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ORIGINAL ARTICLE

Control network reliability reconstruction for Zatonie dam

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Abstract

Absolute horizontal displacements are an important element of dam safety level assessment. Appropriate design of measurement network is a prerequisite for the acquisition of displacement values that meet the reliability requirements. A network of this kind, apart from ensuring the required precision of displacement determination, should be characterised by reliability allowing for elimination of gross errors in the results of geodetic surveys. This study aims to propose a method to improve reliability characteristic of surveying network used for horizontal displacement identification in Zatonie dam. The desired effect (increase in the network's reliability) is obtained by the authors in two stages. The first stage concerns expansion of the existing network by addition of three free stations. As the obtained effect did not prove to be satisfactory, in the second stage so called observation accuracy harmonisation was carried out, which optimally utilises the reliability potential of the measurement construction. In order to successfully carry out the harmonisation, a modification to the procedure's algorithm had to be introduced. A design of a network ensuring detection of a gross error in any given observation was obtained as the result of the performed actions.

Key words: network reliability, accuracy harmonisation, dam control network, Zatonie dam

1 Introduction

The issue of surveying a network's robustness to gross errors, also known as network reliability (Prószyński and Kwaśniak, 2002) has been of interest to researchers for half a century. Professor Baarda is regarded as the precursor of the research in this field (Baarda, 1967, 1968).

Acquisition of an appropriate level of reliability generally was not considered a priority when designing surveying networks. This approach was dictated by economic reasons (achieving the objective entailed an increase in the number of observations). A slightly better situation was observed in relation to control networks used to study displacements, where the aim was to ensure high precision and reliability for displacements of the controlled points.

The control network of the Zatonie dam located in Polish-German-Czech border region is the subject of this study. The dam was built in 1966 as a retention reservoir being a part of the water supply system for Turów, Hirschwelde and Berzdorf power plants. It is a concrete, pillar dam with an inclined upstream wall. The dam is 306 m long and its maximal damming capability is equal to 34.6 m.

The control network for the monitoring of horizontal displacements for this dam was originally designed as an angular network. With widespread use of precise electro-optical distance meters, the network was upgraded and became a linear-angular network after 1991. In 2007 the network was expanded by four control points located in the lower part of the dam and signalised with prism targets.

2 Reliability of geodetic network

The reliability of measurement network to gross errors means the ability to detect a gross error, and in turn its location through identification of the distorted observation and possibility to remove it from the set of observations. Achieving the appropriate level of network reliability is to a large extent, dependent on the number of surplus (in relation to number of unknown) observations. The variance-covariance matrix of the alignment corrections R is considered to be the numerical indicator of the network's reliability. R parameter is calculated using the formula:

$$R = I - \left(A^T PA\right)^- A^T P \quad (1)$$

where A stands for a factor matrix of observation equations, I is the identity matrix and P is the weight matrix of observations. R is an idempotent ($R = R^T R$) and singular ($det(R) = 0$) matrix. The main diagonal of the matrix is the most important from the perspective of the network's reliability analysis. Each of its elements provides an answer to the question what the reaction of a correction to the observation will be to an occurrence of a gross error in that observation. Zero value corresponds to an uncontrolled observation in explicit constructions (no surplus observations). In turn, high value of the coefficient on the matrix's main diagonal corresponds to a situation, when the observation is well controlled by other observations. A gross error in such observation will cause a reaction during alignment, in the form of an increased observation correction for the same observation. The authors, along with Prószyński (1994), assume the dependency:

$$R_{ii} > 0.5 \quad (2)$$

where R_{ii} stands for a diagonal element of reliability matrix as sufficient criterion for the reliability indicator of the observation.

3 Zatonie dam control network

The control network for horizontal displacement observation for the Zatonie dam currently consists of eight observation stations, twelve targets on the dam, and fifteen reference points. The issue of horizontal displacement observation in the Zatonie dam was the subject of a study (Odziemczyk, 2014). Placement of network points is presented in Figure 1.

Angular and linear observations are taken from stations I – VIII. Both reference points and control points are observed from each of the stations. For the majority of the points on the dam, the observations fall into the angular category. For reference points and points newly fixed on the dam, both angles and distances are measured. What is more, angles and distances to the neighbouring stations are measured as well. Points on the dam are observed from multiple stations, whereas in the case of reference points, a situation when the point is surveyed only from one station is quite common.

4 Reliability reconstruction of the control network

As in the case of control networks on water dams, the main aim of geodetic surveys is the identification of control point displacements, and the authors decided to limit the analysis to a segment of observations between the stations and control points. This objective was achieved by assuming that all of the reference points are constant.

In the initial variant corresponding to the last cycles of measurement, the network consisted of 191 observations, of which 42 were observations of control points. Mean direction measurement error equal to $\pm 15^{cc}$ and mean distance measurement error of 1 mm were used for the purpose of the calculations. Analysis of the observation reliability indicator revelled that 31 of the observations did not meet the reliability criterion expressed by formula (2). The number is made of 23 directions and 8 distance observations. In all of the cases, this concerned the observation to control points. Their placement is presented in Figure 2.

A detailed analysis revealed that two control points (3 and 9) were observed only from two stations. Observations to these points were characterised by reliability coefficient $R_{ii} = 0$.

In order to increase the reliability of the network to possible network gross errors, it was decided that reliability reconstruction would be carried out. An addition of free stations was considered to be the most effective method of reconstruction. Such stations do not require costly monumentation using concrete pillars. As for this network, since the results of surveys are adjusted using a differential method (differences of observations are adjusted instead of observations), it is advisable to retain repeatability of the stations' placement with accuracy allowing the relation between a change of the position of the instrument and the change of the direction to the nearest observed point to be treated as linear.

The addition of a free station increases the number of observations. However, this also increases the number of unknowns. The authors, according to Nowak (2013), assume that the network's global reliability characteristic does not deteriorate when the number of observations measured from a station is not smaller than the doubled number of unknowns generated through the addition of a measurement station. In the case of horizontal network, assuming measurement of directions from each station, addition of a free station generates three unknowns (dx, dy, Orientation). This implies that the minimal number of observations from a free station equals 6. They can be obtained by measurement of three points signalised by prisms (Hz and D values are measured) or six points signalised by target plates.

Methods of data processing using measured directions to stable points allowed to eliminate the impact of the orientation errors.

By analysing different variants of free station placement, an optimal one with three stations (S1, S2 and S3) was chosen. Their placement is presented in Figure 3 (blue circles).

An angle measurement from each of the free stations to nine control points on the dam, and angle and distance measurement to the remaining control points, neighbouring permanent stations, and reference points was planned.

Extension of the observation system did indeed change the structure of the network. The number of observation increased to 296, of which 93 are observations to control points. Unfortunately, despite a significant improvement of reliability indicators, 12 observations still remained insufficiently controlled, which was confirmed by their reliability indicators presented in Table 1. Those were direction observations only. The distances were mainly measured between measurement stations and were characterised by satisfactory reliability indicators. Majority of the problematic observations (11) consisted of observations to control points on the dam.

Even a brief analysis of Table 1 leads to a conclusion that the biggest number of "problematic" observations are the observations from free stations, especially the directions form S3 station. The low reliability indicator signalises a limited possibility of gross error detection in the investigated observation.

The solution to the problem of reliability deficiency for a minority sub-set of observations can be found through, so called, accuracy harmonisation proposed in the paper (Nowak, 2011). That process utilises the fact that the modification of a priori observation error also changes the reliability indicator. An increase in the observation's accuracy (decrease of the a priori error) causes a decrease in the reliability indicator, and vice

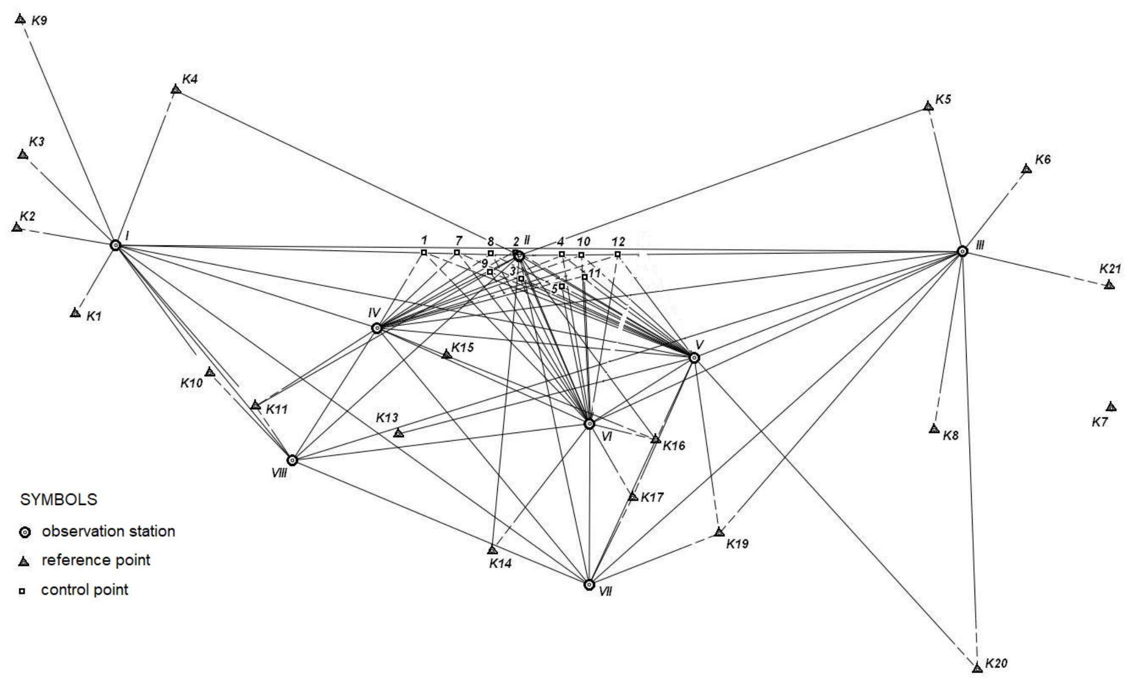

Figure 1. Study presenting points belonging to linear–angular network of the Zatonie dam (authors' own elaboration on the basis of Turów power plant materials)

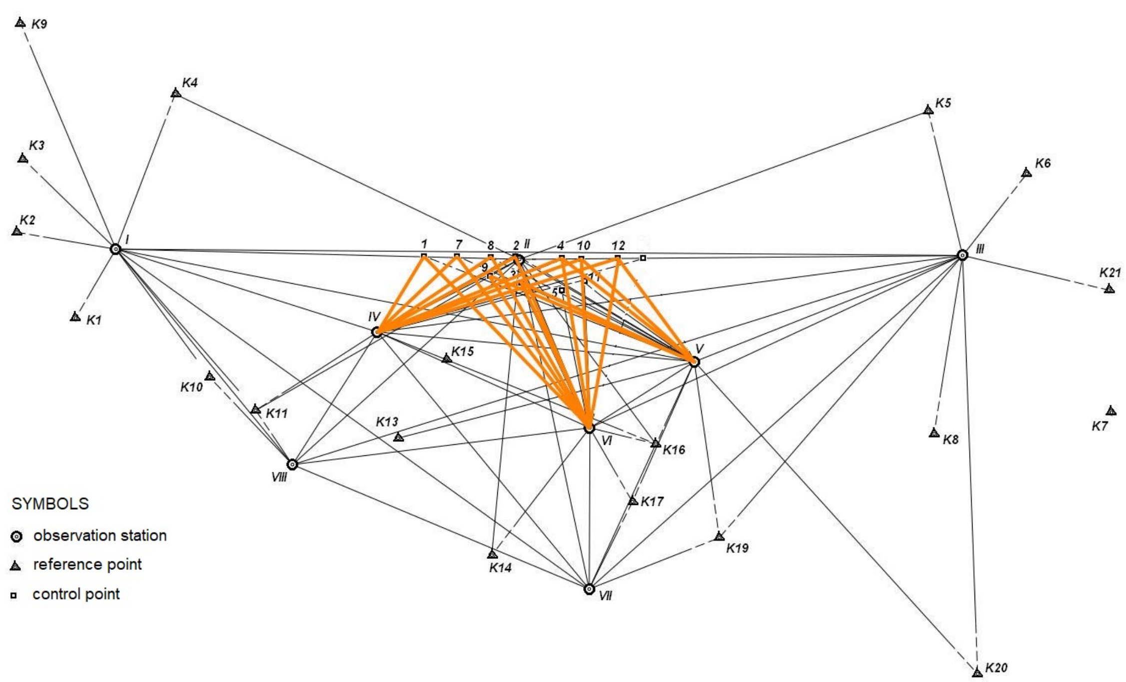

Figure 2. Placement of 31 observations not meeting the reliability criterion – initial variant (authors' own elaboration on the basis of Turów power plant materials)

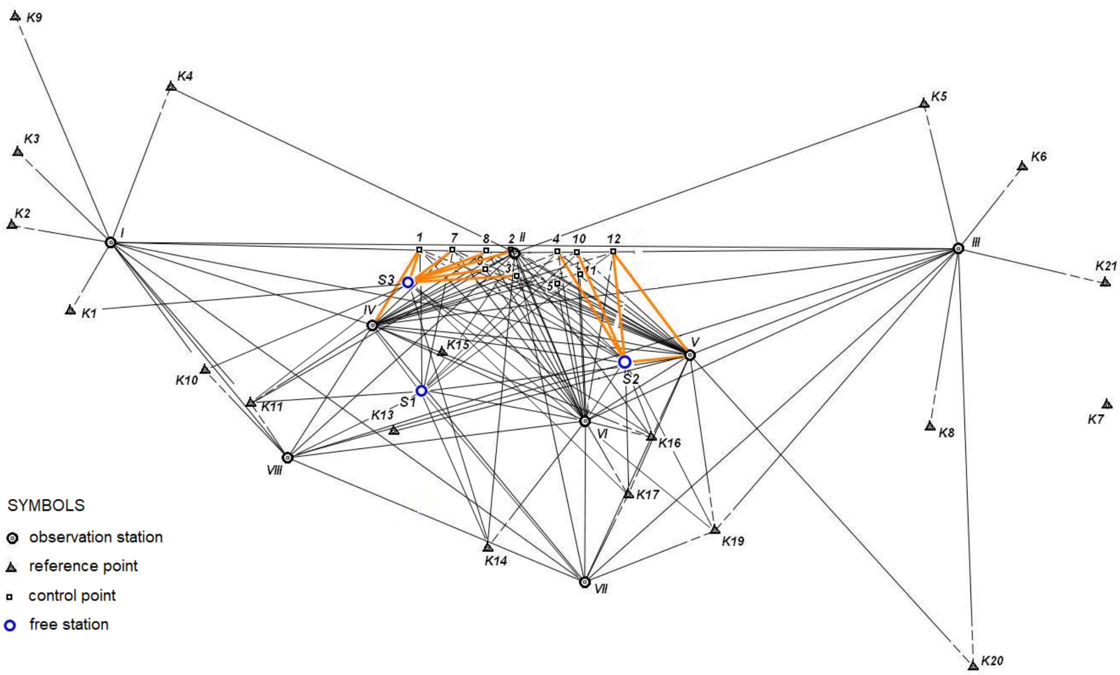

Figure 3. Placement of twelve observations not meeting the reliability criterion after the addition of three free stations (authors' own elaboration on the basis of Turów power plant materials)

Table 1. List of observations with unsatisfactory reliability indicator after the addition of free stations

Station	Target	m [cc]	R
IV	C_1	15.0	0.495
V	C12	15.0	0.463
S2	V	15.0	0.483
S2	C_4	15.0	0.490
S2	C10	15.0	0.470
S2	C12	15.0	0.466
S3	C_1	15.0	0.277
S3	C_2	15.0	0.467
S3	C_3	15.0	0.362
S3	C_7	15.0	0.325
S3	C_8	15.0	0.402
S3	C_9	15.0	0.215

Table 2. Course of network reliability reconstruction using harmonising coefficient

Iteration	Total number of $R < 0.5$ exceedances
0	12
1	10
2	7
3	7
4	5
5	3
6	4
7	4
8	4

versa weakening of observation results in an increase in the reliability indicator.

By defining:

h – standard deviation change coefficient of the i^{th} observation ($m_i' = hm_i$),
n – number of observations,
u – number of unknowns

one can formulate:

$$R_{ii}' = \frac{R_{ii}h^2}{1 - R_{ii} + R_{ii}h^2} \tag{3}$$

The h coefficient can be selected in a way that any value of R_{ii}' can be obtained. In particular case it can be an average value for the whole network ($R_{ii}' = R_{avr}$). The h coefficient can be then obtained as H:

$$H^2 = \frac{1 - R_{ii}}{R_{ii}} \frac{n - u}{u} \tag{4}$$

Then, H coefficient becomes a harmonising coefficient. Fulfilment of inequality $R_{avr} > 0.5$ is the boundary condition for the success of the harmonisation process.

In the case of the Zatonie dam's control network the addition of free stations resulted in $R_{avr} = 0.8$, which allows one to expect that the harmonisation procedure would be a success.

The adopted harmonisation algorithm modifies only the observation for which $R_{avr} > 0.5$. The modification consists in replacement of the default mean a priori observation error m_i with $m_i' = H \cdot m_i$ where H is the harmonising coefficient obtained through 4 formula. 8 iterations were carried out using this algorithm. The results are presented in Table 2.

The procedure resulted in a failure. Despite a decrease in total number of $R_{ii} < 0.5$ exceedances in the initial iterations, the 5^{th} iteration brought about stabilisation and the process of improvement stopped. After eight iterations, the procedure was terminated.

Table 3. Course of the reconstruction of the reliability network using the modified algorithm

Iteration	Total number of $R < 0.5$ exceedances
0	12
1	4
2	3
3	2
4	0

The analysis of R_{ii} reliability coefficients led to a conclusion that the cause of the procedure's failure lays in too big changes in a priori errors conditioned by the value of the harmonising coefficient obtained through 4 formula resulting from the mean value of the R_{ii} coefficient for the whole network. Observations where the R_{ii} coefficient only slightly exceeded the critical value of 0.5 where not modified in the given iteration. However, they were often influenced by the modifications in the neighbouring observations resulting in their R_{ii} obtaining values lower than 0.5 in the subsequent iteration.

In order to avoid the destructive effect of the harmonising coefficient based on Otrębski theorem and the mean value of the R_{avr} reliability coefficient, the assumptions for the iteration process were modified.

First of all, the subset of the observations subject to modification was expanded. In each and every iteration, the observations for which $R_{ii} < 0.55$ were modified. Secondly, the target reliability level was reduced from $R'_{ii} = R_{avr}$ to $R'_{ii} = 0.6$. The relative change of the a priori error for i^{th} observation is expressed by the formula 5.

$$h^2 = \frac{R'_{ii}\left(1 - R_{ii}\right)}{R_{ii}\left(1 - R'_{ii}\right)} \tag{5}$$

The course of the procedure using the modified algorithm is presented in Table 3.

It is clearly visible that only 4 iterations were necessary to complete the operation. As the result of the applied procedure, the values of a priori error obtained for each of the observation guaranteed fulfilment of the reliability condition (2). This means, that in the case of an occurrence of a single gross error in any of the observations it will reveal itself in the form of an increased alignment correction for that observation.

It has to be noted, that the success was reached by increasing mean errors of the selected observations. Changes in accuracy characteristics of the network points are the side effect of this operation. This aspect of accuracy harmonisation was not analysed in this paper. In practical case a final check is needed to ensure that the final accuracies of the network points fulfil the requirements. Another aspect of the harmonisation stems from the fact, that new (weaker) accuracies of observations de-

As the result of the undertaken measures, a successful method to improve the situation was proposed. The first stage or network reliability reconstruction focused on the addition of

termine the sensitivity of the local outlier test. Bigger mean errors of the observations imply that the outliers have to be bigger in order to be identified by the local test.

5 Concluding remarks

The control network used to monitor horizontal displacements in Zatonie is a construction characterised by unsatisfactory parameters in respect to reliability. Unfortunately, this concerns the observations to the targets located on the dam's crown, which are key to detection of dam's displacements.
free stations. This approach significantly increased the reliability, however, it did not solve all of the problems. In order to guarantee satisfactory reliability parameters for all of the observation accuracy, harmonisation was performed. A set of observation a priori errors was obtained as a result, for which the $R_{ii} > 0.5$ condition is fulfilled for all of the observations.

It has to be noted that the effect was obtained without the necessity to introduce additional modifications to the network's project. A necessity to modify the algorithm proposed in the publication (Nowak, 2011) emerged in the course of the analyses. Some values being key to the modification like target $R'_{ii} = 0.6$, as well as $R_{ii} = 0.55$, critical for selection of the observations to be modified, were defined arbitrarily. Determination of the optimal values for those parameters requires a separate study.

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