# CONTRIBUTIONS TO REMOVING INDETERMINATION IN OBTAINING THE FIXED LANDMARKS ELEVATIONS OF THE REFERENCE NETWORK, IN THE STUDY OF VERTICAL BEHAVIOUR OF BUILDINGS

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***Abstract:*** *In the study of the in situ building behavior, of a particular importance are the data on vertical deformations and displacements. In the group of geodetic methods, the most used method is high-precision geometric levelling.*

*The geodetic measurement principle consists in cyclical determination of the elevations of settlement marks built in the building, in relation to several fixed landmarks, surface or groundwater.*

*It presents a method for removing the indetermination in obtaining the fixed landmark elevations, in comparison to which, in each cycle of observations, both vertical deformations and vertical movements, settlements or raisings of the studied building are determined.*

***Keywords:*** *behaviour, vertical deformation, geometric levelling, elevation, building.*

## 1. Introduction

The *in situ* behaviour of buildings defines the manifestation way of physical and chimical changes which undergo in the process of interaction with the natural and technological environment and with themselves. Knowledge of the causal laws of the occurance and development of behavioural phenomena of buildings has allowed to define some behaviour properties. They can be defined qualitatively by attributes, or quantitatively by sizes and parameters. Thus, settling, cracking, corrosion, strain degree, humidity, etc., are used to define behavioural properties, such as physical and chemical strength, plane and vertical stability, stiffness, etc.

Monitoring the *in situ* behaviour of buildings, in implementation and operation, interweaves behaviour tracking, discovering inconsistencies, with expectations and removal interventions, with a view to ensuring operating skills.

In the study of the buildings, geodetic methods are widely used, both in experimental laboratory test phase and in tracking the *in situ* behaviour of buildings, in execution and operation. Improving tools and geodetic equipment, methods and technologies of measurement and automatic data processing, has created new possibilities for use in the study of buildings.

In the study of the *in situ* behaviour of buildings, of a particular importance are data on deformations and their vertical displacements, called *settlings* for negative sizes, and *raisings* or *bulgings*, for positive sizes. In the geodetic methods group, the wider use has the high precision geometric leveling method. The monitoring network is accomplished under polygonal form, by geometric levelling traversing method, which includes both fixed landmarks of reference / basis and mobile landmarks (settling marks), embedded in the studied building.

The principle of geometric levelling measurements is to determine cyclical elevations the settling landmarks in relation to several fixed, surface or deep landmarks, built in stable grounds outside the building influence area. Fixed landmarks are designed to achieve a horizontal comparison / reference plane against which to determine the settling marks elevations, and hence, vertical deformations and displacements. Settling marks are meant to show as true as possible the vertical components of displacements of separate elements or of the building as a whole. They are embedded into the strength elements of the building, under the action of static or dynamic charges, and by repeated measurements on them, to establish values of vertical deformations and displacements.

The paper presents a method of removing indeterminacy in obtaining fixed, basis settling landmarks elevations against which the vertical behaviour of the studied building is determined.

## 2. Method presentation

In order to measure vertical deformations and displacements of industrial constructions a reference tracking network is accomplished, which includes fixed, basis settling landmarks, evenly distributed in the area, and the settlement marks, built in the studied building in operation. Depending on the size and importance of the construction, a number at least two fixed landmarks are made. Their location and construction must take into account the geotechnical and hydrological conditions of the land, the need to ensure optimal measurement conditions, land systematization around the studied building. Fixed, surface and depth, landmarks, are built at least three months before the start of the construction performance monitoring, in order to achieve their stabilization and prior determination of the fixed, basic landmarks elevations.

In high-precision geometric leveling, choice of instruments, equipment and measurement methods is made in terms of the accuracy required to determine the vertical deformations. In geometric leveling traversing one should take into account prior checking and correction of devices, eliminating or reducing the influence of systematic errors and to minimize the influence of random errors. High precision geometric leveling traversings, performed with a view to determine vertical deformation, is performed as based on the technical prescriptions of 1st or 2nd order state geometric-geodetic levelling. Determining level differences is done by middle-way geometric leveling, sight lines lengths, backsight and foresight, lengths being 25-50 m. Measurements are performed by means of high precision levels and 1.75 m or 3 m long invar tape staffs.

The advantage of reference polygonal networks is determined by the building configuration that is going to be studied, relying on fixed, basis landmarks. Each new polygon leads to obtain an additional control of the land measurements and precision components growing condition. Additional links lead to a decrease in the size of a compensated element weight inversion, in the expression:

$$\mu_F = \pm\mu\sqrt{\frac{1}{p_F}} = \pm\mu\sqrt{Q_{FF}} \quad , \tag{1}$$

where $\mu_F$ - mean square error of a single compensated element; $\mu$ - weight unit error; $p_F$ - the weight of the compensated element. It is worth mentioning that the tracking network, containing fixed and mobile landmarks, is compensated by the rigorous method of indirect weighted measurements.

In principle, the fixed basic landmarks elevations, in relation to which the mobile landmarks elevations are calculated, are determined in a local reference system, with an accuracy corresponding to the 1st or 2nd order state geometric-geodetic levelling. They can be determined before beginning the building behaviour tracking, and then in every cycle of observations, this being most recommended. In practice, it was found that in case of the existence of 2-3 depth landmarks, in a period of 1-2 years, there have been settlements of landmarks, at values of the orde of millimeters. By changing fixed landmarks elevations, the settlement marks corresponding to each cycle of observations will change. By this, the basic network appears as indefinite, the elevation of each fixed landmark being accepted as a basis for the network compensation, leaving open the question - which fixed landmark has changed its position on the vertical?

It is recommended that the basic levelling network to be made in each cycle of observations, carried out to check the building settlement, together with the compensation of measurement results. Thus, analysis of each fixed landmark position can be done, and then the indeterminacy in obtaining elevations for the measured network in each observation cycle can be remove.

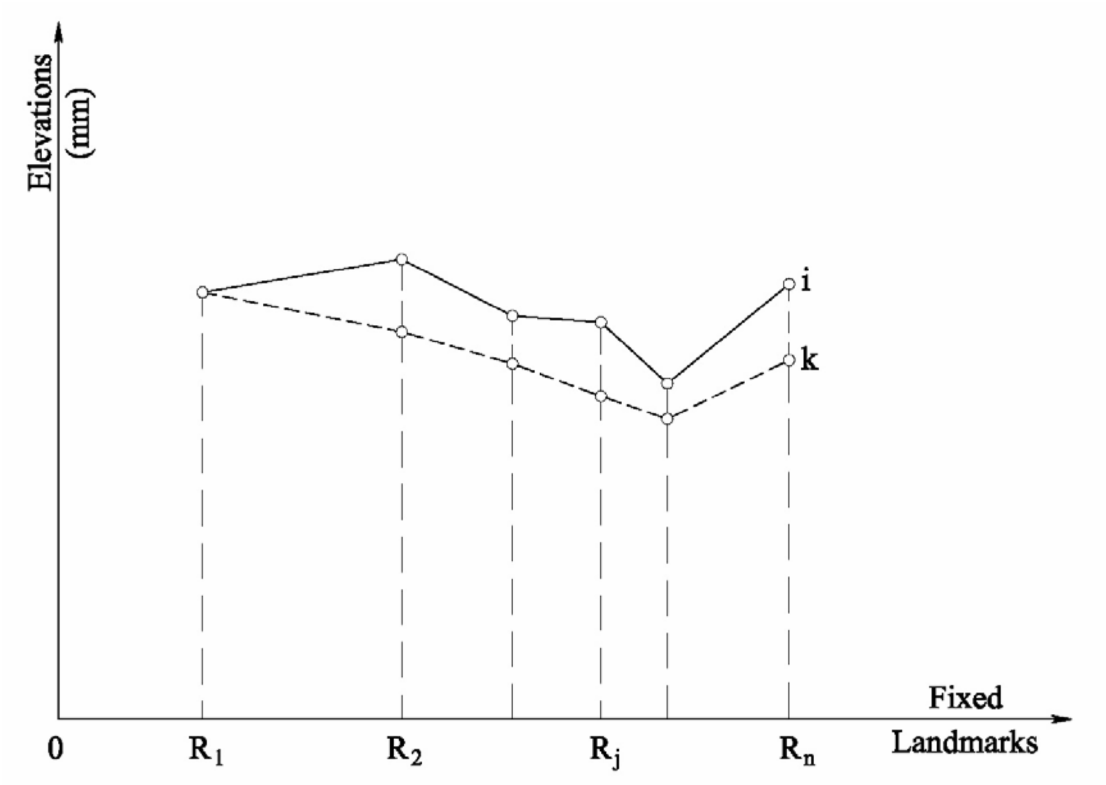
This method consists in the following:

The fixed, basic landmarks elevations $H_{1i}$, $H_{2i}$, …, $H_{ji}$, …, $H_{ni}$ , are considered, where $j = \overline{1-n}$ , obtained after the compensation of the basic network in keeping wih the data base „*i*” levelling measurements cycle data. The elevations of the same basic fixed landmarks, obtained from „*k*”cycle levelling measurements, will be: $H_{1k}$, $H_{2k}$, …, $H_{jk}$, …, $H_{nk}$ . It is considered that in both cycles, only the same elevation of the first landmark served as a basic landmark, so there is the equality of the two cycles elevations, $H_{1i} = H_{1k}$ .

The diferences between the basic landmarks elevations are performes, resulting:

$$\begin{aligned} h_{1,ik} &= H_{1k} - H_{1i} \ , \\ h_{2,ik} &= H_{2k} - H_{2i} \ , \\ &\dots\dots\dots\dots\dots\dots \\ h_{n,ik} &= H_{nk} - H_{ni} \ . \end{aligned} \qquad (2)$$

In Figure 1, the sizes of the $h_{j,\,ik}$ differences are the results from corresponding height differences. It is obvious that provided the levelling measurements were not affected by errors and landmarks have not changed position on vertical, then all differences $h_{j,\,ik}$ would equal zero. In fact, the equality to zero would be only the first time, $h_{1,\,ik} = 0$, when the first landmark was taken as the basis, in both cycles of observations, *i* şi *k*. All the other differences $h_{j,\,ik}$ will be zero because their sizes have two components: the first is given by the leveling errors differences admitted for each landmark, in the two cycles of measurements, $v_{j,\,ik}$ and the second is given by changing position on vertical by the landmark (its settling), in the period between the two cycles of observations, marked $\delta_{j,\,ik}$ .




Thus, differences will be written as:

$$\begin{aligned} h_{1,ik} &= v_{1,ik} \ , \\ h_{2,ik} &= v_{2,ik} + \delta_{2,ik} \ , \\ &\dots\dots\dots\dots\dots\dots \\ h_{n,ik} &= v_{n,ik} + \delta_{n,ik} \ , \end{aligned} \quad (3)$$

where $v_{1,\,ik} = 0$. Thus, the value $\delta_{1,\,ik}$ of the first landmark elevation change in $k$ cycle will be found, by which the elevations of all landmarks in this cycle can be corrected. The amount of residual deviations shall be subjected to the condition:

$$\left[ v_{j,\,ik} + \delta_{j,\,ik} \right] \rightarrow \min . \quad (4)$$

The notation $v_{j,\,ik} + \delta_{j,\,ik} = \Delta_{j,\,ik}$ is made and considering $j = \overline{1-n}$, the equalities will be written:

$$\begin{aligned} \Delta_{1,\,ik} &= v_{1,\,ik} + \delta_{1,\,ik} \ , \\ \Delta_{2,\,ik} &= v_{2,\,ik} + \delta_{2,\,ik} \ , \\ &\dots\dots\dots\dots\dots\dots \\ \Delta_{n,\,ik} &= v_{n,\,ik} + \delta_{n,\,ik} \ . \end{aligned} \quad (5)$$

The relations (5) have the form of error equations, although the $\Delta_{j,\,ik}$ sizes are not independent from each other, resulting in compensation. Solving the (3) and (5) equations under the condition (4), it comes out:

$$n\,\delta_{1,\,ik} + \left[h_{j,\,ik}\right] = 0\ , \tag{6}$$

hence

$$\delta_{1,\,ik} = -\frac{\left[h_{j,\,ik}\right]}{n}\ . \tag{7}$$

Based on these sizes, compensation of the sizes of $h_{1k}$ of the differences in $k$ cycle, by means of which the probable elevations of all fixed landmarks in this cycle are calculated, is made. Based on the methodology presented, of removing indeterminacy in obtaining fixed landmarks elevations, against which to determine the vertical behaviour of the studied building, further on a case study is presented.

## 3. Case study

To measure vertical deformations and displacements of some industrial buildings, a reference levelling network was done, the composition of which includes a number of four fixed landmarks, two deep and two surface, as well as a large number of settlement marks, fixed on the building.

Because the fixed landmarks vertical stability also depends on the stability of the horizontal plane of comparison, it was decided that in each cycle of observations both the fixed landmarks basic network and the entire tracking network to be measured simultaneously. In time, not only building, but also the fixed landmarks are subject to changes in the vertical position, due both to measurement errors and to settlements or liftings. In this situation an indeterminacy appears: which should be the chosen landmark, against which to make determinations of settlements or liftings of the studied building.

Based on high precision geometric levelling measurements, performed on the basic network in each cycle of observations, level differences compensation was made, on which the elevation of basic network points were calculated, consisting of four landmarks. Their sizes are shown in Table 1, corresponding to a number of observations of six observation cycles.

Table 1

| **Landmark number** | **Fixed landmarks elevations (mm)** | | | | | |
|---|---|---|---|---|---|---|
| | **1993** | | **1994** | | **1995** | |
| | **25.05** | **20.10** | **15.04** | **09.10** | **03.04** | **12.09** |
| ***0*** | ***1*** | ***2*** | ***3*** | ***4*** | ***5*** | ***6*** |
| 1 | 250.0 | 250.0 | 250.0 | 250.0 | 250.0 | 250.0 |
| 2 | 625.3 | 625.7 | 624.1 | 624.6 | 624.9 | 625.4 |
| 3 | 756.6 | 758.6 | 757.8 | 758.6 | 755.5 | 758.7 |
| 4 | 1122.6 | 1121.3 | 1118.6 | 1119.3 | 1119.6 | 1119.9 |

As a known elevation, for each cycle of measurements, landmark 1 elevation was used, $H_1$ = 250.0 mm, established at the compensation of the first cycle of observations. The calculation of sizes $\delta_{1,\ ik}$ for cycles 2-6 and obtaining the likely elevations of the fixed landmarks in each of these cycles are shown in Table 2.
Thus, for the second cycle the differences between the elevations of cycle 2 and the elevations of cycle 1, taken from Table 1, are calculated

$$h_{1,12} = H_{1,2} - H_{1,1} = 250.0 - 250.0 = 0.0\ mm\ ,$$
$$h_{2,12} = H_{2,2} - H_{2,1} = 625.7 - 625.3 = 0.4\ mm\ ,$$
$$h_{3,12} = H_{3,2} - H_{3,1} = 758.6 - 756.6 = 2.0\ mm\ ,$$
$$h_{4,12} = H_{4,2} - H_{4,1} = 1121.3 - 1122.6 = -1.3\ mm\ .$$

The values obtained are recorded in the 2nd column of Table 2. The algebraic sum of the differences is made

$$\left[h_{12}\right] = h_{1,12} + h_{2,12} + h_{3,12} + h_{4,12} = 1.1\ mm\ ,$$

then the size of correction is calculated

$$\delta_{1,12} = -\frac{\left[h_{12}\right]}{n} = -\frac{1.1}{4} = -0.3\ mm\ .$$

The 2nd cycle differences are compensated, the results are listed in column 3, Table 2

$$h^c_{1,12} = 0 - 0.3 = -0.3\ mm\ ,$$
$$h^c_{2,12} = 0.4 - 0.3 = 0.2\ mm\ ,$$
$$h^c_{3,12} = 2.0 - 0.3 = 1.7\ mm\ ,$$
$$h^c_{4,12} = -1.3 - 0.3 = -1.6\ mm\ .$$

As a compensation check it is require that $\left[h^c_{j,12}\right] = 0$.

Finally, the probable landmarks of the second cycle will be

$$H^c_{1,2} = H_{1,1} + h^c_{1,12} = 250.0 - 0.3 = 249.7\ mm\ ,$$
$$H^c_{2,2} = H_{2,1} + h^c_{2,12} = 625.3 + 0.2 = 625.5\ mm\ ,$$
$$H^c_{3,2} = H_{3,1} + h^c_{3,12} = 756.6 + 1.7 = 758.3\ mm\ ,$$
$$H^c_{4,2} = H_{4,1} + h^c_{4,12} = 1122.6 - 1.6 = 1121.0\ mm\ ,$$

they are listed in Table 2, column 4.

Table 2

| **Landmark number** | **Landmarks elevations in cycle 1 (mm)** | **Cycle 1-2** | | | **Cycle 1-3** | | | **Cycle 1-4** | | | **Cycle 1-5** | | | **Cycle 1-6** | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | **$h_{12}$** | $h_{12}^c = h_{12} + \delta_{12}$ | **Probable elevations in cycle 2** $H_{j,12}^c = H_{j,1} + h_{12}^c$ | **$h_{13}$** | $h_{13}^c = h_{13} + \delta_{13}$ | **Probable elevations in cycle 3** $H_{j,13}^c = H_{j,1} + h_{13}^c$ | **$h_{14}$** | $h_{14}^c = h_{14} + \delta_{14}$ | **Probable elevations in cycle 4** $H_{j,14}^c = H_{j,1} + h_{14}^c$ | **$h_{15}$** | $h_{15}^c = h_{15} + \delta_{15}$ | **Probable elevations in cycle 5** $H_{j,15}^c = H_{j,1} + h_{15}^c$ | **$h_{16}$** | $h_{16}^c = h_{16} + \delta_{16}$ | **Probable elevations in cycle 6** $H_{j,16}^c = H_{j,1} + h_{16}^c$ |
| ***0*** | ***1*** | ***2*** | ***3*** | ***4*** | ***5*** | ***6*** | ***7*** | ***8*** | ***9*** | ***10*** | ***11*** | ***12*** | ***13*** | ***14*** | ***15*** | ***16*** |
| 1 | **250.0** | 0 | - 0.3 | 249.7 | 0 | 1.0 | 251.0 | 0 | 0.5 | 250.5 | 0 | 1.1 | 251.1 | 0 | 0.1 | 250.1 |
| 2 | 625.3 | 0.4 | 0.2 | 625.5 | - 1.2 | - 0.2 | 625.1 | - 0.7 | - 0.2 | 625.1 | - 0.4 | 0.7 | 626.0 | 0.1 | 0.2 | 625.5 |
| 3 | 756.6 | 2.0 | 1.7 | 758.3 | 1.2 | 2.2 | 758.8 | 2.0 | 2.5 | 759.1 | - 1.1 | 0.1 | 756.7 | 2.1 | 2.3 | 758.9 |
| 4 | 1122.6 | - 1.3 | - 1.6 | 1121.0 | - 4.0 | - 3.0 | 1119.6 | - 3.3 | - 2.8 | 1119.8 | - 3.0 | - 1.9 | 1120.7 | - 2.7 | - 2.6 | 1120.0 |
| | $[h]$ | + 1.1 | 0 | - | - 4.0 | 0 | - | - 2.0 | 0 | - | - 4.5 | 0 | - | - 0.5 | 0 | - |
| $\delta_{1k} = -\frac{[h_{1k}]}{n}$ | | $\delta_{12} = -\frac{1.1}{4} = -0.3$ | | | $\delta_{13} = +\frac{4}{4} = +1.0$ | | | $\delta_{14} = +\frac{2}{4} = +0.5$ | | | $\delta_{15} = +\frac{4.5}{4} = +1.1$ | | | $\delta_{16} = +\frac{0.5}{4} = +0.1$ | | |

Table data allow to analyze changes of one and the same landmark between any two cycles of observations. Assessment will be even safer, as sizes as $\delta_{j,\ ik}$ are higher, compared with errors resulting from network compensation. If the difference of the same landmark elevations does not exceed the double of the mean square error of the the appropriate level differences, then it can be appreciated that that one cannot speak of landmarks vertical position changing.

This may remove the indeterminacy in the choice of basic elevation in each cycle of observations; the elevation of any fixed landmark can be taken as basic landmark. The shown method corresponds to the case when landmarks elevations will be the mean values of the elevations, by taking as the basis each of the old landmarks, after one and the same compensation of the level differences of the considered cycle. Thus, in Table 3, for the cycle 4 of observations the elevations of all fixed landmarks were calculated successively, taking as reference landmark each of the basic landmarks 1, 2, 3 and 4.

Tabelul 3

| **Landmark number** | **Level diferences compensated in cycle 4** | **Fixed landmark elevations (mm)** | | | | |
|---|---|---|---|---|---|---|
| | | **Against landmark 1** | **Against landmark 2** | **Against landmark 3** | **Against landmark 4** | **Probable (medium) elevations** |
| ***0*** | ***1*** | ***2*** | ***3*** | ***4*** | ***5*** | ***6*** |
| 1 | - | **250.0** | 250.7 | 248.0 | 253.3 | 250.5 |
| 2 | 374.6 | 624.6 | **625.3** | 622.6 | 627.9 | 625.1 |
| 3 | 134.0 | 758.6 | 759.3 | **756.6** | 761.9 | 759.1 |
| 4 | 360.7 | 1119.3 | 1120.0 | 1117.3 | **1122.6** | 1119.8 |

Based on results for fixed landmarks, by using the of level differences compensated in cycle 4, the second column (marked with 1), in the last column (marked with 6) the most probable landmark elevations were calculated, as arithmetic means of the four values obtained. The most probable elevations are the same with the elevations sizes obtained in Table 2, measurements cycle 4.

## 4. Conclusions

The presented method eliminates the indeterminacy in the choice of fixed landmarks elevations, against which, the vertical deformations and displacements in the settlement marks are calculated in each levelling measurement cycle. By taking the initial elevation of any fixed landmark, the results in each cycle of observations will be the same.

## 5. References

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