TESTING COORDINATES OF NETWORK CONTROL POINTS FOR MONITORING HORIZONTAL DISPLACEMENTS OF HYDROTECHNICAL CONSTRUCTIONS

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Abstract: *Monitoring the horizontal displacements of hydrotechnical constructions is performed in geodetic networks with control points which are considered fixed in relation to the various cycles of measurements. The proper determination of the horizontal displacement vectors depends directly on the stability in time of these points and also on the superior accuracy of the coordinates obtained in the initial cycle. Dragomirna dam, which is placed near Suceava city, was chosen for the current case study. The paper proposes an algorithm for testing coordinates of network control points, using statistical hypotheses, in a particular cycle of measurements chosen for research within the framework of the determination of the dam's horizontal displacement vectors.*

Keywords: *monitoring, network, displacement, dam, statistic*

1. INTRODUCTION

The activity of monitoring the displacements of constructions, regulated by law, is generally performed in our country by means of geodetic methods with results in the sequence following the adjustment of the measurements. For tracking horizontal displacements of hydrotechnical constructions in time, it is necessary to design geodetic networks whose control points require good stability throughout the period of measurement cycles. Therefore, at the beginning of each new cycle of measurements, a prior testing of the position of these points is recommended, and whenever there is a change in the operational plan, by changing either the equipment or the measurement method, there should be a test of all the coordinates of the network control points.

The objective chosen for this study was Dragomirna dam, located on the Dragomirna Brook, about 1 km upstream of Suceava City (figure1).

Figure 1- Dragomirna dam

The solid accumulation dam is made of homogeneous earth with trapezoidal cross section with berms, total land requirement width of 348 m, canopy width of 20 m and height of 21.50 m. Front sealing length is 920 m. The dam is equipped with a tower and two underground galleries, in which the exhaust pipes are located.

The water accumulation has the functions of transiting flows pumped from Suceava River to the water treatment station for drinking and industrial water supply of Suceava city and supplementation of the Suceava river flow during periods of deficiency.

2. MATERIALS AND METHODS

2.1. Geodetic monitoring equipment

Geodetic equipment used to monitor horizontal displacements of the dam is composed of 9 pilaster points (P_2,...,P_{10}), 7 points on the upstream berm (109…115), 2 points on Tower (T_1, T_2) and an azimuthal point on the downstream berm (P_{11}). Location of the geodetic equipment available for horizontal tracking of the dam is shown in Figure 2. All horizontal points are standard, with the forced centring with cylindrical hole of Φ17, 22.5 mm depth and external thread M30x1, made of bronze.

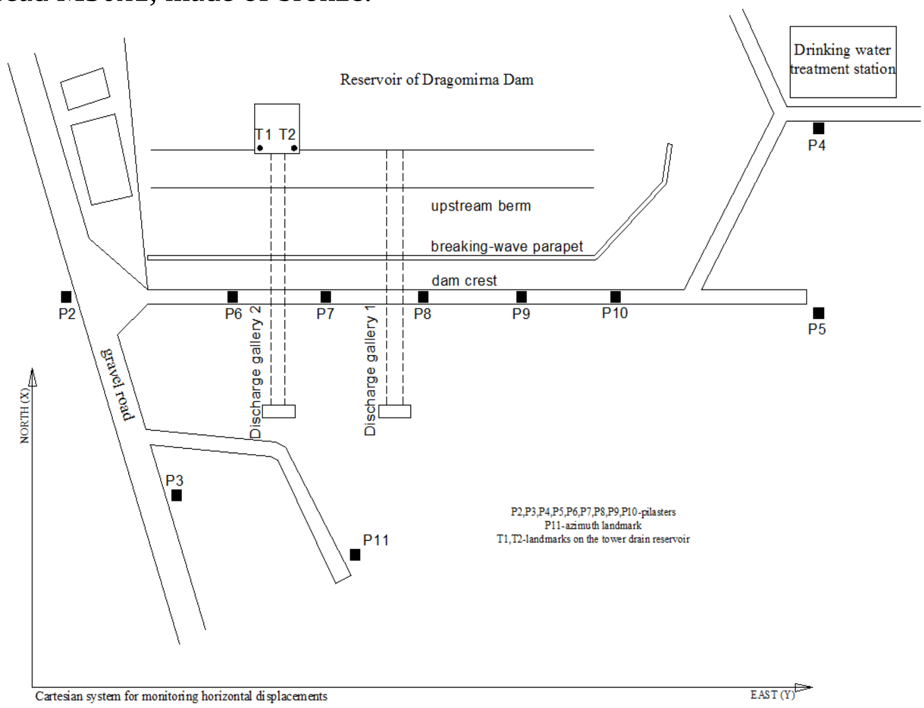

Figure 2 – Location of geodetic equipment used to monitor the horizontal displacements (Dragomirna dam)

2.2. Geodetic measurements in horizontal network

Geodetic measurements in horizontal network were made during the period 10-14.07.2010, using a theodolite Theo 010 and the method of complete series (*Popia, 2010*). The scheme of azimuthal directions measurements is shown in Figure 3. For performing azimuthal observations white conical benchmarks were used, fixed into the interior opening of the bolts with forced centring. The positioning of theodolite was performed on a special metallic turntable, screwed on the exterior threads of bolts.

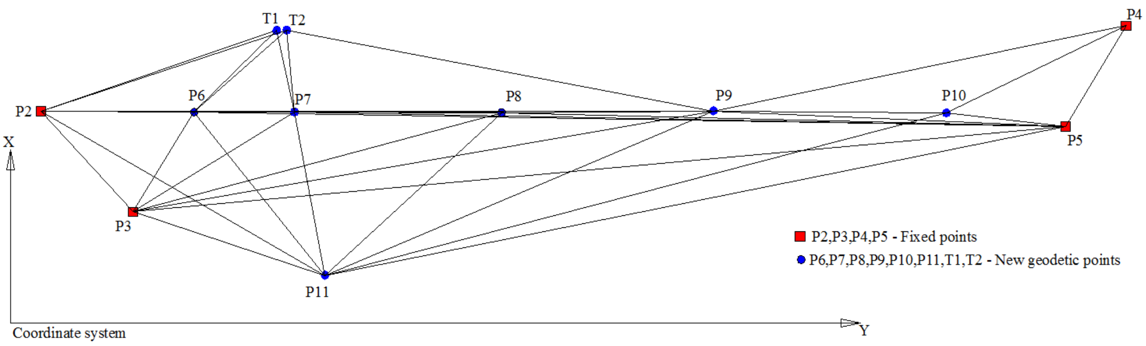

Figure 3 –Scheme of azimuthal directions measurements in horizontal network

As a result of the adjustment of measurements in the station, a standard deviation of one direction was enclosed in the range between 1 – 5^{cc}. The four border points, represented by pilasters P_2, P_3, P_4 and P_5, were considered the fixed points of the network. The horizontal rectangular coordinate system imposed for the geodetic network is a local one, with its OX axis in the direction of downstream-upstream and its OY axis in the right-left bank shore direction.

2.3. Geodetic data filtering in the adjustment of the network phase

Before adjustment of the network under various working hypotheses, measurement data need to be checked by means of a statistical analysis that would clearly point out the presence of blunders affecting negatively the final coordinates of the points. To detect these blunders, a minimally constrained network adjustment was performed, which excludes the possibility of negative influence of control points coordinates affected by errors. In this case, the only influence taken into account is the measurement at the location itself that observes the network geometry.

For statistical detection of blunders, the *Baarda model* (1948) was used, which is based on the covariance matrix of residual errors:

$$V = -Q_{vv} P \varepsilon$$

where: $Q_{vv} = P^{-1} - BQ_{xx}B^T$, with relation $B(B^T PB)^{-1} = Q_{xx}$.

From this, a standardized residual error is calculated using the diagonal element related to Q_{vv} matrix, as:

$$\overline{v_i} = \frac{v_i}{\sqrt{q_{ii}}}$$

where $\overline{v_i}$ is the standardized residual, v_i is the computed residual and q_{ii} is the diagonal element of the Q_{vv} matrix.

A statistical test t can be further defined, using a rejection level. The corresponding equation depends on S_0, which can be calculated during the final iteration of a free network adjustment:

$$\overline{v_i} = \frac{|v_i|}{\sqrt{q_{ii}}} > S_0 \cdot rejection\ level$$

Thus, for blunders detection, first of all the residual errors shall be identified, which meet the rejection criterion, the greatest error that has been detected shall be removed, then the adjustment shall be carried out again, after which the process above will be repeated until all errors are detected and eliminated.

2.4. Methods used in testing the stability of control points

In the adjustment of horizontal network, the existence of a control points displacement, but also the use of the coordinates which are affected by errors from previous cycles of measurement, lead to a negative influence upon all determinations on the network. To eliminate this influence a minimally constrained adjustment should be performed in the first phase. In this case, the reference data consist of a known point of coordinates (X, Y) and the azimuth direction. By the minimally constrained adjustment, the geometric configuration of the network, given only by angular measurements, is retained.

A second step is to perform a fully constrained network adjustment, followed by application of a statistical test to compare the reference variance obtained in the minimally and fully constrained adjustment. With the exception of any significant differences, the ratio should be 1. Otherwise, there may be two possible causes. The first cause lies in the existence of errors in the coordinates of the control points, either because of their displacements or due to previous erroneous measurements. The second cause is the existence of systematic errors in measurements.

After one considers systematic errors identified and removed from the original data, the adjustment procedure must be rebuilt. It is necessary to use different combinations of control points in partly constrained adjustments, until the problem is isolated (*Ghilani - Wolf, 2006*).

In the case study presented, testing of control points coordinates has been carried out through two complementary methods, using confidence intervals and statistical hypotheses, respectively (*Ghițău, 2009*).

To determine the confidence interval in which lies the ratio of two corresponding reference variances of selections from the data population the distribution of Fisher is used. It implies that for a confidence level (α), the values for the limit on the right and the left of the distribution should be determined. The confidence interval with a given probability, for reference variances ratio is calculated from the relation:

$$\frac{1}{F_{\alpha/2,\upsilon_1,\upsilon_2}} \cdot \frac{S_1^2}{S_2^2} < \frac{\sigma_1^2}{\sigma_2^2} < \frac{S_1^2}{S_2^2} \cdot F_{\alpha/2,\upsilon_2,\upsilon_1}$$

where:

σ_1^2, σ_2^2 - are the theoretical variances of the two selections of data population;

S_1^2, S_2^2 - are the variances derived from estimates for the two selections;

$1/F_{\alpha/2,\upsilon_1,\upsilon_2}$ - represents the critical value of F distribution, with υ_1 and υ_2, as the number of degrees of freedom for the two selections.

The method of statistical assumptions is important to clarify whether a statistical selection is consistent in relation to the entire population. On the basis of the bilateral test F, a statistical hypothesis was built in order to compare the ratio of reference variances of fully and additionally constrained network:

- The null hypothesis: H_0: $\frac{S_1^2}{S_2^2} = 1$ $(S_1^2 = S_2^2)$
- The alternative hypothesis : H_a: $\frac{S_1^2}{S_2^2} \neq 1$ $(S_1^2 \neq S_2^2)$

The statistical test that will be used to determine the rejection of the null hypothesis is:

$$F = \frac{S_1^2}{S_2^2} \text{ or } F = \frac{S_2^2}{S_1^2} \qquad F = \frac{\text{larger selection variance}}{\text{smaller selection variance}}$$

The null hypothesis should be rejected when the following condition is fulfilled:

$$F > F_{\alpha/2,\upsilon_1,\upsilon_2}$$

3. RESULTS AND DISCUSSIONS

In the case of horizontal network for monitoring Dragomirna dam, a prior adjustment as minimally constrained network was performed, choosing two fixed points (P_2 and P_3). The coordinates of these points remained unchanged in the process of adjustment. Verification of post-adjustment of the observations was performed for a rejection level of $3.29 \cdot S_0$ for blunders detection, where S_0 is the resulting standard deviation ($S_0 = \pm 0.77$).

On the basis of the report made under the programme of adjustment, it was observed that all the observations made in the network have a smaller value of the residual standard errors than the limit value calculated (2.54), and therefore do not contain blunders. By analysing the number of redundancy for each observation according to the covariance matrix of residual errors, it was found that the average amount of 0.56 observations proves that they have a high degree of internal verification. This demonstrates that there are minimal chances that the observations would contain blunders.

3.1. Testing control points coordinates using confidence intervals

For the horizontal network at Dragomirna dam the fully constrained network adjustment was first performed by indirect observations method based on a specialized program using all 4 fixed points of the network (P_2, P_3, P_4, P_5). In the final process of adjustment, the standard deviation was calculated:

$$s_0 = \sqrt{\frac{[p \cdot v \cdot v]}{r - n}}$$

where **r - n** represents the number of degrees of freedom in the network (**r** = number of equations of corrections for the measured directions and **n** = number of unknown parameters).

Then, a minimally constrained network adjustment was performed using a combination of fixed points in P_2-P_3. The mean square errors values, of reference variances and of degrees of freedom in minimally and fully constrained network, are centralized in table 1.

Table 1 - Results of minimally and fully constrained network adjustment

Type of adjustment	**Combinations**	**Standard deviation** S_0	**Number of measurements** ***r***	**Number of unknowns** ***n***	**Number of degrees of freedom** $\upsilon = r - n$	**Reference variance** S^2
Fully constrained	**P_2-P_3-P_4-P_5**	2.923074	54	25	29	8.544362
Minimally constrained	**P_2-P_3**	0.812465	54	29	25	0.660099

Next, the confidence interval of 95% probability for ratio of reference variances obtained from minimally and fully constrained network adjustment was calculated (table 2).

Table 2 - Determination of the confidence interval for the ratio of reference variances

Fully constrained network	Minimally constrained network	Ratio of reference variances S_1^2 / S_2^2	$F_{\alpha/2,\upsilon_1,\upsilon_2}$	$F_{\alpha/2,\upsilon_2,\upsilon_1}$	Confidence interval	$S_1^2 / S_2^2 = 1$
P_2-P_3-P_4-P_5	**P_2-P_3**	12.944	2.19	2.14	$[5.910; 27.725]$	No

As a result of the test carried out, one can notice that the confidence interval does not contain the value 1 with a probability of 95%, so it can be affirmed that there are discrepancies between the network and the measured elements. Because data from measurements were checked and do not contain systematic errors or blunders, is likely that displacements of control points should exist or that fixed point coordinates are not correct.

To identify control points showing displacements, an additional constraint was performed, where combinations of 3 of the 4 points of reference were considered fixed. 4 combinations (P_2-P_3-P_4, P_2-P_3-P_5, P_2-P_4-P_5, P_3-P_4-P_5) resulted, which led to confidence intervals with 95% probability for the ratio of reference variances with additional and fully constrained adjustment.

The mean square errors values, of reference variances and of degrees of freedom for each combination in the additional and fully constrained network are presented in table 3.

Table 3 - Results of additional and fully constrained network adjustment

Type of adjustment	Combinations	Standard deviation S_0	Number of measurements *r*	Number of unknowns *n*	Number of degrees of freedom $\upsilon = r - n$	Reference variance S^2
Fully constrained	**P_2-P_3-P_4-P_5**	2.923074	54	25	29	8.544362
Additional constrained	**P_2-P_3-P_4**	2.752977	54	27	27	7.578882
	P_2-P_3-P_5	3.021998	54	27	27	9.132472
	P_2-P_4-P_5	0.827207	54	27	27	0.684271
	P_3-P_4-P_5	0.859391	54	27	27	0.738553

For all the combinations taken into account, there were calculated confidence intervals for the ratio of reference variances in the case of fully constrained network and each of the cases of additional constraint. The results are presented in table 4.

Table 4 - Determination of the confidence interval for the ratio of reference variances

Fully constrained adjustment	**Additional constrained adjustment**	**Ratio of reference variances** S_1^2 / S_2^2	$F_{\alpha/2,\upsilon_1,\upsilon_2}$	$F_{\alpha/2,\upsilon_2,\upsilon_1}$	**Confidence interval**	$S_1^2 / S_2^2 = 1$
P_2-P_3-P_4-P_5	**P_2-P_3-P_4**	1.127	2.14	2.12	$[0.526; 2.390]$	Yes
	P_2-P_3-P_5	0.936	2.14	2.12	$[0.437; 1.984]$	Yes
	P_2-P_4-P_5	12.487	2.14	2.12	$[5.829; 26.473]$	No
	P_3-P_4-P_5	11.569	2.14	2.12	$[5.401; 24.527]$	No

As a result of the applied test, it is shown that confidence intervals do not contain the value 1 for the combinations *P_2-P_4-P_5* and *P_3-P_4-P_5* with a probability of 95%. This means that the selections do not behave the same way as the population and can be considered stable. For *P_2-P_3-P_4* and *P_2-P_3-P_5* combinations, the value 1 is included in the confidence interval, showing the inclusion in the population. This fact demonstrates that the common points P_2 and P_3 are moved, instead of P_4 and P_5 which are stable.

3.2. Testing control points coordinates using the statistical hypothesis method

In this case it was established a statistical test on the stability of the control points using selections of 3 points in relation to the total population of all network points.

For calculating critical values $F_{\alpha/2,\upsilon_1,\upsilon_2}$ used in the statistical test for the ratio of additionally and fully constrained network, a statistical program was used, whose results are presented in table 5.

Table 5 - Statistical test for the null hypothesis

Additional constrained network	**Fully constrained network**	**Value** F	**Critical value** $F_{\alpha/2,\upsilon_1,\upsilon_2}$	**Null hypothesis validation H_0**
P_2-P_3-P_4	**P_2-P_3-P_4-P_5**	1.127	2.14	accept
P_2-P_3-P_5		0.936	2.14	accept
P_2-P_4-P_5		12.487	2.14	reject
P_3-P_4-P_5		11.569	2.14	reject

In conclusion, due to the fact that for the last two combinations the null hypothesis is rejected, in the network there are discrepancies between the selection and the full network, which demonstrates that the selection is stable in relation to the mobile full network.

Because for the first two combinations the null hypothesis is accepted, and in these the common points are P_2 and P_3, it is very likely that they are being moved, and the P_4 and P_5 past combinations to be stable.

3.3. Determination of the displacements in the case of unstable points and final verification

For the determination of displacements of the identified control points P_2 and P_3 an adjustment was performed by indirect observations method, in which these points were considered new points, and P_4 and P_5 as old points. The differences between the old and the new coordinates of the mobile points are presented in table 6.

Table 6 - Determination of the displacements of P_2 and P_3 control points

Point	Previous coordinates		New coordinates		Coordinates differences	
	X(m)	**Y(m)**	**X(m)**	**Y(m)**	**ΔX (m)**	**ΔY (m)**
P_2	1000.000	1000.000	999.9998	999.9549	-0.0002	-0.0451
P_3	905.8662	1088.5582	905.8561	1088.5111	-0.0101	-0.0471

To verify the new coordinates of P_2 and P_3 points, a fully and minimally constrained network adjustment was performed by using the same combination of points. Applying the statistical test F was determined confidence intervals for the ratio of reference variances proper minimally and fully constrained network.

The mean square errors values, the reference variances and the degrees of freedom for the two cases are presented in table 7.

Table 7 - Results of minimally and fully constrained network adjustment

Type of adjustment	**Combinations**	**Standard deviation** S_0	**Number of measurements** ***r***	**Number of unknowns** ***n***	**Number of degrees of freedom** $\upsilon = r - n$	**Reference variance** S^2
Fully constrained	P_2-P_3-P_4-P_5	0.754377	54	25	29	0.569085
Minimally constrained	P_2-P_3	0.812466	54	29	25	0.660101

For the combination taken into account, it was calculated the confidence interval for the ratio of reference variances for the adjustment of minimally and fully constrained network. The results are presented in table 8.

Table 8 - Determination of the confidence interval for the ratio of reference variances

Fully constrained network	**Minimally constrained network**	**Ratio of reference variances** S_1^2 / S_2^2	$F_{\alpha/2,\upsilon_1,\upsilon_2}$	$F_{\alpha/2,\upsilon_2,\upsilon_1}$	**Confidence interval**	$S_1^2 / S_2^2 = 1$
P_2-P_3-P_4-P_5	P_2-P_3	0.862	2.19	2.14	$[0.394;1.845]$	Yes

As a result of the test carried out shows that the confidence interval contains the value 1 with a probability of 95%. It can be concluded that there is no discrepancy between measurements and network. It turns out that the change of P_2 and P_3 points coordinates was correctly.

4. CONCLUSIONS

Errors with different probabilities are used to evaluate the precision of the adjustment process. Frequently an error with 95% probability is used, which is the error of magnitude 2σ, that determining a confidence interval is accepted most of geodetic measurements from a set of data.

For the identification of displaced control points in geodetic networks the Fisher test is used, which allows the comparison of reference variances of some selections of points in relation to the totality of them. For a given probability, a confidence interval for the ratio of these reference variances can be determined. The same result can be obtained by completing certain statistical tests which validate the null or alternative hypothesis, depending on the critical value of the distribution F.

For the application of statistical tests in a geodetic network the next steps must be followed:

- Filter data and removing those that contain blunders and systematic errors. This can either be done in the a priori phase, by observing free terms or by checking the errors in network circuits, either in the post-adjustment phase, when the set-off must be carried out as a minimally constrained network testing residual errors of observations. For the studied horizontal network filtering data was performed in the post-adjustment phase with a level of rejection of 3.29·So.

- Testing the stability of control points, which can either be done by the method of confidence intervals, either by the method of statistical hypotheses. The adjustment for the minimally constrained network was taken into account, whose variance was compared to that of the fully constrained network adjustment. The results have shown some discrepancies due to control points coordinates, without being able to highlight at this stage which of these are affected by errors. Therefore, it was took into account the variations of adjustment as additional constrained network, which allowed determination of the displaced points. As a result, horizontal displacements were shown on the two axes of coordinates (-0.0002, 0.0451 m) at the P_2 and (-0.0101, 0.0471-m) at the P_3 benchmark.

- To verify the accuracy of the new coordinates of the two points, a fully network constrained adjustment was finally performed, which includes changes to fixed points P_2 and P_3. After adjustment the standard deviation was S_0 = 0.7544 different from the old value S_0 = 2.9231. Errors of determination for the new points have been reduced from 0.71 … 2.68 mm to 0.18 ... 0.71 mm on the X-axis and from 1.12 ... 7.36 mm to 0.36...1.90 mm on the Y axis. A final check was also achieved by the method of confidence intervals, resulting that the selections behave like the population, therefore the network can be considered stable.

For all the statistical studies carried out, specialized programmes of statistical calculation (*Stats*) and rigorous processing by the method of least squares (*Adjust*) - (*Ghilani, 2006*) were used.

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