battle of finding the elements that certifies the correctness of projection calculations, the knowledge of geometrical form’s modifications and their displacements has considerable importance. The measurement of those modifications is one of the most interesting problems in experimental researches which allow us to obtain precious indications of the elastic behaviour and material’s endurance and of the field’s behaviour 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 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 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.

2 The purpose and location of the work

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 tower for office spaces in Bucharest. Sky Tower has 5 basements, ground floor and 36 upper floors with a total area of 50400 square meters and held a footprint of just 1300 square meters.

Sky Tower is located between two of the most important Streets in the north of Bucharest, Floreasca Street and Barbu Văcărescu Street, as can be seen in the figure below. 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. The Sky Tower will become the main point of attraction in the new business district of Bucharest and is not only the landmark of the city, visible virtually from all parts of Bucharest, but also provides its tenants and visitors with a unique view over the city thus creating a strong corporate presence and identity. [1]

2.1 Recognition of the field

To effectuate the vertical displacements of Sky Tower building 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.

There were also three intermediate points (PIL1, PIL2 and PIL3) materialised by forced centring pilaster, those points were positioned in the building yard, so they could be considered affected by the displacements of the building.

In order to verify the stability of the reference points and intermediate 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.

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 \((E)\):

\[
E = \frac{D^2}{2R}
\]

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:

\[
\alpha = \frac{A_1 - B_1 + B_2 - A_2}{d_1 - d_2 + d_3 - d_4}
\]

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. [2]

3 The measurement program

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 Sky Tower building 28 object points (PM01 – PM28) were positioned at the 5th basement 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.2.

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.

In order to assure the precision required in the monitoring program an additional 4 object points (M1 – M4) have been placed at the ground floor on top of the diaphragm walls of the basements.

Fig. 2 – Object points position in the 5th basement

The additional object points, M1 – M4, were sealed on top of the diaphragm wall for its proper monitorisation, which is constructed after the “Milano Method”, the top being tilted inward to support the total weight of the construction.
3.2 Displacements determination

The measurement program was divided into three parts because the reference points were sealed in old buildings near the construction site and the object points had to be positioned in the 5th 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 established in the monitoring program, up to the additional object points positioned near the construction, on top of the diaphragm walls, as it can be seen in fig. 4. Second part consisted in making measurements by combined method using a steel tape and two digital levels, one at the ground floor and one in the 5th basement, repeated measurements were performed simultaneously. For high precision determination the combined method was applied in two places, as shown in fig. 3, and a third determination was made by performing a levelling line through the auto access, from the ground floor down to the 5th basement to assure the accuracy of the method used.

In the 3rd part measurements were made between all 28 object points positioned in the 5th basement of the construction, as shown in fig 2.

Since October 2011 until May 2013 a total of 19 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 three floors (almost one month), when the construction was built entirely a measurement run was made at every three months. Only in exceptional cases, when the hydrostatic level raised and 5 basement flooded was made a special leveling traverse. In present the measurement runs are made at every six months.

In all the 19 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.[3]

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:

\[ v_{ij} = x_j - x_i + l_{ij}; P_{ij} \]  \hspace{1cm} (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:

\[ l_{ij} = (H_{ij}^0 - H_{ij}^0) - \Delta h_{ij} \]  \hspace{1cm} (4)

In the relation above the notations means:
- \( H^0 \) – provisional elevation;
- \( \Delta h_{ij}^0 \) – provisional elevation difference.

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

\[ P_{ij} = \frac{l_{ij}}{n} \]  \hspace{1cm} (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:

\[ H_i = H_i^0 + x_i \]  \hspace{1cm} (6)

Following the calculation of corrections with elevation differences and provisional elevation differences can be calculated compensated elevation differences - \( \Delta h_{ij} \).

\[ \Delta h_{ij} = \Delta h_{ij}^0 + v_{ij} \]  \hspace{1cm} (7)

Evaluation of measurement accuracy for each stage:

\[ s_{oi} = \pm \sqrt{\frac{\left[ P_{0i} \right]}{n - u + d}} \]  \hspace{1cm} (8)

In which:
- \( s_{oi} \) is empirical standard deviation in the phase "i" of measurements;
- \( n \) – number of equations;
- \( u \) – number of unknown values;
- \( d \) – rank defect.

In the table below is presented a numerical example of the reference points, intermediate points and additional object points used in the exterior levelling line calculated with the algorithm presented above.

<table>
<thead>
<tr>
<th>Name</th>
<th>Levels Run 0</th>
<th>Levels Run 1</th>
<th>Levels Run 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>RN01</td>
<td>88.9655</td>
<td>88.9656</td>
<td>88.9656</td>
</tr>
<tr>
<td>RN02</td>
<td>87.1035</td>
<td>87.1035</td>
<td>87.1034</td>
</tr>
<tr>
<td>RN03</td>
<td>85.5214</td>
<td>85.5215</td>
<td>85.5215</td>
</tr>
<tr>
<td>PIL1</td>
<td>84.3263</td>
<td>84.3264</td>
<td>84.3264</td>
</tr>
<tr>
<td>PIL2</td>
<td>84.6438</td>
<td>84.6437</td>
<td>84.6438</td>
</tr>
<tr>
<td>PIL3</td>
<td>83.7281</td>
<td>83.7283</td>
<td>83.7282</td>
</tr>
<tr>
<td>M1</td>
<td>83.4295</td>
<td>83.4304</td>
<td>83.4317</td>
</tr>
<tr>
<td>M2</td>
<td>83.5218</td>
<td>83.5228</td>
<td>83.5242</td>
</tr>
<tr>
<td>M3</td>
<td>83.5103</td>
<td>83.5112</td>
<td>83.5125</td>
</tr>
<tr>
<td>M4</td>
<td>83.4558</td>
<td>83.4568</td>
<td>83.4581</td>
</tr>
</tbody>
</table>
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:

\[ H_0 : E\{\hat{X}_i\} = E\{\hat{X}_j\} \]  

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.

\[ d = X_j - X_i \]  

\[ Q_{dd} = Q_{xx} + Q_{xy} = N_i^+ + N_j^+ \]  

\[ s_0 = \pm \sqrt{s_{01}^2 + s_{02}^2} \]

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

\[ F = \frac{d^T Q_{dd} d}{s_0 h} \]

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

- If \( F \leq F_{lim} = F_{k,\alpha,1}\lim \Rightarrow E\{\hat{X}_i\} = E\{\hat{X}_j\} \Rightarrow \) hypothesis \( H_0 \) is true (there are no deformations)
- If \( F > F_{lim} = F_{k,\alpha,1}\lim \Rightarrow E\{\hat{X}_i\} \neq E\{\hat{X}_j\} \Rightarrow \) 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:

<table>
<thead>
<tr>
<th>Benchmark</th>
<th>t value</th>
<th>Theoretical value</th>
<th>Observations</th>
</tr>
</thead>
<tbody>
<tr>
<td>RN01</td>
<td>1.23738</td>
<td>stable</td>
<td></td>
</tr>
<tr>
<td>RN02</td>
<td>1.76327</td>
<td>stable</td>
<td></td>
</tr>
<tr>
<td>RN03</td>
<td>-1.68396</td>
<td>stable</td>
<td></td>
</tr>
<tr>
<td>PIL1</td>
<td>1.76658</td>
<td>stable</td>
<td></td>
</tr>
<tr>
<td>PIL2</td>
<td>-1.30931</td>
<td>stable</td>
<td></td>
</tr>
<tr>
<td>PIL3</td>
<td>1.46185</td>
<td>stable</td>
<td></td>
</tr>
<tr>
<td>M1</td>
<td>-4.52153</td>
<td>unstable</td>
<td></td>
</tr>
<tr>
<td>M2</td>
<td>-4.56866</td>
<td>unstable</td>
<td></td>
</tr>
<tr>
<td>M3</td>
<td>-4.55244</td>
<td>unstable</td>
<td></td>
</tr>
<tr>
<td>M4</td>
<td>-3.68504</td>
<td>unstable</td>
<td></td>
</tr>
</tbody>
</table>

4.3 Locating the deformations

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

4.3.1 The Student test

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

\[ H_0 : E\{d_{ij}\} = 0 \]

For Student statistical test application use the following formulas:

\[ s_j = s_0 \sqrt{Q_{dd}} \]

\[ t_j = \frac{d_j}{s_j} \]

\[ t_{lim} = t_{j,\alpha,1} \]

Student test decision is determined by the following relations:

- If \( t \leq t_{j,\alpha,1} = t_{lim} \Rightarrow (H_0) \) is true, \( E\{d_{ij}\} = 0 \Rightarrow \) point is considered stable (there are no deformations)
- If \( t > t_{j,\alpha,1} = t_{lim} \Rightarrow (H_0) \) is false, \( E\{d_{ij}\} \neq 0 \Rightarrow \) 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 on top
of the diaphragm walls of the basements are unstable, as presented in table 3.

4.3.2 The Multiple F Test

In the Multiple test F, the same hypothesis H0 is carried out, in which case there is no movement, points are considered stable.

\[ H_0 : E\left[ \tilde{X}_2 \right] = E\left[ \tilde{X}_1 \right] \]  

(18)

For this test is used the following formula:

\[ F_k = \frac{d_j Q_k d_j}{s^2 \times 2} \]  

(19)

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

- If \( F_k \leq F_{\text{line}} = F_{2,111-\alpha} \Rightarrow E\left[ \tilde{X}_2 \right] = E\left[ \tilde{X}_1 \right] \) hypothesis \( H_0 \) is true (there are no deformations)
- If \( F_k \geq F_{\text{line}} = F_{2,111-\alpha} \Rightarrow E\left[ \tilde{X}_2 \right] \neq E\left[ \tilde{X}_1 \right] \) hypothesis \( H_0 \) is false (there are deformations)

From the table below it is shown that the additional object points were unstable as well as in the Student test.

<table>
<thead>
<tr>
<th>Benchmark</th>
<th>( F_k )</th>
<th>( F_{\text{limit}} )</th>
<th>Observations</th>
</tr>
</thead>
<tbody>
<tr>
<td>RN01</td>
<td>2.01584</td>
<td></td>
<td>stable</td>
</tr>
<tr>
<td>RN02</td>
<td>2.36679</td>
<td></td>
<td>stable</td>
</tr>
<tr>
<td>RN03</td>
<td>2.65919</td>
<td></td>
<td>stable</td>
</tr>
<tr>
<td>PIL1</td>
<td>3.77398</td>
<td></td>
<td>stable</td>
</tr>
<tr>
<td>PIL2</td>
<td>3.26472</td>
<td>6.9442719</td>
<td></td>
</tr>
<tr>
<td>PIL3</td>
<td>4.13315</td>
<td></td>
<td>stable</td>
</tr>
<tr>
<td>M1</td>
<td>13.5235</td>
<td></td>
<td>unstable</td>
</tr>
<tr>
<td>M2</td>
<td>16.07192</td>
<td></td>
<td>unstable</td>
</tr>
<tr>
<td>M3</td>
<td>13.35462</td>
<td></td>
<td>unstable</td>
</tr>
<tr>
<td>M4</td>
<td>12.73017</td>
<td></td>
<td>unstable</td>
</tr>
</tbody>
</table>

It can be seen that by applying the localization of deformations tests were determined the movement of marks M1-M4, reference points and intermediate points are considered stable.

Likewise were localized movements for both levelling network created in the 5th basement of the building and in the rest of the stages monitored. [4]

4.4 Vertical displacements of the object points

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 from the 5th basement at some of the observation runs.

<table>
<thead>
<tr>
<th>Object point</th>
<th>Height difference since</th>
<th>Level of object point</th>
</tr>
</thead>
<tbody>
<tr>
<td>PM1</td>
<td>0</td>
<td>67.0437</td>
</tr>
<tr>
<td>PM2</td>
<td>0</td>
<td>67.0303</td>
</tr>
<tr>
<td>PM3</td>
<td>0</td>
<td>67.1783</td>
</tr>
<tr>
<td>PM4</td>
<td>0</td>
<td>67.1165</td>
</tr>
<tr>
<td>PM5</td>
<td>0</td>
<td>67.1011</td>
</tr>
<tr>
<td>PM6</td>
<td>0</td>
<td>67.1548</td>
</tr>
<tr>
<td>PM7</td>
<td>0</td>
<td>67.1944</td>
</tr>
<tr>
<td>PM8</td>
<td>0</td>
<td>67.1634</td>
</tr>
<tr>
<td>PM9</td>
<td>0</td>
<td>67.1776</td>
</tr>
<tr>
<td>PM10</td>
<td>0</td>
<td>67.1060</td>
</tr>
<tr>
<td>PM11</td>
<td>0</td>
<td>67.1323</td>
</tr>
<tr>
<td>PM12</td>
<td>0</td>
<td>67.1289</td>
</tr>
<tr>
<td>PM13</td>
<td>0</td>
<td>67.0787</td>
</tr>
<tr>
<td>PM14</td>
<td>0</td>
<td>67.0985</td>
</tr>
<tr>
<td>PM15</td>
<td>0</td>
<td>67.0514</td>
</tr>
<tr>
<td>PM16</td>
<td>0</td>
<td>67.0510</td>
</tr>
<tr>
<td>PM17</td>
<td>0</td>
<td>67.0918</td>
</tr>
<tr>
<td>PM18</td>
<td>0</td>
<td>67.0879</td>
</tr>
<tr>
<td>PM19</td>
<td>0</td>
<td>67.1963</td>
</tr>
<tr>
<td>PM20</td>
<td>0</td>
<td>67.0851</td>
</tr>
<tr>
<td>PM21</td>
<td>0</td>
<td>67.0924</td>
</tr>
<tr>
<td>PM22</td>
<td>0</td>
<td>67.0970</td>
</tr>
<tr>
<td>PM23</td>
<td>0</td>
<td>67.1065</td>
</tr>
<tr>
<td>PM24</td>
<td>0</td>
<td>67.0979</td>
</tr>
<tr>
<td>PM25</td>
<td>0</td>
<td>67.1849</td>
</tr>
<tr>
<td>PM26</td>
<td>0</td>
<td>66.9801</td>
</tr>
<tr>
<td>PM27</td>
<td>0</td>
<td>67.1231</td>
</tr>
<tr>
<td>PM28</td>
<td>0</td>
<td>67.1805</td>
</tr>
</tbody>
</table>

The vertical displacements of the object points measured were between 33.2 mm and 44.7 mm (as you can see in Table 6), 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.
the pressure on the foundation of the tower block exercised by its own weight. Given all these and the difference in time between phases performed, a second representation was done in a parallel coordinate system, as can be seen in Figure 6. It aims to visualize and interpret the importance of temperature, hydrostatic level, pressure on the foundation and the difference of time between consecutive stages of construction settlement.

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 a 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.

References: