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Application of trigonometric levelling for geodetic monitoring of pressure water supply at Tereblya-Ritska hydroelectric power plant

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Abstract: The purpose of this study is to determine the vertical displacements of the intermediate supports of the pressure pipeline of the Tereblya-Ritska hydroelectric power plant (HPP), which is under the influence of technogenic load caused by the cyclic operation mode of the hydroelectric power plant. The displacements are established based on the results of high-precision trigonometric levelling of control marks located on the foundations of the supports. Special attention is paid to the analysis of the feasibility of replacing classical geometric levelling with the inclined beam method. The work uses the method of precision trigonometric levelling using a robotic electronic total station, taking into account the influence of atmospheric refraction. This approach provides increased measurement accuracy while significantly reducing the time of field work. As a result of observations conducted during 2014–2023, data on the vertical displacements of control marks on the foundations of the intermediate supports of the pressure pipeline of the Tereblya-Ritska HPP were obtained. Based on the results of high-precision trigonometric levelling, vertical displacements of control marks caused by man-made loads arising from the specifics of the operating mode of the Tereblya-Ritska HPP were established for the first time. The developed method of monitoring vertical displacements can be effectively used to increase the reliability and safety of operation of hydraulic structures that are exposed to variable man-made loads. The use of precision trigonometric levelling allows you to significantly reduce the duration of measurement work, while achieving accuracy comparable to geometric levelling of class II.

Keywords: geodetic monitoring, hydraulic structures, trigonometrical levelling, vertical displacements, vertical refraction

INTRODUCTION

Monitoring of hydrotechnical structures is a key task for ensuring the safety of people and property. Monitoring methods have developed from initial manual inspection, basic geodetic measurements and qualitative assessment to currently used automated structure monitoring systems that integrate high-precision data acquisition, analysis and disaster prediction functions.

Large hydroelectric facilities are typically situated within the influence zones of anomalous structural and tectonic features. During the final stages of their construction, particularly when reservoirs are being filled, changes occur in the hydrodynamic loading on rock masses. For instance, the impoundment of the Koyna Dam reservoir in India in 1967 triggered an induced earthquake in a region previously considered seismically inactive (Gupta and Rastogi, 1976). The earthquake reached a magnitude of 6.5. A correlation was established between variations in water levels and seismic activity (Kumar *et al.*, 2012).

The construction of the Aswan Dam in Egypt and the subsequent filling of its artificial reservoir led to continuous seismic activity, with earthquakes reaching magnitudes of up to 5.5. Following the commissioning of the Quebec reservoir in Canada, repeat levelling data revealed relative uplift of the Earth's surface by up to 4 cm (Lambert, Liard and Mainville, 1986).

Studies conducted at the Açu reservoir in Brazil (Telesca *et al.*, 2012) demonstrated that water diffusion into rock formations serves as an additional trigger for induced seismicity, particularly in regions under tectonic stress. The operational characteristics of hydroelectric plants contribute to further anthropogenic loading and alterations in the hydrodynamic regime.

Research by Sarnavskyi and Ovsiannikov (2005) and Sarnavskyi (2006) has shown that the construction of hydroelectric complexes intensifies anthropogenic stress within natural geodynamic zones, resulting in increased strain within rock masses. The redistribution and release of this strain can destabilise the rock structure. At such facilities, the natural stress level exceeds the geostatic due to tectonic contributions, with horizontal components being up to three times greater than vertical ones. This imbalance leads to horizontal displacements in the rock mass, potentially causing unpredictable outcomes (Sarnavskyi, 2006). The main goal of any hydrotechnical object monitoring program is to identify, as early as possible, any anomaly in the dam responses, which can result in upcoming danger and allow the dam owner a sufficient time to implement a corrective measure (Prakash *et al.*, 2022; Zaczek-Peplinska and Kowalska, 2022; Deng *et al.*, 2025).

In the case of the Tereblya Reservoir, a clear link has been observed between seismicity and reservoir operation and filling cycles. The increasing frequency of seismic events indicates a redistribution of stress and strain, often accompanied by fracturing of rock formations. Fragmented rock elements possess greater volume and rigidity compared to dense crystalline material, causing expansion within the rock mass and contributing to horizontal ground movements and the formation of new seismic foci.

Furthermore, the high incidence of seismic events at zero depth suggests stress release and the activation of exogenous processes such as landslides and rockfalls. Such processes are entirely natural and represent the rock mass's response to anthropogenic interference (Kablak *et al.*, 2024). To ensure operational safety, comprehensive monitoring is essential. Without adequate integrated oversight, these hazardous processes may severely compromise the integrity of hydraulic structures.

Geodetic monitoring involves determining geometric relationships between the location of specific measurement points on the controlled structure. Periodically recorded changes are the result of various phenomena occurring in the case of a given structure. Geodetic monitoring allows for determining the occurrence of changes between the information contained in the project, in the behaviour forecast and the actual state. It also allows for control of the dynamics of the following changes. Geodetic monitoring of dams includes classic measurement techniques: tachymetry, precise geometric levelling (currently no possibility of automation) and trigonometric, Global Navigation Satellite System (GNSS) satellite measurements (Tretyak and Sidorov, 2005).

The location of the HPP and its engineering structure design pose challenges to the problem of conducting geodetic monitoring of a unique structure. Thus, large elevation differences in mountainous terrain complicate the implementation of geometric levelling, the afforestation of the territory and the mountainous terrain complicate the use of GNSS observations due to the lack of a high-quality satellite signal and Internet connection. The use of high-precision trigonometric levelling is due to the consideration of atmospheric influences on the results of monitoring observations.

The purpose of this study is to determine the vertical displacements of the intermediate supports of the pressure pipeline of the Tereblya-Ritska hydroelectric power plant (HPP), which are subjected to anthropogenic loading due to the cyclic operation of the station. In particular, the effectiveness of high-precision trigonometric levelling for fixing vertical deformations of the supports is assessed. An additional goal is to study the possibility of replacing traditional geometric levelling with an alternative method of measuring inclined distances and angles using electronic total stations.

MATERIALS AND METHODS

The objective of this study is to determine the vertical displacements of the intermediate supports of the pressure pipeline at the Tereblya-Ritska hydroelectric power plant (HPP) which is subject to anthropogenic loading resulting from the plant's cyclical operation. Vertical displacements are assessed using high-precision trigonometrical levelling of control benchmarks located on the foundations of the pipeline's intermediate supports. Based on the completed cycles of trigonometrical levelling, the study aims to explore the feasibility of replacing geometric levelling with inclined beam measurements.

In related deformation studies of the Mavrovo earth dam (Bulgaria), using GNSS and high-precision linear-angular measurements, the differences in coordinates derived from the two methods ranged between 1–4 mm (Srbinoski and Bogdanovski, 2010). The linear-angular measurements were carried out using a precision total station with angular accuracy of 0.5" and distance accuracy of 1 mm per 1 km. Observations using GNSS were conducted at stations with maximum sky visibility.

For coordinate determination via independent terrestrial methods, the Leica TCRP-1201 robotic total station (Total Station Positioning System, TSPS) was employed. The standard deviation of horizontal and vertical angle measurements per set was 1", with comparable precision for distance measurements. Observations were conducted in both forward and reverse directions across eight sets, using two vertical circle positions of the instrument.

During terrestrial measurements, one of the main limiting factors affecting the attainable instrumental accuracy is vertical refraction. One of the most effective ways to mitigate its influence is the method of simultaneous bidirectional observations (Litynskyi, 2001; Perii, 2001). However, the application of this method within a spatial network comprising numerous points is impractical. Therefore, a technique involving non-simultaneous observations during specific times of the day was proposed.

As a result of conducting non-simultaneous bidirectional observations, and incorporating meteorological corrections (accounting for temperature, pressure, and humidity at the observation sites) as well as target and instrument height adjustments, calculations were made for horizontal and vertical angles and inclined distances. Elevation differences obtained through bidirectional levelling were processed using a method involving fluctuations in zenith distances to apply vertical refraction corrections (Perii, 2001; Tretyak *et al.*, 2015).

The methodology of our research is to use non-simultaneous bilateral trigonometric levelling for geodetic monitoring of hydraulic structures in mountainous conditions at the Tereblya-Ritska HPP site using modern high-precision robotic electronic total stations and simultaneous consideration of vertical refraction due to fluctuations in zenith distances during observations (Perii, 2001; Perii, 2015; Tretyak *et al.*, 2015). The use of such a technique allows to significantly increase the accuracy, efficiency and reduce the cost of measurements compared to traditional geometric levelling and not always high-quality GNSS measurements in difficult mountainous conditions.

RESULTS AND DISCUSSION

The Tereblya-Ritska hydroelectric power plant is a unique engineering structure and the only hydroelectric power plant in the world that stands simultaneously on two rivers. It is located in the valleys of the Tereblya and the Rika Rivers in the Khust district (Transcarpathia). It was built in 1949–1955. After the construction of the dam (height – 46 m, length – 153 m), the Vilshany reservoir with a volume of 23.7 mln m^3 with a water mirror area of 1.6 km^2 was formed.

The two rivers – Tereblya and Rika – are located almost parallel, with a watershed along the Bovtsar ridge, but at different levels. This arrangement made it possible to locate the hydroelectric power plant using a natural difference of 210 m: water from the basin of the Tereblya River is discharged into the basin of the Rika River, which significantly increased the power of the water flow (Fig. 1).

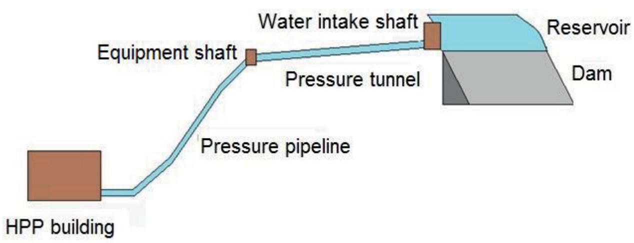

Fig. 1. Schematic drawing of the principle of operation of the Tereblya-Ritska hydroelectric power plant (HPP); source: own study

A 3.7 km long derivation tunnel was built between the rivers in the rocks at a slight slope, through which the waters of the Tereblya River enter the Rika River through the hydroelectric power station. The tunnel ends with a metal pipe of 350 m length that has a slope of 37°.

As you can see, on the Figure 1, a unique hydropower structure needs constant monitoring in the planned and high-altitude position. Scientists of Lviv Polytechnic have been monitoring the stability of the pressure water supply system and the dam of hydroelectric power plants for 30 years.

To determine the deformations of the pressure pipeline of the Tereblya-Ritska HPP the geodetic monitoring starts in 1989. A special spatial geodetic network was created (Fig. 2). Determination of deformations was carried out by the method of trilateration, and starting from the 45th cycle (May 2000) by the method of satellite geodesy using GPS measurements.

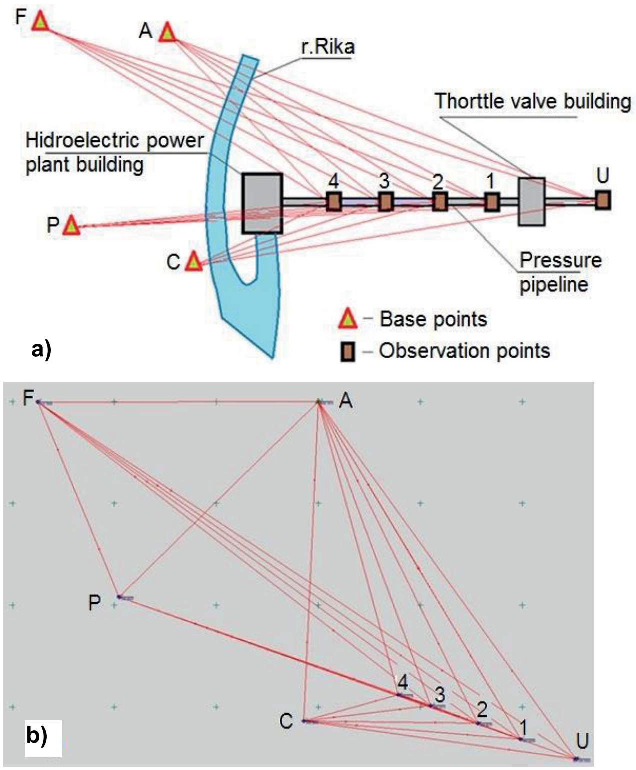

Fig. 2. Scheme of the geodetic monitoring network of the pressure water supply system of the Tereblya-Ritska HPP hydroelectric power plant: a) functional diagram, b) sketch of the measurement network; source: own study

For the period from May 1989 until August 2017, 67 observation cycles were performed. Measurements were carried out by Leica SR-1200, TrimbleR7 GPS receivers in static mode of GPS data acquisition and precision electronic total station TCRP 1201 (Leica).

In 2014, experimental observations were carried out at the points of the pressure water supply of hydroelectric power plants. The complex of observations included GNSS-observations made by two frequency receivers and high-precision linear and angular measurements using a robotic electronic total station TCRP-1201 from Leica (see Figs. 2–5). Measurements with a robotic electronic total station were performed by the method of receptions in two positions of the vertical circle with automatic pointing to the reflectors at the maximum of the reflected signal. In total, according to the program, 10 observation techniques were performed at each point, which made it possible to assess the quality of measurements, and in addition to the average values of measurements, to calculate their fluctuations as mean square deviations from the average values. In the process of measurements at observation points, the state of weather, wind, atmospheric pressure, temperature and humidity, which were introduced into the results of measurements of vertical angles and line lengths (Baran, Solovyov and Chornokin, 1997; Litynskyy, 2001; Perii, 2015), were assessed and recorded.

In the length of the lines, the corrections were calculated according to the Leica recommended Barrel–Sears formula.

Fig. 3. View from point U to network points; A, C, F, P = points as in Fig. 2; source: own study

Fig. 4. View from point 3; point 3 as in Fig. 2; source: own study

The measured excess $h_{AB}^{\text{meas.}}$ is obtained from multiple one-sided observations of the specified line by an electronic total station according to the formula programmed in it:

$$h_{AB}^{\text{meas.}} = D_{AB}\cos Z_{AB} + \frac{D_{AB}^2 \sin^2 Z_{AB}}{2R} + i - v \qquad (1)$$

where: D_{AB} = the inclined distance between observation points A and B; Z_{AB} = measured zenith distance along the line AB at point A; R = the average radius of curvature of the Earth; i = the height of the electronic total station above the observation point A; v = the height of the sighting target above the observation point B.

Exceedances from bilateral non-simultaneous trigonometric levelling were obtained by calculating the average values of measured forward and reverse exceedances with the introduction of corrections for the anomalous value of vertical refraction obtained from the measured exceedances in proportion to the fluctuations of zenith distances (Eq. 2) (Perii, 2015):

$$h_{AB}^{\text{bil.trig.}} \cong \frac{h_{AB}^{\text{meas.}} - h_{BA}^{\text{meas.}}}{2} - \left(\frac{m_{Z_{AB}}^2 - m_{Z_{BA}}^2}{m_{Z_{AB}}^2 + m_{Z_{BA}}^2}\right)\left(\frac{h_{AB}^{\text{meas.}} + h_{BA}^{\text{meas.}}}{2}\right) \qquad (2)$$

where: $h_{AB}^{\text{meas.}}$ and $h_{BA}^{\text{meas.}}$ = measured exceedances taking into account the heights of instruments, sighting targets and curvature of the Earth in the corresponding directions of observation (1); fluctuations $m_{Z\ AB}$ and $m_{Z\ BA}$ fluctuations of the appropriately measured zenith distances of the forward and reverse directions of observation, which serve as weighting coefficients in the distribution of anomalous residual.

The results of the pre-processed measured data were balanced using the Credo DAT software package.

The average measured (pre-processed) exceedances along the corresponding lines of the network and the corrections and exceedances obtained from the equilibrium of the bilateral non-simultaneous trigonometric levelling of the monitoring geodetic network of the Tereblya-Ritska HPP are given in Table 1.

Fig. 5. View from point 4; point 4 as in Fig. 2; source: own study

The mean square errors (*MSE*) of the magnitude of the corrections in the excess was 1.8 mm. The maximum values were obtained along the P-2 line – 5.0 mm. This opens up the possibility of replacing class II geometric levelling in difficult conditions (Tretyak *et al.*, 2015; Perii, 2015; Perii *et al.*, 2017) with a non-simultaneous trigonometric one, taking into account the total angles of vertical refraction.

The intermediate supports of the pressure pipeline P1–P15 (15 supports) are located between its anchor supports A1, A2, A3, and A4. Control of their elevation position is carried out according to control marks laid in the foundations of the supports. The pressure pipeline consists of three purlins. Inside each run, there are two reference benchmarks AH-1', AH-2' (first run), AH-2", AH-3' (second run) and AH-3", AH-4' (third run). The heights of the intermediate supports were determined twice from each reference benchmark of the run by the method of high-precision trigonometric levelling. The middle of the two definitions was taken as the final value. The altitude position of the reference benchmarks of the runs was determined by high-

Table 1. Results of trigonometric levelling of the Geodetic Monitoring Network of the Tereblya-Ritska hydroelectric power plant

Robotic electronic total station	Target	Horizontal projection (m)	*h* average (m)	Correction (mm)	*h* equilibrium (m)
1	C	427.3128	−155.6062	1.4	−155.6048
	A	772.8703	−136.7750	0.6	−136.7744
	F	1,155.4465	147.8092	−0.6	147.8087
	P	835.2837	70.7246	1.9	70.7265
	2	89.7176	−48.4284	−0.1	−48.4284
2	P	745.5791	119.1599	−5.0	119.1549
	3	98.4385	−73.2863	0.2	−73.2861
	C	341.7784	−107.1741	−2.3	−107.1764
	4	165.2662	−105.8955	−0.2	−105.8957
	A	705.0694	−88.3454	−0.5	−88.3460
3	4	66.8377	−32.6096	0.0	−32.6096
	C	251.2106	−33.8910	0.7	−33.8903
	P	647.1548	192.4386	2.4	192.4410
	F	974.5173	269.5228	0.4	269.5232
F	U	1,267.0804	−86.7342	0.0	−86.7342
Average				**–0.08**	
MSE				**1.76**	

Explanations: A, C, F, P, 1, 2, and 3 = points as in Fig. 2, *MSE* = mean square error.
Source: own study.

precision trigonometric levelling by a precision robotic electronic total station Leica TCRP1201. The electronic total station was installed on the first reference benchmark of the pair and focused on the prism reflector installed on the second reference benchmark. Next, measurements of vertical angles and distances were performed on the reflector, which were sequentially rearranged on the control marks of the intermediate supports of the pressure pipeline. After that, the electronic total station and reflector were reversed and the measurement process was repeated. The layout of the control marks is shown in Figure 6.

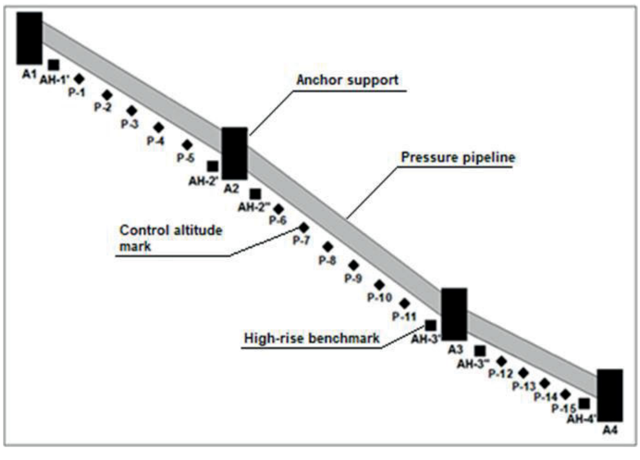

Fig. 6. Diagram of the location of the control marks of the pressure pipeline; P1–P15 = the intermediate supports of the pressure pipeline, A1, A2, A3, A4 = anchor supports, reference benchmarks AH-1', AH-2' (first run), AH-2'', AH-3' (second run) and AH-3'', AH-4' (third run); source: own study

To determine the heights with high accuracy on the control marks installed on the intermediate supports of the pressure pipeline, we have developed and manufactured special mobile geodetic marks (Photo 1). The stamp is equipped with three lifting screws and a level for setting the stamp vertically above the point. This solution is especially relevant when measuring on inclined surfaces, which is the concrete base of the intermediate support of the pressure pipeline.

The height of the control mark on each intermediate support was determined from two reference benchmarks. The determination of the heights of reference marks by the method of trigonometric levelling is shown in Photo 2.

Vertical displacements of control marks on the intermediate supports of the pressure pipeline of Tereblya-Ritska HPP for the period from November 2018 to December 2021 are presented in Table 2.

The vertical displacements of the reference benchmarks and control marks on the intermediate supports of the pressure pipeline are in the period of 2018–2021 in the range from –3.4 mm to +2.3 mm (Tab. 2). For the period of 2020–2021 vertical displacements are in the range from −1.6 to +2.1 mm.

Graphs of vertical displacements of reference and control marks on the intermediate supports of the pressure pipeline are shown in Figure 7.

Initial observations of the vertical displacements of the intermediate supports of the pressure pipeline were carried out according to the differences in the readings along the vertical rail of the relative inclined beam, which was set using a theodolite and a special mark, i.e. the values of the heights of the intermediate supports themselves are unknown.

Photo 1. Special mobile geodetic mark (phot.: *I. Sidorov*)

Photo 2. Determination of the heights of reference marks by the method of trigonometric levelling (phot.: *I. Sidorov*)

Table 2. Vertical displacements of control marks on the intermediate supports of the pressure pipeline of Tereblya-Ritska HPP (period from November 2018 to December 2021)

Brand name	Vertical displacement (mm)					
	2018–2019	2018–2020	2018–2021	2019–2020	2019–2021	2020–2021
AH-1'	–0.9	–0.3	–1.3	0.6	–0.4	–1.0
P1	–1.5	–2.1	–0.8	–0.6	0.7	1.3
P2	–2.1	–2.7	–3.5	–0.6	–1.4	–0.8
P3	–1.5	–3.3	–3.4	–1.8	–1.9	–0.1
P4	–0.9	–0.8	–1,8	0.1	–0.9	–1.0
P5	–1.3	–3.0	–1,2	–1.7	0.1	1.8
AH-2'	–0.9	–2.4	–1,4	–1.5	–0.5	1.0
AH-2"	–1.7	–2.5	–1,6	–0.8	0.1	0.9
P6	–2.3	–0.2	0,3	2.1	2.6	0.5
P7	0.3	1.2	1,0	0.9	0.7	–0.2
P8	–2.0	0.3	1,4	2.3	3.4	1.1
P9	–1.2	–0.8	1,3	0.4	2.5	2.1
P10	–2.3	0.7	1,2	3.0	3.5	0.5
P11	–2.1	0.7	2,3	2.8	4.4	1.6
AH-3'	–1.5	–0.1	0,8	1.4	2.3	0.9
AH-3"	–	–	–	–0.8	–1.0	–0.2
P12	–	–	–	2.8	2.4	–0.4
P13	–	–	–	2.1	0.5	–1.6
P14	–	–	–	1.7	0.5	–1.2

Explanations: brands as shown in Fig. 6.
Source: own study.

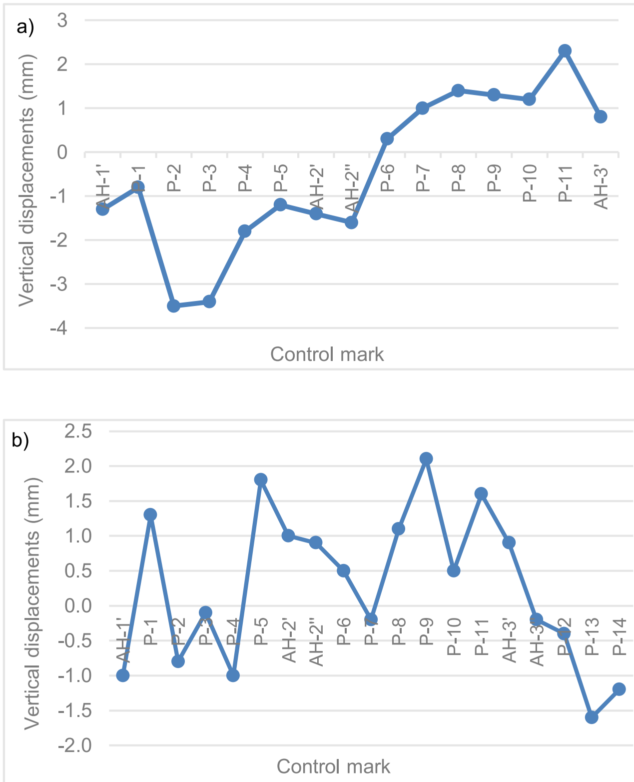

Fig. 7. Vertical displacements of reference benchmarks and control marks on the intermediate supports of the pressure pipeline of Tereblya-Ritska hydroelectric power plant for the period: a) from November 2018 to December 2021, b) from October 2020 to December 2021; source: own study

To determine the altitude position of the intermediate supports, we based on the observations of 1967 and the values of the distances between the intermediate supports measured in 2018–2021. Their heights for the period of 1967 were calculated. The heights of intermediate supports and vertical displacements for the period of 1967–2021 are presented in Table 3.

Table 3. Nominal heights and vertical displacements of control marks on the intermediate supports of the pressure pipeline of the Tereblya-Ritska hydroelectric power plant for the period 1967–2021

Brand name	Height of stamps by year (m)		Vertical displacement (mm)
	1967	2021	
P-1	455,3504	455,3518	1.4
P-2	446,7156	446,7173	1.7
P-3	438,0482	438,0476	−0.6
P-4	429,4411	429,4393	−1.8
P-5	420,8224	420,8243	1.9
P-6	403,9349	403,9353	0.4
P-7	393,3432	393,3422	−1.0
P-8	382,7019	382,7012	−0.7
P-9	372,1169	372,1232	6.3
P-10	361,3944	361,4039	9.5
P-11	350,6956	350,6966	1.0
P-12	333,2213	333,2209	−0.4
P-13	324,9017	324,8995	−2.2
P-14	316,5339	316,5326	−1.3

Explanations: brands as shown in Fig. 6.
Source: own study.

As can be seen in Table 3, the vertical displacements of intermediate supports for the period 1967–2021 are in the range from −2.2 to +9.5 mm.

It was found that the accuracy of the obtained displacements using trigonometric levelling corresponds to the standards of geometric levelling of class II, the mean square error of the magnitude of corrections for overshoot was 1.8 mm. Therefore, the results of the study confirm the possibility of using non-simultaneous bilateral trigonometric levelling taking into account vertical refraction for image fluctuations as a replacement for geometric levelling of class II.

CONCLUSIONS

Ensuring the reliability and safety of the operation of hydraulic structures requires the use of high-precision geodetic monitoring methods capable of performing levelling in areas with significant elevation differences. One of such effective tools is the method of precision trigonometric levelling.

Within the framework of this study:

1) a method for determining the elevation displacements of control marks fixed on the foundations of the intermediate supports of the pressure pipeline of the Tereblya-Ritska hydroelectric power plant (HPP) was developed and implemented, with a root-mean-square error of no more than ±3 mm;
2) the spatial coordinates of the control marks were determined by the method of linear-angular measurements using a precision robotic total station taking into account corrections for atmospheric refraction;
3) a method for taking into account vertical refraction was developed based on the results of non-simultaneous bilateral observations and analysis of fluctuations in zenith distances;
4) according to the results of trigonometric levelling on lines 0.5–1.0 km long, the elevation was obtained with an accuracy that meets the requirements of geometric levelling of class II.

To ensure a reliable assessment of displacements, long-term monitoring of control points on structural elements of the structure and reference base points is necessary. Analysis of the observation results has revealed seasonal fluctuations in the position of marks and deformations caused by the geometry of the pipeline and the direction of the load on its individual sections. In particular, opposite trends in displacements were established in the upper part of the pipeline with a greater slope and the lower part with a smaller one.

Long-term observation data for the period 1967–2021, as well as short-term ones – 2018–2021, demonstrate the consistency of the results.

The results of monitoring the Tereblya-Ritska HPP are indicators of the stability and durability of the structure and associated water management systems. Further systematic monitoring and comprehensive analysis of changes in the position of control points will allow for timely identification of critical displacements that may cause exceeding the design stresses and, as a result, deformation or destruction of pipeline elements.

CONFLICT OF INTERESTS

All authors declare that they have no conflict of interests.

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