Analysis of vertical deformations and displacements of a building using high precision leveling in the absence of the fixed reference network

Gheorghe NISTOR, Professor Ph.D eng., Technical University "Gheorghe Asachi" of Iasi, ROMANIA, ghnistor@yahoo.fr
Gheorghe SĂLCEANU, Ph.D Candidate, eng., City Hall of Iasi, Office GIS-Cadastre, gis_iasi@yahoo.com

Abstract: *The determination of the magnitudes of the vertical deformations and displacements is essential when is analized the in situ behaviour of buildings. Negative vertical defromations are known as settlements, while positive ones are known as uplifts.*
Finding the vertical deformations of a building is performed through cyclic determinations of the elevations of control points (settlement marks) located in the studied building, in relation to several fixed points which make up the local reference leveling network. The vertical deformations and displacements are determined by analyzing the distribution of the cyclically-determined elevation of the control points. For a complete analysis of the behaviour of the building, and in order to investigate the origin of these displacements as well as to prevent their occurrence, the vertical defromation analysis must be complemented by a detailed survey of the groundwater variations of the characteristics, foundation soil, etc.
The paper presents a method proposed to determine the vertical settlements of an industrial building in the absence of a fixed reference leveling network.

***Keywords**: vertical, deformations, building, leveling, precision, reference, network, elevation.*

1. Introduction

When is analysed the in-situ behaviour of contructions, the data which describe the vertical deformations and dispalcements are essential. Following a sign convention, settlements are assigned negative values while uplifts have positive values.

The behaviour of the building studied from the point of view of the cooperation between contruction and the foundation soil presents a remarkable importance for a sensible projection of the foundations, for the assurance of the stability and exploitation in security conditions.

For a sensible projection of the foundations it is necessary the knowing, with enough exactness, of the coming defromations and vertical displacements. The problem of settlement estimation of the buildings could not get a enough correct solution with proper practical results, because of a great number of factors and conditions which influence the setling of a building. Some of these facts are not well specified by theory and practice. For this reason the only objective criterion of accurate knowing of the building settlements, is their straight measuring.

The direct measurements of the deformations and displacements follows a double aim and namely: a technical aim to ensure the safety and normal exploitation of the buildings and a scientific one, to supply necessary data for improving the estimate method of the foundations and for checking up of new hypoteses of projection. For this reason, it is necessary to accomplish a great number of systematic measurements at varied kind of buildings, founded on various conditions of soil.

At the measurement of the deformations and vertical displacements, geodetic methods are used on a wide scale, representing an efficient solution for knowing the behaviour of the buildings, in general, and the massive constructions in special. Among the geodetical methods of precision or high precision the most uses one is the geometric leveling method. The principle of measuring of the displacements and vertical deformations, settlements or uplifts consists in the cyclical determination of the control point elevations called settling benchmarks, positioned on studied building by respcet to many fixed marks located on undeformable fields out of the influence zone of the building, making up the reference leveling network. Analizing the distribution of the elevations of the control points cyclically determined, the deformations and vertical displacements of the studied building are established. The settlements or uplifts are accomplished either by the leveling traversing method of mid-points geometric leveling, supported or in closed circuit, or by polygonal networks contrained in the fixed marks of the reference network by respect to which the determinations are realized.

The leveling measurements are conducted on the basis of a pursuit project and a preliminary study ensuring the precision of the measurements from the state geometric-geodetic leveling network of order 0, I and II. The operations of the leveling measurements are achieved by double leveling with a high precision levels and a measuring staff of precision of 1,75m or 3m.

One of the basic condition which assures a thoroughly succes to the measurements represents the projection and achievement on the ground, of the reference network constituted from minimum two fixed marks of surface or deepness which materializes the reference plane by respect to which should be accomplished the measurements of the deformations and vertical displacements. In absence of this network, the correct emphasis of the position change of studied construction become practically impossible.

With all these, in the following, a method of estimation of the existence of the vertical deformations of a building and its evolution, in absence of the reference network should be presented. This is the situation when the continuation of the production activity in security conditions is imperatively required. The fact that this method will correspond to a limit situation which need not have a statute of generality is underlined.

2. Presentation of the study method

There are limit-situations when, in absence of certain fixed marks on surface or deepness, one impose the measurement of the deformations and vertical displacements of the resistance structure of a building, because of some deteriorations with rapid evolutions in time.

In the frame of the proposed method, the establishing of the settlements or uplifts is obtained from analysis of the variations in size of the level differences measured in each cycle of measurements. The measuring of the deformations and vertical displacements in the control points from the studied building, by semi-rigorous method is achieved by Gh. Nistor algorithm which consists in that follow [1], [3] :

In the resistence structure of a industrial hall there are fixed control points denoted by P_j , j=$\overline{1, n-1}$, and materialized by console marks at a height of about 0,5m above the soil (Fig.1).

In order to maintain unchanged the mid-station points as number and position, these are materialized by metallic bolts. In this way, in each observation cycle, the length of the visas from the level to the control points will be maintained. In each cycle, the achievement of the geometric leveling measurements of precision is performed with two horizons of the instrument and with readings on the both graduated scales of the precision measuring staff. In the case when a division of the micrometer has 0,05m, will be accepted as maximum of the deviation for level differences calculated from two readings on the measuring staff, in a single horizon, does not overtake 5 divisions. Also, it is admitted as the deviation between the level differences calculated with the two horizons does not exceed three divisions [1], [3].

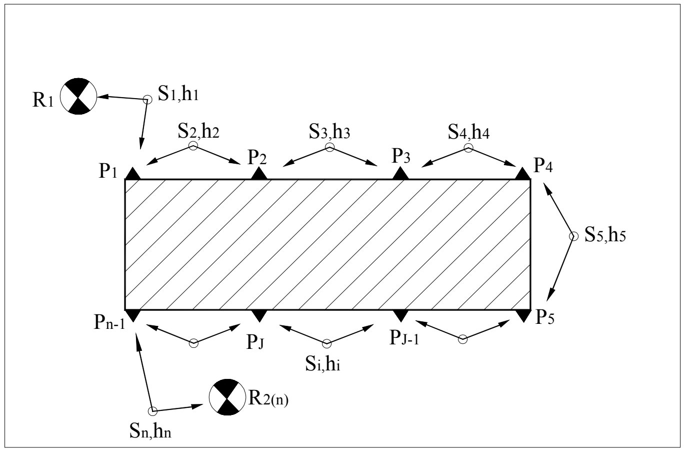

Fig.1

In each cycle of measurements, the magnitudes of the level differences should be obtained as an arithmetic mean of the values measured with the two horizons of the intrument. Thus in the station S_i, where i=$\overline{1,n}$, accordingly to initial/zero cycle and to current one t, t=$\overline{1,N}$, these magnitudes should be:

(1) $$h_i^o = \frac{1}{2}(h_i^{0,I} + h_i^{0,II}),\; h_i^t = \frac{1}{2}(h_i^{t,I} + h_i^{t,II}),$$

The magnitudes of the displacements and vertical deformations as fonctions of the variations of level differences cyclically measured, can be expressed as direct fonction of the increments of the level differences from the two cycles. Thus, for the control point j, j=$\overline{1,n-1}$, the displacement and vertical deformation produced between cycles is:

(2) $$\Delta H_j^t = \sum_{i=1}^{j}(h_i^t - h_i^0) - K^t \sum_{i=1}^{j} D_i ,$$

where K^t is a corrective term, expressed as

(3) $$K^t = \sum_{i=1}^{n}\left(\frac{h_i^t - h_i^0}{D_i}\right),$$

its magnitude varying in each cycle, begining with the second t=1, according to the measurement errors. Magnitude D_i represents the lenght of the visa from station S_i.

The dispalcement and final/total deformattion from the control point j, produced between the initial/zero cycle and the final one N, is expressed by realtion:

(4) $$\Delta H_j^N = \sum_{i=1}^{j}(h_i^N - h_i^0) - K^N \sum_{i=1}^{j} D_i .$$

Beginning with the third cycle of the measurements it is important to know not only the magnitudes of the displacements and vertical deformations between initial cycle and current one, but its partial magnitudes, produced between two conjugated cycles. These should be expressed through the differences of the total magnitudes as

(5) $$\Delta H_j^{t,p} = \Delta H_j^t - \Delta H_j^{t-1} ,$$

To evaluate the precision of the measurements of the displacements and total vertical deformations, settlements or uplifts in each control point from the building under consideration, the relation

(6) $$s_{\Delta H_j^t} = \pm K_t \sqrt{n_j (n - n_j)} ,$$

is used [3], where the magnitude K_t is calculated on the basis of the deviations between the magnitudes of the level differences, measured with the two horizons in each cycle of measurements

(7) $$d_{0i}= h_i^{0,I} - h_i^{0,II}, \; d_{ti}= h_i^{t,I} - h_i^{t,II},$$

with formula

(8) $$K_t=\frac{1}{2n}\sqrt{\sum_{i=1}^{n}(d_{oi}^2 + d_{ti}^2)}.$$

Here n denoted the total number of stations and means the number of the stations from the initial point of the considered point.

Finally, the trust interval where should be located the true magnitudes of the deformations and vertical displacements from each control point, for a probability P=68,3% which correspond to the mean square errors will be expressed by the double inegality

(9) $$\Delta H_j^t - s_{\Delta H_j^t} \le \overline{\Delta H_j^t} \le \Delta H_j^t + s_{\Delta H_j^t}.$$

When the determination of the displacements and vertical deformations by respect to the fixed marks of surface does not correspond to the proposed exactingness, their establishing one can obtained from the analysis of the distribution of the level differences measured in each cycle between the control points.

In this case the following method is proposed: first, one calculates the differences between the mean values(1) of the level differences measured in initial cycle and in the cycle t, t=$\overline{1,N}$. For the level difference i, i=$\overline{1,n}$, this will be

(10) $$\pm D_i^t = h_i^t - h_i^0,$$

where h_i^0 is the level difference measured in initial cycle, and h_i^t the level difference measured in cycle t. The magnitudes of differences (10) include two components: the first component is given from the influence of the measuring instruments with random character in each cycle of measurements and the second one represents the displacement and vertical deformation produced in the interval of time between the two measurements. If the differences are considerable greater then the anticipated errors, then one can appreciate that there are a vertical deformation (settlement or uplift). From the magnitudes of the differences one can eliminate the influence of the systematic errors or the settlement. For this reason, the mean magnitude of the differences, (10) is calculated, and it results:

(11) $$D_{ave}^t = \frac{1}{N}\sum_{t=1}^{N} D_i^t,$$

With the help of this value one calculate the deviations between the differences (10) and the mean difference (11) :

(12) $$d_i^t = D_i^t - D_{ave}^t, \rightarrow [d_i^t] = 0.$$

This, is the row d_i^1, d_i^2,..., d_i^N is approaching to the distribution of the random numbers, proper to the random errors of witch values could be analized in advance [3], then it means that the vertical deformations have not produced. This ascertainment can be made also from the analysis of the differences $D_i^1, D_i^2,..., D_i^t,..., D_i^N$ which will have small values and varied signs.

When the deviations (12) beginning with certain cycle, or from very beginning do not respect more the random/normal distribution, it means that one can talk about the existence of certain vertical deformations, settlements or uplifts depending on their signs.

To characterize the mean stability of the building under consideration on the basis of the deviations (12) one recommends the computing of the mean square errors, using formula

(13) $$s_0 = \pm\sqrt{\frac{[d_i^t d_i^t]}{(N-1)(n-1)}}.$$

It is observed that for the appreciation of the differentiate settlement process of the studied building it is recommended the use of the magnitude of the dispersion, calculated for each cycle of observations t, with the relation :

(14) $$D^t = \frac{\sum_{i=1}^{n}(D_i^t - D_{ave}^t)^2}{n-1} = \frac{[d_i^t d_i^t]}{n-1},$$

where: D_i^t are the differences between the magnitudes of the level differences measured in the present and initial cycles, and D_{ave} is the mean difference in each cycle, calculated with relation :

(15) $$D_{ave}^t = \frac{1}{n}\sum_{i=1}^{n} D_i^t$$

When the magnitudes of the dispersion in a cycle of measurement t is considerable near to zero, it means that the settlement is uniform. When the dispersion is different to zero, one can estimate a settlement differentiated of the building.

3. Case study

At an production hull it is emphasized the effect of the exagerate settlement of the central pillar with certain deteriorations at the upper part of the pillar with glass foundation and of the two beams, so that aris the problem to stop the whole production process.

The rash conclusions of certain specialists taken on the basis of same doubtful measurements, have created a complicated situation. In this situation, one of the most important problems was the measuring of all pillars and especially of the velocity of the settlement. Concomitant with certain measures taken for strength, have been fixated marks of settlement of console type on each of the 12 pillars for the measuring of the vertical deformations denoted by $P_1, P_2, \ldots, P_{12}$ (Fig.2).

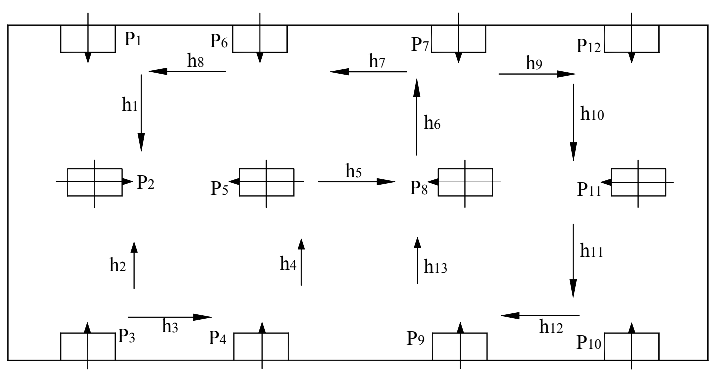

Fig.2

As the two marks of surface proved to be inadequate till realization of the two marks of deepness, during more than an year, have been started the geometric leveling measurements of precision, using a Zeiss Ni 007 level and the staff with invar rod with a 1,75 m span. The measuring conditions especially in winter, were difficult because of steams, condense, insufficient light. It was necessary to use certain short visas and local lighting of the staff during accomplishing the readings.

In the absence of the reference fixed network, the exceptional situation led us to a study of the resistance structure, by measuring the level differences between the control points/settling marks, in two horizons of the instrument, maintaining the location of the mid-station and implicitly the number of stations.

In the accomplished study, according to presented method, the number of the level differences was n=13, being denoted by $h_1, h_2, \ldots, h_i, \ldots, h_{13}$, Fig.2, including the measuring direction indicated by arrow. The number of cycles was N=18 to which is added the initial/zero cycle. The study has been achieved for all level differences, but for space reason we present only data for h_1, h_5, h_6, h_7, h_{12} an h_{13}. The magnitudes of the differences D_i, according to 18 cycles of observations, are given in Table 1 and the values mean differences (11) accordingly to each considered level difference are given on the last row of Table 1.

Table 1

No. cycle	Magnitudes of differences (mm)					
	D_1	**D_5**	**D_6**	**D_7**	**D_{12}**	**D_{13}**
0	0,00	0,00	0,00	0,00	0,00	0,00
1	+0,21	-0,36	-0,34	+0,17	+0,23	+0,17
2	+0,11	-0,17	-0,06	+0,13	+0,28	-0,64
3	+0,08	-0,45	-0,08	+0,24	-0,05	-0,60
4	-0,05	-0,22	-0,24	+0,41	-0,18	-0,81
5	+0,20	-0,59	+0,17	+0,38	-0,13	-0,84
6	+0,03	-1,03	+0,05	+0,36	+0,02	-1,10
7	+0,03	-1,08	+0,80	+0,34	-0,14	-1,16
8	+0,16	-1,33	+0,87	+0,24	+0,12	-1,24
9	-0,07	-1,49	+0,75	+0,44	+0,32	-1,77
10	+0,06	-2,01	+1,26	+0,51	+0,08	-2,64
11	-0,17	-1,88	+1,79	+0,22	+0,19	-2,35
12	+0,15	-1,93	+1,82	+0,41	+0,28	-2,89
13	+0,27	-2,38	+1,98	+0,39	+0,05	-3,04
14	-0,02	-3,09	+2,16	+0,26	-0,03	-3,80
15	+0,38	-2,84	+2,85	+0,14	-0,23	-3,47
16	+0,35	-2,86	+2,87	-0,01	-0,27	-4,25
17	-0,18	-3,58	+3,84	-0,24	+0,07	-5,56
18	+0,06	-5,67	+5,25	+0,07	-0,09	-5,38
D^t_{ave}	**+0,084**	**-1,735**	**+1,380**	**+0,235**	**+0,027**	**-2,177**

Data analizis in Table 1 show us that differences D_1,D_7 and D_{12} from the level differences h_1(1-2), h_7(7-6) and h_{12}(10-9) have small magnitudes and varied signs indicating that the pillars 1,2,6,7,9 and 10 have a good vertical stability. At the same time, the differences D_5,D_6 and D_{13} from the level differences h_5(5-8), h_6(8-7) and h_{13}(9-8) have the same signs, and increases in absolute value, pointing out a displacement and vertical deformation phenomenon. The general analysis of the level measurements of precision yields the conclusion that single vertical displacement have been produced on the level differences h_5(5-8), h_6(8-7) and h_{13}(9-8). In this manner the settlements of the central pillar 8, measured from the pillars stable along the vertical, 5,6, and 9, have been :

ΔH^{I}_{8}(D_5)= -5,67 mm, ΔH^{II}_{8} (D_7)= -5,25 mm, ΔH^{III}_{8} (D_{13})= -5,38 mm.

The settlement on the whole of the pillar 8, the most affected from the point of view constructive, proposed in the interval of time between the first cycle of observations and the lost one, 18 months on the whole, have been given by the arithmetic mean of the tree magnitudes

$$\Delta H_8 = \frac{1}{3}(\Delta H^{I}_{8} + \Delta H^{II}_{8} + \Delta H^{III}_{8}) = -5{,}43\text{mm}.$$

The settlement velocity of the control pillar, on the considered interval of time is

$$V_8 = \frac{\Delta H_8}{T} = \frac{-5{,}43mm}{18months} = -\,0{,}30 \text{ mm/month}.$$

With the help of the average differences registred in the lost row of Table 1, the deviations (12) have been calculated; their values are presented in Table 2.

Table 2

No. cycle	**Magnitudes of deviations (mm)**					
	$\mathbf{d_1}$	$\mathbf{d_5}$	$\mathbf{d_6}$	$\mathbf{d_7}$	$\mathbf{d_{12}}$	$\mathbf{d_{13}}$
1	−0,084	+1,735	−1,280	−0,235	−0,027	+2,177
2	+0,126	+1,375	−1,720	−0,065	+0,203	+2,347
3	+0,026	+1,565	−1,440	−0,105	+0,253	+1,537
4	−0,004	+1,285	−1,460	+0,005	−0,077	+1,577
5	−0,134	+1,515	−1,140	+0,175	−0,207	+1,367
6	+0,116	+1,145	−1,210	+0,145	−0,157	+1,337
7	−0,054	+0,705	−1,330	+0,125	−0,007	+1,077
8	−0,054	+0,655	−0,580	+0,105	−0,167	+1,017
9	+0,076	+0,405	−0,510	+0,005	+0,093	+0,937
10	−0,154	+0,245	−0,630	+0,205	+0,293	+0,407
11	−0,024	−0,275	−0,120	+0,275	+0,053	−0,463
12	−0,054	−0,145	+0,410	−0,015	+0,163	−0,173
13	+0,066	−0,195	+0,440	+0,175	+0,253	−0,713
14	+0,186	−0,645	+0,600	+0,155	+0,023	−0,863
15	−0,104	−1,355	+0,780	+0,025	−0,057	−1,623
16	+0,296	−1,105	+1,470	−0,095	−0,257	−1,293
17	+0,266	−1,125	+1,490	−0,245	−0,297	−2,073
18	−0,264	−1,845	+2,460	−0,475	+0,043	−3,383
19	−0,024	−3,935	+3,870	−0,165	−0,117	−3,203
Sum	**+0,004**	**+0,005**	**0,000**	**−0,005**	**+0,007**	**−0,007**

The analysis of the data in Table 2 show us the same conclusions. Thus, if the deviations $d_{1,}$ d_7 and d_{12} have small values and various signs having a distribution of the random numbers/errors, indicating a stability along the vertical of the marks between which the level differences have been measured, the deviations $d_{5,}$ d_6 and d_{13} do not respect the values of the random distribution, these situations indicating the deformations and vertical displacements, emphasizing especially the displacement of the central pillar 8.

One emphasize the fact that after the construction of the two fixed marks of deepness (till 14m), the level measurements have been repeated on a route of a supported traversing, including a great number of stations. The processing has been accomplished semi-rigorously with the algorithm presented in the first part of this work, the deformations and vertical displacements being calculated direct on the control points. The results in these stages confirm the correctness of the proposed method.

In Fig.3 is presented the settlement diagrama of the pillar 8, according to the observation cycles t=1,5,10,15 and 19.

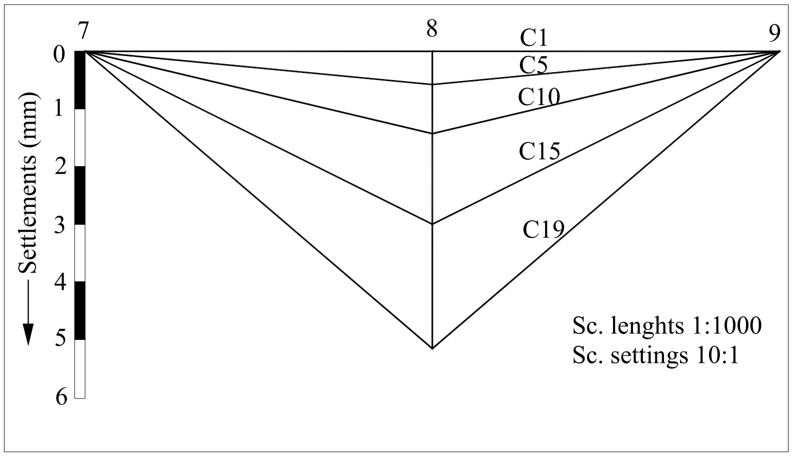

Fig. 3

4. Conclusions

The pursuit of the behaviour along the vertical of the resistance structure of a building, by geometric leveling measurement of the precision and high precision and the analysis of the results by the proposed method, led us to the possibility of emphasizing the settlement and the velocity of the settlement, the analysis of its causes and to take measures of immediate strengthening.

The use of the presented method to determine the settlements of the resistence structure even in absence of the fixed network of reference led us to the best results, it beeing also confirmed after achievement of two fixed marks of deepness.

The method could be applied in amergency cases, in conditions of apperance of some phenomena with a rapid evolution which impose the knowing of some minimal data conserning the security during service of the building.

5. References

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