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IMPACT OF NON-TIDAL ATMOSPHERIC LOADING ON CIVIL ENGINEERING STRUCTURES

The paper analyzes the vertical displacements of the GNSS sites of civil engineering structures caused by non-tidal atmospheric loading (NTAL). The object of the study is the Dnister Hydroelectric Power Plant No. 1 (HPP-1) and its GNSS monitoring network. The initial data are the RINEX-files of 14 GNSS stations of the Dnister HPP-1 and 8 permanent GNSS stations within a radius of 100 km, the NTAL model downloaded from the repository of German Research Centre for Geosciences GFZ for 2019–2021, and materials on the geological structure of the object. Methods include comparison and analysis of the altitude component of GNSS time series with model values of NTAL as well as interpretation of the geodynamic vertical displacements, taking into account the analysis of the geological structure. As a result, it was found that the sites of the GNSS network of the Dnister HPP-1 undergo less vertical displacements than the permanent GNSS stations within a radius of 100 km. This corresponds to the difference in thickness and density of the rocks under the GNSS sites and stations, so they undergo different elastic deformations by the same NTAL. In addition, the research detected different dynamics of vertical displacements of GNSS sites on the dam and on the river banks. It leads to cracks and deformations of concrete structures in the dam-bank contact zones. During the anomalous impact of NTAL, the altitude of even nearby sites can change if the geological structure beneath them is different. The work shows that for civil engineering structures it is necessary to apply special models to take into account NTAL deformations for high-precision engineering and geodetic measurements.

Key words: GNSS time series; vertical deformations; non-tidal atmospheric loading; the Dnister HPP-1.

Introduction

The use of the Global Navigation Satellite Systems (GNSS) method is one of the key ones both for the determining of modern geodynamic processes in a region and for monitoring large engineering structures. Traditionally, the detection of geodynamic processes is carried out based on the analysis of the time series of changes in the coordinates of GNSS stations.

Quite often in the analysis of short time series (up to 30 days) it is possible to detect shifts and displacements in the spatial position of the GNSS station. In addition, similar synchronous displacements are detected at neighboring GNSS stations. This indicates that they are influenced by a certain factor.

The vertical displacements of permanent GNSS stations in the European region were recorded at the end of December 2019 during 4–10 days [Brusak, & Tretyak, 2020]. At a number of permanent GNSS stations, the vertical displacements correlate with models of atmospheric loadings in the European region. However, it has been shown in research [Brusak, & Tretyak, 2021] that for some regions it would be appropriate to take into account the geological features of the territories. Thus, Fig. 1 shows the conditional division of the territory of western Ukraine by the magnitude of the vertical displacements. The line divides the GNSS stations into two groups with vertical displacements up to and over 15 mm. Vertical displacements smaller than 15 mm do not correspond to the model values of atmospheric loadings.

It is also noticeable that at civil engineering structures the displacements of the GNSS stations are weakly interrelated with the model values of the atmospheric loadings and require additional research [Tretyak, et al., 2021a; 2021b]. This study is conducted to analyze the impact of non-tidal atmospheric loading (NTAL) on civil engineering structures.

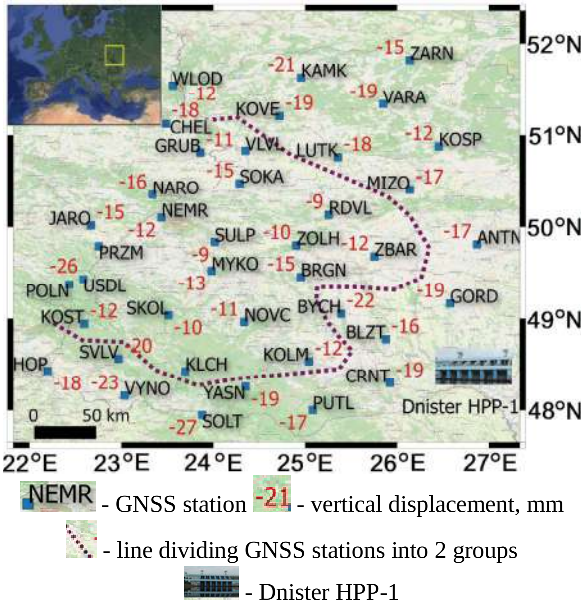


Fig. 1. Analysis of the dynamics of the vertical displacements of Geoterrace network in December 2019 [Brusak & Tretyak, 2021]

Environmental loadings

Environmental factors influencing the results of the GNSS time series include both tidal and non-tidal loadings. Nowadays tidal factors are quite easy to model for a long time and they depend on the tidal forces of the Moon and the Sun, respectively. At present, the International Earth Rotation Service conventions recommend taking into account the modeled deformations in software products caused by tidal loadings to GNSS time series. At the same time, there are no such recommendations for non-tidal models.

Non-tidal loading (NTL) also deforms the Earth's surface, adding to the variability of the coordinates of geodetic stations. NTL includes non-tidal atmospheric loading (NTAL), which depends on the redistribution of atmospheric masses, non-tidal ocean loading (NTOL). It is primarily formed by redistribution of masses on the ocean bottom and corresponding pressure changes, and hydrological changes in the region's river network. It is known that the variability of vertical land motions decreases on average by up to 20 % when correcting the GNSS series for non-tidal atmospheric and oceanic loading employing either barotropic or baroclinic ocean models [Mémin et al., 2020]. The influence of NTL on the results of other geodetic networks is also investigated in particular observations of Very Long Baseline Interferometry (VLBI) stations [Petrov, & Boy, 2003; Glomsda, et. al, 2019].

Loading caused by atmospheric pressure

The Earth reacts elastically to atmospheric pressure loading (APL), which is caused by the redistribution of atmospheric masses and some tidal effects. Subtracting from APL the tidal components, which can be modeled in advance (e.g., solar diurnal and semidiurnal), we obtain such elastic deformations of the Earth's surface that depend on the redistributing of atmosphere masses in different areas. We will call it non-tidal atmospheric loading (NTAL).

Correcting GNSS time series for the influence of APL is still under investigation [Tregoning, & van Dam, 2005; Rodrigues, 2007; Tregoning, & Watson, 2009; Dach, et al., 2011; Yue, et al., 2020; Kalinnikov, et al., 2020]. In order to improve the accuracy of GNSS solutions, Tregoning & Watson [2009] recommend taking into account both tidal and non-tidal atmospheric loads, as well as including these models in the current software packages which have already been implemented. Rodrigues [2007] estimates the effect of vertical displacements of the Earth's crust from the atmospheric loading effects on 45 GNSS stations in Europe and Asia. The researcher also finds a high correlation between the vertical motions of some continental GNSS stations and atmospheric loading. For mainland China, deformations of the upper crust are calculated according to GNSS stations. It is found that the maximum corrections for the northern region of China under the influence of atmospheric loading can reach 24 mm [Yue, et al., 2020].

There are several institutions that calculate models of the effects of changes in atmospheric phenomena and provide data to the public. APL models can be downloaded from the International Mass Loading Service [Petrov, L., 2015] and from the Vienna Mapping Functions Open Access Data [VMF]. The German Research Centre for Geosciences GFZ, namely Earth System Modelling group [ECMGFZ], provides NTAL models. Comparing the altitude component of the time series of these three models for the territory of western Ukraine, we can state that they are almost identical with deviations from 1 to 3 mm.

The study uses NTAL models for the center of figure downloaded from the ECMGFZ repository [http://esmdata.gfz-potsdam.de]. Model is derived from non-tidal atmospheric surface pressure given by 0.5×0.5° 3-hourly ECMWF operational data. Atmospheric tides were removed by harmonic analysis of 12 major tidal constituents. Non-tidal atmospheric surface pressure is resampled on a regular 0.125×0.125° global grid. To determine the NTAL [ECMGFZ], we analyzed the surface pressure time-series reanalysis of ERA-40, ERA-Interim, projected onto a time-invariant reference topography and the time-variable atmospheric density structure.

Depending on their geological structure, the regions will respond in a heterogeneous manner to the same loading, including atmospheric, if the rocks have different physical properties. However, in [Petrov, 2015] it is shown that the mean Earth's density ($\rho_{\oplus}$) is used for modeling the influence of non-tidal loadings. The authors emphasize on the importance of studying the influence of atmospheric loadings on the territory with the known geological structure. It is necessary to compare the elastic deformations for the sites under rocks of different densities, thicknesses, and age. The dense network of GNSS stations also needs to be taken into account. For this purpose, we consider the monitoring of the networks of hydroelectric power plants. They are provided with a dense network of GNSS stations for monitoring displacements and having a well-studied geological structure. There is an investigation of the impact of APL on the results of GNSS measurements for the Zagorskaya HPP-2 [Kalinnikov, et al., 2020]. The authors point out the need to use special models of APL for the correction of satellite measurements by the PPP method as an effective tool for monitoring complex engineering structures.

Condition of the Dnister HPP-1 facilities

Today a number of HPPs have been in operation for about half a century in Ukraine. Their dams are of the highest hydrodynamic danger of a man-made nature [Tretyak, et al., 2014; 2015]. The construction of HPP and the creation of reservoirs is an example of active intervention in geological, geodynamic, and hydrological conditions [Tretyak, et al., 2017]. As a result of this operation for half a century, a number of geodynamic phenomena can lead to the intensification of the deformation processes of engineering structures, which can lead to deaths, accidents, destruction, and material damage.

In the study, we consider the Dnister HPP-1 (see Fig. 1), which is a part of the Dnister Hydropower Complex built on the Dnister River and is located 60 km northwest of Mohyliv-Podilskyi, in the Vinnytsia region (48° 35′ 37″ N, 27° 27′ 8″ E). Fig. 2 shows a general view of the Dnister HPP-1. The purpose of the Dnister HPP-1 includes the following main tasks: electricity generation, regulation of water in the river due to spring and rain floods, land irrigation, water supply to nearby settlements. The building of the HPP is of complex and spillway type. Its length across the river is 153 m, and width along the river is 75 m.

Fig. 2. General view of the Dnister HPP-1

An inspection of the facilities of the Dnister HPP-1 in autumn, 2019 revealed cracks, and deformations in the body of the dam, which require detailed analysis. Fig. 3 shows the following damage and subsidence.

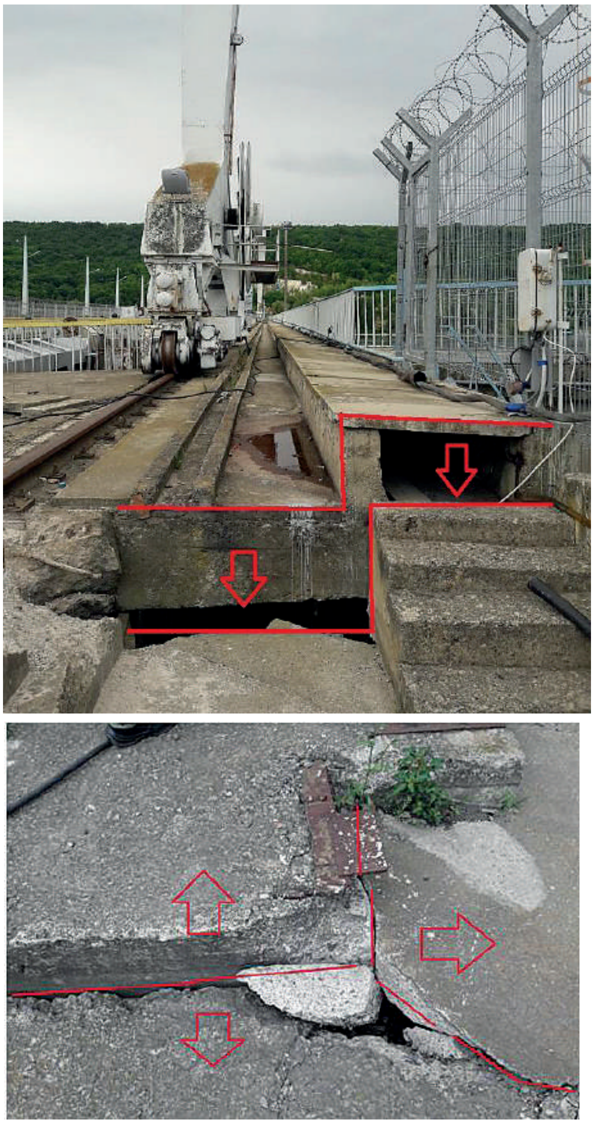


Fig. 3. Cracks and deformations in the body of the Dnister HPP-1 dam (photo autumn, 2019)

Similar hydropower facilities with different dam structures and shapes are actively monitored around the world. [Behr, et al., 1998; Dardanelli, et al., 2014; Yavaşoğlu, et al., 2018; Barzaghi, et al., 2018]. The study of the Pakoyma Dam in California, USA is one of the first successful experiments to ensure the reliability of the monitoring of dams by the GNSS method [Behr, et al., 1998]. The change in the water level in reservoirs is obtained from estimates of the water surface based on remote sensing data. It shows a correlation with the displacements of the GNSS continuous monitoring system for earth-dams. [Dardanelli, et al., 2014]. The study of the stability of the dam was based on the analysis of a series of GNSS observations as well as linear-angular measurements of the Ataturk Dam in Turkey which made it possible to identify the areas that were undergoing the greatest deformation [Yavaşoğlu, et al., 2018]. After evaluating and comparing the deformation of a dam in Italy using the classical and GNSS methods, Barzaghi et al., [2018] concluded that GNSS monitoring is a reliable method of monitoring HPPs.

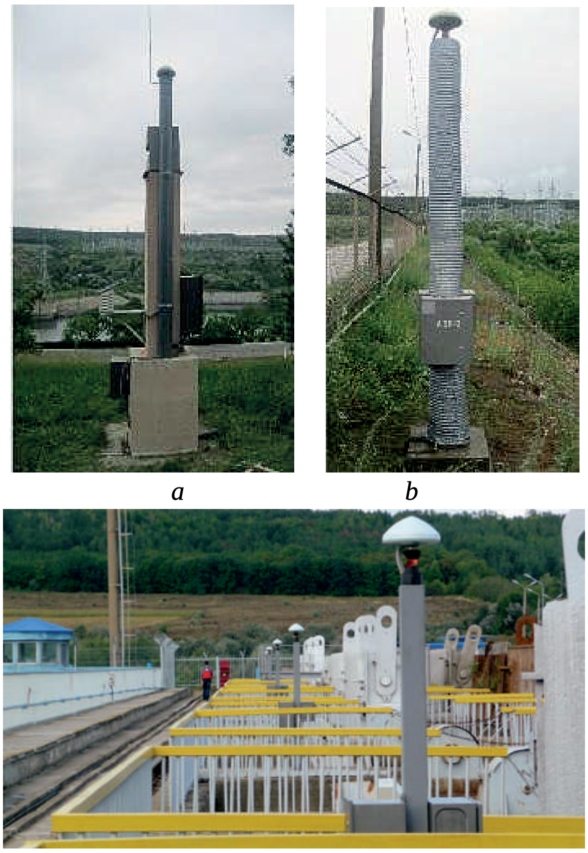
In order to increase the safety of the Dnister HPP-1 dam, the Private Joint Stock Company “Ukrhydroenergo” established an automated system for monitoring the condition of structures [Bysovetskyi et al., 2011]. Its integral part is the System for Monitoring the Spatial Displacements of Structures (SSMSDS). SSMSDS is a modern software and hardware complex that includes multisystem GNSS receivers, robotic electronic total stations, precision inclinometers, and telecommunications equipment [Tretyak, et al., 2016]. The work of SSMSDS is carried out for the purpose of mathematically processing and determining reliable parameters for the displacements and deformations of concrete and soil dams in real-time [Mohylnyi, et al., 2010].

In order to determine the velocity field of network points, supplementary data post-processing is performed in addition to defining the real-time deformation parameters. In this study, we focused on the assessment and detailed analysis of the NTAL’s impact on the GNSS network of SSMSDS of the Dnister HPP-1 to establish their kinematics and response to atmospheric loads.

The object of the study is the Dnister HPP-1; and the subject is its monitoring according to the GNSS network of the SSMSDS of the Dnister HPP-1 (Fig. 4, 5). The altitude GNSS time series of 14 sites were used for the study. Each site is equipped with a GNSS receiver Leica GMX902 GG and AR10 antenna. The reference sites of the Dnister HPP-1 are DSR1 and DSR2 (see Fig. 5, a). The sites are located on the right bank furthest from the concrete dam. They are additionally equipped with a robotic total station TM30 and a meteorological sensor DTM for regular monitoring by linear-angular measurements.

Fig. 4. Geodetic SSMSDS network of the Dnister HPP-1

Sites that are located directly on the dam are marked MP01-MP06 (see Fig. 5, c). The studies [Tretyak, et al., 2021a; 2021b] confirm the common kinematics for sites MP02-MP05, while the time series of site MP01 has different kinematics according to the results of GNSS analysis. ACP1-ACP2 are active control sites (see Fig. 5, b), and sites WP1-WP4 complement the geometry of the GNSS network.


a *b*

c

Fig. 5. General view of the GNSS sites DSR1-DSR2 (a), ACP1-ACP2 (b), and MP01-MP06 (c)

Geological position of the Dnister HPP-1

The Dnister HPP-1 is geologically located on the southwestern edge of the Eastern European Platform (EEP). We briefly present the geological structure of the Dnister HPP-1 according to the study [Geological map, 2008]. The EEP foundation within the area of the Dnister HPP-1 is composed of Proterozoic granites of the Berdychiv ultra-metamorphic complex (γmPR1bd). They are represented by biotite granites and migmatites. With stratigraphic and angular discrepancies, these intrusive formations are overlapped by Vend formations, which are united into several stratigraphic subdivisions (suites) such as Hrushkiv (V1gr), Mohyliv (V2mg), Yaryshiv (V2jr), Nagoryan (V2ng) Danyliv. Lithologically, these stratigraphic complexes are represented by sandstones, siltstones and argillites. Siltstones and argillites predominate. The occurrence of these complexes is close to horizontal with a slight drop to the southwest. Vend sediments in the study area are overlapped by Mesozoic, which are isolated in the lowland and Pelipchane suite of the Lower Cretaceous period (K1-2nz+pl). They are composed of quartz-glauconite sandstones, sands, and limestones. The age of the lowland suite on the basis of faunal remains is defined as Cenomanian. The Ozarinets suite (K2oz) is composed of limestones with layers of clays and silicon deposits. Neogene formations are composed of rocks of the Baden (N1pd) and Sarmatian (N1p+v) eras. Baden rocks consist of sands and sandstones and in the upper part they consists of clay sandstones. Sarmatian sediments are represented by different genetic types such as marine, lagoon and continental. Lithologically, they are represented by clays, sands and limestones. The youngest formations in the study region are Quaternary alluvial deposits.

The rocks described above are broken by a system of rupture faults of north-western and south-eastern orientation. These faults mainly belong to the discharges. Also, previous research has revealed a fairly dense network of lineaments [Bubniak, et. al., 2020].

The area is tectonically active and located within a transition zone between isosets of 6 and 7 in magnitude. It should also be noted that the filling of the reservoir causes an increase in the pressure level of the sides of the Dnister valley. This leads to the deflection of the bed and an increase in the slope, thus, causing crust earthquakes. [Sarnavskyi, & Ovsyannikov, 2005]. The modern study of the displacements of daily solutions according to the GNSS measurements and analysis of seismic data during the continuation of construction, exploitation of new units, and operation of the Dnister Hydropower Complex, also allows for the tracing of the increase of local seismic activity in the region [Savchyn, & Pronyshyn, 2020].

GNSS data processing strategy

The initial data are the RINEX-files of the GNSS network of SSMPZS of the Dnister HPP-1 (30-second sampling, daily 24 hour files). The automatic Bernese Processing Engine module and RNXtoSNX strategy in the Bernese GNSS Software version 5.2 are used to calculate the daily solutions of GNSS sites [Dach, et al., 2015]. IGS stations around the Dnister HPP-1, which are stably operated during the period, are selected as GNSS reference stations. . The result of the calculations is a network solution based on the strategy of double differences.

The tidal loadings models are taken into account during the processing, but no corrections are made for the influence of non-tidal ocean and atmospheric loadings according to the present models. Therefore, it is appropriate to compare these GNSS coordinate series with models of NTL. The impact of NTOL is low, because the GNSS stations in the study are located far from the shores of the ocean. Therefore, we neglect it in the study.

Vertical displacements from 23 to 30 December 2019

Having analyzed the effects of the geodynamic phenomenon in December 2019, it is seen that within the European continent there were vertical displacements, which reached a subsidence of up to 30 mm for 5–10 days [Brusak & Tretyak 2020]. The study [Brusak, & Tretyak, 2021] shows that for GNSS stations at a distance of less than 100 km from the Geoterrace network, namely CRNT (Chernivtsi), BLZT (Bilche-Zolote) and GORD (Gorodok) such subsidence reaches 16–19 mm (Fig. 1), which corresponds to the NTAL model within the limits of errors. In December 2019, a permanent GNSS station near the Dnister HPP-1 still was not installed. Having considered the model values of NTAL for the region, we can see that it does not coincide with the subsidence of the GNSS sites of SSMSDS of the Dnister HPP-1. Fig. 6 shows graphs of the altitude GNSS time series of sites DSR1, ACP1, ACP2, and MP03 with the corresponding value of the NTAL model for the region.

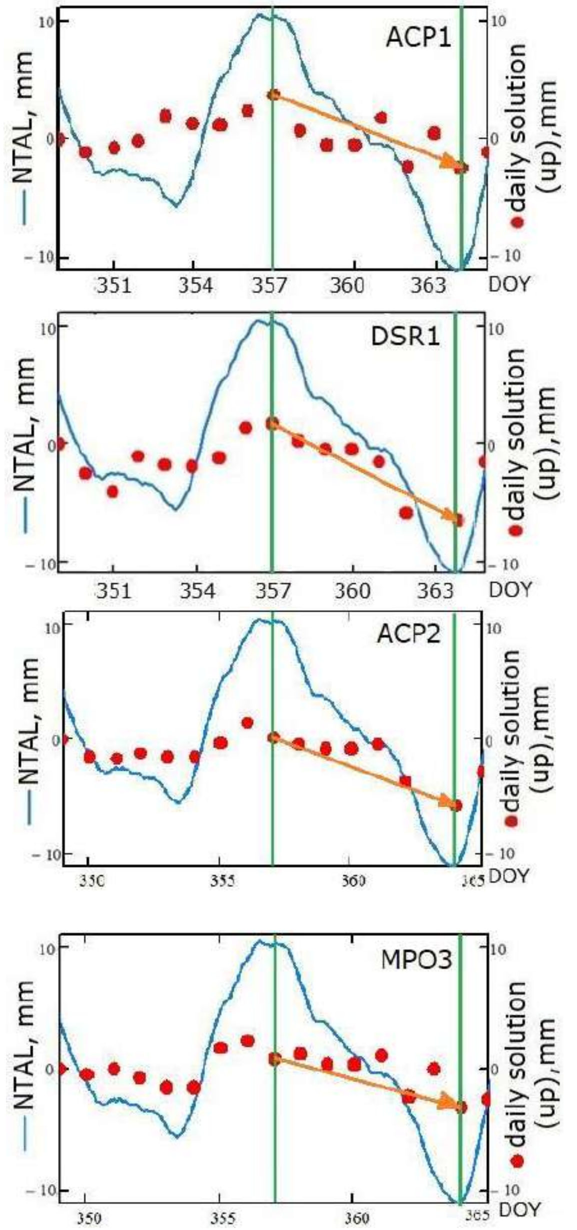
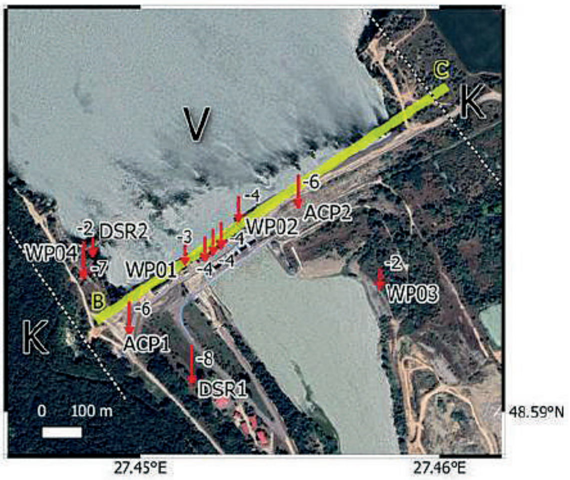


Fig. 6. Altitude time series of GNSS sites DSR1, ACP1, ACP2, MP03 of the Dnister HPP-1 and NTAL model from 15 to 31.12.2019 (349–365 DOY)

Accordingly, we built a map of the vertical displacements from 23 to 30 December 2019 (357–364 days of the year (DOY)) for all sites of the network. This period corresponds to the largest vertical deformations caused by NTAL. The map of the vertical displacements of the GNSS network of SSMSDS of the Dnister HPP-1 from 23 to 30 December 2019 is shown in Fig. 7.

Analyzing Fig. 7, we can see that the sites reacted differently to the elastic deformations caused by NTAL. In particular, the largest subsidence is 6–8 mm for sites DSR1, ACP1, WP04, and ACP2. However, the sites of the dam MP02-MP04 subside to 4 mm. The smallest subsidence is for sites WP01, WP03, DSR2 (2–3 mm). This can be partly explained by the geological structure of the territory and the engineering structure of the building. In particular, the sites with greater subsidence correspond to the structures that lie on the Vend rocks. They have a natural occurrence with cracks and, accordingly, are more susceptible to subsidence in contrast to the solid concrete dam, which stands on granite. We give a detailed analysis of the geological structure with the corresponding profiles further in the study.



DSR1 – GNSS site, ↓-8 – vertical displacements (subsidence), mm

🟩 - Engineering-geology profile (fig.16)

Age of sediments: V – Vend K – Cretaceous

Fig. 7. The map of the vertical displacements of the GNSS network sites from 23 to 30 December 2019

Vertical displacements from 9 to 18 February 2021

In February 2021 there were Vertical displacements similar to December 2019, but twice less in amplitude, which is also confirmed by the NTAL models [VMF, ESMGFZ]. As of 2021, a number of new stations of the Geoterrace network have been installed in the study region. In particular, the permanent GNSS station NDST (Novodnistrovsk), which is close (up to 2 km) to the Dnister HPP-1 was installed. We also analyze KLMN, GORD, VOVK stations of the Geoterrace network and TULC, EDIN, SORO stations, which are processed by System Solutions network (https://systemnet.com.ua). The location of the GNSS stations is shown in Fig. 8. The RINEX observation data (30-second sampling, daily

24 hour files) of these stations for the specified period were also processed in Bernese GNSS Software similarly.

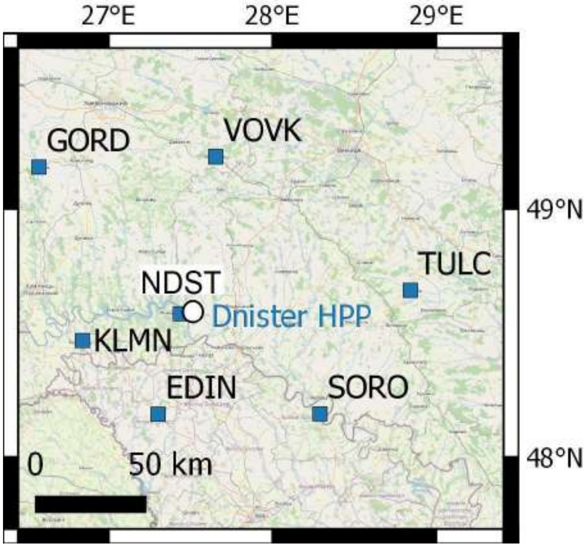


Fig. 8. Permanent GNSS stations around the Dnister HPP-1, in the time series of which vertical displacements correlated with NTAL

There was seen to be a noticeable correlation between the vertical displacements and the influence of NTAL in the period from 9 to 18 February 2021 (40–49 DOY) at these GNSS stations.

For example, Fig. 9 shows the altitude time series of the GNSS stations EDIN, KLMN, VOVK, and TULC, at which the offset coincides or is close to the model value of NTAL for the period.

Fig. 10 shows the altitude time series of GNSS stations NDST, sites DSR1, ACP2, WP02, and the model value of NTAL for the period.

The common kinematics of the reaction to elastic deformations caused by NTAL becomes noticeable, while comparing the vertical displacements between the permanent GNSS station NDST, KLMN, and VOVK. Instead, analyzing the vertical displacements of station NDST and sites DSR1, ACP2, WP02 it is obvious that the dynamics of the vertical displacements are different, that is the altitude of the station for the period from 9 to 18 February 2021 (40–49 days) is gradually decreasing, even though the NTAL model value shows a short-term decrease in the loading on the Earth's surface, while DSR1 site undergoes less subsidence. This trend is similar for most GNSS sites of the Dnister HPP-1.

Fig. 11 shows a map of the vertical displacements of the GNSS network of SSMSDS of the Dnister HPP-1 from 9 to 18 February 2021 (40–49 DOY).

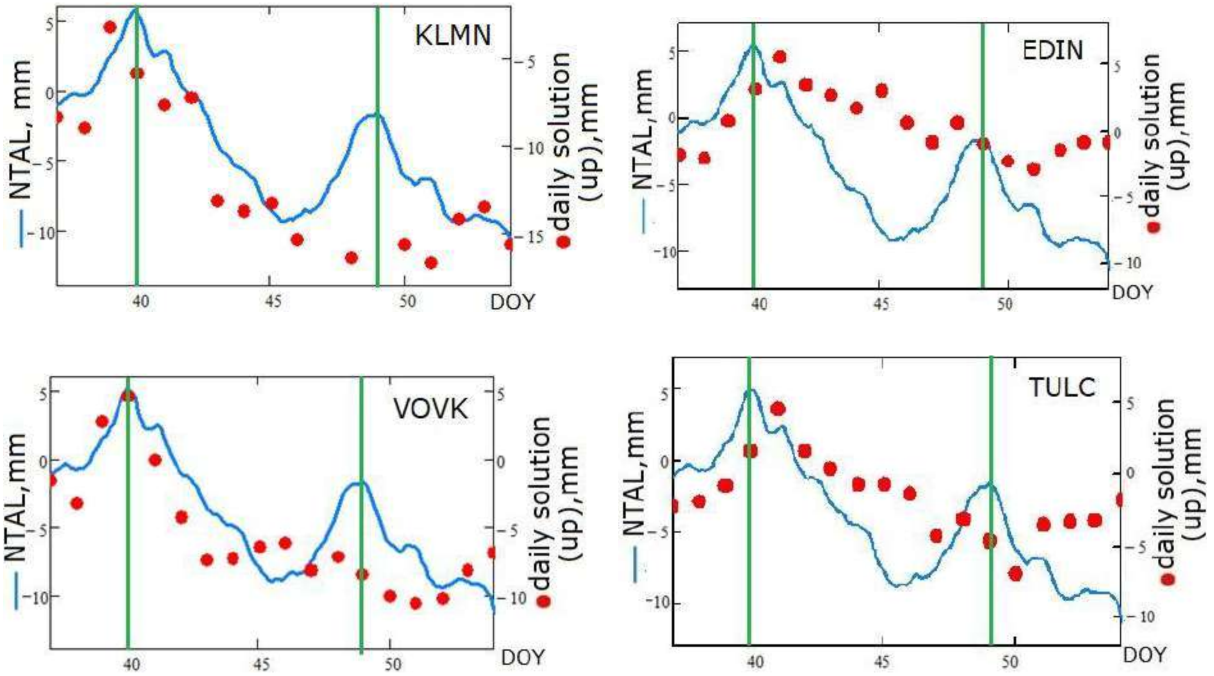


Fig. 9. Altitude time series of GNSS stations EDIN, KLMN, VOVK, TULC and NTAL model from 06 to 23.02.2021 (37–54 DOY)

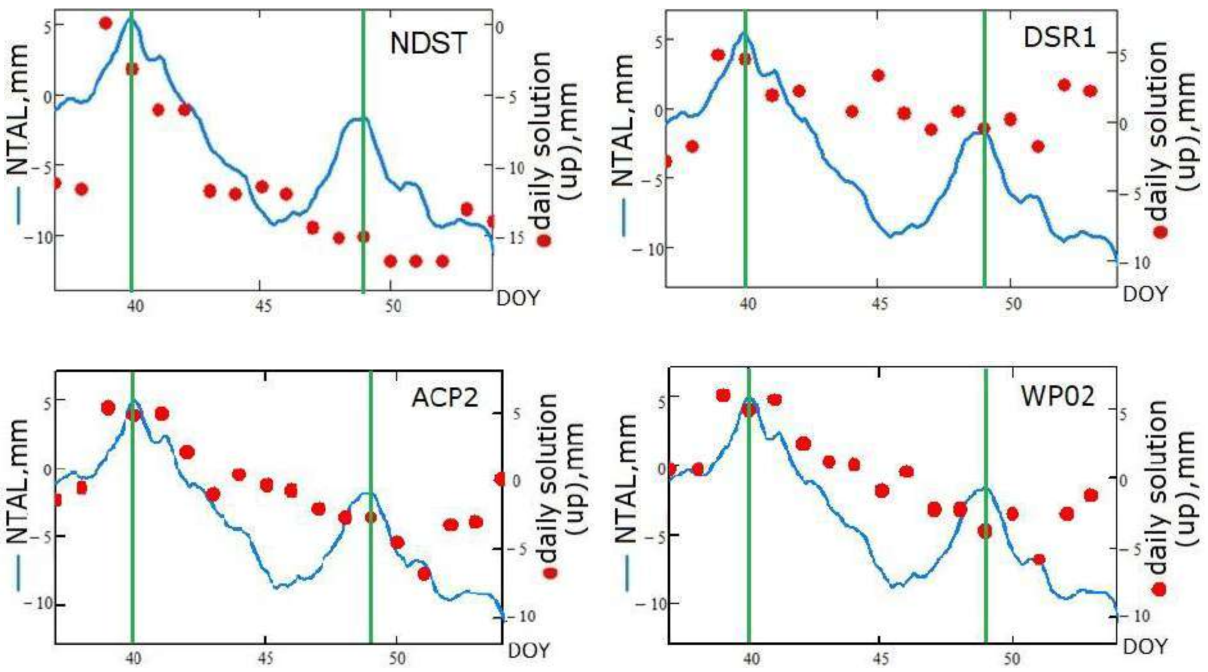
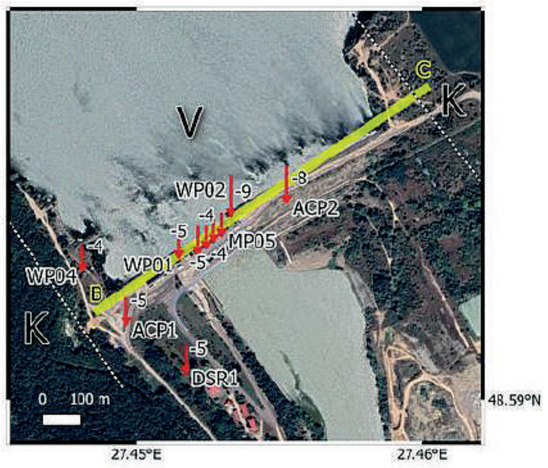


Fig. 10. Altitude time series of GNSS station NDST, GNSS sites DSR1, ACP2, WP02 of the Dnister HPP-1 and NTAL model from 06 to 23.02.2021 (37–54 DOY)



DSR1 – GNSS site, -8 – vertical displacements (subsidence), mm

▨ – Engineering-geology profile (fig.16)

Age of sediments: V – Vend K – Cretaceous

Fig. 11. A map of the vertical displacements of the GNSS network sites from 9 to 18 February 2021

In order to confirm the sites' subsidence in an alternative way, the vertical displacements of sites CP01-CP18 are considered. These points are equipped with reflectors, which are monitored from site DSR1 by a robotic total station Leica TM30 with an interval of 6 hours. The location of the points is shown in Fig. 12. Sites CP01-CP06 are located in the body of the dam from the bottom side and GNSS sites MP01-MP06 are located on the ridge of the dam.

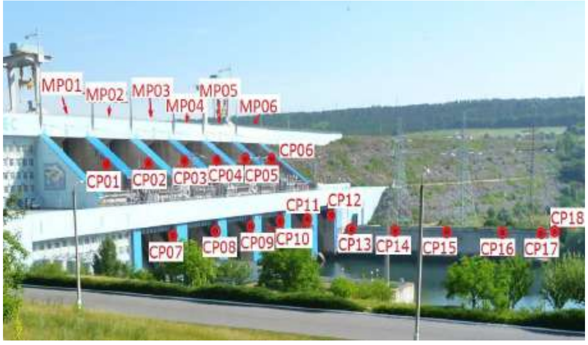


Fig. 12. Reflector sites CP01-CP18 determined by linear-angular methods and GNSS sites MP01-MP06 (view from point DSR1)

In general, the dynamics of the vertical displacements of all the sites CP01-CP18 are similar to the dynamics of subsidence of the GNSS sites MP02-MP05. For example, Fig. 13 shows sites CP04 and MP04, which are located on the same section of the dam.

The table shows the characteristics of the vertical displacements of the GNSS sites of the Dnister HPP-1. The estimation of the accuracy of the height shift trend is performed. The root mean square errors are 2–3 mm, which for most sites is half the amount of the vertical displacements.

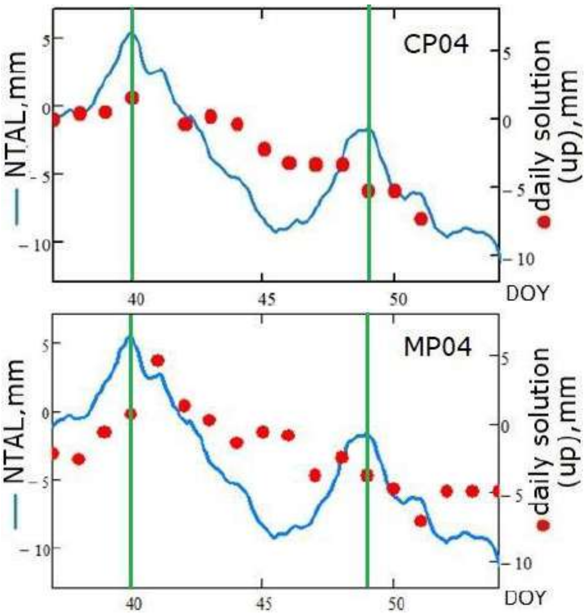


Fig. 13. Altitude time series of GNSS site MP04 and reflector CP04 and NTAL model from 06 to 23.02.2021 (37–54 DOY)

Table

Vertical displacements of the GNSS network of SSMSDS of the Dnister HPP-1

Name of GNNS site	Vertical displacements (from 23 to 30 December 2019), mm	Vertical displacements (from 9 to 18 February 2021), mm
ACP1	–6.1	–4.8
ACP2	–5.8	–7.5
DSR1	–8.1	–5
DSR2	–2.1	*
MP02	–3.8	–5.2
MP03	–4.1	–3.6
MP04	–4.1	–4.5
MP05	*	–3.6
WP01	–3.3	–4.6
WP02	–3.8	–8.7
WP03	–2.4	*
WP04	–7.1	–4.2

* Insufficient data for the period of observations due to interference during repairing and maintenance works, in particular, the movement of the nodal crane

Vertical displacements of sites on the left bank such as ACP2 and WP02 from 9 to 18 February 2021 (40–49 DOY) are –8 and –9 mm, which is two times more than the subsidence of the dam and the right bank sites.

These displacements will affect the results and accuracy of precision engineering and geodetic works, which are systematically carried out on the HPP, especially during the maximum effect of NTAL, as the distances between sites with different vertical displacements (3–5 mm) are in the range of 100–500 m. The values of the differences in the altitude of the neighboring geodetic sites are much higher than the possible errors of high-precision leveling of I and II classes or the required accuracy for a number of engineering works for the installation of special equipment. Therefore, special models ought to be applied to take into account NTAL deformations, which should be based on the geological structure of the civil engineering constructions. Vertical displacements of geodetic sites on the river banks are also twice as large as for the sites of the dam from 23 to 30 December 2019. This pattern is illustrated by the fact that most of the cracks and subsidence (see Fig. 3) of the dam are mainly located in the dam-bank contact zones.

We also analyzed changes in the water level in the upper reservoir and the dynamics of vertical displacements of GNSS sites on the dam. In our opinion, the increase in the water level in the upper reservoir should put more pressure on the dam, and the alltitude of the GNSS sites will decrease. Such changes in water level reach up to 5–7 meters in the annual cycle. However, for the period 2019-2021, there is no interrelations between the dynamics of vertical displacements of sites on the dam and changes in water levels.

Interrelation between displacement and geological structure of the territory

In order to analyze the difference in the dynamics of displacements between the permanent GNSS station NDST and sites of the Dnister HPP-1 network, we built a geological profile at points ABC according to the geological map of the region [Geological map, 2008]. Fig. 14 shows the position of the profile on the topographic map of the area.

The length of the ABC profile is 3000 m, part AB of which is 1800 m, and BC is 1200 m. The profile extends from South-West to North-East. The geological profile along the ABC line is shown in Fig. 15. Fig. 16 shows the engineering-geological profile along the BC line.

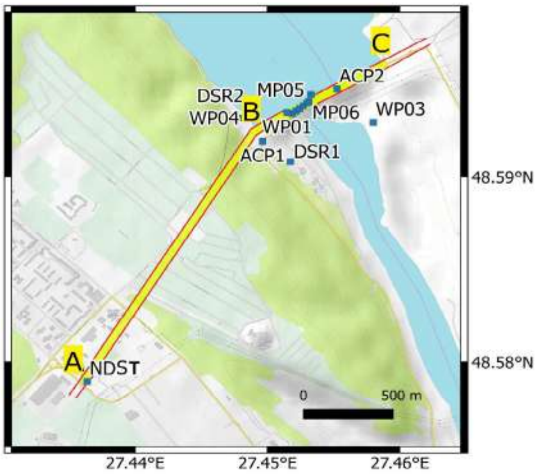
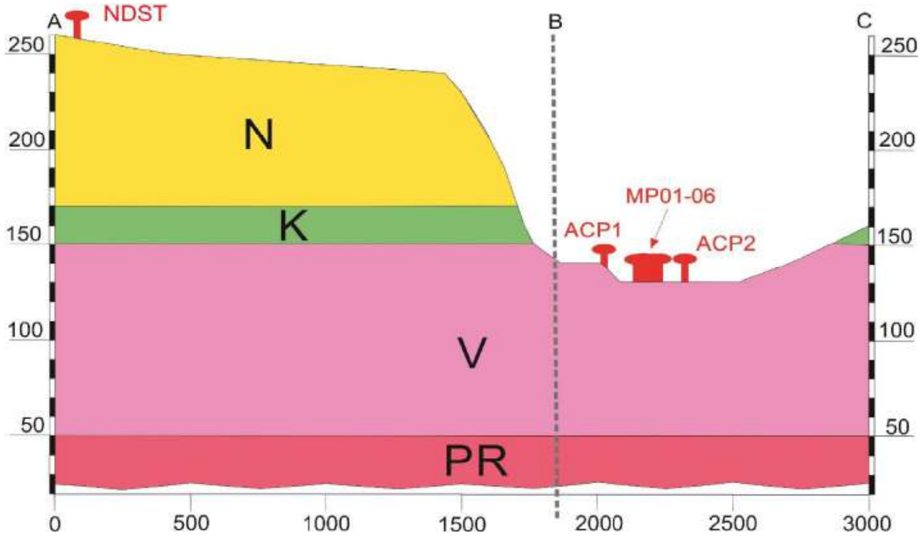


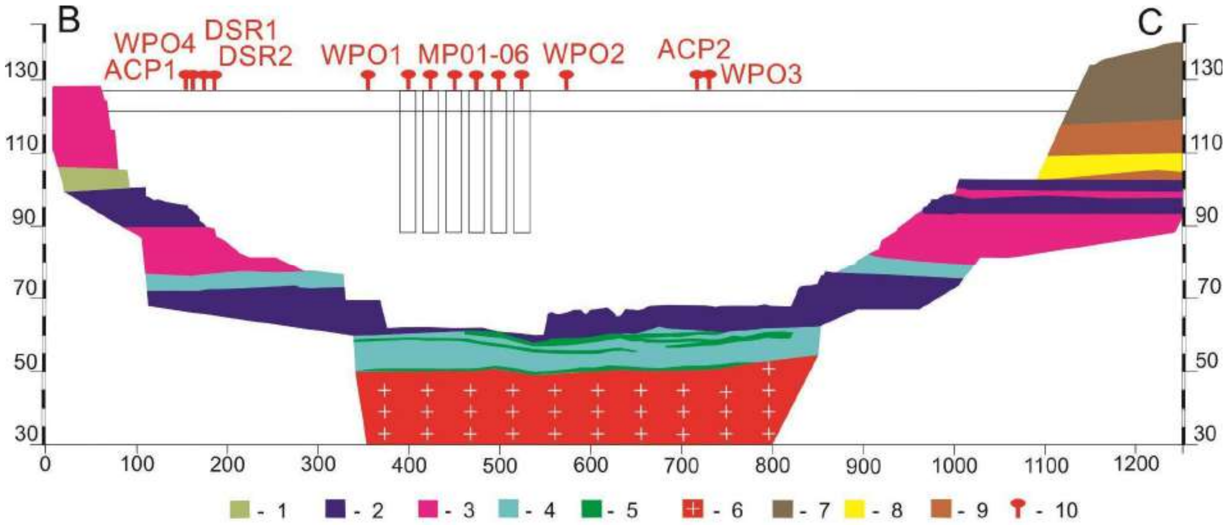
Fig. 14. Position of ABC profile on the topographic map



Age of sediments: N – Neogene K – Cretaceous
V – Vend PR- Proterozoic

⊤ – GNSS sites projected on the profile

Fig. 15. Geological profile along the ABC line and schematic representation of sediments by age, by [Geological map, 2008]



Legend: 1 – argillite; 2 – sandstone; 3 – siltstone; 4 – uneven layering of siltstone and sandstone with argelites; 5 – gravelite; 6 – granite; 7 – loam and clay; 8 – gravel and pebbles in the sand aggregate; 9 – gravel and pebbles in the sandy-loam aggregate;10 – GNSS sites projected on the profile

Fig. 16. Engineering-geology profile BC (parallel to the dam of the Dnister HPP-1) according to the materials [Ukrhydroproject PRJSC, 2017]

Fig. 15 shows that the GNSS station NDST is located on the deposits (top to bottom) of the Neogene, Cretaceous, Vend. They lie on the base of the EEP, which is represented by Proterozoic granites. Instead, the GNSS sites of the Dnister HPP-1 network are located on Vend deposits. The engineering-geological profile shows that the base of the dam (see Fig. 16, items MP01-06) is located on a layer of siltstones, argillites, and sandstones.

There is a difference in the values of vertical displacements recorded under the influence of NTAL for station NDST and for the GNSS network of SSMSDS for the Dnister HPP-1. It is necessary to answer the question: What is the reason for these differences? The GNSS station NDST subsided about 15 mm, and the GNSS sites of the Dnister HPP-1 subsided only for 4–8 mm from 9 to 18 February 2021. In our opinion, this fact can be explained as follows. Vend rocks are quite dense (siltstones, argillites, partly sandstones). They lie on granites. But Neogene and Cretaceous rocks are represented by limestones, sands, clays, which have significantly different physical properties relative to elastic deformations (density).

There are also differences in the vertical displacements between GNSS sites on concrete dams and GNSS stations on the banks of the Dnister. The smallest subsidence is typical for sites of the dam (MP01-06), and subsidence on the banks is mostly twice as large (DSR1, ACP1, ACP2, WP02). The connection between elastic deformations and geological structure can be traced again. GNSS sites on the dam are located on a conditionally monolithic and homogeneous concrete structure. In turn, it is located on granites, on which low-capacity (15 m) Vend deposits lie. GNSS stations on the river banks are located on the rocks of the Vend age with a thickness of 80 m. These rocks are layered (siltstones, argillites, sandstones). Also in many cases, they are broken by cracks. These factors will affect the dynamics of deformation and nonuniform subsidence. This in turn leads to the formation of cracks and deformations of the dam body in areas of contact with the banks.

Conclusions

1. The research established and analyzed vertical displacements of the GNSS network of SSMSDS of the Dnister HPP-1 caused by NTAL in December 2019 and February 2021. We establish that the sites of the Dnister HPP-1 network undergo smaller vertical displacements than permanent GNSS stations are situated within a radius of 100 km. It is shown that this corresponds to the difference in power and density of rocks under the corresponding sites, which undergo different elastic deformations under the influence of the same NTAL.
2. The study shows differentiation of vertical displacements of GNSS sites located in different places of the Dnister HPP-1 (dam and banks). The sites on the dam subside less than the model values of NTAL. This is due to the fact that the influence of non-tidal loadings of the mean Earth’s density is used for modeling. However, the GNSS sites of the Dnister HPP-1 are located on dense Vend rocks (siltstones, argillites, partly sandstones), which lie on granites. In addition, the GNSS results are confirmed by a monitoring system of linear-angular measurements. The heterogeneity of the dynamics of the sites obviously leads to the appearance of cracks in the structural elements of the HPP, especially in dam-bank contact zones.
3. We assume, as the geodetic basis reacts heterogeneously to NTAL, it leads to the change of excesses between the sites. It also influences the accuracy of the precision engineering and geodetic works which are carried out on objects in such periods. An important issue is the analysis of the impact of NTAL on high-precision altitude determination measurements. In our opinion, during the anomalous impact of NTAL, the altitude of even nearby sites may change if the geological structure beneath is different. But the influence of other factors should not be exluded. The study shows that sites within an area of about 100–500 meters subside variously. Such differences in the vertical displacements of the sites are up to 3–5 mm, which is much higher than the accuracy for high-precision leveling at such distances.
4. Based on the research, we assert that special corrections for NTAL models could be used for civil engineering constructions that have a different geological structure. Further research is also needed on the territory of other HPPs in Ukraine.

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ВПЛИВ НЕПРИПЛИВНОГО АТМОСФЕРНОГО НАВАНТАЖЕННЯ НА ВЕЛИКІ ІНЖЕНЕРНІ СПОРУДИ

Проаналізовано висотний зсув ГНСС-пунктів великого інженерного об’єкта, спричинений неприпливним атмосферним навантаженням (NTAL). Об’єкти дослідження – Дністровська ГЕС-1 та її ГНСС-мережа моніторингу. Вихідними даними є RINEX-файли 14 ГНСС станцій Дністровської ГЕС-1 і вісім перманентних ГНСС-станцій у радіусі 100 км, модель NTAL, завантажена із репозиторію Німецького дослідницького центру геонаук GFZ за 2019–2021 рр., та матеріали щодо геологічної будови об’єкта. Методика передбачає порівняння та аналіз висотної складової часових рядів ГНСС з модельними значеннями NTAL й інтерпретацію їх геодинамічних зміщень, враховуючи аналіз їх геологічного розташування. У результаті встановлено, що пункти мережі Дністровської ГЕС-1 зазнають менших змін висоти, ніж перманентні ГНСС-станції у радіусі 100 км. Це відповідає різниці потужностей та щільності гірських порід під відповідними пунктами, тому вони зазнають різних пружних деформацій під впливом однакового навантаження NTAL. Окрім цього, виявлено різну динаміку зміщень пунктів на греблі та на берегах річки, що призводить до тріщин та деформацій у зоні контакту гребля – берег. Під час аномального впливу NTAL висоти навіть близько розташованих пунктів можуть змінитися, якщо геологічна будова під ними різна. У роботі показано, що для великих інженерних об’єктів варто застосовувати спеціальні моделі та поправки у високоточні інженерно-геодезичні виміри для урахування NTAL.

Ключові слова: часові ГНСС-ряди; вертикальні деформації; неприпливне атмосферне навантаження; Дністровська ГЕС-1.

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