STUDY OF THE STABILITY OVER TIME OF MICROTRIANGULATION NETWORK STATION POINTS, USED AS A REFERENCE SYSTEM FOR THE DETERMINATION OF THE HORIZONTAL DEFORMATIONS VECTOR OF THE STUDIED CONSTRUCTIONS

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***Abstract**: The determination of the vector of horizontal deformations of the studied constructions, subjected to a complex of static and dynamic forces, is done by several geodetic precision methods, the most used in the case of massive constructions being micro-triangulation. It also includes fixed / station points, made in non-deflecting soils and outside the area of influence of the studied construction. From these, cyclic geodesic measurements are made to the control points fixed on the construction, which change their spatial position with the construction. Based on the angular and linear cyclical measurements, the vector of the horizontal deformation at each control point on the construction is determined. In this sense, the station points must have a fixed position in space, so that the differences between the cyclical measurements to be only due to the changes in the position of the studied construction.*

In conclusion, in each observation cycle it is mandatory to check / test the stability conditions in the position of the fixed station points, against which the positions of the control points on the construction are reported. There are presented some ways to test station point stability with respect to the reference and orientation points, within the time interval between two observation cycles.

***Key words**: station points, stability, network, horizontal deformation vector, control points, construction.*

1. Introduction

All activities related to the construction and use of buildings are aimed at meeting the requirements of the beneficiaries. They can focus on three fundamental requirements: safety, comfort and economy. Buildings meet these requirements by their qualities that make them suitable for exploitation. Maintaining the ability to exploit constructions throughout their service life is ensured by monitoring their behaviour in situ, namely by tracking the evolution of their behavioural performance. This is done in order to find out the deficiencies that may arise on one hand, and the necessary maintenance and rehabilitation interventions to eliminate these deficiencies and counteract their effects, on the other. Monitoring of construction behaviour in situ must be an officialised job, managed by the public state authorities. The activities related to this profession must ensure the safety of the life and activity of the citizens of the country as well as the quality of life of the population and the protection of the environment.

When using the microtriangulation method, the determination of the vector of horizontal deformation of the control points fixed on the studied structure is performed in relation to a reference system. The microtriangulation network used to track the behaviour of an arc dam is shown in figure 1. The structure of the network includes several categories of points: control points ($P_1, P_2, ..., P_{N-1}, P_N$) fixed on the downstream face, station points *(A, B, C, D)* fixed on non-deflecting soils and outside the area of influence of the construction, reference points *(K_1, K_2, K_3, K_4)* from which possible changes in station points position can be determined and points of orientation *(O_1, O_2, O_3, O_4)* located in more remote lands with a high degree of stability.

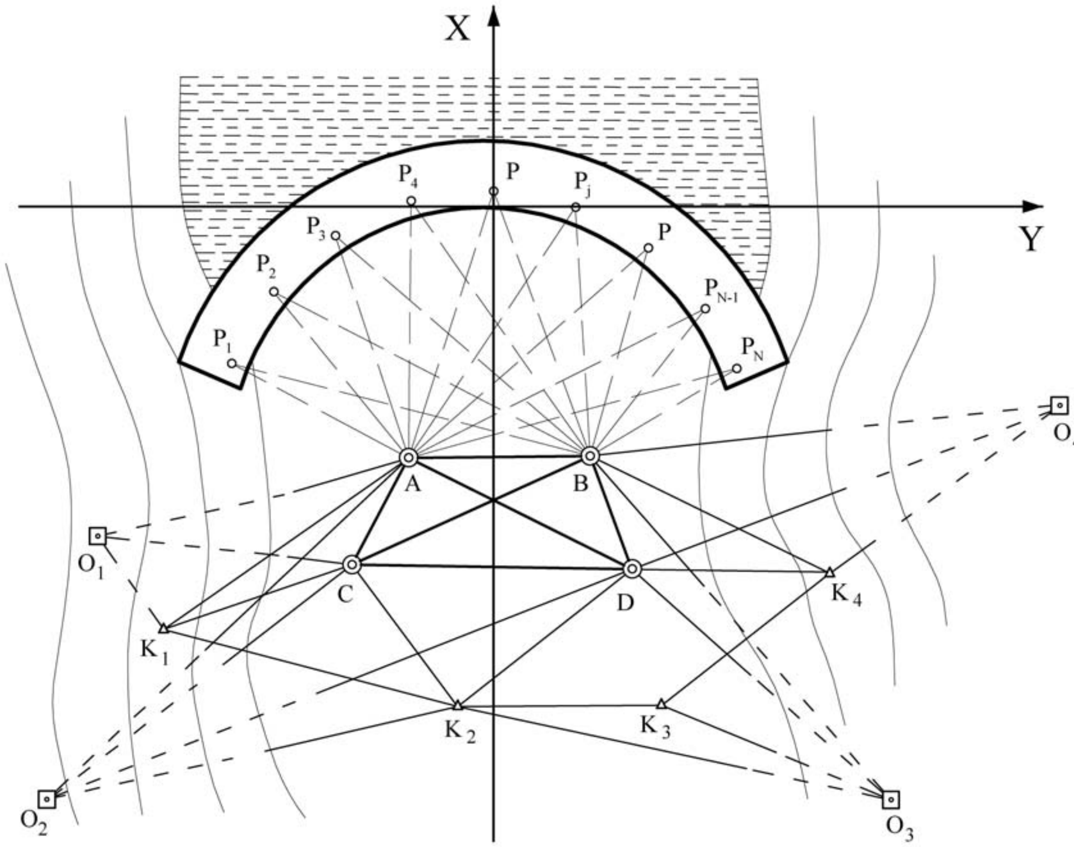

Fig. 1. Microtriangulation network

The operation of determining the horizontal deformation vector involves performing cyclic, angular and / or linear geodetic measurements in the microtriangulation network with the same precision as originally constructed (cycle 0). Adjustment calculations must be performed rigorously, using the smallest square method, in order to obtain the most probable values of the horizontal deformation vector [1,2]. The station points of the network are materialized by concrete pilasters with a deep foundation, having at the top clamping and centering parts for the theodolite / performant total station, and the reflective targets. From these points, azimuthal observations are made both to the control points fixed on the construction and to the reference and orientation points, from which possible cyclical changes in the position of the station points are determined. Recording azimuth observations for the points of the network is performed with the predetermined precision for the measurement methods used. During the measurements, all measures are taken to completely eliminate the influence of systematic errors and to minimize the influence of random errors.

When calculating horizontal deformations of structures, the angles, orientations and coordinates of the points from the initial measurement cycle become, after adjustment, reference elements against which all the elements obtained in subsequent observation cycles are related to. In each cycle, the stability in the position of the station points from which the measurements are performed shall be checked. In the case of the displacement of some of them, some corrections will be made in order to bring the azimuth observations to the original state of the undisplaced point (s).

2. Verifying the reference microtriangulation network station points stability

In each observation cycle, performed to determine the horizontal deformation vector of the studied construction, one of the most important problems is the verification of the stability conditions of the fixed station points, to which all control points embedded on the construction relate to. The fixed points network, orientation and reference, is positioned and constructed so that it is not subjected to the external influences that cause deformation or displacement of the studied structure. The correctness of the determination of the parameters characterizing the state of effort and deformation of the construction depends on the quality of the measurements in the network. In turn, the quality of the observations is influenced by the errors occurring in the case of not taking into account the displacement of the reference system, which is made up of fixed station points, leading to change / alteration of the results, therefore influencing the value and precision of the cyclical measurements, and implicitly of the final results.

Verification / testing of station points stability is done by means of measurement data, in relation to reference points and network orientation points. Corresponding to a time span between two conjugated cycles, the proof of the station points stability in relation to the other fixed points will be equal to the magnitudes of the azimuth directions (angles or sides) measured in the respective stations, equality which needs to be understood within certain limits, given by errors inherent in the measurement process.

When the displacement in plan of the fixed station points is detected, it is necessary to enter some corrections in the original adjusted data in the station. In this way, the new azimuth directions, corrected by bringing them to parallelism with the directions of the initial / zero cycle of observations, respectively at the undisplaced position of the point, will lead to the correct calculation of the horizontal deformation vector.

The initial position of the microtriangulation network station point A is considered. From it, the reference or orientation points O_i , $i = \overline{1-n}$ are targeted, by measuring the angular values of the azimuth directions α (Figure 2).

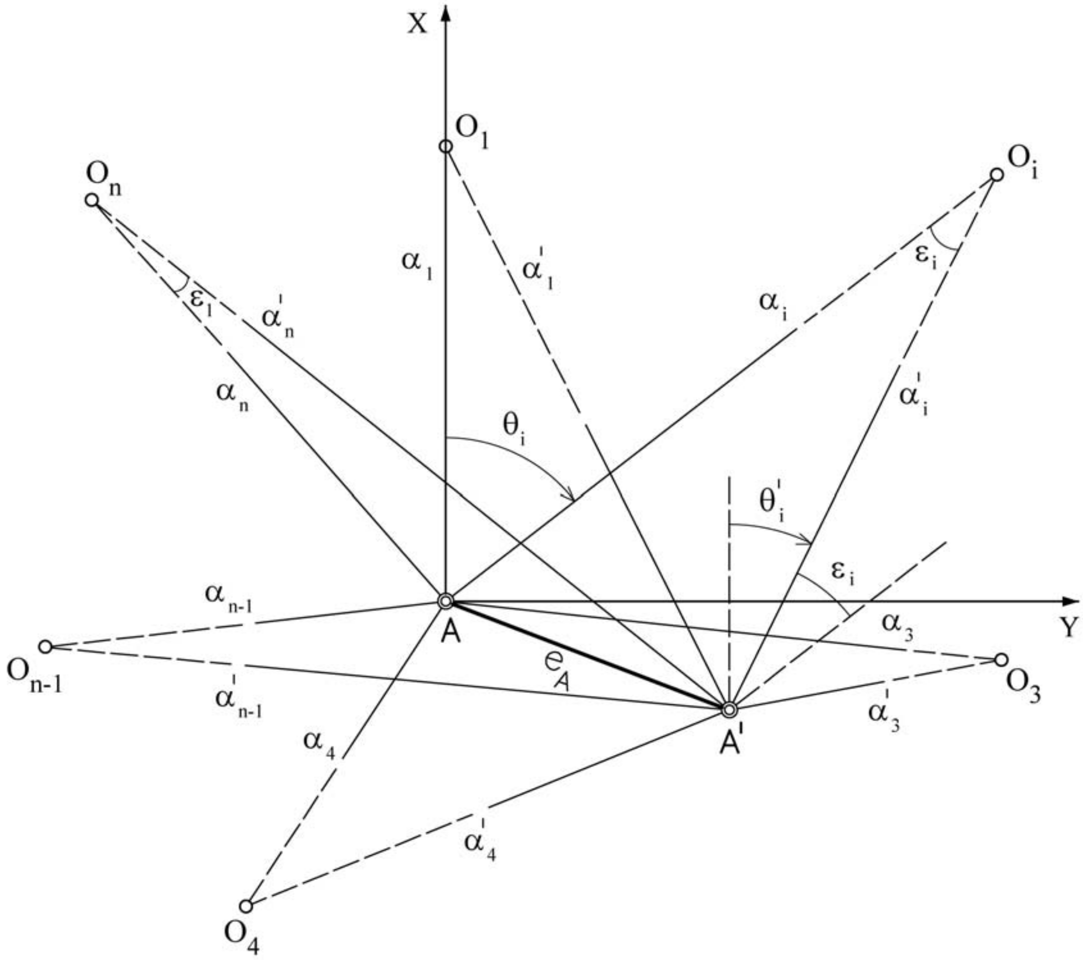

Fig. 2. The scheme of the azimuth directions measured in the two observation cycles

Subsequently, due to complex causes, the station point will move from the initial position *A* to the current position *A'*. Comparing the values of the azimuth directions from point *A* and the orientation / reference point O_i , resulted from the initial cycle α_i and the current cycle $\alpha_i^{'}$, it is found that an adjustment ε_i must be introduced in order to achieve the parallelism between the two directions.

$$\theta_i = \theta_i^{'} + \varepsilon_i \ , \ i = \overline{1-n} \tag{1}$$

To assess the stability of station point *A*, there are compared the angular values of the azimuth directions measured in the two cycles and it is determined the mean square error of the resulting differences. The size obtained is compared to a limit error, accepted according to the type of construction. If the resulting error does not fall within this limit, it means that the station point has shifted, and therefore the directions measured at the displaced point (the current cycle) must be corrected. Thus, proceed as follows:

• First, the mean square errors of the azimuth directions are measured and adjusted in the station, in the initial cycle S_α and current cycle S'_α, using the general formula [1]

$$S_\alpha = \sqrt{\frac{[dd] - \frac{1}{n}\sum_{k=1}^{t}[d]_k\,[d]_k}{t\,(t-1)\,(n-1)}}\,, \tag{2}$$

where: $d_k^{(i)}$ are the differences between the mean values and the measured and reduced values at origin, n –number of directions, t – number of measurement series ($i = \overline{1-n}$; $k = \overline{1-t}$).

• Next, the differences between the adjusted magnitudes of the azimuth directions are calculated, being measured in the current and initial cycles

$$\Delta_i = \alpha'_i - \alpha_i\ ,\ i = \overline{1-n}, \tag{3}$$

and based on them, the mean square error of a single angular difference is calculated

$$s_\Delta = \pm\sqrt{s_\alpha^2 + s_{\alpha'}^2}\ . \tag{4}$$

• The algebraic sum of the differences is calculated

$$[\Delta_i] = \Delta_1 + \Delta_2 + \ldots + \Delta_n \tag{5}$$

In the case $[\Delta_i] = 0$, it means that the differences Δ_i will be considered as random errors. If these differences contain both random errors and systematic errors due to the displacement of the station point, the algebraic sum will be different from zero, $[\Delta_i] \neq 0$. In this case, since the algebraic sum of random errors is zero, according to property II, it means that this sum can be used to define an average value of systematic errors

$$\Delta_0 = \frac{[\Delta_i]}{n} \tag{6}$$

From each difference Δ_i, which contains both types of errors, the average systematic error will be subtracted, resulting only the influence of random errors

$$\delta_i = \Delta_i - \Delta_0 \tag{7}$$

These new differences will have to meet the condition $[\delta_i] = 0$, being the differences from the average.

• The average square error of a single angular difference δ_i, depending on the deviation from the mean difference, will be

$$(s_\Delta) = \sqrt{\frac{[\delta\delta]}{n-1}}\ . \tag{8}$$

• In order to check the stability of station point A, it is calculated

$$(s_0)_{calc} = (s_0) = \frac{(s_\Delta)\sqrt{2}}{s_\Delta}\ , \tag{9}$$

the magnitude of which being compared to an admitted value (s_0), indicating whether the station point A has changed its position in plane or not. So, if

$$(s_0)_{calc} < (s_0)_{admis}\ , \tag{10}$$

means that the station point is stable, and if

$$(s_0)_{calc} > (s_0)_{admis}\ , \tag{11}$$

means that the station point has shifted between the two measurement cycles and, as a conclusion, the azimuth directions of the current cycle must be corrected.

In this sense, in the station stability assessment operation, several tests were proposed.

Thus, W. Lang proposed a simple test of assessement, based on the mean square error of the partial differences (7) and the limit error, resulted as the double average square error of the directional differences (3), according to which the inequalities would indicate:

$$(s_{\Delta}) < 2s_{\Delta} \Rightarrow \text{stable point}, \tag{12}$$

$$(s_{\Delta}) > 2s_{\Delta} \Rightarrow \text{displaced point}. \tag{13}$$

Subsequently, T. Lazzarini proposed a more complete test, expressed through inequalities:

$$(s_0) < (s_0)\, k \Rightarrow \text{stable point}, \tag{14}$$

$$(s_0) > (s_0)\, k \Rightarrow \text{displaced point}, \tag{15}$$

where:

$$k = \frac{1 \pm \dfrac{0.7071}{\sqrt{n-1}}}{1 \pm \dfrac{0.7071}{\sqrt{(n-1)(t-1)}}} . \tag{16}$$

Also for the Lazzarini test, when the error ratio (8) and (4) is approximately equal to the unit

$$\frac{(s_{\Delta})}{s_{\Delta}} \approx 1 , \tag{17}$$

then it can be appreciated that the station point has kept its position in plane, so it is stable, and the azimuth directions can be used in the calculation of the rigorous adjustment in order to determine the vector of the horizontal deformation in the control points embedded on the studied construction.

The disadvantage of these tests is that the displacement of the station point is expressed only in angular size, with no indication of the linear elements. B. Ney has developed a test that establishes the dependence of the linear deviation according to the differences in measured horizontal angles. Determination of the linear displacement according to the differences of the horizontal angles is made from two combinations, depending on the number of reference or orientation points of the network

$$r = C_n^2 = \frac{n(n-1)}{2} , \tag{18}$$

where n – number of directions. Because the horizontal angles resulted from the azimuth directions of the two cycles, β_j și $\beta_j^{'}$, are affected by inherent measurement errors

$$\beta_j = \alpha_{i+1} - \alpha_i , \ \beta_j^{'} = \alpha_{i+1}^{'} - \alpha_i^{'} , \tag{19}$$

where $i = \overline{1-n}$ și $j = \overline{1-r}$, then their differences will include both random errors and systematic errors due to the change in plan of the station point

$$\Delta\beta_j = \beta_j^{'} - \beta_j . \tag{20}$$

Based on the square average errors of the adjusted azimuth directions S_{α} and $S_{\alpha}^{'}$, the mean square errors of the horizontal angles can be calculated

$$s_{\beta} = \pm s_{\alpha}\sqrt{2}\ ,\ \ s_{\beta'} = \pm s_{\alpha'}\sqrt{2}\ , \tag{21}$$

after which the average square error of the angular differences (20), will be

$$s_{\Delta\beta} = \pm\sqrt{s_{\beta}^{2} + s_{\beta'}^{2}} \approx \pm s_{\beta}\sqrt{2} \tag{22}$$

Based on the differences between the angular values of the two cycles, the average angular difference error is calculated

$$(s_{\Delta\beta}) = \pm\sqrt{\frac{[\Delta\beta_j^2]}{r}}\ . \tag{23}$$

Based on the azimuth lengths and the angles between them, corresponding to the r combinations, the linear displacement of the station point *A* in the *A'* position is calculated using the formula

$$e_A = \frac{\sqrt{2}}{\rho^{cc}} K_A\, s^{cc}_{\Delta\beta_A}\ , \tag{24}$$

where

$$\frac{\sqrt{2}}{\rho^{cc}} = 0.0022214mm\ , \tag{25}$$

$$K_A = \sqrt{\frac{\sum_{j=1}^{r} \frac{D_{1j}^2\, D_{2j}^2}{D_{1j}^2 + D_{2j}^2 - 2D_{1j}\, D_{2j}\cos\boldsymbol{\beta}_j}}{r}} = \sqrt{\frac{[K_j^2]}{r}}\ , \tag{26}$$

$$s_{\Delta\beta_A} = \sqrt{s_{\Delta\beta}^2 - (s_{\Delta\beta})^2}\ . \tag{27}$$

The coefficient K_A is a parameter of the station point *A* of the microtriangulation network, which remains constant across all measurement cycles.

Determining the uncertainty that this movement contains (24), is done with the relation

$$s_{e_A} = \frac{e_A}{\sqrt{2(r-1)}}\ . \tag{28}$$

The testing criterion for the stability of the station point is represented by the inequality

$$e_A - s_{e_A} < (e_A) \Rightarrow \text{stable point}\ , \tag{29}$$

where the average accepted error is *$(e_A) = 0{,}3 \ldots 0{,}5$ mm*.

Considering that e_A values have a normal distribution, applying the principles of mathematical statistics, it will result

$$s'_{e_A} = s_{e_A} \cdot q_{\beta}^{(r)}\ , \tag{30}$$

where $q_{\beta}^{(r)}$ is an amplification coefficient, whose value depends on the number of measurements and the probability size, and s'_{e_A} represents the limit error. This increases the degree of uncertainty, which corresponds to practical requirements. In this way, the stability criterion of the station point will be represented by the inequality

$$e_A - s'_{e_A} < (e_A) \Rightarrow \text{stable point}. \tag{31}$$

3. Case study

The verification of the stability of a station point A of the reference network has been made in relation to the orientation points ($O_1, O_2, \ldots, O_6$) on the basis of the distances and adjusted directions obtained from the measurements made in the initial / zero and current cycles (Table 1).

Table 1. Precision measurement calculation of azimuth directions

Station point	Sighted point	Distances (m)	Adjusted directions (g c cc)	
			Initial cycle	Current cycle
A	O_1	231,425	0.00.00,0	0.00.00,0
	O_2	200,993	45.77.28,8	45.77.53,2
	O_3	261,147	75.71.27,0	75.71.57,5
	O_4	241,612	148.63.22,5	148.63.42,6
	O_5	190,335	214.75.65,7	214.75.36,3
	O_6	202,496	254.63.40,1	254.62.90,2
Average square errors			$s_\alpha = \pm 3^{cc},12$	$s'_\alpha = \pm 2^{cc},88$

The number of horizontal angles measured at the station point, corresponding to the number of points of orientation, will be (18)

$$r = C_n^2 = \frac{6(6-1)}{2} = 15$$

The horizontal angles between the two cycles β_j and β'_j will be affected by inherent measurement errors, and the differences between them (20)

$$\Delta\beta_j^{cc} = \beta'_j - \beta_j \; ; \; j = \overline{1-r} \quad ,$$

will include both errors inherent to the measurements and errors due to the influence of the station point movement. The mean square errors of the angles, depending on the adjusted directions errors, are (21):

$$s_\beta = \pm s_\alpha \sqrt{2} = \pm 4^{cc},41 \; ; \; s_{\beta'} = \pm s_{\alpha'} \sqrt{2} = \pm 4^{cc},07$$

Based on these, the *mean square error of an angular difference* (22) is calculated:

$$s_{\Delta\beta} = \pm \sqrt{s_\beta^2 + s_{\beta'}^2} = 6^{cc},00$$

Table 2 summarizes the elements required to calculate the mean square error of the measured angular difference, based on the differences between the angles from the current and initial cycles from all 15 combinations. The *mean square error of the measured angular difference* (23) is:

$$(s_{\Delta\beta}) = \pm\sqrt{\frac{[\Delta\beta_j^2]}{r}} = 46^{cc},64$$

Table 2. Mean square error of the measured angular difference calculation

Angle no.	**Combination**	**Horizontal angles** β $(g\ c\ cc)$	**Horizontal angles** β' $(g\ c\ cc)$	$\Delta\beta_j^{cc}$	$\Delta\beta_j^2$
1	1-2	45.77.28,8	45.77.53,2	27,4	750,76
2	1-3	75.71.27,0	75.71.57,5	30,5	930,25
3	1-4	148.63.22,5	148.63.42,6	20,1	404,01
…	…	…	…	…	…
15	5-6	39.87.74,4	39.87.53,9	-20,5	420,25
				$[\Delta\beta^2] = 32634,65$	

In table 3 it is presented, in part, the calculation of K_j , $j = \overline{1-r} = \overline{1-15}$ parameters, required for the calculation of the station point parameter K_A.

Table 3. Calculating the size of K_A parameter

Angle no.	**Distances** D_{1j} (m)	**Distances** D_{2j} (m)	β_j $(g\ c)$	$\cos\beta_j$	K_j^2
1	231,425	200,993	45.77	0.7525	90265.3
2	200,993	261,147	75.71	0.3724	47468.5
3	261,147	241,612	148.63	-0.6917	16445.4
…	…	…	…		…
15	190,335	202,496	39.88	0.8101	100064.7
				$[K_j^2] = 653768,3$	

Its size is given by the relation (26):

$$K_A = \sqrt{\frac{[K_j^2]}{r}} = 208,77$$

It is calculated *the mean square error of the difference in horizontal angles*, which includes only the influence of systematic errors caused by the displacement of the station point, (27):

$$s_{\Delta\beta_A} = \sqrt{s_{\Delta\beta}^2 - (s_{\Delta\beta})^2} = 46^{cc},25$$

The magnitude of the displacement of the station point, as an average of the 15 combinations, is (24):

$$e_A = \frac{\sqrt{2}}{\rho^{cc}} K_A\, s^{cc}_{\Delta\beta_A} = 21,45\,mm$$

The final evaluation of the displacement size e_A is made after considering the uncertainty it contains, given the independent determinations e_j, with relation (28):

$$s_{e_A} = \frac{e_A}{\sqrt{2(r-1)}} = \frac{21.45}{\sqrt{2(15-1)}} = 4{,}05\,mm$$

Testing the stability of station point A is done by checking the inequality (29):

$$21{,}45\,mm - 4{,}05\,mm > 0{,}3...0{,}5\,mm$$

Because $17{,}40\,mm > 0{,}3...0{,}5\,mm$, it results that the station point has moved in plane between the two observation cycles.

Applying the principle of mathematical statistics, for the amplification coefficient $q_\beta^r = 1.05$, taken from the probability table, for a number of n = 6 points and a probability P = 95%, it will result (30):

$$s'_{e_A} = s_{e_A} \cdot q_\beta^r = 4{,}05\,mm \cdot 1.05 = 4{,}25\,mm$$

On this basis, inequality (31) becomes:

$$e_A - s'_{e_A} < (e_A) \Rightarrow 21{,}45\,mm - 4{,}25\,mm > 0{,}3...0{,}5\,mm,$$

confirming the movement of the station point. In this case, it was necessary to correct the measurements of the directions measured in the current observation cycle.

4. Conclusions

The station points stability test operation, from which angular measurements are performed on the embedded / fixed control points on the studied construction, is extremely important in each observation cycle in order to obtain the most probable values of the components of the vector of deformation and displacement of the structure studied.

Based on the effected study and the practical simulation of station point displacement over time between two measurement cycles, it has been demonstrated that the most correct test criterion for station point stability is that developed by B. Ney, by establishing the linear dependence based on the differences in cyclically measured horizontal angles.

If the stability test on station points has highlighted the displacement of points, it is absolutely necessary to first calculate the adjustments which have to be applied to the measured and adjusted directions in the current cycle, in order to achieve the parallelism with the initial directions [3].

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