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GEODYNAMIC FEATURES OF TERRITORIES AROUND UKRAINE'S HYDROELECTRIC POWER PLANTS BASED ON GNSS CORS DATA

The study presents an assessment of the geodynamic characteristics of territories around Ukrainian hydroelectric power plants based on GNSS observations from countinious operating reference stations (CORS) of GeoTerrace and System.Net networks for the period 2019–2025. Daily solutions are computed using Bernese 5.2 software and subsequently transformed into the ETRF-2020 reference frame. The methodology includes the estimation of linear trends and annual horizontal velocities of GNSS stations in the north and east components. A filtering procedure was applied to exclude GNSS stations with insufficient observation duration, incomplete data series, suboptimal spatial configuration, as well as results affected by significant errors. The analysis encompasses GNSS networks located around Dnister Hydropower Complex, Dnipro Hydro Power Plant (HPP), and Kremenchuk HPP. For each of these sites, regional deformation vectors were determined, reflecting crustal compression or extension; motion of major lithospheric blocks; tectonic activity of rift zones; deep-seated faulting; and distributed stress fields. Dilatation distribution maps are constructed for each HPP territories, and the dilatation parameter at the dam location was estimated. Finally, the cumulative deformation of the dams induced by long-term geodynamic processes over their operational lifetimes was evaluated, showing deformation magnitudes at the millimetre level for all studied structures. The proposed methodology, based on permanent GNSS station networks, could be applied to other large engineering facilities in Ukraine and worldwide/

Keywords: recent geodynamics, crustal deformation, hydroelectric power plants, horizontal crustal motions, GNSS station velocities, GeoTerrace GNSS network, System.Net GNSS network.

Introduction

Hydropower complexes in Ukraine constitute critical infrastructure, whose structural stability directly affects the balancing of the national power system, the availability of emergency reserves, and the reliability of energy supply during crisis periods. According to publicly available information from *Ukrhydroenergo*, the company operates hydropower cascades on the Dnipro and Dnister Rivers, including the Dnipro and Kremenchuk Hydroelectric Power Plants (HPPs) and the Dnister Hydropower Complex with its pumped-storage power plant (PSPP), which defines them as strategic nodes of Ukraine's Unified Energy System [Ukrhydroenergo, 2025].

Global practice in monitoring hydraulic structures is based on a multisensor approach. High-precision geodetic networks particularly GNSS/CORS are widely used alongside inclinometers, total stations, and piezometric systems. Remote-sensing technologies are being actively implemented, including interferometric radar techniques (InSAR, PS/MT-InSAR) and distributed fibre-optic sensing systems (DFOS/DTS), which provide continuous, high-sensitivity measurements. Internationally, numerous studies analyse long-term GNSS trends [Reguzzoni et al., 2022; Abdelhamid et al., 2025; Sokoła-Szewioła & Siejka, 2021; Siejka & Kosek, 2025], develop reflectors for precision InSAR monitoring [Kukhtar et al., 2023], or combine multiple sensors to obtain integrated monitoring solutions [Barzaghi et al., 2018; Scaioni et al., 2018; Maltese et al., 2021].

In Ukraine, similar approaches have been documented in the development of monitoring systems for the Dnipro and Dnister hydropower cascades and in the verification of GNSS networks used for geodynamic investigations [Tretyak et al., 2024a]. GNSS has also demonstrated its capacity for detecting low-magnitude seismic events and assessing horizontal crustal deformation across Ukraine, highlighting the value of satellite-based monitoring [Doskich et al., 2023].

Research conducted at Ukrainian hydropower facilities confirms the effectiveness of such approaches: permanent GNSS stations have been deployed at the Dnipro, Kremenchuk, Middle Dnipro, and Dnister HPPs, with additional studies evaluating the stability of automated geodetic monitoring points [Tretyak et al., 2014; Tretyak et al., 2024a]. The geodynamics of the Dnister Hydropower Complex, in particular, have been examined in detail using repeated GNSS campaigns [Savchyn & Vaskovets, 2018] and through combined GNSS–seismic analyses [Savchyn & Pronyshyn, 2020].

At several HPP sites, seismogeological studies (microzonation, seismic hazard assessment) have confirmed moderate seismicity levels and the absence of highly hazardous local zones [Sapuzhak et al., 2021].

At the national scale, state GNSS networks provide refined velocity estimates for Ukrainian stations in global and regional reference frames, which is essential for the proper transformation and interpretation of velocities in engineering monitoring tasks. At the same time, it has been demonstrated that in the context of the full-scale war, CORS operation has become significantly more challenging due to power outages, communication disruptions, and electronic warfare/spoofing, necessitating enhanced data quality control and processing measures [Brusak et al., 2024].

However, a review of the literature reveals a substantive gap: far fewer works focus on systematic monitoring of the *surrounding territories* of hydropower sites those lying outside the boundaries of the engineered structures themselves. This *background geodynamic state* (slow natural deformation of riverbanks, terraces, and tectonically driven displacements) is crucial for interpreting the actual structural movements of the facilities and for distinguishing anthropogenic influences from natural ones [Tretyak et al., 2014; Tretyak et al., 2024a]. As shown in [Tretyak et al., 2006], the components of GNSS displacement vectors can be separated into internal deformation and external geodynamic influences. Existing publications predominantly focus on the behaviour of the structures and their local monitoring networks, whereas harmonized maps of residual velocities of the surrounding areas in a unified reference frame have been only partially presented [Tretyak et al., 2024b].

Taking these challenges into account, the present study focuses specifically on the geodynamics of the territories surrounding three of Ukraine's largest hydropower facilities: the Dnipro HPP (Zaporizhzhia city), the Kremenchuk HPP (Kremenchuk city), and the Dnister Hydropower Complex (Novodnistrovsk city). Fig. 1 presents a generalized schematic of their locations within the Dnipro and Dnister river cascades.

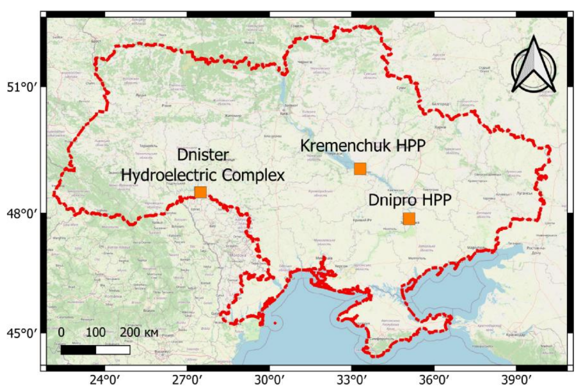

Fig. 1. Location of Ukrainian hydroelectric power plants considered in the study.

For each of the study areas surrounding the hydroelectric power plants, horizontal velocity fields are constructed using a unified methodology based on observations from permanent GNSS stations for the period 2019–2024. This approach made it possible to quantitatively characterize the *background* slow deformation processes, assess spatial gradients and local anomalies, and provide an appropriate geodynamic context for engineering monitoring systems of hydraulic structures.

Methodology

The displacement vector of any GNSS station can be defined as:

$$\boldsymbol{d} = (d_E, d_N, d_U)^T \tag{1}$$

The vector ***d*** includes a component describing the station motion caused by the drift of the lithospheric plate. In the global ITRF coordinate systems, the displacement velocity is given as:

$$d_{(ITRF)} = \Omega \times \boldsymbol{r} \tag{2}$$

After removing the global component $d_{(ITRF)}$ from the vector ***d***, the motion associated with regional geodynamic processes remains

$$d_{(region)} = d - d_{(ITRF)} \tag{3}$$

The vector of regional deformations is a manifestation of compression or extension of the Earth's crust; movements of large blocks of the lithosphere; tectonic activity of rift zones; deep faults; distributed stress fields (post-earthquake relaxation, slow tectonic shifts, isostatic effects).

Accordingly, the vector $d_{(region)}$ for the European continent is the sum of the velocity vectors in the ETRF system and local deformations of the Earth's surface:

$$d_{(region)} = d_{(ETRF)} + d_{(loc)} \tag{4}$$

The local deformation vector plays an important role in dam monitoring, as it determines the real deformations of the structure and foundation. This component includes the effects of:

- settlement of individual blocks;
- deflections or tilts of structures;
- local base displacements [Tretyak et al., 2021];
- temperature and seismic effects [Brusak, et al., 2025; Savchuk & Doskich, 2025];
- deformations caused by changes in the water level in the reservoir [Tretyak, K., et al., 2024].

The determination of local deformation vectors is possible only through the processing of long-term time series of displacements of control points within hydropower facilities, derived from high-precision geodetic measurements.

However, the vector $d_{(ETRF)}$ manifests itself as a systematic influence on the deformations of engineering structures, and its consideration makes it possible to account for the long-term systematic component of deformation accumulation. Removing this component allows the analysis to focus on relative changes that reflect the actual condition of the engineering structure. Ignoring the displacement vector $d_{(ETRF)}$ would lead to an artificial overestimation of the assessed rates of local deformations. Without compensation for regional motion, it is not possible to correctly evaluate the stress–strain state of a structure, as tectonically induced trends would be superimposed on local low-amplitude thermo-hydrostatic effects.

To detect and quantitatively assess deformations caused by the displacement vector $d_{(ETRF)}$ around hydropower complexes, data from permanent GNSS stations were used. The raw data for this study were obtained from the GeoTerrace and System.Net GNSS CORS networks, which provide continuous monitoring of station positions and, for long time series, enable geodynamic investigations [Khoda, 2024; Tretyak et al., 2024b].

The input data consisted of daily RINEX files processed using Bernese GNSS software, enabling high-precision vector processing of observations. Data processing was performed using the double-difference method, with stations from the IGS network employed as reference points. The computations were based exclusively on GPS observations. Current IGS20 standards for phase centre variations and other required corrections were applied to ensure high accuracy of GNSS-derived coordinates.

The processing workflow began with preliminary phase data processing for each baseline using triple-difference techniques. Cycle slips were resolved through analysis of various linear combinations of the L1 and L2 frequencies, while unreliable data points were removed or recalibrated to improve solution quality. An elevation cut-off angle of 7° was applied to mitigate the influence of low-elevation observations.

Tropospheric delays were modelled using the GMF and DRY-GMF models with a two-hour update interval, allowing for the consideration of variable atmospheric conditions. Ionospheric effects were mitigated using the ionosphere-free dual-frequency linear combination, improving ambiguity resolution and reducing ionospheric disturbances. Satellite orbits and Earth orientation parameters were obtained from the most precise available IGS products, ensuring high accuracy of the estimated coordinates.

Station coordinates were estimated using a weighted least squares algorithm that incorporates ionospheric corrections derived from reference stations. This approach enhances coordinate accuracy and reduces the impact of systematic errors. Overall, the accuracy of daily coordinate solutions typically ranged from approximately 2–3 mm in the horizontal components and 7–8 mm in the vertical component.

The results of the daily solutions were compiled into GNSS time series and used for subsequent analysis. Data filtering was applied to all stations, as sporadic data outliers were observed due to GNSS signal jamming and spoofing during hostilities in Ukraine. In addition, time series for most stations were manually corrected to account for antenna and equipment changes. A statistical approach using the weighted least squares criterion is applied to remove seasonal signals from GNSS time series and is used to estimate the linear trend [Nistor, et al., 2021; Santamaría-Gómez & Ray, 2021; He, et al., 2025].

This study utilized GNSS station data surrounding the hydropower facilities, including 9 stations for the Dnister Hydropower Complex, 7 for the Dnipro HPP, and 11 for the Kremenchuk HPP. A previous study [Tretyak et al., 2024b] demonstrated that annual GNSS station vectors for the period 2021–2023 over Ukraine exhibit high consistency with residual values of the ITRF-2020 model, obtained by subtracting the maximum value over the territory of Ukraine.

In the present work, substantially longer GNSS observation time series were employed, covering up to seven years for some stations. Furthermore, the analysis was conducted separately for each hydropower facility, enabling a more detailed characterization of local geodynamic conditions. To assess regional activity and ensure correct interpretation, the derived velocities were expressed in the ETRF-2020 reference frame.

The following sections present a detailed analysis of GNSS time series, an assessment of their data integrity, and the results of deformation field modelling for each hydroelectric power plant individually.

Dnister Hydropower Complex

The Dnister Hydropower Complex (Dnister HPP-1, HPP-2, and the pumped-storage power plant) is one of the key nodes of Ukraine's energy system. It is located in a tectonically complex region at the intersection of the Volyn–Podillia and Moldavian uplands along the Dnister River valley. According to current building regulations, the area belongs to a zone of moderate seismicity (6–7 points on the MSK-64 scale). Both natural seismicity and so-called triggered events associated with reservoir level fluctuations have been reported in the literature [DBN, 2014; Verbytskyi et al., 2019]. Under such conditions, regular GNSS CORS monitoring of the surrounding territory represents an important tool for the correct interpretation of deformations of hydraulic structures.

For the analysis, continuous daily observations from eight permanent stations of the GeoTerrace and System.Net networks were used: KLMN, NDNS, RALI, VINK, VINT, VOVK, VRBK, and YAMP.

The main selection criteria were high integrity of daily solutions, operational stability, and a favourable network geometry. Based on these data, displacement time series and annual velocities in the V_N (north) and V_E (east) components were derived in the ETRF-2020 reference frame (Fig. 2).

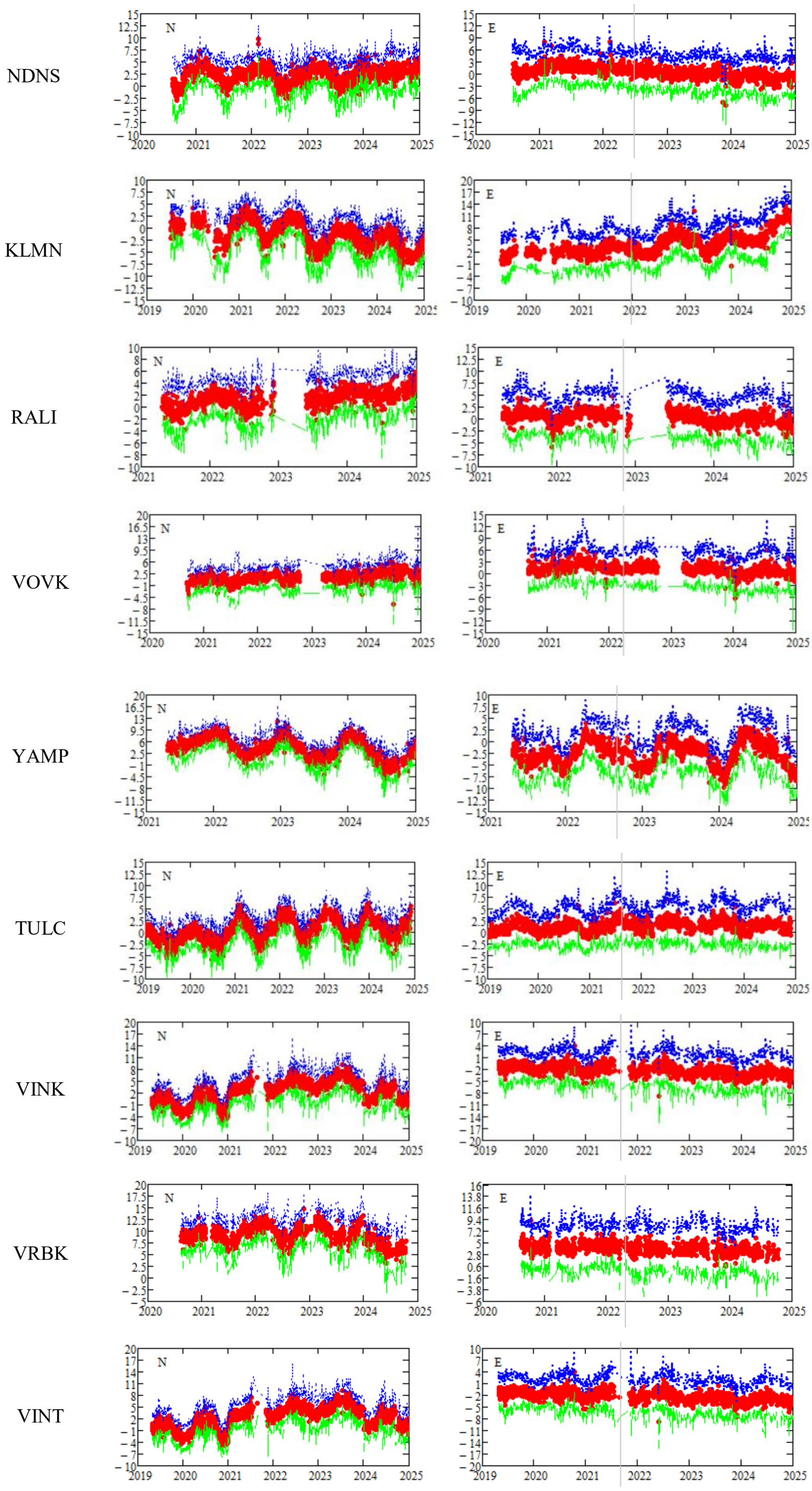

Fig. 2. Time series of displacements of GNSS stations located around the Dnister Hydropower Complex.

As can be seen from the plots (see Fig. 2), most stations exhibit a pronounced seasonal component in *N* component, whereas *E* component is relatively more stable. Such seasonality is typical of regions with pronounced thermo-hydrological variability and confirms the necessity of removing seasonal displacements prior to long-term trend analysis.

Data integrity is presented in Table 1.

Table 1

GNSS data integrity located around the Dnister Hydropower Complex, %

Station Name	2019	2020	2021	2022	2023	2024
KLMN	27	64	98	92	95	87
NDNS	–	38	93	91	98	89
RALI	–	–	61	75	59	84
TULC	81	96	93	78	80	55
VINK	58	95	59	66	80	66
VINT	64	95	83	77	89	77
VOVK	–	29	87	69	71	86
VRBK	–	37	72	71	58	52
YAMP	–	–	60	85	96	92

Data quality and integrity. Most stations (KLMN, NDNS, VOVK, partly VINT) demonstrated high data integrity (>80 %). At the same time, in 2023, there was a significant decrease in the integrity and stability of data acquisition for RALI (59 %) and VRBK (58 %), which is explained by the complications of CORS operation during the war (blackouts, communication failures, electronic warfare and spoofing effects [Brusak et al., 2024]. Table 2 below shows the annual velocities and their standart deviations SDs for GNSS stations around the Dnister Hydropower Complex.

Table 2

Annual velocities and their SDs for GNSS stations around the Dnister Hydropower Complexin the ETRF-2020 system

GNSS station	Annual velocities, mm/year			UPC annual velocities, mm	
	V_N	V_E	V_L	V_N	V_E
NDNS	–1.1	–1.7	2.0	0.1	0.1
RALI	–1.7	–2.0	2.6	0.1	0.1
VOVK	–1.1	–1.7	2.0	0.1	0.1
YAMP	–5.0	–2.3	5.5	0.2	0.1
KLMN	–1.8	–0.7	2.0	0.1	0.1
TULC	–0.1	–0.6	0.6	0.1	0.1
VINK	–0.0	–0.5	0.5	0.1	0.1
VINT	0.2	–0.4	0.4	0.1	0.0
VRBK	–5.2	–3.8	6.4	0.2	0.2

Fig. 3 shows the annual station velocities and the condensed vector field of GNSS stations around the Dnister Hydropower Complex.

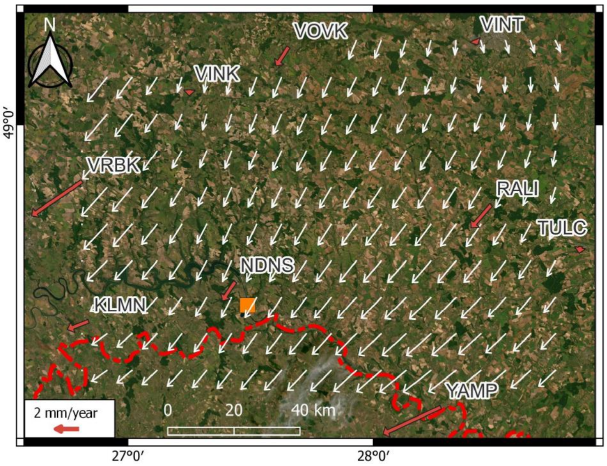

Fig 3. Annual station velocities and condensed vector field of GNSS stations around the Dnister Hydropower Complex.

The annual velocities range from 0.4 to 6.4 mm/yr. The maximum values were recorded at stations VRBK (V_L = 6.4 mm/yr; V_N = −5.2 mm/yr, V_E = −3.8 mm/yr) and YAMP (V_L = 5.5 mm/yr; V_N = −5.0 mm/yr, V_E = −2.3 mm/yr). The smallest velocity magnitudes were observed at VINT (0.4 mm/yr), VINK (0.5 mm/yr), and TULC (0.6 mm/yr).

The annual station velocities and the densified vector field indicate an increasing gradient from the northeast towards the southwest, reaching approximately 5 mm/yr, with a predominantly south-western direction of motion. The natural residual geodynamic deformation at the location of the Dnister Hydropower Complex itself reaches approximately 2 mm/yr, characterized by a dominant south-western vector and a spatial gradient from east to west. These results are consistent with independent regional assessments of present-day crustal motions derived from Ukrainian GNSS network data [Tretyak et al., 2024b; Khoda, 2024], confirming the validity and applicability of GNSS monitoring for the surrounding areas of hydraulic structures.

The dilatation map of the territory surrounding the Dnister Hydropower Complex is shown in Fig. 4.

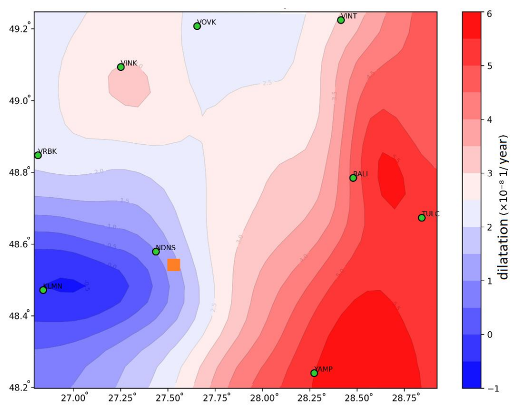

Fig. 4. Map of dilatation distribution in the territory around Dnister Hydropower Complex.

The identified dilatation field reflects slow natural deformations of the surrounding territories, which form the ackground for interpreting the behaviour of the hydraulic structures of Dnister Hydropower Complex. In engineering monitoring practice, such maps make it possible to distinguish anthropogenic and structural responses of the facilities from the regional geodynamic background and to localize potentially sensitive slope and shoreline areas. As shown in Fig. 4, the dilatation parameter at the location of the Dnister Hydropower Complex is approximately -1.7×10^{-8} 1/year.

Kremenchuk Hydroelectric Power Plant

To investigate the geodynamic characteristics of the area surrounding the Kremenchuk HPP, an approach analogous to that applied for the Dnister Hydropower Complex was used. The primary data sources were continuous observations from GNSS stations of the System.Net network, which provide high-precision determination of spatial coordinates.

Following the same presentation sequence, the results for the Kremenchuk HPP are discussed below. The coordinate time series of GNSS stations located in its vicinity are shown in Fig. 5.

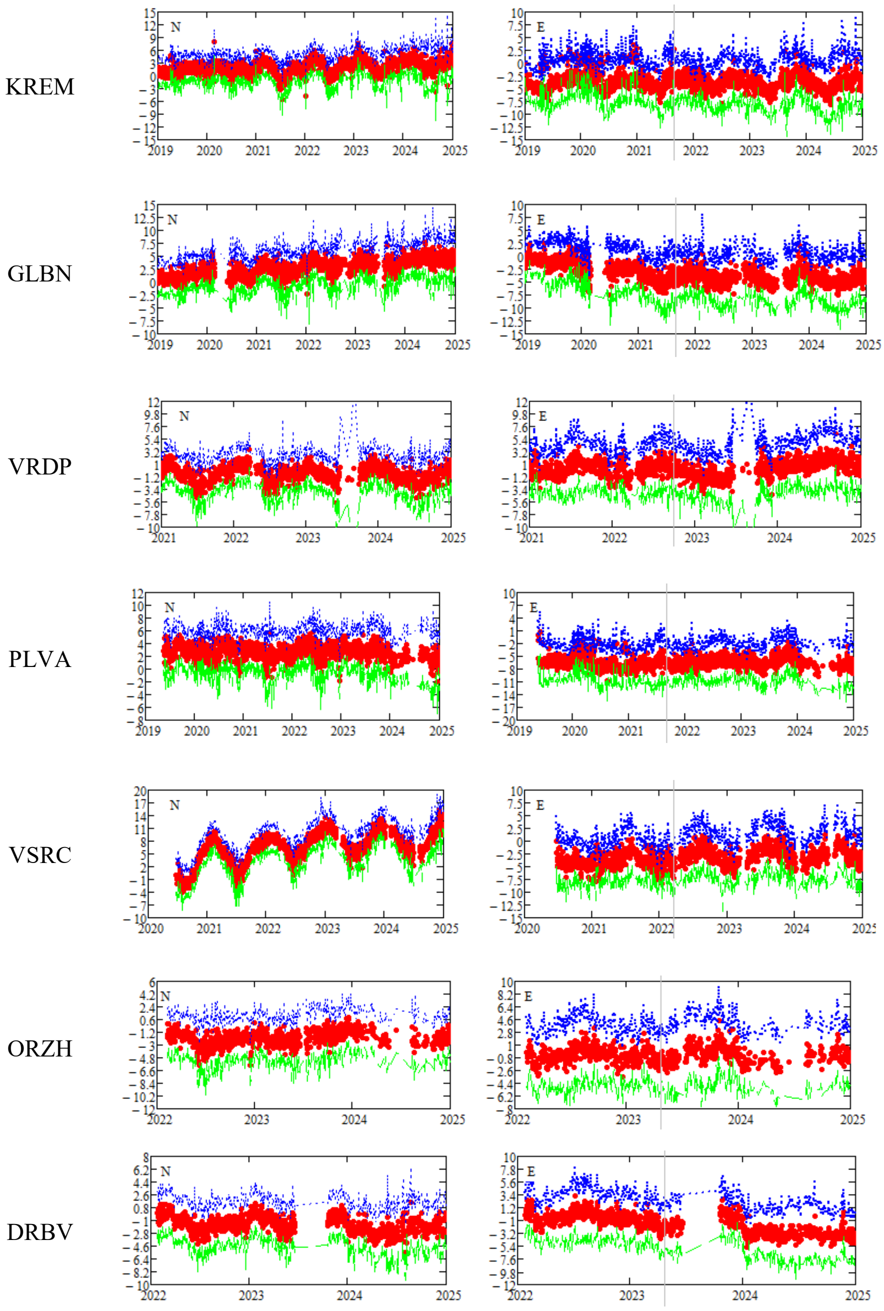

Fig. 5. Time series of displacements of GNSS stations located around the Kremenchuk HPP.

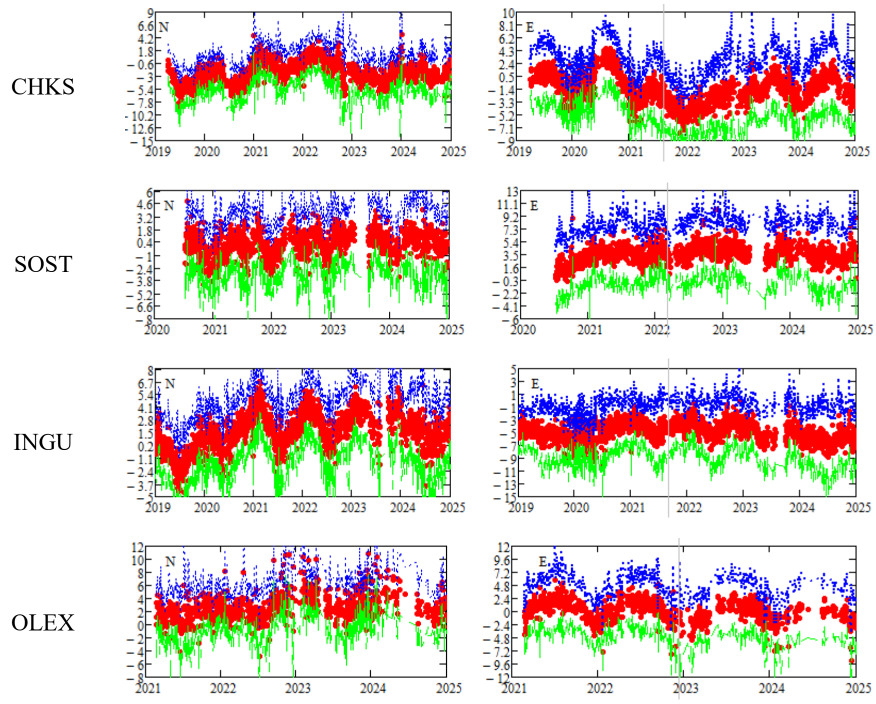

Fig. 5. (Continuation). Time series of displacements of GNSS stations located around the Kremenchuk HPP.

To ensure data homogeneity and exclude potential anthropogenic artefacts, a quality assessment of the daily solutions was performed. The data integrity of GNSS stations located in the vicinity of the Kremenchuk HPP is presented in the table below.

Table 3

Data integrity of GNSS stations around the Kremenchuk HPP, %

Station Name	2019	2020	2021	2022	2023	2024
DRBV	–	–	–	88	63	77
ORZH	–	–	–	83	87	36
VSRC	–	52	91	81	76	69
CHKS	58	87	95	75	83	70
GLBN	80	72	96	73	71	79
PLVA	51	96	90	93	88	35
KREM	80	87	97	87	84	74
SOST	–	44	92	83	70	64
INGU	86	95	90	92	57	77
OLEX	–	–	71	81	67	36
VRDP	86	95	90	82	67	84
DRBV	–	–	–	88	62	78
ORZH	–	–	–	83	86	36
VSRC	–	52	91	81	76	69

The data cover the period 2019–2024, with the largest number of observations corresponding to 2022–2024. For most stations, the proportion of annual observations ranged between 70 % and 90 %, which is considered a satisfactory level for geodynamic analysis. The smallest data availability in 2024 was observed for the OLEX, PLVA, and ORZH stations; therefore, the annual velocities for these stations were not considered for that year.

The annual displacement velocities of GNSS stations in the vicinity of the Kremenchuk HPP are presented in the table below.

Table 4

Annual velocities and their UPCs for GNSS stations around the Kremenchuk HPP (ETRF-2020)

GNSS station	Annual velocities, mm/year			UPC annual velocities, mm	
	V_N	V_E	V_L	V_N	V_E
VRDP	0.3	0.0	0.3	0.1	0.1
KREM	0.2	–0.0	0.2	0.1	0.1
GLBN	0.1	–0.3	0.3	0.1	0.1
PLVA	–0.1	1.2	1.2	0.1	0.1
VSRC	–1.8	–0.3	1.8	0.1	0.1
DRBV	–1.0	–1.1	1.6	0.1	0.1
ORZH	1.0	0.6	1.1	0.1	0.1
CHKS	–0.1	–0.5	0.5	0.1	0.1
SOST	–0.8	–1.6	1.8	0.1	0.1
OLEX	–0.2	0.2	0.3	0.1	0.1
INGU	0.2	0.2	0.3	0.0	0.1

Based on the processed data, the area surrounding the Kremenchuk HPP is characterized by overall kinematic stability, although some stations exhibit local deviations. The largest vector magnitudes were recorded at stations GLVK and ZPRZ, amounting to V_L = 2.5 mm/yr (V_N = −2.4 mm/yr, V_E = −0.6 mm/yr) and V_L = 1.5 mm/yr (V_N = 1.1 mm/yr, V_E = 1.1 mm/yr), respectively. These deviations may indicate the influence of local geological conditions or the geomorphology of the Dnipro River valley.

Fig. 6 presents the annual station velocities and the densified GNSS vector field surrounding the Kremenchuk HPP.

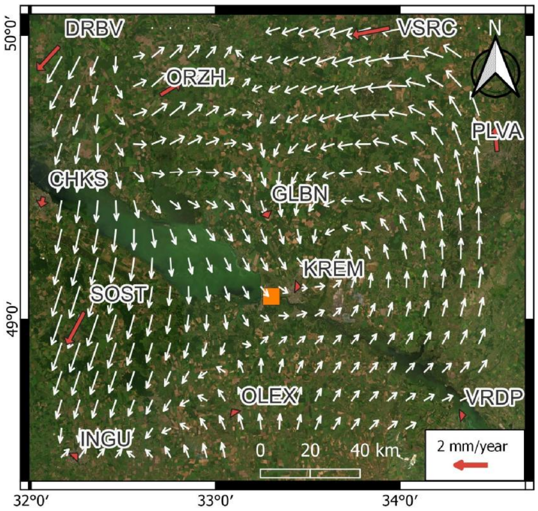

Fig. 6. Annual station velocities and condensed vector field of GNSS stations around the Kremenchuk HPP.

Fig. 7 shows a map of the dilation of the territory around the Kremenchuk HPP.

As can be seen from the figure, the largest extensional zones are observed in the eastern part of the study area, particularly around the SOST station, whereas compressional features are evident in the northern sector.

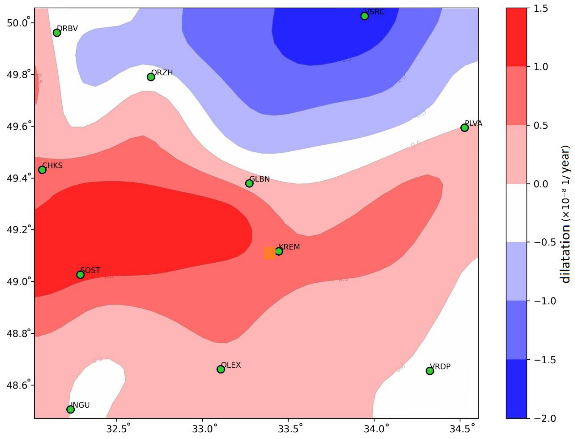

Fig. 7. Map of dilatation distribution in the territory around the Kremenchuk HPP.

Dnipro Hydroelectric Power Plant

Based on the processed data, the area surrounding the Kremenchuk HPP is characterized by overall stability, with the extensional strain at the dam location estimated at approximately $+0.7\times10^{-8}$ 1/year. To analyse the geodynamic characteristics of the area surrounding the Dnipro Hydropower Complex, data from seven permanent GNSS stations of the System.Net network were used. The primary criteria for station selection included the duration of operation, stability of antenna monumentation, and adequate spatial coverage of the reservoir influence zone. Fig. 8 shows the displacement time series of GNSS stations located in the vicinity of the Dnipro HPP.

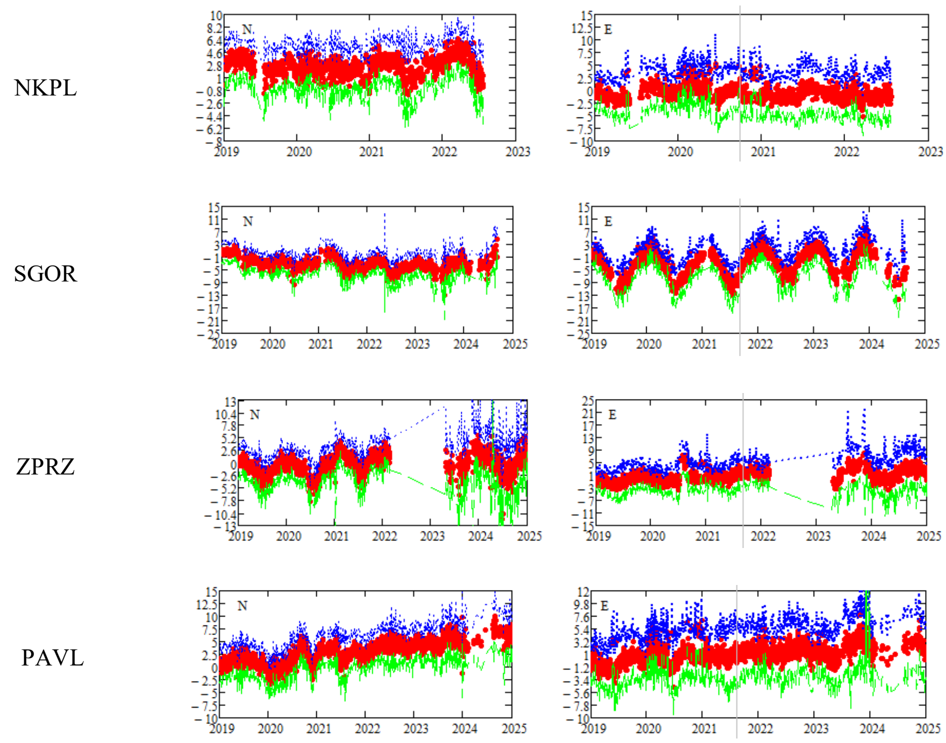

Fig. 8. Time series of displacements of GNSS stations located around the Dnipro HPP.

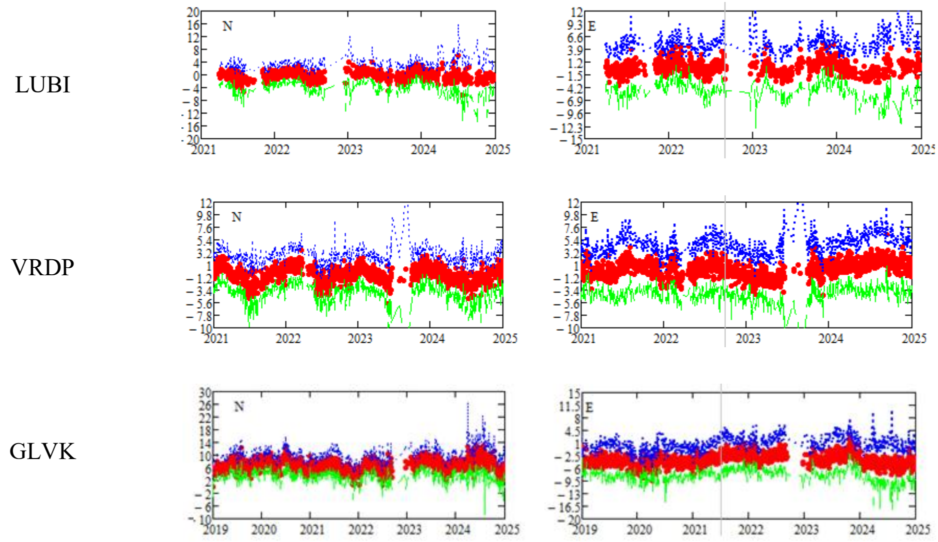

Fig. 8. (Continuation). Time series of displacements of GNSS stations located around the Dnipro HPP

As can be seen from Fig. 8, most stations exhibit a clear annual seasonal pattern in the data. A visually discernible increasing trend is observed at stations ZPRZ and PAVL. Data homogeneity was also analysed, and the results are presented in Table 5.

Table 5

Data integrity % of GNSS stations located near the Dnipro HPP, %

Station Name	2019	2020	2021	2022	2023	2024
VRDP	86	95	91	82	67	84
LUBI	–	–	50	58	64	51
PAVL	85	96	83	89	87	28
ZLST	84	89	90	81	81	87
GLVK	71	88	90	61	69	72
NKPL	75	96	88	52	–	–
ZPRZ	82	85	90	14	34	84
SGOR	74	91	78	86	61	21

As shown in Table 5, data are available for all stations from 2019 to 2024, except for LUBI and NKPL. In addition, low data integrity is observed for PAVL in 2024 and for ZPRZ in 2022 and 2023. These years were therefore excluded from the analysis for the respective stations. The annual displacement velocities of GNSS stations near the Dnipro HPP in the ETRF-2020 reference frame are presented in Table 6.

Based on the processed data, the area surrounding the Dnipro HPP is characterized by overall kinematic stability, although certain stations exhibit local deviations. The largest vector magnitudes were recorded at stations GLVK and ZPRZ, amounting to V_L = 2.5 mm/yr (V_N = −2.4 mm/yr, V_E = −0.6 mm/yr) and V_L = 1.5 mm/yr (V_N = 1.1 mm/yr, V_E = 1.1 mm/yr), respectively. These patterns may indicate the influence of local geological conditions or the geomorphology of the Dnipro River valley.

Table 6

Annual displacement rates of GNSS stations near the Dnipro HPP (ETRF-2020)

GNSS station	Annual velocities, mm/year			UPC annual velocities, mm	
	V_N	V_E	V_L	V_N	V_E
NKPL	–1.5	–0.9	1.7	0.1	0.1
GLVK	–2.4	–0.6	2.5	0.1	0.1
LUBI	–0.1	–0.2	0.2	0.1	0.1
PAVL	0.6	0.4	0.8	0.1	0.1
SGOR	–0.3	0.1	0.3	0.1	0.1
VRDP	0.3	0.0	0.3	0.1	0.1
ZPRZ	1.1	1.1	1.5	0.1	0.1

Fig. 6 presents the annual station velocities and the densified GNSS vector field surrounding the Dnipro HPP.

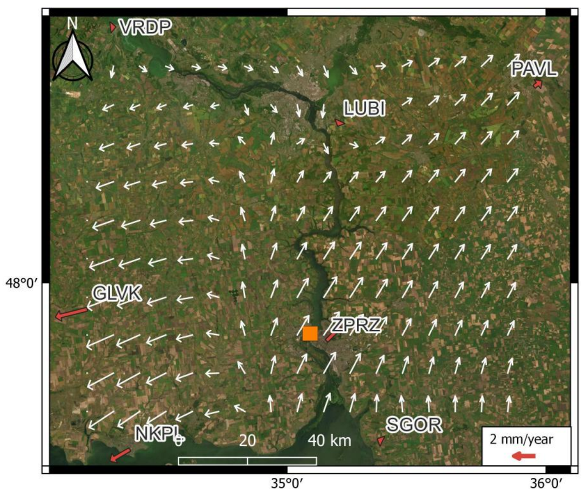

Fig. 9. Annual station velocities and condensed vector field of GNSS stations around Dnipro HPP.

Fig. 10 shows a map of the dilation of the area around the Dnipro HPP.

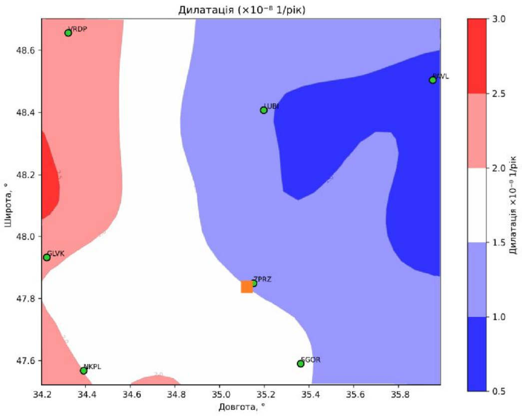

Fig 10. Map of dilatation distribution in the territory around the Dnipro HPP.

The map shows that the entire territory is subject to expansion. At the same time, in the area of the Dnipro hydroelectric power station dam, it is $+1.5\times10^{-8}$ 1/year.

Calculation of dam deformations

At the final stage of the study, the deformation of the dams over their operational lifetimes was evaluated under the influence of regional geodynamic deformation processes. It was assumed that the present-day deformation rates identified for the period 2019–2024 are representative of the entire service life of the structures. It is acknowledged that geodynamic deformation processes may vary over the course of a century due to various endogenous and exogenous factors; however, they can only be quantitatively assessed using GNSS CORS network data, which have been available in the HPP regions only since 2019.

The Dnipro HPP is considered in greater detail. The official start of its construction dates back to 1927; therefore, the operational lifetime of this hydropower facility approaches one century. Such a long period of operation imposes increased requirements for assessing the long-term stability and reliability of the structure, as loads accumulated over decades may exert gradual, subtle, yet potentially critical effects on its integrity.

As noted above, the dilatation in the vicinity of the dam is approximately $+1.5 \times 10^{-8}$ yr^{-1}. The total length of the structure is about 1000 m (216 m of the water intake section of HPP-1 and 760 m of the spillway dam). For this dilatation value, the expected elongation of the dam is approximately $+1.5 \times 10^{-2}$ mm/yr, which corresponds to roughly +1.5 mm over a century-long operational period.

At first glance, such deformations may appear negligible; however, their analysis is of considerable practical importance. In long-lived infrastructure, even small-scale deformation processes can serve as indicators of systematic changes in the geological environment or in the load-bearing elements of the structure.

A similar analysis was performed for the Kremenchuk HPP. The dam length is 10,500 m, and construction began in 1954, corresponding to an operational period of approximately 70 years. The dilatation determined in this study for the Kremenchuk HPP dam is $+0.7 \times 10^{-8}$ yr^{-1}. Accordingly, the annual deformation amounts to $+0.74 \times 10^{-2}$ mm/yr, resulting in a cumulative deformation of approximately +0.5 mm over 70 years.

The Dnister Hydropower Complex consists of HPP-1, a pumped-storage power plant (PSPP), and HPP-2. As an example, the dam of HPP-1 is considered; its total length is 1082 m, including both embankment and concrete sections. Construction of Dnister HPP-1 began in 1973, i.e., about 50 years ago. The dilatation at the dam site indicates compression of -1.7×10^{-8} yr^{-1}, corresponding to an annual deformation of -1.7×10^{-2} mm/yr, which results in approximately −0.9 mm over a 50-year period.

Although the total deformations accumulated over the operational lifetimes of the hydropower facilities are small, the methodology proposed in this study is universal and can be applied to assess long-term deformations of other dams. In particular, earthen and concrete protective dams at ponds and landfills may also be analysed using this approach [Savchyn et al., 2020]. Such structures can extend over several kilometres, which further increases the relevance of the proposed analysis. The use of GNSS data enables the derivation of objective, instrumentally validated estimates of regional-scale deformations, which is especially important in regions characterized by complex geodynamic conditions. The relevance of this issue is further enhanced by several factors: increased loading on hydraulic structures due to climate change [Kopiika et al., 2025a], hydrological extremes and irregular water-level fluctuations [Tretyak et al., 2024c]; ageing of structures, for which accumulated micro-deformations may serve as indicators of material degradation; regional geodynamic activity capable of modifying background deformation processes; and wartime threats, which require a deeper understanding of the actual structural condition and the ability of facilities to withstand additional extreme impacts, as well as prioritization of infrastructure restoration [Kopiika et al., 2025b]

The assessment of slow deformation processes, even when their magnitudes are very small, is of strategic importance for long-term forecasting of the condition of hydraulic structures, early detection of potentially adverse trends, and enhancement of the reliability and resilience of hydropower facilities under challenging operational conditions.

This approach is particularly relevant for areas with pronounced deformation gradients–for example, mountainous regions–where tectonic processes, landslide activity, or uneven ground settlement may generate significantly larger and spatially heterogeneous deformation fields. Under such conditions, GNSS-based monitoring provides critically important information to ensure the safety and stable operation of hydropower facilities.

Conclusions

This study presents an assessment of the geodynamic characteristics of areas adjacent to hydroelectric power plants in Ukraine based on data from permanent GNSS stations of the GeoTerrace and System.Net networks. Observations covering the period 2019–2025 were used, processed with Bernese 5.2 software and transformed into the ETRF-2020 reference frame. As the integrity of the time series varies among stations, only GNSS stations with observation periods ranging from 3 to 7 years were included in the final analysis.

The research focuses on territories surrounding the Dnister Hydropower Complex, the Dnipro HPP, and the Kremenchuk HPP. For each of these areas, dilatation maps were constructed separately to represent the spatial distribution of deformation processes. Linear trends were determined and annual horizontal velocities were calculated for all stations. In the vicinity of the Dnister Hydropower Complex, horizontal velocities range from 0.4 to 6.4 mm/yr, reflecting elevated geodynamic activity and indicating significant deformation processes around the hydraulic structures. For the Kremenchuk HPP, annual GNSS station velocities range from 0.3 to 1.8 mm/yr, while for the Dnipro HPP they range from 0.2 to 2.5 mm/yr, indicating a more moderate level of deformation in these regions.

The applied methodology made it possible to estimate the integrated dam deformations accumulated over their entire operational lifetimes as a result of regional geodynamic processes. The obtained values amount to approximately +1.5 mm for the Dnipro HPP, +0.5 mm for the Kremenchuk HPP, and −0.9 mm for Dnister HPP-1. Although these magnitudes are small relative to the long service lives of the structures, their quantification is of considerable engineering importance, as they characterize the background geodynamic influence acting on the facilities.

The proposed methodology is universal and can be applied to deformation analysis at other hydroelectric power plants worldwide, particularly given the current density of permanent GNSS station networks. Prospects for further research include applying this approach to assess geodynamic impacts on other large-scale engineering structures such as hydropower complexes, nuclear power plants, and other strategic facilities both in Ukraine and abroad. Earthen and concrete dams of landfills, ponds, and other structures also represent important potential targets for analysis using this methodology.

Despite the relatively small deformations identified over the operational periods of Ukrainian HPPs, the results confirm the effectiveness and versatility of the proposed approach for assessing slow geodynamic processes based on permanent GNSS station data. The method enables the derivation of objective, instrumentally validated estimates of regional deformations, which is particularly important in complex tectonic settings.

The analysis of slow deformation processes is of strategic importance for long-term forecasting of the condition of hydraulic structures, timely identification of adverse trends, and enhancement of their reliability. This approach is especially relevant in regions with pronounced deformation gradients, such as mountainous areas, where tectonic activity, landslides, and uneven ground settlement may generate significant spatial contrasts in deformation fields.

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ГЕОДИНАМІЧНІ ОСОБЛИВОСТІ ТЕРИТОРІЙ ДОВКОЛА ГЕС УКРАЇНИ ЗА ДАНИМИ ПЕРМАНЕНТНИХ ГНСС-СТАНЦІЙ

У роботі здійснено оцінку геодинамічних особливостей територій навколо гідроелектростанцій України на основі даних перманентних ГНСС-станцій GeoTerrace та System.Net за 2019–2025 рр. Добові файли обчислено у Bernese 5.2 та переобчислено у систему координат ETRF-2020. Методика передбачає визначення лінійного тренду та щорічних горизонтальних швидкостей ГНСС-станцій за компонентами на північ та схід. Виконано фільтрацію ГНСС-станцій, які розглядали за тривалістю, цілісністю спостережень та оптимальним розташуванням, а також вилучено результати зі значними помилками. Розглянуто ГНСС-мережі довкола Дністровського гідроенергокомплексу, Дніпровської та Кременчуцької ГЕС, для яких визначено вектори регіональних деформацій, які є проявом стиснення або розтягнення земної кори; рухів великих блоків літосфери; тектонічної активності рифтових зон; глибинних розломів; розподілених полів напружень. Для кожної території довкола ГЕС побудовано картосхеми поля розподілу дилатацій та визначено параметр дилатації у місці розташування греблі. На останньому етапі оцінено деформації греблі, спричинені геодинамічним впливом за час експлуатації, який на міліметровому рівні для усіх розглянутих споруд. Запропонована методологія, що ґрунтується на мережах ГНСС-станцій, може бути використана і для інших великих інженерних об’єктів в Україні та у світі.

Ключові слова: сучасна геодинаміка, деформації земної кори, гідроелектростанції, горизонтальні рухи земної кори, швидкості зміщень ГНСС-станцій, ГНСС-мережа GeoTerrace, ГНСС-мережа SystemNet.

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