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GEODETIC DETERMINATION OF VERTICAL DISPLACEMENT OF BUILDINGS DURING CONSTRUCTION

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Abstract:

The methodology of planning and performing geodetic activities in determining vertical displacement of engineering objects or specific structural elements and units is presented in this paper. Data from observation of a building for students' accomodation in Banja Luka, collected during its construction, are presented. The geodetic control of geometry and deformation analysis of the performed building construction are primary tasks of the engineering geodesy in the construction of objects. Vertical displacement and deviations of objects are caused by numerous factors. The geodetic tehnical documentation, developed during implementation of these tasks, represents a valuable basis for the development of observation projects during exploitation of objects and for forming an engineering building information system.

Keywords: vertical displacement, engineering geodesy, Pelzer method.

ГЕОДЕТСКО ОДРЕЂИВАЊЕ ВЕРТИКАЛНИХ ПОМЈЕРАЊА ОБЈЕКАТА У ТОКУ ИЗГРАДЊЕ

Резиме:

У раду је приказана методологија планирања и извођења геодетских радова за одређивање вертикалних помјерања инжењерских објеката или појединих конструктивних елемената и цјелина. Представљени су подаци осматрања објекта за смјештај студената у Бањој Луци, прикупљени у току изградње. Геодетска контрола геометрије и деформациона анализа изведене конструкције објекта основни су задаци инжењерске геодезије при изградњи објеката. Вертикална помјерања и одступања објеката узрокована су многобројним факторима. Геодетска техничка документација, настала реализацијом ових задатака, представља драгоцјену основу за израду пројекта осматрања у току експлоатације објекта и формирање информационог система инжењерског објекта.

Кључне ријечи: вертикална помјерања, инжењрска геодезија, метода Пелцера.

1. INTRODUCTION

By the influence of various internal, external, as well as other causal factors, to soil and objects (buildings), vertical and horizontal displacements of objects occur. We define displacement as a change of the position of a point in space, which is divided into a horizontal and a vertical component. The consequence of deformation is the stress of the structure, unpredicted by calculations, which causes cracks and/or damages, and in extreme cases even collapse of objects or some structural parts.

Vertical displacements can be lifting or subsidence of objects [1]. According to the intensity of displacement in the course of time, subsidence can be equal or unequal. Equal subsidence may occur if the pressure from an object is equally distributed to all points of the object, which is positively reflected to the stability and firmness of the object. Unequal subsidence occurs when the pressure of different intensity affects some parts of an object and it has a far greater impact, very often a negative one, to the stability and firmness of the object.

Causes for subsidence of objects are divided into two basic groups: general (characteristics of soil, temperature and groundwater level, wind effect, etc.), and special (defects in soil testing, designing and constructing buildings, etc.). The most common forms of deformations, which are a consequence of unequal subsidence of soil, are: inclination, bending, distortion, twisting, and cracks. The direction, size and character of deformations are the basic indicators which enable the interpretation of measurement results, due to: assessment of the construction state, assessment of the state of the object related to the process of construction, remediation, reconstruction of the object, or verification of theoretical assumptions.

Deformation measurement methods can be divided into geodetic and geotechnical (physical) [2]. Geotechnical methods and instruments can only be used to measure relative deformations. Geodetic methods and instruments are used to determine displacements and deformations of objects in the absolute system, on the ground of a referent network in a deformation free zone. The method of precise geometric leveling is most often used for determining vertical displacement of objects during construction [3], [4], [5]. For some objects, due to conditions of performing measurement and positions of points, the trigonometric leveling is also used.

This paper gives the theoretical bases of designing geodetic works for determining vertical displacements of buildings during construction, which consists of: a) designing the geodetic control 1D network, and b) statistical determining of displacement of points on objects through the deformation analysis methods. The represented methodology has been applied in observing the Pavilion 4 of the students' accommodation building in Banja Luka. Final values of vertical displacements of points on the building have been obtained by the Pelzer method.

2. DESIGNING GEODETIC WORKS FOR DETERMINING VERTICAL DISPLACEMENT

A quality performance of geodetic works is possible only if there are quality projects of geodetic works. The geodetic determination of vertical displacement of characteristic points of engineering objects includes: establishment of the geodetic control 1D network

(GC1DN) and determining the stability of points by application of a specific statistical method.

Bearing in mind the specificities of applying geodetic methods and techniques in engineering and technical areas, the success of geodetic works depends on the quality of establishing geodetic networks. For geodetic networks in the deformation analysis the term geodetic control networks is used. They are designed by the optimization method principles. There are four basic orders of optimization [6]:

- Zero order − choice of the datum,
- First order − choice of an observation plan,
- Second order − defining the precision of measurements, and
- Third order − adding new network points (changing of geometry).

For designing geodetic control networks, all orders are used simultaneously. The designing is conducted with research and analytical methods [6]. The research procedure is used for defining the criteria which a geodetic network needs to meet in terms of: geodetic datum and observation plan, measurement precision and calculating accuracy [7]. If some of the defined criteria are not met, then the geometry of the network, observation plan or measurement precision changes. The analytical method means the implementation of a unique series of mathematical steps for directly meeting the defined criteria.

Defining of the quality criteria requires cooperation with civil engineers, with respect to the principles of geodesy. The task of civil engineers is to define, for a particular object, the size of displacement that is necessary to be determined "with certainty" between two measurement epochs, to define characteristic points and the period of repeating measurements. The quality of geodetic networks is defined by measures of precision and reliability, and the price of the project implementation depends on the criteria set [6]. The reliability of geodetic networks is a measure of possibility to detect gross errors of geodetic measurements (internal), and the impact of undetected gross errors to assessments of unknown parameters (external) [7] [8].

2.1. DESIGINING GEODETIC CONTROL 1D NETWORK

The procedure of designing geodetic control networks can be defined as an algorithm, shown in Figure 1, with steps corresponding to the content of a technical report of the geodetic works design.

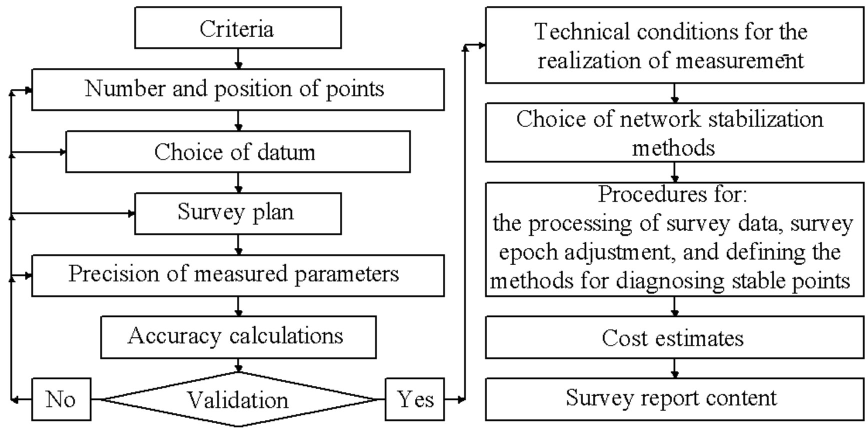


Figure 1. Algorithm of designing geodetic control networks [6]

The GC1DN for determining vertical displacement of objects consists of a group of points (benchmarks) that are not influenced by the engineering object mass and possible deformations, and a set of points at characteristic places of an engineering object.

Some criteria for designing the GC1DN are defined for each observed object, while some are known and common in the geodetic theory and practice. The most important criteria are:

- Size of displacement which can be detected by measurements in the GC1DN (dp) between two measurement epochs,
- Standard deviation of the height of GC1DN points,
- Local measure of internal reliability of individual measurements, and
- Marginal gross error which can be discovered for each measurement through the gross error presence test.

The standard deviation of the height of network points is defined based on the displacement size value as

$$\sigma_{\mathrm{POL/GKM}} \leq \frac{\mathrm{dp}}{5}. \qquad (1)$$

The value of the internal reliability local measure that is to be achieved for each measurement in the GC1DN is $r_{ii} \geq 0.2$. The last criteria also refers to the reliability of geodetic networks and it means that the value of the marginal gross error which can be detected by the gross error test, should be in the interval from $5\sigma_{l_i}$ to $7\sigma_{l_i}$, where σ_{l_i} is a standard deviation of individual measurements.

The geodetic basic 1D network (GO1DN) should have minimally 3 points stabilized outside the impact of a construction site, object mass or possible deformations. When choosing the position of basic network points, it is very important to have data on composition and bearing capacity of soil and stability of the object into which they are installed, so that the installed points could be stable in the course of time. Correct data and conclusions of the "stable soil" can be given by geologists and geomechanitians. In choosing points for discretization of objects in geometrical sense, attention should be paid that the chosen points are placed on constructions where the biggest deformations or displacements are expected [2].

The GC1DN datum for determining vertical displacements is defined in two ways:

- As the minimal trace of the cofactor matrix at all points, and
- As the minimal trace of the cofactor matrix at a part of points (stable points).

Defining the datum through the minimal trace of the cofactor matrix at all points is used in Zero order of observing objects, and the minimal trace of the cofactor matrix at some of points is used in all the others epochs of observing objects (minimum trace only at stable points).

The optimal number of height differences to be measured in the geodetic control 1D network is determined in accordance to the expression 2, based on the value of the global measure of the internal r_{ii} reliability. We strive to have its value from 0.2 to 0.3.

$$n = \frac{u - d}{1 - \overline{r}} \qquad (2)$$

The necessary accuracy of measured values in the GC1DN is defined on the basis of the previously determined standard deviation of the height of points, by calculation, which ensures that the adopted precision of measured height differences has a minimum impact on determining the network point height. The calculation of accuracy of measured size in the GC1DN depends on the type of planned measured sizes in the network. For activities in the engineering geodesy area, a precise geometrical and trigonometric leveling are usually used.

The required standard deviation of the height difference measurement, by a precise geometric leveling, can be expressed in the function of the point height standard deviation as

$$\sigma_{\Delta H} = \sigma_{H_R} \sqrt{2} = \sigma_{POL/GKM} \sqrt{2} \ . \qquad (3)$$

After calculating the accuracy, it is necessary to perform a project design verification, by comparing the values of the defined network quality criteria and values acquired by calculation. If the obtained values of all the criteria are less than or equal to defined values, it is considered that the project design is correct and it is transferred to defining technical requirements for the implementation of measurements. If the obtained value of a criterion is greater than the defined value, it is considered that the project design is not correct and the procedure goes back to some of designing phases. Which designing phase will be corrected or changed depends on which criterion has not been met.

The defining of technical requirements for the project realization includes:

- Defining the manner of network point stabilization,
- Detailed elaboration of a measurement method (choice of instruments and tools, procedure and requirements for measurements),

Defining criteria for measurement monitoring and control.

2.2. DETERMINING THE GEODETIC CONTROL 1D NETWORK STABILITY

For the conventional deformation analysis in space, two classes of models are used. A model based on the geometric test of congruence of characteristic points in different time epochs is called the congruence method. There are several methods of determining deformations under this method, which were named after authors' names (surnames). For practical calculations shown in the paper, the Pelzer method was used, in literature also known as the Hanover process. The process of determining the stability of the GC1DN points with this method can be represented in the form of an algorithm (Figure 1). Due to the enormity of the method, only basic settings have been explained.

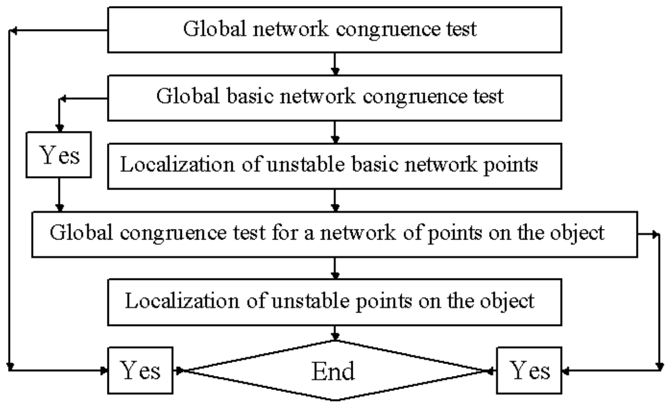


Figure 2. Algorithm of determining the stability of points by the Pelzer method

The basic characteristic of this method is testing global congruence by using the calculated "intermediate failure" (splitting) of a network measured twice and testing whether statistically significant displacement of points is present, which emerged between two surveys of the network - two measurement epochs.

Network congruence means the stability of points in that network, i.e. points are congruent if they have kept their position between two epochs. The network congruence is checked by testing the null (H_0) and alternative hypothesis (H_a)

$$\mathrm{H}_0: \mathrm{M}(\mathbf{x}_0) = \mathrm{M}(\mathbf{x}_1) \quad \text{or} \quad \mathrm{M}(\hat{\mathbf{d}}) = 0 \tag{4}$$

$$\mathrm{H}_a: \mathrm{M}(\mathbf{x}_0) \neq \mathrm{M}(\mathbf{x}_1) \quad \text{or} \quad \mathrm{M}(\hat{\mathbf{d}}) \neq 0 \tag{5}$$

where

$\mathbf{x}_0$, is the vector of assessed height of zero (starting or previous) epoch points,

$\mathbf{x}_1$, is the vector of assessed height of the current epoch points, and

$\hat{\mathbf{d}} = \hat{\mathbf{x}}_1 - \hat{\mathbf{x}}_0$, is the vector of differences of assessed height of points between epochs.

Accepting the zero hypothesis means that point heights are congruent, while rejection of the zero hypothesis means that point heights are not congruent in both epochs. For the purpose of checking these hypotheses the "intermediate failure" or splitting is calculated as follows

$$\theta^2 = \frac{\hat{\mathbf{d}}^{\mathrm{T}} \mathbf{Q}_{\hat{\mathbf{d}}}^{+} \hat{\mathbf{d}}}{\mathrm{h}} \tag{6}$$

where

$\mathrm{h} = \mathrm{rang}\mathbf{Q}_{\hat{\mathbf{d}}}$, is the rank of the cofactors matrix of height difference,

$\mathbf{Q}_{\hat{\mathbf{d}}} = \mathbf{Q}_{\hat{\mathbf{x}}_0} + \mathbf{Q}_{\hat{\mathbf{x}}_1}$, is the cofactors matrix of height differences, and

$\mathbf{Q}_{\hat{\mathbf{d}}}^{+}$, is the pseudo-inversion of cofactors matrix of height differences.

The null hypothesis statistics test is calculated as

$$\overline{\mathrm{T}} = \frac{\theta^2}{\hat{\sigma}_0^2}, \tag{7}$$

where $\hat{\sigma}_0$ is a priori of the dispersive factor, which, in case of the null hypothesis follows the central F-distribution

$$\mathrm{T} \sim F_{h,f}, \tag{8}$$

In the case of the alternative hypothesis, the statistics test follows the non-central F-distribution

$$\mathrm{T} \sim F_{h,f,\lambda}, \tag{9}$$

where:
f=f0+f1, is a unified number of freedom degrees from the zero and first epoch, and
λ, is the non-central distribution parameter.
If the zero hypothesis H_0 is not rejected, there is no significant displacement and then the assessments $\hat{\sigma}_0$ and θ may differ within random errors. The remaining non-closing must be explained by the measurement accuracy [3]. If H_0 is rejected, the existence of statistically significantly displaced points is very certain. The represented general test is used for a further analysis: testing the stability of basic geodetic network points, finding unstable geodetic basic network points and for determining the displacement of points on objects.

3. CASE STUDY - OBSERVATION OF THE STUDENT'S HALL IN BANJA LUKA DURING ITS CONSTRUCTION

Pavilion 4 of the students' accommodation building has been constructed in the University City in Banja Luka (Figure 3). It consists of two parts, a building with floors as follows C+GF+5, and a building with floors as follows C+GF, separated by dilatation (Figure 4). The buildings are built from reinforced concrete. The subject of geodetic observation of vertical displacement was the part of the building with C+GF+5 floors. The observation of the building was carried out from 25 July 2014 until 2 June 2015 in five independent geodetic measurement epochs, that is, during concreting of every other concrete slab and during the installment of finishing work elements.

Having in mind the importance, function and construction of the building and characteristics of the soil on which the building was built, an internal observation project was developed, which basically included: defining of geodetic network geometry, defining of coordinate system and geodetic network datum, defining of the type and number of measured sizes in the geometric network, defining the accuracy of measured sizes and calculation of accuracy of networks. The basic aim of the observation was to determine thevertical displacement of points on the building, the size of which was less than or equal to 1 mm [9].

Figure 3. Position of Pavilion 4 in the University City

Figure 4. Pavilion 4 - appearance of the constructed building

The geodetic control 1D network (Figure 5), intended for the observation of the vertical displacement of Pavilion 4 of the students' accommodation building, consisted of a total of 12 geodetic points. Three of those points were of the basic 1D network, and nine points were on the building. The basic 1D network points were marked by R1, R2, and R4, and the points on the building were marked by RD1-RD9. The points on the building marked by RD7, RD8 and RD9 were stabilized in the building's cellar (in the main corridor), while the remaining points on the building were stabilized on the exterior of the building into the concrete of the first concrete slab (approximately in the height of the physical soil surface). The allocation of GC1DN points had been made in such a way that the measurements in the geodetic control network were performed as soon as possible and that all possible deformations on the building were established correctly.

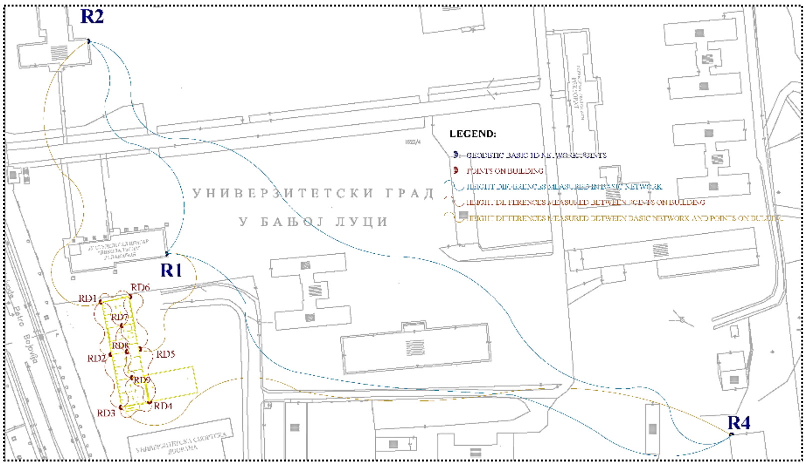


Figure 5. Sketch of the geodetic control 1D network [9]

Points on the building were stabilized with the previous consultation with the main project designer of the building and the designer of the building's construction. The materialisation of points was carried out with appropriate marks, shown in Figure 6 and Figure 7.

Figure 6. Points of geodetic basic 1D networks [9]

Figure 7. Points on the building [9]

During the final works on the building (plastering, installment of locksmiths, and façade), 6 points on the building (RD1, RD2, RD4, RD5, RD8, and RD9) were destroyed or damaged, which affected the network geometry and the observation plan in the final (fifth) epoch. The protection of the installed points on the building was a contractor's duty.

The measurement of height differences in the geodetic control 1D network was carried out under the method of precise geometric leveling. In the first four epochs, 19 height differences were measured in each epoch, while in the fifth epoch 9 height differences were measured due to the change of the network geometry. The planned measurements of height differences were carried out with the instrument Leica DNA 03, combined with a couple of fiberglass slats with the barcode division.

The point height assessment and the geodetic control 1D network accuracy assessment were obtained by the direct leveling of the measured height differences under the least squares method, by applying the Gauss-Markov model.

The GC1DN coordinate system was local, and the approximate values of point heights were obtained by adopting the value of the point height $H_{R1} = 100,000$ m and based on the value of the measured height differences. The network datum has been defined by the approximate values of the height of all network points (minimum trace on all points) and the minimal trace at the basic network points in using the Pelzer method for establishing the stability of points on the building.

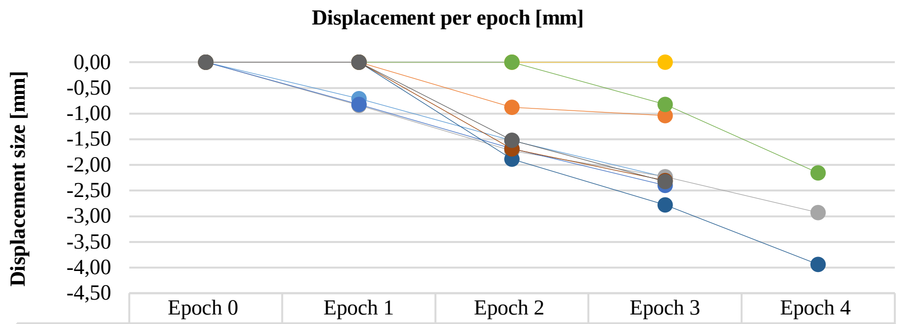
A standard deviation of height difference of 0.1 mm per station has been adopted in leveling. The assessment of standard deviation of height difference per station has been obtained on the basis of the value of height non-closing of the leveling polygon.

The network accuracy assessment has been shown through the assessment of precision measures (standard deviation of point heights), and the reliability measures (local measure of the internal reliability and the marginal gross error which can "certainly" be obtained by the data snooping test. By leveling the geodetic control 1D network per epoch, the following results have been obtained:

- Minimum value of the local measure of the internal reliability is 0.2 and maximum is 0.6, and
- Average value of the standard deviation of the height of points is 0.1 mm.

Determining the stability of the geodetic control 1D network points was performed through applying the Pelzer method. Determining the heights of the network points was conducted for all measurement epochs, separately, by direct leveling under the least squares method, with the application of the Gauss-Markov model. The datum requirement in leveling measurement epochs was defined by a minimum trace on all points, and in

application of the Pelzer method, by a minimum trace on the basic network stabile points. Based on the results obtained, it has been concluded that the GB1DN points were stable during all measurement epochs.
Conclusions on vertical displacements of the points on the building can be made based on the numerical and graphical data shown in Figure 8.



	Epoch 0	Epoch 1	Epoch 2	Epoch 3	Epoch 4
RD1	0,00	-0,71	-1,52	-2,23	
RD2	0,00	0,00	-0,88	-1,04	
RD3	0,00	-0,84	-1,72	-2,23	-2,93
RD4	0,00	0,00	0,00	0,00	
RD5	0,00	-0,82	-1,68	-2,40	
RD6	0,00	0,00	0,00	-0,82	-2,15
RD7	0,00	0,00	-1,89	-2,78	-3,94
RD8	0,00	0,00	-1,69	-2,30	
RD9	0,00	0,00	-1,52	-2,32	

Figure 8. Representation of point displacements per epoch - all points [9]

4. CONCLUSION

The successful designing of a geodetic network is possible with defining the quality criteria in cooperation with civil engineers, respecting the principles of the geodetic profession. The task of civil engineers is to define, for a particular object, the size of displacement which is necessary to be determined "with certainty" between two measurement epochs, to define characteristic points, and to define the period of measurement repetition. The quality of geodetic networks is defined by the measures of precision and reliability, and the price of the project implementation depends on the criteria set.
For the purpose of timely registering of object construction deformations for all objects, the geodetic control of geometry and testing of deformations by applying geodetic measurement methods are initiated. The project of geodetic determining of vertical displacement of objects and constructive elements should be developed in the course of developing a construction project and the project of geodetic marking. Today's trend in the area of deformation measurements, regardless of whether they are conducted during the construction or exploitation of buildings, is based on research of displacements in time and space. This approach most certainly follows the development of new measurement

methods and technologies. As a consequence, the obligation of interdisciplinary cooperation during the analysis and determining of causes and physical characteristics of observed objects emerges.

The practical application shows that the required size of displacement can be identified "with certainty," respecting the described methodology of designing and performing the geodetic determining of vertical displacement of objects during their construction.

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