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DNISTER PSPP CONTROL GNSS NETWORK OPTIMIZATION

Goal. The development of conceptual frameworks and proposals to optimize the geometry of Dnister PSPP control GNSS network and to identify ways to improve the accuracy of GNSS measurements. **Methodology**. To select optimal geometric deployment of new and to clarify the position of existing points of Dnister PSPP control GNSS network it was developed a special methodology of optimizing the geometric configuration of the network. It foresees detecting of points position at which the value of optimization criteria will be minimal. As optimization criterion it was used the determinant of covariance matrix. **Results**. A methodology for optimizing the geometric network configuration using mathematical modeling was devised. As a result of the in-field inspection of points as well as detailed analysis conducted and processed measurements there were highlighted three key challenging groups of points of Dnister PSPP control GNSS network: points with poor reception of satellite signal; points centered using a tripod; points damaged during construction works. In order to improve rigidity and accuracy of Dnister PSPP control GNSS network it is necessary: to exclude the application of 4 GNSS measuring points (Portal-2, Nyzhniy, OZS-1-1 and OZS-23-2); to strengthen 4 points (GZ-10, GZ-11A, GZ-11B and GZ-12) with joint satellite angular and linear measurements; to replace 4 existing points (PP-221, PP-100, Obryv and OGZ-1) and set new 4 points (GZ-21, GZ-22, GZ-23 and GZ-24). To install the new points four areas were determined and they need monitoring. Optimization of Dnister PSPP control GNSS network using the devised methodology resulted in improved accuracy (by 8.3-10.0 %) depending on the amount of used GNSS receivers. **Scientific novelty and practical significance**. A new methodology of optimizing the geometric network configuration using mathematical modeling is proposed. Using this methodology Dnister PSPP control GNSS network was optimized. The methodology can also be applied to optimize other geodetic monitoring networks.

Key words: optimization; D -criterion, GNSS network, the geometric configuration of Dnister PSPP control GNSS network.

Introduction

In 2003 to support construction and observation of strains slopes near major hydropower plants was created Dnister PSPP control GNSS network. The network consisted of 15 points, conventionally divided into a framework and a working network, which respectively included 7 and 8 points [Tretyak, 2012; Sidorov, 2015]. Since 2004 periodic static satellite measurements (seasonal cycle) are conducted using the network points. The analysis and processing of measured data revealed that the mean square error (MSE) of determining the coordinates do not exceed 2 mm – for forced centering points and 3 mm – for points centered from a tripod [Tretyak, 2012]. This methodology is considered to be a classic one in satellite measurements, which foresee simultaneous measuring between two or more fixed GNSS receivers. Duration of observations depends on the length of the measured lines, while the number of visible satellites, types of receivers and the required accuracy. This methodology is widely used to monitor a number of Ukrainian HPPs such as Kyiv HPP (2003, 2004 – Ukrynzhheodezyya 2009 – PE “InjGeo”); Kaniv HPP (May, October 2007, 2010 – NU “LP”); Kremenchug HPP (2000, 2001 – Ukrynzhheodezyya, 2007 – NU”LP”); Dniprodzerzhynsk HPP (May, October, 2007 – NU “LP”); Dnipro HPP (1997 (2 cycles) – Ukrynzhheodezyya, 2005, 2010 – NU “LP”) [Bisovetskiy, 2011]. It should be noted that for these objects during the period of observations the accuracy of the horizontal displacement was 2 mm, and vertical – 3 mm. In [GPS Technology Used in Three Gorges Reservoir Landslide Deformation Monitoring, Liu et al., 2008] it is described the way of using this methodology to monitor displacement at the world's most powerful Three Gorges HPP (China). The use of static methodology provided the coordinates accuracy of 1 mm.

The analysis confirms the feasibility of multiday satellite measurements and their subsequent post-processing via specialized software. However, the use of this observation methodology imposes certain requirements on the geometry of the network, the quality of geodetic points setting and their afield location.

Dnister PSPP control GNSS network was expanded and refined during the station construction (Fig. 1), so now there are 43 observation points within the studied area [Duma, 2016].

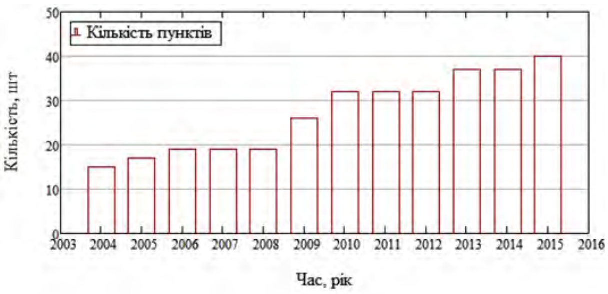


Fig. 1. Refining and expanding of Dnister PSPP control GNSS network

However, the process of refinement and expansion of Dnister PSPP control GNSS network was conducted without the design and optimization methodology. The result is that this network is significantly extended northward along the Dnister and is not balanced; the density of points is not uniform; a significant number of points are weak due to poor satellites visibility in particular. In this regard, for qualitative detection and consideration of the impact produced by these factors Dnister PSPP control GNSS network requires periodical analysis of problem areas and clarification of points configuration. These measures will provide the best control.

Goal

The goal of this study is to develop conceptual frameworks and proposals to optimize the geometry of Dnister PSPP control GNSS network and to identify ways to improve the accuracy of GNSS measurements for maximum control.

Methodology

One of the main surveyor's objectives is to determine the spatial position of the points placed on different objects. The set of points necessary to determine the spatial object position is called geodetic network. According to [Berne, 2004] all the points in a geodetic network can be divided into three groups: deformation, reference, orientation. The points in each group are located according to the shape, size, topographical and geological features of monitoring object. According to [Grafarend, 1974] there are four designing and optimization stages of geodetic networks for different purposes:

Zero-Order Design: an optimal reference frame. At this stage you are looking for optimal network coordinate system. However, you can skip this stage if you are designing local networks.

First-Order Design: choice of the optimal network configuration. At this stage, you choose the optimal geometric shape for the network, the optimal number and location of geodetic points and measurement schemes.

Second-Order Design: choice of optimal weight of observation. At this stage you determine what accuracy should be achieved. The main characteristic of this stage is accuracy.

Third-Order Design: improving an existing network. At this stage you add (or delete) extra points and observations for improving an existing network.

For example, in [Amiri-Simkooei, 2001] it is presented an optimization algorithm for geodetic monitoring network, which includes first, second and third stages. The "weak" network points are replaced by the hard ones at the first stage. At the second stage, a number of redundant measurements are increased in points which located on the network perimeter. And at the third stage it should be added inverse measurements to improve reliability of "weak" lines. In [Amiri-Simkooei, 2007; Berne, 2004] it is presented optimization algorithms for location geometry of the network points. In the first case, the optimization is made with the use of reliability parameters, in the second case with the use of covariance matrix determinant value. In both cases a geometric network shape should be chosen where the values of accuracy and reliability of measurements are the best.

To select the optimal geometric location of new points and to refine the existing points location of Dnister PSPP control GNSS network it was developed a special optimizing methodology of the geometric network configuration. This methodology consists in finding the position of points in which the value of optimization criteria will be minimal. To do this MathCAD14 software is used. Previously it was conducted a detailed analysis of the main optimization criteria, namely trace of covariance matrix $-A = tr(Q)$, the determinant of covariance matrix $D = \det(Q)$, the maximum eigenvalue of covariance matrix – $E = \lambda_{\max}$ and the ratio of maximum to minimum eigenvalue of covariance matrix $-I = \frac{\lambda_{\max}}{\lambda_{\min}}$. In [Al-Zubaidy, 2012] it is presented the use of A and D-criteria to optimize the micro geodetic networks. It is established that optimization of such constructions while using such criteria leads to a significant improvement in accuracy. D-criterion is also used to optimize active geodetic monitoring networks of the Dnipro, Dnister-1 and Kaniv HPPs [Savchyn, 2015]. The use of this criterion, and a multipurpose optimization methodology made it possible to improve processing accuracy 1.5–2.8 times more at the reliability loss of 2.0–7.0 %. We know that the determinant corresponds to the volume of hyperellipsoid of the errors produces by a correlation matrix. Therefore, minimization of this criterion is a good methodology to improve the accuracy of the network. So it was decided to use this criterion in our methodology.

Structurally the optimization methodology of geometric network configuration using mathematical modeling consists of 3 interconnected blocks (Fig. 2).

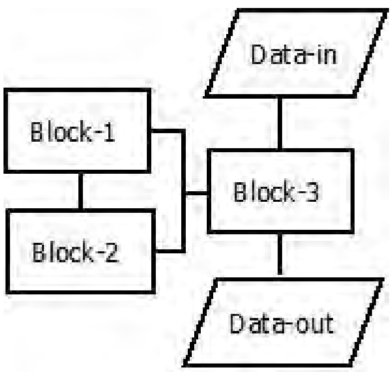


Fig. 2. Relationship between methodological units to optimize geometric network configuration

Block-1: Calculation of optimization criteria. This block is designed to adjust measurements in a given network with parametric method and calculate determinant of covariance matrix. In this block is being formed a parametric matrix A and weights matrix P, based on the input data. We use obtained results to calculate covariance matrix $Q = (A^T PA)^{-1}$. Then we calculate determinant of covariance matrix $D = \det(Q)$.

Block-2: We calculate the movement direction of each point in which the decreasing of optimization criteria is observed. This block is designed to determine the optimal direction for each network point, in which values of optimization criteria are decreased. We use gradient method to search this direction. Gradient method is based on finding of increases of determinant of covariance matrix:

$$\nabla x_i = \frac{F(x_i + l, y_i) - F(x_i - l, y_i)}{2 \cdot l}; \quad \nabla y_i = \frac{F(x_i, y_i + l) - F(x_i, y_i - l)}{2 \cdot l}, \tag{1}$$

where x_i and y_i are initial coordinates of i- th network point; l is constant used to change every coordinate (in this methodology it is recommended to use 1 meter); $F(x, y)$ – objective function to calculate the determinant of the network.

We base our further calculations of movement directions in each point, at which it is observed the decrease of optimization criteria on predefined gradients:

$$tg(\alpha_i) = \frac{\nabla y_i}{\nabla x_i}. \tag{2}$$

Block-3: Calculation of global minimum of the function and identifying optimal geodetic network coordinates. This block is designed for consistent points movement in a given direction (3) and calculation of optimization criteria for new points locations.

$$x_i^I = x_i + S_i^I \cdot \cos(\alpha_i); \quad y_i^I = y_i + S_i^I \cdot \sin(\alpha_i), \tag{3}$$

where S_i^I – the distance for which point moves in a given direction. As point can move toward a given direction to infinity, the optimization problem can lose meaning. In this regard, the optimization process is restricted (radius within which you can move the point – R), as a result objective function becomes:

$$\Phi(x,y) = F(x,y) + \\ + k\begin{cases} (S_i^I - R_i) \le 0 \Rightarrow & k = 0, \\ (S_i^I - R_i) \triangleright 0 \Rightarrow & k = (S_i^I - R_i)\cdot m, \end{cases} \quad (4)$$

where m – a constant that depends on the number of points in the network.

Further we find global minimum of the obtained objective function (4) and coordinate output for optimal geodetic network.

Results

There were highlighted 3 key problem groups of points for Dnister PSPP control GNSS network, as a result of afield points inspection as well as detailed analysis of measurements.

Points with poor reception of satellite signal: GZ-10, GZ-11A, GZ-11B, GZ-12 (all are water outlets of the system), Portal-2, Nyzhniy, OZS-1-1 and OZS-23-2 (all on northeastern slope). GNSS measurements at these points are in adverse conditions: closed horizon, buildings and technological structures, landscape and vegetation, as well as high multipath effect lead to increased errors of coordinates detection. The points installed on the northeastern slope are not critical and important since we believe that they can be excluded from the application of GNSS measurements as they degrade the accuracy of the overall network. Instead, points installed on the water outlets system require constant high-precision control, so we offer namely them to determine the horizontal displacement of joint satellite, angular and linear measurements.

Points centered from a tripod: PP-221 and PP-100. Centering from a tripod introduces additional systematic errors in the designed coordinates. To improve the accuracy it would be desirable to replace these points with points with forced centering.

Points damaged during construction: Obryv and OGZ-1. Point Obryv was damaged as a result of strengthening slope in 2014, and point OGZ-1 was damaged as a result of replacement of the roadway in 2016. To improve the accuracy it would be desirable to replace these points with new ones.

In addition to points that must be removed or replaced in the course of our analysis there were identified several additional areas that need monitoring. Out from bulk there were four such areas detected (the first on the northwest slope, first on the northeast slope, the second on the east side of the buffer reservoir), where it is necessary to install new points to improve rigidity and accuracy of Dnister PSPP control GNSS network. The area was considered to be a limited circle plane with specified radius at any point in which it is possible to set a new point. The size of the area directly depends on the terrain conditions and the availability of nearby buildings usually producing negative impact on the quality of measurements. Fig. 3a presents the scheme of the existing groups of points, and the search area for the best position of new points of Dnister PSPP control GNSS network.

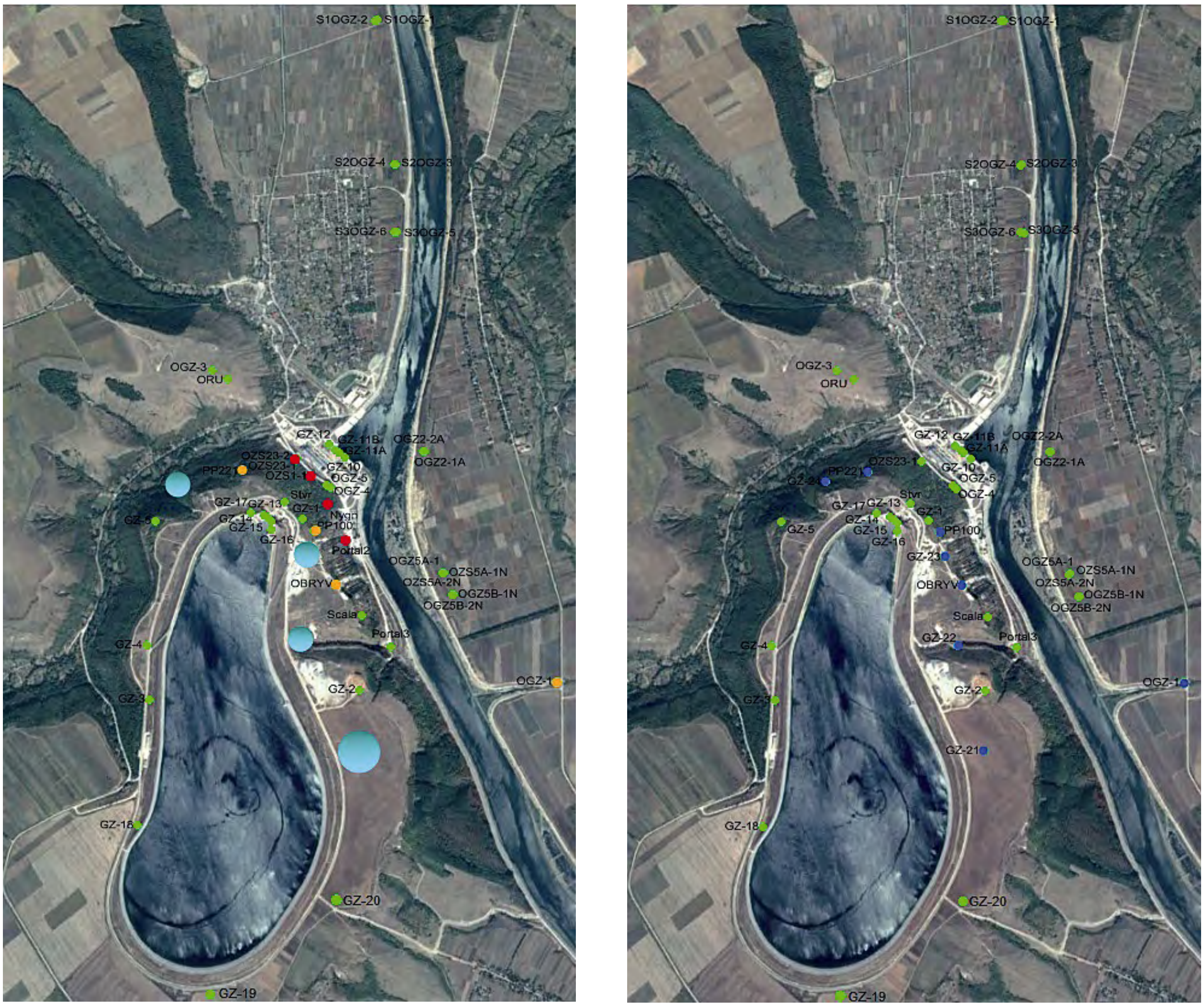
Thus, the analysis has revealed that to improve hardness and accuracy of Dnister PSPP control GNSS network it is necessary to:

- exclude the application of 4 GNSS measuring points (Portal-2, Nyzhniy, OZS-1-1 and OZS-23-2);
- strengthen joint satellite angular and linear measurements of 4 points (GZ-10, GZ-11A, GZ-11B, and GZ-12);
- replace existing 4 points (PP-221, PP-100, Obryv and OGZ-1);
- establish 4 new points (GZ-21, GZ-22, GZ-23 and GZ-24).

It was revealed in this regard that 8 points of Dnister PSPP control GNSS network require optimization. For the optimization it was used the proposed optimization methodology for geometric configuration of network with the help of mathematical modeling to evaluate the accuracy. According to the proposed methodology the areas where it is necessary to replace existing and to establish new points are limited by circles of a given radius. Since the existing necessary to be replaced points are located well, it respect of them the areas with the radius of 10 meters were chosen. To find the best position for new points GZ-22, GZ-23 and GZ-24 the areas with the radius of 20 meters were chosen, while for the point GZ-21 – radius of 30 meters. The main parameters to choose the radius were the terrain conditions and the availability of nearby buildings. As a result, of optimization there were detected new optimal points of Dnister PSPP control GNSS network (Fig. 3, *b*).

We have conducted a priori assessment of accuracy to test the optimized Dnister PSPP control GNSS network. According to [Tretyak, 2005] observations within this network should be season-based and include three cycles. Each cycle has 3 measurement sessions at each point. Given that vectors of Dnister PSPP control GNSS network do not exceed 10 kilometers, the duration of measurements at each point according to previous studies must be at least 6 hours [Galaganov, 2004; Tretyak, 2000]. So, in these network in each cycle is measured about one-third of all possible vectors.

In this regard, for a priori assessment of all possible vectors it was auto-selected the amount determined by dependence $\frac{n\cdot s}{k}\cdot c$, where n – number of points in the network; s –number of sessions at each measurement point; k –the number of available GNSS receivers; c – the number of vectors measured in the same session. The observation in the network was carried out using by 5 to 7 GNSS receivers, so priori accuracy evaluation was conducted for these amounts. Table 1 presents a priori mean square errors (MSE) of coordinates determining of the network points before and after optimization.



a – before optimization *b – after optimization*

Fig. 3. Scheme of points of the reference Dnister PSPP based GNSS network
(● – good-condition points of the network; ● – bad-condition points of the network;
● – points of the network needed to be replaced;
● – zone of finding the optimal position for new points of the network;
● – new points of the network)

Table 1

Priori mean square error of determining the coordinates of the network before and after optimization

Number of GNSS receivers, pc.	MSE determining of the network coordinates		MSE improving of determining of the points coordinates , %
	before optimization, mm	after optimization, mm	
5	2.4	2.2	8.3
6	2.2	2.0	9.1
7	2.0	1.8	10.0

Having analyzed the results shown in Table 1 one can note that the value of the MSE priori determination of the coordinates of network points dropped after the network optimization. It was established that the optimization of Dnister PSPP control GNSS network will improve accuracy by 8.3-10.0 % depending on the number of used GNSS receivers. We should take into account that Dnister PSPP control GNSS network had 43 points, though in the process of optimization4 weak points were removed, 4 new points were installed and position of 4 existing points was minimally modified, the resulting value of network improvement can be considered as good.

To summarise we can say that the optimization of Dnister PSPP control GNSS network fully confirms the efficiency of the optimizing methodology of the network geometric configuration using mathematical modeling.

Scientific novelty and practical importance

We developed a new optimizing methodology of the geometric network configuration using mathematical modeling. We performed the optimization of Dnister PSPP control GNSS network using this methodology. Thus, this methodology can be applied to optimize other geodetic monitoring networks.

Conclusions

We developed the methodology to optimize the geometric configuration of network using mathematical modeling.

There were highlighted 3 key problem groups of points for Dnister PSPP control GNSS network, as a result of afield points inspection as well as detailed analysis of measurements: points with poor reception of satellite signal; points centered from a tripod; points damaged during construction.

To exclude the application of 4 GNSS measuring points (Portal-2, Nyzhniy, OZS-1-1 and OZS-23-2); strengthen joint satellite angular and linear measurements of 4 points (GZ-10, GZ-11A, GZ-11B and GZ-12); replace existing 4 points (PP-221, PP-100, Obryv and OGZ-1) and set new 4 points (GZ-21, GZ-22, GZ-23 and GZ-24). To install new points in the highlighted four areas that needs monitoring.

Optimization of Dnister PSPP control GNSS network using the developed methodology resulted in improved accuracy by 8.3–10.0 % depending on the amount of used GNSS receivers.

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ОПТИМІЗАЦІЯ ОПОРНОЇ ГНСС-МЕРЕЖІ ДНІСТРОВСЬКОЇ ГАЕС

Мета. Розроблення концептуальних основ та пропозицій щодо оптимізації геометрії опорної ГНСС-мережі Дністровської ГАЕС, а також визначення способів підвищення точності результатів ГНСС-вимірювань. **Методика.** Для вибору оптимального геометричного розміщення нових, а також уточнення положення наявних пунктів опорної ГНСС-мережі Дністровської ГАЕС розроблено спеціальну методику оптимізації геометричної конфігурації мережі, яка полягає в пошуку положення пунктів, за якого значення критеріїв оптимізації буде мінімальним. Як критерій оптимізації використано детермінант коваріаційної матриці. **Результати**. Розроблено методику оптимізації геометричної конфігурації мережі із застосуванням математичного моделювання. У результаті огляду пунктів на місцевості, а також детального аналізу проведених та опрацьованих вимірювань виділено три основні проблемні групи пунктів опорної ГНСС-мережі Дністровської ГАЕС: пункти із незадовільним прийомом супутникового сигналу; пункти з центруванням зі штативу; пункти пошкоджені під час будівництва. Для покращення жорсткості та точності опорної ГНСС-мережі Дністровської ГАЕС необхідно: вилучити з програми ГНСС-вимірювань чотири пункти (ПОРТАЛ-2, НИЖНІЙ, ОЗС-1-1 та ОЗС-23-2); підсилити спільними супутниковими та лінійнокутовими вимірюваннями 4 пункти (ГЗ-10, ГЗ-11А, ГЗ-11Б та ГЗ-12); замінити 4 наявні пункти (ПП-221, ПП-100, ОБРИВ та ОГЗ-1) та встановити 4 нові пункти (ГЗ-21, ГЗ-22, ГЗ-23 та ГЗ-24). Для встановлення нових пунктів виділено чотири зони, що потребують контролю. Оптимізація опорної ГНСС-мережі Дністровської ГАЕС із використанням розробленої методики покращила точність на 8,3–10,0 % залежно від кількості використаних ГНСС-приймачів. **Наукова новизна та практична значущість.** Запропоновано нову методику оптимізації геометричної конфігурації мережі із застосуванням математичного моделювання. Використовуючи цю методику, виконано оптимізацію опорної ГНСС-мережі Дністровської ГЕС. Наведену методику також можна застосувати для оптимізації будь-яких геодезичних мереж моніторингу.

Ключові слова: оптимізація; D-критерій, ГНСС-мережа, геометрична конфігурація пунктів мережі, Дністровська ГАЕС.

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