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CONTROL OF A GEODETIC 2D NETWORK FOR THE CONSTRUCTION OF A LARGE-SCALE HYDROPOWER SYSTEM USING STATIC GNSS OBSERVATIONS

Abstract:
The paper describes the methodology for controlling the consistency of the geodetic basic 2D network for the construction of a large-scale hydropower system. The research was conducted on the case study of the network for the construction of the Dabar hydroelectric power plant, in an extremely complex karst area. The network was established by GNSS measurements using the relative static positioning method, and the control epoch of measurements using the same technology and methods was performed 10 years later. The results confirm that GNSS technology can achieve millimetre accuracy of horizontal coordinates of points in the network, and that centimetre displacements can be registered based on these measurements. The methodology is based on a processing, adjustment, and estimation of the accuracy of the network in two epochs, followed by testing the homogeneity of the epochs and determining the stability of the points by applying the deformation analysis method. It was concluded that the robust IWST method is suitable for this purpose. The research has shown that complete control of the geodetic network is important for achieving continuity of geodetic works, and that a sufficient number of stable points, even in complex areas, ensures the preservation of the datum and coordinate system of the network.

Keywords: 2D network control, GNSS, IWST method, HPP Dabar, network datum

КОНТРОЛА ГЕОДЕТСКЕ 2Д МРЕЖЕ ЗА ИЗГРАДЊУ ХИДРОЕНЕРГЕТСКОГ СИСТЕМА ВЕЛИКИХ РАЗМЈЕРА КОРИШЋЕЊЕМ СТАТИЧКИХ ГНСС МЈЕРЕЊА

Сажетак:
У раду је описана методологија контроле постојаности геодетске основне 2Д мреже за изградњу хидроенергетског система великих размјера. Истраживање је спроведено на случају мреже за изградњу хидроелектране Дабар, у екстремно сложеном крашком подручју. Мрежа је успостављена ГНСС мјерењима методом релативног статичког позиционирања, а контролна епоха мјерења истом технологијом и методама изведена је 10 година касније. Резултати потврђују да се ГНСС технологијом може остварити милиметарска тачност хоризонталних координата тачака у мрежи, као и да се на основу тих мјерења могу регистровати центиметарска помјерања. Методологија се заснива на јединственој обради, изравнању и оцјени тачности мреже у двије епохе, а затим провјери хомогености епоха и утврђивање стабилности тачака примјеном метода деформационе анализе. Закључено је да је робусна IWST метода одговарајућа за ову намјену. Истраживање је показало да је потпуна контрола геодетске мреже важна за остваривање континуитета геодетских радова, као и да довољан број стабилних тачака, и у сложеним подручјима, обезбијеђује очување датума и координатног система мреже.

Кључне ријечи: контрола 2Д мреже, ГНСС, IWST метода, ХЕ Дабар, датум мреже

1. INTRODUCTION

The development of modern society places strict demands on the construction profession regarding the quality and safety of increasingly large and complex engineering structures. Consequently, the geodetic profession is constantly faced with new and more complex tasks. One of the basic tasks of engineering geodesy in the construction of engineering structures is the realization (staking out and control) of the designed geometry within the limits of defined tolerances, i.e., permissible deviations. To successfully and efficiently complete this task, it is necessary to establish and maintain a basic geodetic network for the engineering structures.

The process of establishing a basic network includes design, materialization of the network with points on the ground, performing measurements in the network, processing and analyzing measurements, and estimating the accuracy of the network. The geodetic basic network is expected to be available and stable throughout the entire construction process, and in a certain number of cases, to continue to be used as a geodetic monitoring network during the use of the engineering structures.

However, the stability of the geodetic network is disrupted by deformations of the horizontal and vertical position of the points, and these changes occur because of the action of various natural influences and human factors. Therefore, it is important to conduct complete and detailed control of the stability of all networks, to timely detect changes and perform corrections, primarily of the coordinates of the points. Such an approach ensures the continuous implementation of tasks related to the geometry of engineering structures in horizontal and vertical terms. In this way, the network is maintained, i.e., the coordinate system of the geodetic network and the entire project is preserved.

The above checks are important in networks for the construction of large and complex engineering structures and systems, especially those whose construction takes a long period of time. Also, this is especially important for networks that are materialized in geologically, geodynamically, hydrologically, and geotechnically challenging areas. Often, networks of systems with the above characteristics are made up of several levels, which further complicates the verification of the consistency of the entire network.

Current scientific knowledge and engineering practice on the control of geodetic networks treat this issue mostly through methods for identifying and quantifying the displacement of points in the corresponding coordinate systems [1], [2], [3], [4], [5]. Although these methods are widely used, their efficiency in geologically specific large-scale areas and in technologically demanding construction conditions requires additional verification of the existing methodology. Also, research is still ongoing on the possibility of applying Global Navigation Satellite Systems (GNSS) technology to establish geodetic networks of complex engineering structures, as well as on the application of deformation analysis methods to verify the stability of points in such established networks [6], [7], [8], [9], [10].

The construction of complex hydropower systems on karst terrain represents a significant engineering challenge due to the presence of caverns, underground channels, and changing groundwater levels. In such conditions, even geodetic points that are considered the "fixed basis" of the entire complex can move. Additionally, displacements can occur due to unforeseen events during mining, movement of heavy machinery, excavation of the terrain, etc. Properly and qualitatively planned network control confirms whether the points have retained their position and allows for the quantification of the changes that have occurred.

This paper investigates the methodology for controlling the geodetic basic 2D network for the construction of a complex hydropower system, where the network was established based on GNSS measurements using the relative static positioning method. The methodology is applied to the example of the Dabar hydroelectric power plant (HPP) system. At this location, which is characterized by extremely complex karst terrain, the network was initially established in 2014, but the question of its long-term geometric stability and consistency remains open. Due to the intensification of the construction works on the system facilities, in 2024, the network control was carried out according to the proposed methodology.

The research aimed to define the procedures to be applied in the process of controlling the basic networks of the above-mentioned properties. The results show that the methodology of complete control of the basic network should include a previous visual inspection of the state of the network points, performing control measurements in the network, processing of measurements, and network adjustment, as well as deformation analysis and interpretation of the registered displacements. This process also includes the estimation of new coordinates of the network points that will be used in future works on the construction of facilities that make up a unique system.

2. DATA AND METHODS

2.1. STUDY AREA – BASIC GEODETIC 2D NETWORK OF HPP DABAR SYSTEM

The research was conducted on the geodetic basic 2D network for the construction of the Dabar HPP subsystem, as a key segment of the "Gornji Horizonti" hydropower system. This system is in the southeastern part of Bosnia and Herzegovina, in the wider area of the Dabarsko polje, i.e., an area with pronounced features of deep Dinaric karst. There are numerous sinkholes, ponors, and underground watercourses, which directly affect the stability of the soil. The construction of a complex system on such terrain implies a complex technology for carrying out construction works and requires a geodetic network of prescribed accuracy and adequate geometry that enables the performance of all geodetic works during the construction of the system. The main structures of the system (Figure 1) are the concrete "Pošćenje" dam, two smaller embankment dams, the entrance building, the intake tunnel, the hydropower tunnel, the pressure pipeline, a weir with overflow chamber, and the powerhouse, all of which were constructed almost simultaneously.

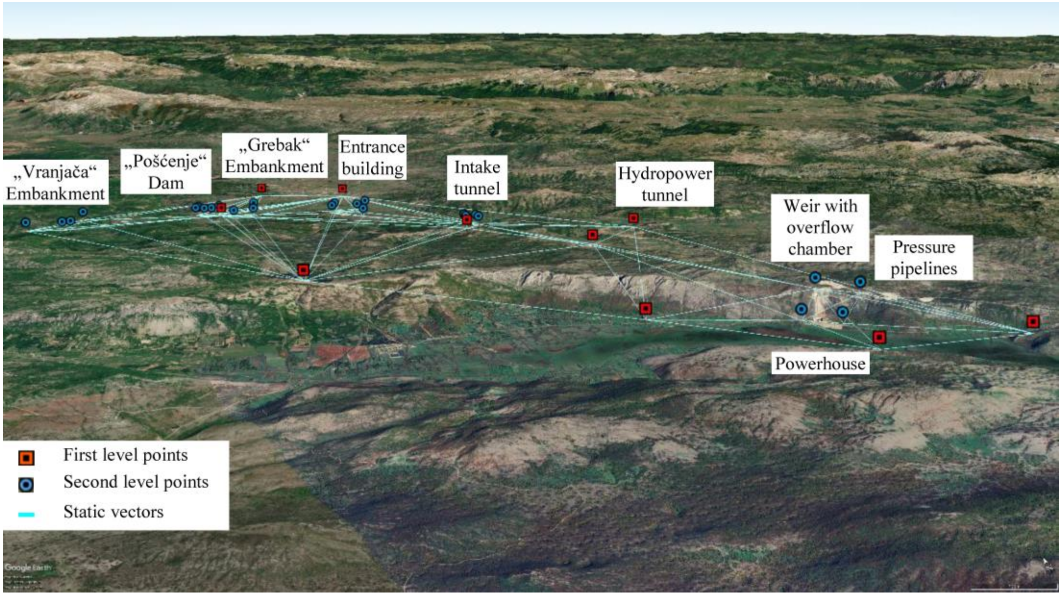

Figure 1. Spatial layout of the Dabar HPP system facilities (edited by author).

The basic geodetic 2D network (Figure 2) is intended for providing geometry and monitoring during the construction of structures in the horizontal plane. It was initially implemented in two levels. The first level, or the primary reference frame of the system, consisted of 12 points. The arrangement of this set of points was strategically planned so that they would be stabilized on stable limestone massifs, outside the zone of influence of works on the objects, and that they would encompass the entire system. This set of points represented the basis for establishing the second level of the network, which consisted of a set of 25 micro-network points of individual structures of the system. Their purpose conditioned the arrangement of this group of points; that is, it was designed to meet the needs of staking out and controlling the geometry of structures under construction, and the very difficult conditions on the terrain where they were stabilized. All points are materialized by massive geodetic pillars equipped with forced-centring devices.

As a first step in the methodology for controlling geodetic networks, a direct and detailed visual inspection of the physical condition of the network (characteristic points) in the field was proposed, along with the collection of all available information on monitoring of areas of interest by other methods (e.g., geotechnical). Direct visual inspection of the Dabar HPP network revealed that 3 points were destroyed or permanently damaged, and it was concluded that they are unusable in the network control process and future activities on the construction of system facilities.

However, considering the geometric specificity of the network, especially micro-networks, as well as the need for enough points from which to provide geometry during construction, one of the micro-network points was renovated, and new ones were added. The renovation was carried out by building a new pillar at approximately the same position, to preserve the accuracy of the network that results directly from its geometry. The changes and expansions of the network posed a challenge for the process of numerical testing of the stability of points and defining datum when estimating new coordinates.

2.2. INPUT DATA - GNSS MEASUREMENTS

The initial establishment of the network, as well as its control, was carried out based on GNSS static measurements, which are used in engineering geodesy when it is necessary to achieve millimeter precision over large distances [6]. The measured quantities that made up the input data set are base vectors (baselines) between network points, determined by the method of relative static positioning using simultaneous observations at several network points. The raw measurement results were available only for the control epoch, whereas the adjusted coordinates and accuracy of the network were available from the initial epoch of network establishment.

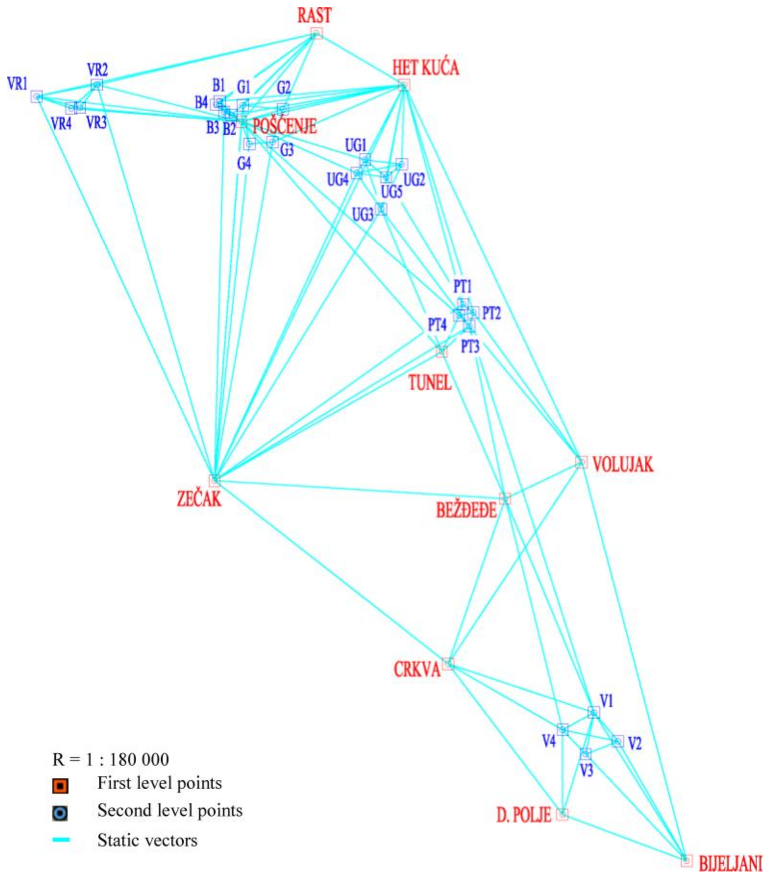

Figure 2. Sketch of the geodetic basic 2D network of the HPP Dabar system (drawing by author).

The observation plan in the control epoch was approximately the same as in the initial one. In 26 linearly independent GNSS measurement sessions, a total of 129 vectors were measured, 4 fewer than in the initial epoch. Measurements were performed with 6 receivers of the geodetic type and the same declared accuracy of 3 mm + 0.5 ppm in the horizontal sense. The minimum length of the measured vector is about 100 m, and the maximum is about 11,500 m.

Observations in the control epoch were carried out under almost the same conditions as in the initial one, to obtain homogeneous measurements and adjusted coordinates of points in both epochs. The length of each observing session is defined depending on the length of the baselines, all to minimize sources of GNSS positioning errors. The minimum duration of the session was 60 min, and the registration interval was 5 s. In order to further improve the accuracy and, above all, the reliability of the performed measurements, in the control epoch, multi-GNSS receivers were used, because the combined use of GNSS systems enables high data redundancy [11].

2.3. PROCESSING AND ANALYSIS METHODS

2.3.1. Preprocessing and analysis of GNSS measurements in the network

The theory of basic mathematical processing of GNSS measurement results involves determining integer values of phase ambiguity of double phase differences, based on simultaneous measurements from the end points of the vector [12]. The basic processing provides estimates of the vector components along the coordinate axes of the WGS84 system, as well as estimates of the standard deviations of these vector components. Also, from this process, the covariance matrices of vector components are estimated as the basis for forming a stochastic model in least squares (LS) adjustment of GNSS measurements.

A special challenge for the basic mathematical processing of vectors in networks of hydropower complexes with the characteristics of the research area is the factors that degrade the quality of GNSS signals. These are primarily the obscuration of the horizon and the occurrence of multipath [11].

After the basic processing of vectors, and before the indirect adjustment that gives them full application in geodetic networks, their quality is controlled by forming loops. The formation of loops is a reliable method for checking the existence of gross and systematic errors in determining the components of basis vectors.

2.3.2. Adjustment of the network and estimation of quality criteria

The coordinates of the network points, as well as the quality criteria, are obtained by adjusting the network using the mathematical model of LS adjustment of GNSS vectors using the least squares method [13], [14]. The stochastic model is formulated as a quasi-diagonal hypermatrix composed of individual covariance matrices of GNSS vectors, obtained in the basic processing.

The datum of the network is defined according to the purpose of the network. However, in the first adjustment iteration of the processed and analyzed measurements, the datum is defined by minimizing the trace of the cofactor matrix of all points (inner constrained) to preserve the mathematical consistency of the network achieved by the measurements, within the limits of their accuracy. In this way, maximum internal quality of the network is achieved, since no point coordinates are fixed and no errors from external datum parameters are propagated into the adjustment. The final datum definition in the control of geodetic networks of engineering structures is defined by minimizing the part of the trace of the cofactor matrix of unknown parameters, namely the part that refers to stable points in the network.

After estimating the basic parameters of the indirect adjustment model, immediately before estimating the accuracy criteria, it is necessary to check the consistency of the model by applying a global test based on χ^2 distribution (Chi-square test). For individual control of each GNSS vector, if the global test shows that the model is not adequate, Data Snooping, Barda's, or Pope's test is applied [14]. These methods identify potential "outliers" resulting from some of the possible sources of errors based on standardized corrections, thus preserving the integrity of the network by individually eliminating bad measurements.

The geometric quality of the network is estimated by analyzing the internal reliability of individual measurements, with high values of the measures used to describe them indicating good geometric quality of the network [13]. The final indicators of network quality, which are important for the conducted research, are the ellipses of point position errors. They describe the precision of the position of each point in the 2D plane. The elongation of the ellipse precisely detects the directions of geometric weakness of the network, which is crucial for controlling the change of point coordinates [7], [15].

The coordinates and accuracy of the network from GNSS measurements are primarily estimated in a spatial rectangular geocentric system. On the other hand, for the establishment of geodetic networks in engineering geodesy using GNSS technology and associated methods, primarily due to the accuracy that can be achieved, only two-dimensional coordinates in the plane of the selected projection are determined. Such is the case for the geodetic basic 2D network used in the research. The above approach imposes the need for a coordinate transformation between global and local systems. Given that the target projection plane is most often the projection plane of the state territory, it is common to use the Helmert seven-parameter similarity transformation, also known as the datum transformation.

2.3.3. Point stability testing and displacement quantification

One of the key steps in the process of geodetic network control is determining the stability of network points or quantifying the displacement of unstable points. For the control of networks used during the construction of engineering structures, the same methods of deformation analysis can be applied as in networks whose purpose is exclusively geodetic monitoring.

Based on previous research [1], [2], [3], [4], [5], it was concluded that robust methods are appropriate for determining the stability of points in basic networks. The application of deformation analysis methods sometimes requires re-adjustment or reconciliation of estimates from the initial and current epochs of measurement in terms of datum definitions.

One of the most advanced known and implemented methods for point stability analysis is the Iterative Weighted Similarity Test (IWST). The procedure for determining deformations using the IWST algorithm has several steps. In the first step, the displacement vector between the initial and current epochs is calculated:

$$\mathbf{d\hat{x}} = \mathbf{\hat{x}_i} - \mathbf{\hat{x}_0} \tag{1}$$

and the corresponding cofactor matrix:

$$\mathbf{Q}_{d\hat{x}} = \mathbf{Q}_{\hat{x}_i} + \mathbf{Q}_{\hat{x}_0} \tag{2}$$

where the data in both epochs must refer to the same datum. If this is not the case, the S transformation is applied

$$\mathbf{d}_{k+1} = \left[\mathbf{I} - \mathbf{G}\left(\mathbf{G}^T\mathbf{W}_k\mathbf{G}\right)^{-1}\mathbf{G}^T\mathbf{W}_k\right]\mathbf{d}_k = \mathbf{S}_k\mathbf{d}_k \tag{3}$$

$$\mathbf{Q}_{d_{k+1}} = \mathbf{S}\mathbf{Q}_{d_k}\mathbf{S}^T \tag{4}$$

which reduces the epoch of interest to a common datum, where:

d – displacement vector for *k* and *k+1* iterations,

I – identity matrix,

k – number of iterations,

S – transformation matrix,

W – displacement weight matrix and

G – inner constraint matrix.

The initial matrix of weights of calculated displacements **W** is taken as the unit matrix $\mathbf{W^0=I}$, while in subsequent iterations, the matrix of weights of calculated displacements **W** changes to:

$$\mathbf{W}_{k+1} = diag\left[1/\mathbf{d}_k + c\right] \tag{5}$$

where *c* (0.0001 mm) is a small-valued constant that prevents zero from appearing in the denominator [3],[5],[8].

The procedure continues iteratively until a difference is obtained $\left|\mathbf{d}_{k+1} - \mathbf{d}_k\right| < 0.1$ mm [8].

The stability of points in individual iterations is checked by applying the global congruency test, which is based on the test statistics:

$$\frac{\mathbf{d}_{\hat{x}}^T\mathbf{Q}_d^+\mathbf{d}_{\hat{x}}}{h\sigma_0^2} \approx F_{h,f,\alpha} \tag{6}$$

were, in addition to the difference vectors $d\hat{x}$

$\mathbf{Q}_d^+$ - pseudo-inverse matrix,

$\sigma_0^2 = \dfrac{f_1\sigma_1^2 + f_2\sigma_2^2}{f_1 + f_2}$ - combined dispersion factors of the current and initial epochs,

f_1 and f_2 - numbers of degrees of freedom from the initial and current epoch,

σ_1^2 and σ_2^2 - dispersion factors from the initial and current epochs,

h – rank of the cofactor matrix, and

α - significance level.

If the test statistic is less than the defined criterion, there are no significantly displaced points, and the process is terminated, concluding that all points are consistent between the two epochs. If the test statistics are greater than the criterion, this means that there are statistically significantly displaced points. In both cases, conclusions are drawn based on the achieved accuracy of the realized epochs of measurements in the network. Then, the significantly displaced point (with the largest deviation) is identified and excluded from the testing process as an unstable point. Then, the process is iteratively continued for the remaining points of the network until the condition is met that the test statistic is less than the expected quantile value.

After determining unstable points, it is necessary to quantify the registered displacements. The components of interest are the displacement magnitudes along the axes of the selected coordinate system, the magnitudes of the total displacement vectors, as well as the orientation of the total displacement vectors.

The displacement vector **d** from the last iteration, and the cofactor displacement matrix $\mathbf{Q}_d^+$ from the last iteration are used to localize deformations, i.e., to determine the stability of geodetic network points. However, in the case of geodetic networks where GNSS baseline vectors are observed, some authors recommend transforming the displacement vector and the cofactor matrix from a rectangular geocentric coordinate system to a local projected coordinate system [8]. The first reason is that displacement results are expressed in directions that are realistic and easier to interpret. The second reason is the need to separate horizontal and vertical analyses due to the significant difference in accuracy, as the precision of GNSS measurements in the vertical component is approximately three times worse than that in the horizontal component. Bearing in mind that, during the measurements, attention was focused exclusively on horizontal positioning, this approach was also adopted in this research.

3. RESULTS AND DISCUSSION

A strict analysis of the quality of the collected data (RINEX files) treated the existence of degrading factors of the GNSS signal, and it was determined that their influence is not significant, that is, that they can be ignored in further processing. All vectors were processed using a precise ephemeris. Basic mathematical processing yielded spatial components of the base vectors with internal accuracy shown in Table 1.

Table 1. Internal accuracy of measured basis vectors

Baseline precision	$\sigma_{\Delta X}$ **[mm]**	$\sigma_{\Delta Y}$ **[mm]**	$\sigma_{\Delta Z}$ **[mm]**
Min	0.1	0.1	0.1
Max	15.0	9.0	14.7
Average	**0.2**	**0.1**	**0.2**

After the basic processing of the vectors, their quality was checked by forming loops. The processed vectors were included in the loops, and the misclosures along the coordinate axes were calculated in the spatial and then in the horizontal and vertical sense. Based on the results obtained (Table 2), it was concluded that there were no gross errors and that the quality of the GNSS measurements performed was high.

Table 2. Loops and misclosures from GNSS vectors

Misclosures	**X [mm]**	**Y [mm]**	**Z [mm]**	**XYZ [mm]**	**Length [m]**	**PPM**	**Ratio**
Min	-29	-16	-20	1	747.2	0.2	1/5646638
Max	34	26	30	41	24410.7	11.4	1/87399
Average	1	2	1	13	10865.3	1.9	1/521947

After it was confirmed by misclosures of the loops and consistency control that there were no gross and systematic errors in the measurements, the GNSS vector network was adjusted using the mathematical model of LS adjustment using the least squares method. The datum of the network was initially defined by minimizing the trace of the cofactor matrix of all network points, whereby the estimated coordinates from the initial epoch were adopted for the values of the approximate coordinates of the points. Both levels of the network are adjusted simultaneously, in a unique coordinate system.

After the indirect adjustment of the network was carried out, the adequacy of the applied model was confirmed by a global test, the most important results of which are shown in Table 3. The null hypothesis that the variations in the observations are exclusively random in nature was tested.

Table 3. Chi-Square Test (95.0%)

Degrees of freedom:	672
Optimization criterion $v^T Pv$	611.20069
σ a-posteriori:	0.95
Critical value lower bound:	0.90
Critical value upper bound:	1.11
Chi-Square Test:	0.91

The results showed high consistency of measurements with the adopted mathematical model, and it was confirmed that the stochastic model adequately describes the measurement conditions in the field. Also, the test confirmed that the performed adjustment provides precise and reliable estimates of the point coordinates.

Considering that the results in the initial epoch were transformed into the Gauss–Krüger projection plane, and that the measurements were focused exclusively on horizontal positioning, the results of the control epoch were transformed using the same set of datum transformation parameters. These parameters were identical to those applied during the initial establishment of the network. After the transformation, the estimated quality criteria in the control epoch were analyzed, and it was concluded that they are similar, even better than in the initial epoch.

The accuracy of the network is expressed by the standard deviations of the point positions along the coordinate axes and the total standard deviation in the horizontal plane of the Gauss–Krüger projection (Table 4).

Table 4. Standard deviation of point positions

Standard deviation	$\sigma_{Y_{DKS}}$ **[mm]**	$\sigma_{X_{DKS}}$ **[mm]**	$\sigma_{P_{YX-DKS}}$ **[mm]**
min	1.0	1.0	1.0
max	6.9	6.9	9.7
average	**2.9**	**2.9**	**4.1**

The accuracy of the coordinates was estimated through the parameters of the error ellipses for a confidence level of 95%. The maximum values of the semi-major axes of the error ellipses at the most distant points are 17 mm, indicating excellent network homogeneity despite the large inter-point distances and the extent of the area.

Internal reliability analysis after adjustment resulted in a high average redundancy value of 88, which confirms that the geometric configuration of the network had sufficient "power" to absorb and detect possible systematic errors caused primarily by multipath or atmospheric influences.

The main objective of the research, which refers to determining the stability of the geodetic network points in the horizontal sense, was realized through a rigorous comparison of the coordinates of the current and zero epochs using a robust method. The focus was placed on the IWST deformation analysis procedure, which determines whether the reference frame has remained unchanged in time.

Bearing in mind the number of 2D network points in the initial and control epoch, as well as the fact that only the results of network adjustment were available from the initial epoch, the datum parameters were harmonized, as foreseen by the IWST method. The datum of the network in the two epochs is agreed on the points of the network determined and remaining from the initial establishment of the network. Previously, in adjustment, the estimated coordinates from the initial epoch were used as approximate coordinates of the points. In this way, the connection with the initial (zero) epoch is maintained, and the corrections (increments) of the coordinates are at the same time the displacement vector components that are determined.

The displacement vectors (Figure 3) were subjected to statistical significance testing to determine whether the observed differences were the result of actual displacement of the points or were generated by random measurement errors and adjustment.

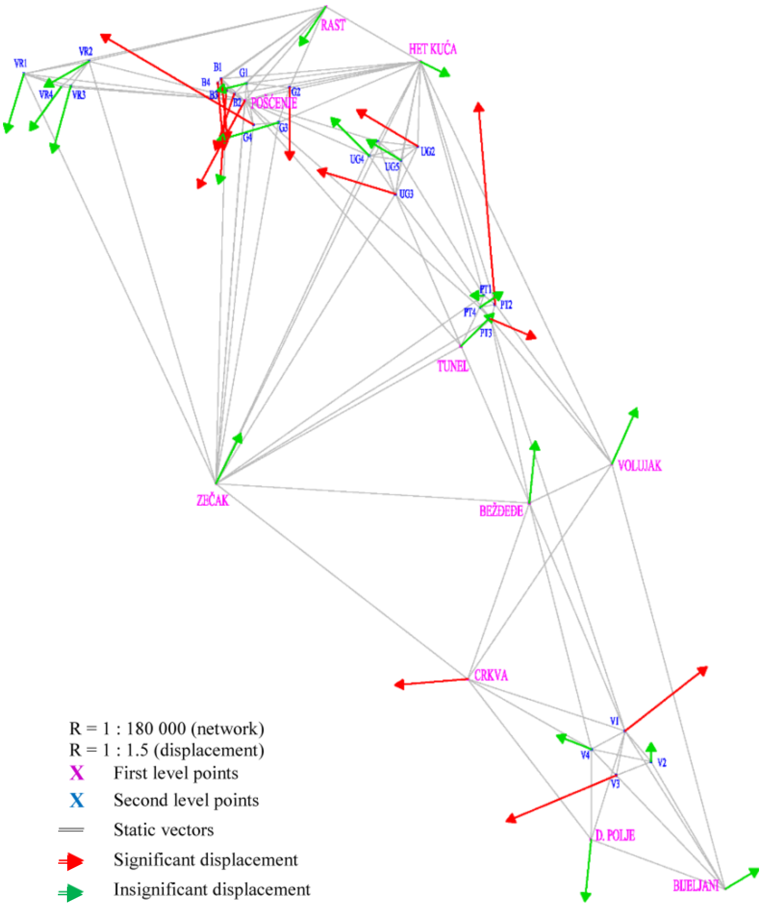

Figure 3. Displacement vectors of points of the geodetic basic 2D network of the Dabar HPP system

Summary results of registered displacements based on the comparison of two epochs are given in Table 5. The data refers to both network levels, i.e., to all points that were found to have been statistically significantly moved.

Table 5. Summary results of registered displacements of points of the basic 2D network

Registered displacements	d_Y **[mm]**	d_X **[mm]**	$d_{P_{YX}}$ **[mm]**
min	-27.0	-16.0	1.0
max	14.0	16.0	31.4
average	**-2.9**	**-1.3**	**10.1**

Based on the data obtained, it was concluded that in the group of primary level points, two out of ten points were statistically significantly moved. The maximum displacement along the coordinate axes is 15 mm, while the maximum intensity of the total displacement vector is 17 mm. By analyzing all available data on possible causes of displacement, it was concluded that the registered displacements are most likely the result of tectonic changes in the area that occurred in the 10 years between the control and initial epochs.

For the group of second-level points, i.e., points near characteristic structures of the system, it was concluded that 13 out of 24 points were statistically significantly moved. The maximum displacement along the coordinate axes is 27 mm, while the maximum intensity of the total displacement vector is 31 mm. The displacements registered in this set of points are primarily the result of the impact of the construction works and the occurrence of local terrain instability at the places where they were performed.

For those points in the network where the statistical significance of the differences in coordinates has not been established, the registered displacements are considered to be solely the consequences of random variations and not physical displacements of the points in space. The confirmed stability of a large number of points of the geodetic basic 2D network provided a reliable basis for the continuity of the geometric accuracy of the construction works that will be performed in the future, in relation to the previously performed works and the expected tolerances of the works.

The final step in the process of controlling the geodetic basic 2D network was the calculation of new coordinates of network points that will be used in all future activities on the construction of the system's facilities and their structural parts. The existing datum definition, preserved by a large number of stable points, was transferred to the coordinates of the renewed and newly established network points by defining the datum in the final adjustment using the minimum trace condition applied to all stable points.

4. CONCLUSION

The research conducted confirmed that the proposed methodology for controlling the basic 2D network of HPP Dabar can generally be used to verify the long-term stability of geodetic networks in extremely complex karst terrains and in technologically demanding conditions for the construction of large-scale engineering structures. The methodology is based on processing, adjustment, and estimation of the accuracy of the network in two independent but homogeneous epochs. Then, the stability of the points is determined using deformation analysis methods. It is concluded that the robust IWST method is suitable for this purpose.

The results confirm that GNSS technology can achieve millimetre-level accuracy of horizontal coordinates even in large-area networks, and centimetre displacements can be registered based on these measurements. The confirmed stability of a large number of points of the geodetic basic network gave the possibility of long-term preservation of the continuity of the reference frame of the engineering complex. The results also indicate that control of the basic network should include the estimation of updated point coordinates to be used in future construction works within the system.

The research conclusions contribute to the improvement of the geodetic network control methodology for future capital infrastructure facilities in the region, stressing that control must be carried out continuously, in accordance with the duration of construction, as well as with any significant changes that may occur in the meantime. Also, the importance of comprehensive and systematic documentation of each phase of network establishment and control, which includes the original measurement results and all relevant metadata, is emphasized to ensure their reuse, independent verification, and eventual reinterpretation of the results.

For future research, the question of providing a unique datum and coordinate system of the network remains open in case it is shown that a smaller number of points of the existing network are stable or that all points are unstable. Also, it is necessary to investigate the possibility of additional verification of the state of the network by independent access. One possible approach is to verify the accuracy of GNSS measurements and strengthen the relative geometry between points by additional total station observations in parts of the network where a line of sight between points is available.

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